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Estimates of Improved Productivity and Health from Better Indoor Environments

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Abstract The existing literature contains strong evidence that characteristics of buildings and indoor environments significantly influence rates of respiratory disease, allergy and asthma symptoms, sick building symptoms, and worker performance. Theoretical considerations, and limited empirical data, suggest that existing technologies and procedures can improve indoor environments in a manner that significantly increases health and productivity. At present, we can develop only crude estimates of the magnitude of productivity gains that may be obtained by providing better indoor environments; however, the projected gains are very large. For the U.S., we estimate potential annual savings and productivity gains of $6 billion to $19 billion from reduced respiratory disease; $1 billion to $4 billion from reduced allergies and asthma, $10 billion to $20 billion from reduced sick building syndrome symptoms, and $12 billion to $125 billion from direct improvements in worker performance that are unrelated to health. Sample calculations indicate that the potential financial benefits of improving indoor environments exceed costs by a factor of 18 to 47. The policy implications of the findings are discussed and include a recommendation for additional research.

Key words Allergies; Asthma; Benefits; Costs; Health; Indoor air quality; Productivity; Respiratory disease; Sick building syndrome.

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Introduction

The economic incentives for investments in buildings and in building operation that improve worker productivity are unquestionable. Worker salaries exceed building energy and maintenance costs by a factor of approximately 100 and exceed annual construction or rental costs by almost as much (Woods, 1989). Thus, even a 1% increase in productivity should be sufficient to justify an expenditure equivalent to a doubling of energy or maintenance costs or large increases in construction costs or rents. Productivity increases of 1% correspond to reduced sick leave of two days per year, reduced breaks from work or increased time at work of 5 minutes per day, or a 1% increase in the effectiveness of physical and mental work.

Current evidence suggests at least four major links between health and productivity and the quality of the indoor environment, where we spend 90% of our lives. These links involve infectious disease, allergies and asthma, acute sick-building health symptoms, and direct impacts of indoor environments on worker performance. Most prior literature on the relationship between indoor environments and productivity has focused on potential direct improvements in workers' cognitive or physical performance. Possible productivity gains and savings in health care costs from reductions in adverse health effects have received much less attention, despite the very high costs of adverse health effects. For example, based on the analyses presented subsequently in this paper, the annual cost of respiratory infections in the U.S. is approximately $64 billion and the annual cost of allergies and asthma is about $13 billion. This paper will consider both direct productivity gains and gains associated with reducing adverse health effects.

The primary purpose of this paper is to synthesize available information pertaining to the linkage between the indoor environment and health and productivity and, based on this synthesis, to develop credible estimates of the total productivity gains that might result from better indoor environments. We recognize that existing data and knowledge are inadequate for precise estimates of potential productivity gains from better indoor environments; however, even imprecise unbiased estimates should be of considerable value to policy-makers and researchers.

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Approach

Computer-based literature searches and personal contacts were used to identify relevant papers and the evidence supporting or refuting the hypothesized linkages was synthesized. Evidence from small studies without sufficient statistical power, or from studies judged to be of poor quality, was disregarded. The potential economic significance of adverse health effects linked to the indoor environment was estimated partly from the results of previous analyses in the literature. The economic results of previous analyses were updated to 1993 to account for general inflation, health care inflation, and increases in population (U.S. Department of Commerce, 1995). Additionally, some judgments and calculations were used to estimate the economic significance. The next and most uncertain step in the analysis was to estimate the magnitude of the decrease in adverse health effects and the magnitude of direct improvements in productivity that might result from improved indoor environments. These estimates are based on findings reported in the literature, our understanding of the linkages, and our understanding of the degree to which relevant indoor environmental conditions could be improved in practice. The costs of improving indoor environments are compared with the value of potential productivity gains and savings in health care costs. In a final section, policy implications are discussed.

This paper is based on the results of many studies that have used statistical models to analyze research data and that report findings in statistical terms. For example, the odds ratio is a statistical parameter commonly used to indicate the statistical association between an outcome (e.g., a health effect) and a risk factor suspected to increase the proportion of the population that experiences the outcome. To make this paper understandable to a relatively broad audience, we have minimized the use of unfamiliar statistical terminology. We have used the published odds ratios plus data on the fraction of the population that experienced the outcomes to *estimate* the percentage increase or decrease in the outcomes when the suspected risk factors are present or absent[1]. Additionally, we have excluded measures of statistical significance from the text. 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 statistically inclined, measures of statistical significance are included in footnotes.

Results and Discussion

In this section, the magnitude of potential productivity gains are estimated for the four previously identified links between the indoor environment and productivity. For each link, the estimate is preceded by a synthesis of the literature. In a final sub-section, the costs of improving indoor environments are compared to the potential productivity gains.

Infectious Disease Transmission

Linkage. The degree to which building and indoor environmental characteristics are likely to influence infectious disease transmission depends on the mechanisms of transmission. If disease transmission occurs due to long-range transport of infectious aerosols[2] through the air over distances of many meters between the source and the recipient, then measures that reduce this long-range transport would be expected to reduce disease transmission. Examples of such measures are better air filtration, increased ventilation (i.e., increased supply of outside air), and reduced air recirculation. If disease transmission is a consequence of short-range transport of infectious aerosols over distances of only a few meters (because the aerosols settle on surfaces or quickly become non-infectious), then measures that increase the separation between individuals may help to reduce disease transmission, e.g., reductions in occupant density and increased use of private work spaces may be helpful. However, improved filters in the recirculated airstreams within ventilation systems and decreased air recirculation may not significantly reduce short-range airborne disease transmission. If disease transmission is primarily due to direct person-to-person contact or to indirect contact via contaminated objects, indoor environmental and building characteristics, except possibly temperature and humidity that may affect the survival of infectious organisms on surfaces, may have a very small influence on transmission.

Numerous laboratory experiments and field-based epidemiological studies have attempted to determine the significance of different potential routes of transmission of common infectious diseases. Most laboratory research has focused on selected viral infections, such as rhinovirus infections that are responsible for an estimated 30% to 50% of acute respiratory illness (Jennings and Dick, 1987). For rhinovirus infections, laboratory experiments demonstrate that transmission is possible as a consequence of both direct and indirect contact (e.g., Gwaltney et al., 1978; Gwaltney and

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[1] Because of the defination of odds, the ratio of symptom prevalence is smaller than odds ratio by an amount that depends on the proportion of the population that experiences symptoms.

[2] Examples of infectious aerosols are small aerosols produced by coughing and sneezing that contain a high virus concentration.

Hendley, 1982) and also from infectious aerosols (e.g., Dick et al., 1987; Jennings and Dick, 1987; Couch et al., 1966); however, there is contradictory evidence regarding the relative significance of the transmission routes. The airborne route of transport is also known or thought to be significant for a number of other respiratory infections including adenovirus infections, coxsackievirus infections, influenza, measles, and tuberculosis (Couch et al., 1966; Couch, 1981; Knight, 1980; Sattar and Ijaz, 1987; Nardell et al., 1991). In general, however, the relative importance of transmission mechanisms for such infectious diseases remain controversial.

Several field studies provide evidence that building characteristics significantly influence disease incidence. Most important is a multi-year study, involving a large number of subjects, performed by the U.S. Army (Brundage et al., 1988), which determined that rates of acute respiratory disease with fever (disease confirmed clinically) were 50% higher among recruits housed in newer barracks with closed windows, low rates of outside air supply, and extensive air recirculation, compared to recruits in older barracks with frequently open windows, more outside air, and less recirculation[3]. This study provides strong evidence that some building-related factor(s) can have a significant influence on rates of disease transmission. Because of the potential for confounding by other factors that may have differed between the types of barracks, this study does not prove that low ventilation rates or mechanical air recirculation increase disease transmission. However, there are theoretical reasons to suspect that low ventilation and recirculation are risk factors.

Several additional studies provide relevant information on this topic. In a study by Jaakkola and Heinonen, (1993), office workers with one or more roommates were about 20% more likely to have more than two cases of the common cold during the previous year than workers with no room-mates[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 (Warshauer et al., 1989). In an older study of New York schools (N.Y. State Commission on Ventilation, 1923), there were 170% as many respiratory illnesses[5] and 118% as many absences due to illness[6] in fan-ventilated classrooms compared to 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 Saudia Arabia during the Gulf War (Richards et al., 1993). The study results suggest that the type of housing (air-conditioned buildings, non-air-conditioned buildings, open warehouses, and tents) influenced the incidence of symptoms associated with respiratory disease. Housing in air-conditioned buildings (ever versus never housed in an air-conditioned building while in Saudia Arabia) was associated with approximately a 37% increase in the incidence of sore throat[7] and a 19% increase in the incidence of cough[8]. For housing in non-air-conditioned buildings (ever versus never), which had a lower occupant density and presumably a higher ventilation rate than air-conditioned buildings, the corresponding increases in the incidences of sore throat and cough were smaller, approximately 24% and 12%, respectively[9]. For housing in tents and warehouses (ever versus never), which presumably had much higher ventilation rates than buildings, there were no statistically significant increases in sore throat or cough.

Jails are not representative of other buildings because of severe crowding and a population that is not representative of the general public. However, disease transmission in such facilities remains an important 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. (1994). There were significantly fewer cases of disease among inmates with 7.4 m^2 (80 ft^2) or more of space[10]. The disease attack rate was about 95% higher in the types of cell with the highest carbon dioxide concentrations and the lowest volume of outside air supply[11].

Cost of Infectious Respiratory Disease. In the U.S., upper respiratory disease causes about 160 million days lost from work and 300 million workdays of restricted activity (Garibaldi, 1985; Dixon, 1985, adjusted for population gain). Assuming a 100% and 25% decrease in productivity on lost-work and restricted-activity days, respectively, and a $36K average annual

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

[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.

[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] For sore throat, adjusted odds ratio=1.36 (95% CI 1.13–1.64). For cough, adjusted odds ratio=1.21 (95% CI 1.01–1.46).

[10] p=0.03

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

compensation (U.S. Department of Commerce, 1995), the annual value of lost work is approximately $35 billion. The annual health care costs for upper and lower respiratory tract infections is about $29 billion (Dixon, 1985, adjusted for population gain and health care inflation); thus the total annual cost of respiratory infections is approximately $64 billion.

Potential Savings from Changes in Building Factors[12]. An ability to substantially change the building-related factors that influence disease transmission is critical to the realization of 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, and reduced space-sharing have at least the theoretical potential to reduce people's inhalation exposures of infectious aerosols by more than a factor of two. Also, occupant density can be decreased if future studies confirm that decreased density reduces the incidence of respiratory disease. (Attempts to reduce the costs of workspace by increasing occupant density may be counterproductive.) Changes in building codes could help to stimulate widespread adoption of technologies that are proven to be effective.

Based on the previous analyses, each one percent decrease in respiratory disease in the U.S. would result in approximately $0.64 billion annual savings. The studies cited above suggest that building and ventilation characteristics can influence the rates of respiratory disease by a factor of approximately 1.2 to 2, with the strongest study (Brundage, et al. 1988) yielding a factor of 1.5.

While the evidence that the incidence of common respiratory infections could be reduced by improving indoor environments is relatively strong, the complexity of the disease transmission process makes it difficult to estimate the magnitude of the reduction that could practically be achieved throughout the U.S. population. For example, reducing disease transmission in one setting, such as an office or school, should lead to reduced disease transmission in other settings, e.g., at home; however, we do not attempt to quantify or account for this effect.

The amount of time spent in a building should influence the probability of disease transmission within the building. The period of occupancy in the studies cited above ranged from approximately 40 hr per week (24% time) in offices and schools to 100% time in jails. If efforts to reduce disease transmission were implemented primarily in commercial and institutional buildings[13] that people occupy approximately 40 hours per week, smaller reductions in respiratory disease would be expected in the general population than are indicated by the research literature. To adjust the reported increases in respiratory disease for time spent in buildings, we estimated the percentage of time that occupants spend in each type of building (100% of time in jails, 66% in barracks and housing, and 24% in offices and schools) and assumed that the magnitude of the influence of a building factor on the incidence of respiratory disease varies linearly with time spent in the building. After this adjustment, the studies cited above suggest that building and ventilation characteristics influence the rates of respiratory disease by a factor of approximately 1.2 to 1.7, with the strongest study (Brundage et al., 1988) yielding a factor of 1.2. The range is much smaller, approximately 1.1 to 1.3, if the factor of 1.7 from the NY State Study of Schools is disregarded. We will adopt this narrower range, i.e., 10% to 30%, for the potential reduction in respiratory disease. The corresponding range in the annual economic benefit is $6 billion to $19 billion.

Allergies and Asthma

Linkage. Approximately 20% of the U.S. population have environmental allergies and approximately 10% have asthma (Committee on Health Effects of Indoor Allergens, 1993). The prevalence of asthma, asthma-related hospitalization, and asthma-related mortality is increasing substantially (Committee on Health Effects of Indoor Allergens, 1993). The symptoms of allergies and of the portion of asthma caused by airborne allergens can be triggered by a number of allergens in indoor air, including fragments of house dust mites, allergens from pets, fungi, and insects, and pollens that enter buildings from outdoors (Committee on Health Effects of Indoor Allergens, 1993). Several studies indicate that occupants of homes or schools with evidence of dampness (or presence of molds) have approximately a 30% to 50% higher prevalence of asthma or lower respiratory symptoms (e.g., Brunekreef, 1992; Dales et al., 1991; Spengler et al., 1993; Smedje et al., 1996). Moisture and related microbiological problems were

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[12] In theory, reduction of disease transmission in ships and on airplanes should be possible through implementation of similar measures, although costs of measures may be considerably higher on airplanes. In commercial airplanes that already have high-efficiency filters in the recirculated air (these filters should efficiently remove infectious aerosols), the substitution of increased outside air for recirculated air is unlikely to reduce disease transmission.

[13] 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.

also linked to respiratory symptoms in office workers more than a decade ago (Division of Respiratory Disease Studies, 1984). Asthma symptoms may be triggered by irritating chemicals in indoor air, including environmental tobacco smoke (Evans et al., 1987) and by infectious respiratory diseases. Thus, the evidence of a linkage between the quality of the indoor environment and the incidence of allergic and asthma symptoms is 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. The estimated cost of asthma-related illness in the U.S. during 1990 was $6.2 billion (Weiss et al., 1992) which includes $3.6 billion in direct medical expenditures and $2.6 billion in indirect costs, e.g., loss of work. Excluding increases in asthma prevalence but adjusting for population gain, for general inflation of indirect costs, and for health care inflation of medical costs, yields an estimated total cost in 1993 of $7.9 billion. McMenamin (1995) estimated the direct (health care) and indirect costs of allergic rhinitis plus the cost of the portion of four airway disorders (asthma, chronic sinusitis, otitis media with effusion, and nasal polyps) allocable to allergy. Excluding the portion of these costs associated with asthma and adjusting to 1993 yields a cost of $4.9 billion. Combining this figure with the asthma cost yields an annual total of $12.8 billion.

Potential Savings from Changes in Building Factors. Many of the exposures that elicit symptoms of allergies and asthma are allergens in the form of airborne particles. Technologies for reducing indoor concentrations of airborne particles generated indoors are readily available (e.g., better air filtration and increased ventilation). Better filtration of the outside air entering mechanically ventilated buildings can also greatly diminish the entry of outdoor allergens into buildings. Some allergens, e.g., from dust mites, are large particles that have high gravitational settling velocities and are less effectively controlled by air filtration; however, exposures to allergens may also be decreased by reducing indoor allergen sources through better cleaning practices, elimination of surfaces most likely to be reservoirs of microbiological material (e.g., carpets), and better control of indoor moisture (e.g., water leaks). Chemical exposures (e.g. tobacco smoke) that elicit asthma symptoms can be decreased by limiting indoor sources (e.g. smoking) or through better ventilation. Reduced respiratory infections, as discussed above, will also reduce asthma symptoms. Thus, there is a strong theoretical basis for the hypothesis that the symptoms of allergies and asthma can be substantially decreased by improving indoor environments.

Various measures have been found effective in reducing indoor concentrations of allergens (Harving et al., 1991; Ingram and Heymann, 1993; Pollart et al., 1987). Unfortunately, we have identified relatively few published studies of the effect of changes in building conditions on the symptoms of allergies and asthma. Measures to reduce exposures to dust mite allergen, such as improved cleaning and encasement of mattresses in non-permeable materials, have reduced symptoms in some but not all studies (Ingram and Heymann, 1993; Pollart et al., 1987; Harving et al., 1991; Antonicelli et al., 1991). Nelson et al. (1988) reviewed research on the use of residential air cleaning devices to treat allergic respiratory disease. All nine of the studies reviewed indicated that air filtration devices and air-conditioning reduced seasonal allergic symptoms, but the subjects of most of the studies were not blinded. For perennial allergic disease, six of eight studies suggest improvement with air filtration. Despite these generally positive results, Nelson et al. (1988) indicated that current data were inadequate to support recommendations for the use of air cleaners. There is evidence (e.g., Arshad et al., 1992) that reduced exposures to allergens in the first months of life can reduce the incidence of allergy at an age of about one year, but these studies have generally included reduced exposures to food allergies.

With the limited data available, it is tempting to conclude that no estimate of potential savings is possible without additional research. However, the theoretical basis for the hypothesis that symptoms of allergies and asthma can be substantially decreased by improving indoor environments is strong and the limited experimental data available tend to support this hypothesis. The most credible estimate of savings is clearly some number greater than zero. Through implementation of suitable control measures, reductions in indoor allergen exposures by more than 50% should be readily attainable. Control measures can be targeted at the homes or offices of susceptible individuals, reducing the societal cost. We will estimate that a 10% to 30% reduction in symptoms and associated costs is feasible and practical. With this estimate, the annual savings would be ~$1 billion to $4 billion.

Sick Building Syndrome Symptoms

Linkage. Characteristics of buildings and indoor environments have been linked to the prevalence of acute health symptoms among office workers, often called sick building syndrome (SBS) symptoms. These symptoms include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing. The existing literature suggests that these symptoms are experienced by a substantial proportion of all office workers (e.g. 5% to 40% of workers depending on the symptom), not just by workers in the well publicized sick buildings (e.g., Fisk et al., 1993; Nelson et al,. 1995). Although psychosocial factors such as the level of job stress are known to influence SBS symptoms, several characteristics of buildings and indoor environments are also known or suspected to influence these symptoms, including: the type of building ventilation system, type or existence of humidification equipment, the rate of outside air ventilation, the chemical and microbiological pollution in the indoor air and on indoor surfaces, and indoor temperature and humidity (Mendell, 1993; Sundell, 1994). In 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 (Mendell, 1993). Therefore, there is little doubt that SBS symptoms are linked to features of buildings and indoor environments.

Cost of SBS Symptoms. SBS symptoms are a distraction from work and can lead to absence from work (Preller et al., 1990) and visits to doctors. When problems are severe and investigations of the building are 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 costly litigation. Some employers have moved their staff to a different building, incurring large moving costs. Clearly, SBS imposes a significant societal cost, but quantification of this cost is very difficult. However, it is possible to make some estimates of potential productivity losses from SBS.

Our 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 EPA's 1989 report to Congress (U.S. Environmental Protection Agency, 1989), the average self-reported productivity loss due to poor indoor air quality was 3%. Woods et al. (1987) completed a telephone survey of 600 U.S. office workers; 20% of the workers 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. (1990), workers that 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 was about 4%[14]. 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., (1993). Workers that reported any SBS symptoms, took 7% longer to respond in a computerized neurobehavioral test[15] and had a 30% higher error rate in a second computerized neurobehavioral test[16].

Given the lack of more definitive data, we must base our estimate of the productivity loss from SBS symptoms on the only information available. The measured data of Nunes et al., (1993) provide substantial evidence that SBS symptoms actually decrease performance; however, it is very difficult to relate the increases in response times and error rates in the specific computerized tests to the magnitude of an overall productivity decrement from SBS symptoms. The self-reports discussed above suggest a productivity decrease of approximately 4% due 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, workers who are unhappy with the indoor environment 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 equal to 2%, recognizing that this estimate is highly uncertain. Since SBS is primarily associated with office buildings and the annual gross national product of office workers is approximately $2.5

[14] 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% of workers 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%.

[15] $p<0.001$

[16] $p=0.07$

trillion (Traynor et al. 1993), the estimated annual cost of SBS is $50 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, the numerous findings (Mendell, 1993; Sundell, 1994) of associations between SBS symptoms and building and environmental factors, together with our knowledge of methods to change building and environmental conditions, is evidence that SBS symptoms can be reduced. Many SBS studies[17] 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[18]. In a few blinded experimental studies (reviewed in Mendell, 1993; Sundell, 1994), specific indoor environmental conditions have been changed to investigate their influence on symptoms. Some of these studies have also demonstrated that increased ventilation rate, decreased temperature, better surface cleaning, and use of ionizers can diminish SBS symptoms, while no significant benefit was evident in other studies. In summary, the existing evidence suggests that substantial reductions in SBS symptoms, of the order of 20% to 50%, should be possible through improvement in individual indoor environmental conditions. Multiple indoor environmental factors 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 of the order of $10 billion to $20 billion.

Direct Impacts of Indoor Environments on Human Performance

Background. The previous discussion has focused on the potential to improve worker productivity by improving the indoor environment in a manner that reduces adverse health effects. However, indoor environmental conditions may 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 two characteristics of the indoor environment: thermal conditions and lighting. Existing standards define the boundaries of recommended thermal and lighting conditions in buildings. These standards exist, in part, because conditions far from optimal have an obvious adverse influence on worker performance.

Research on this topic is difficult because of the complexity of defining and measuring human performance in real-world environments and because many factors influence performance. Additionally, worker motivation affects the relationship between performance and environmental conditions (e.g., highly motivated workers are less likely to have reduced performance in unfavorable environments). Indicators of human performance have included measures of actual work performance, results of special tests of component skills (e.g., reading comprehension) deemed relevant to work, and subjective self-estimates of performance changes.

A large number of papers, including many older papers, provide information pertinent to an assessment of the direct influence of environmental factors on human performance. A review of all identified papers was not possible; therefore, the following discussion is based on a review of selected papers, emphasizing more recent research with performance measures that are more closely related to actual work performance, and with environmental conditions more typical of those found in non-industrial buildings.

Linkage between Thermal Environment and Performance. Several papers contain reviews of the literature on the linkage between the thermal environment (primarily air temperature) and selected indices of work performance. Based on these literature reviews and on original reports of research, there is substantial evidence of an association between work performance and air temperature, for the range of temperatures commonly experienced in buildings. However, not all studies have found such associations. Emphasizing the relationship of temperature to mental performance and light manual work, a brief summary of positive findings follows:

1. Laboratory studies by the New York State Commission on Ventilation, (1923) found that performance of manual work was significantly influenced by air temperature but that performance of mental work was not affected by temperature. However, a re-analysis of a portion of the Commission's data (Wyon, 1974) found that subjects performed 18% to

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[17] 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.

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

49% more typewriting work[19] at 20°C compared to 24°C.

2. Meese et al. (1982) investigated factory-workers' performance on fourteen tasks that simulate factory work. Worker's performance on eight of the tasks, differed significantly[20] (generally lower performance) at an 18°C air temperature compared to 24°C.
3. Automobile drivers of a special test vehicle missed 50% more of the signals introduced via instruments and rear view mirrors at 27°C compared to 21°C and response time was 22% slower at 27°C (Wyon, 1993).
4. Pepler and Warner (1968) investigated the learning performance of university students at six temperatures ranging from 16.7°C to 33.3°C. Students studied a programmed text and were required to respond to questions on critical points. Air temperature significantly influenced two out of four measures of learning performance: errors per unit time and times required to complete assignments. Error rates were about 20% smaller at 26.7°C than at 20°C or 33.3°C[21]. The time to complete assignments was 5% to 10% higher at 26.7°C compared to the temperature extremes.
5. Existing literature suggests a complex relationship between temperature and mental work performance that varies with the type of work. In a study of reading speed and comprehension, performance was superior at 20°C and 30°C compared to 27°C (Wyon, 1976). Similarly, based on simulated high-school classroom conditions, the following findings were reported (Wyon et al., 1979): reading speed was 20% better at 23°C and 29°C compared to 26°C; multiplication speed in males was ~20% higher[22] at temperatures above and below 27–28°C; word memory in males was best (~20% higher) at an intermediate temperature of around 26°C[23]; and word memory performance for females increased with temperature between 24°C and 26°C, but did not fall as temperatures increased further to 29°C.

The previous discussion suggests that temperature can influence mental performance in some settings. For some types of mental work (e.g., 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. Temperatures just below the point that causes sweating may cause workers to relax and work less to prevent sweating. Given that the optimum temperature for a task depends on the nature of the task, will vary among individuals, and will vary over time (e.g., since tasks change), some papers have advocated the provision of individual control of temperature as a practical method to increase productivity (Kroner and Stark-Martin, 1992; Wyon, 1993, 1996). A study in an insurance office, using the number of files processed per week as a measure of productivity, suggested that the provision of individual temperature control increased productivity by approximately 2%. However, studies of individual control may be criticized because these studies cannot be performed blind, i.e., occupants know if they have individual control. With assumptions about workers' use of individual control, Wyon (1996) has estimated that providing workers with ±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. Larger productivity increases would be predicted if the reference building did not maintain the average neutral temperature.

Linkage between Lighting and Human Performance. As discussed by NEMA (1989), lighting has at least 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, while limited, is consistent with this expectation. For example, Romm (1994) reports a 6% increase in the performance of postal workers during mail sorting after a lighting retrofit that improved lighting quality and also saved energy. A review of the relationship between lighting and human performance (NEMA, 1989) provides additional examples, such as more rapid production of drawings by a drafting group after bright reflections were reduced.

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[19] $p<0.05$

[20] $p<0.002$ to $P<0.01$

[21] $p<0.05$

[22] $p<0.05$

[23] $p<0.05$ for the performance improvement between 24°C and 26°C

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. As an example, in one visual test subjects must identify the location of an open section in a circle (called a Landolt C) that is briefly shown on a computer monitor. Many of these studies have identified statistically significant differences in people's performance on these visual tests with changes in lighting (e.g., Berman et al., 1993, 1994; NEMA, 1989); 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 aspects of reading performance, such as reading comprehension, reading speed, or accuracy of proofreading. Some of these studies have failed to identify statistically significant effects of illuminance (Veitch, 1990; Smith and Rea, 1982). 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 (Smith and Rea, 1979; Tinker, 1952). Low levels of illuminance seem to have a more definite adverse influence on the performance of older people (Smith and Rea, 1979; NEMA, 1989), a finding that may become increasingly important as the workforce becomes older.

Clear and Berman (1993) explored economically optimum lighting levels by incorporating equations that relate illumination to performance within a cost-benefit model. Their resulting recommended illumination levels varied a great deal with the visual subject (size and contrast), the age of the person, and the model used to relate illumination to performance. It is not possible to generalize from the findings; however, the variability in optimum illumination indicates that occupant-controllable task lighting may be helpful in increasing productivity.

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 (Boray et al., 1989; Veitch et al., 1991; NEMA, 1989) there seems to be no strong or consistent scientific evidence of benefits of full spectrum lighting.

Berman et al., (1993; 1994) have found that changes in the spectrum of light (with illuminance unchanged) influence both pupil size and performance in visual tests. They suggest that the smaller pupil size when light is rich in the blue-green portion of the spectrum reduced the adverse effects of optical aberrations. Additionally, Berman (1992) argues that the required illuminance to maintain work performance, hence the required lighting energy use, could be decreased by 24% if standard cool-white lamps were replaced by those with a larger portion of light output in the blue-green spectrum. The associated annual reduction in energy use for the U.S. would be $4.2 billion.

A few studies have examined the influence of different lighting *systems* on self-reported productivity or on cognitive task performance. The lighting systems compared resulted in different illuminance and also different lighting quality (e.g., differences in reflections and glare). In a study by Hedge et al., (1995), 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[24]. Katzev, (1992) studied the mood and cognitive performance of subjects in laboratories with four different lighting systems (both conventional and energy-efficient). The type of lighting system influenced occupant satisfaction and one energy-efficient system was associated with better reading comprehension[25]. Performance in other cognitive tasks (detecting errors in written material, typing, and entering data into a spreadsheet) was not significantly associated with the type of lighting system.

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 were small in size; hence, these studies would not be expected to identify small (e.g., few percent) increases in performance that could be economically very significant despite their small size. Also, the majority of research subjects have been young adults and lighting is expected to have a larger influence on the performance of older adults.

Summary of Findings Regarding Direct Impacts of Environments on Human Performance. Much of the research on the direct linkage between human performance and environmental conditions is from laboratory experiments, and the relevance of laboratory findings to real-world settings is uncertain. Numerous studies suggest

[24] $p<0.01$

[25] $p<0.01$

that the thermal environment can influence performance of some aspects of mental work by a few percent to approximately 20%; however, other studies suggest that modest changes in environmental conditions will not influence performance. There is also evidence that improved lighting quality can have a strong positive (e.g., 6%) influence on work performance when the work requires excellent vision; however, the potential to improve the performance of more typical largely cognitive work by changing the lighting within buildings remains unclear.

Potential Value of Productivity Gains. Once again, the limited existing information makes it very 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 workforce are the only avenue at present available for estimating the potential value 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, are not readily related to the magnitude 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, quick responses, or excellent vision, while most workers spend only a fraction of their time on these types of task. Third, the changes in environmental conditions (e.g., temperatures and illuminance) within many of the 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 the 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 reports performance changes of 2% to 20% (with one 49% improvement disregarded). We assume that only half of people's work is on tasks likely to be significantly influenced by practical variations of temperature or lighting; thus, the 2% to 20% performance changes are divided by a factor of two. Next, we assume that performance changes should be divided by another factor of two because the research has generally been based on large differences in temperature and lighting, e.g., temperature differences used in research are often twice as large as the changes in temperature likely to be made in most buildings. Based on this logic, the estimated range for potential productivity increases in the building stock becomes 0.5% to 5%. Considering only U.S. office workers, responsible for an annual GNP of approximately $2.5 trillion (Traynor et al. 1993), the 0.5% to 5% estimated performance gain translates into an annual productivity increase of $12 billion to $125 billion.

The Cost of Improving Indoor Environments

The purpose of this section is to illustrate the costs of improving indoor environments relative to the potential productivity gains and health care cost savings discussed previously. As examples, two methods of improving indoor environments are considered: increased outside air ventilation and improved particle filtration.

Increased Outside Air Supply. Increasing the rate of outside air ventilation is one obvious method of reducing indoor exposures to indoor-generated air pollutants that may contribute to infectious disease, to some allergies, and to sick-building symptoms. The costs of increased ventilation have been estimated, based on model predictions reported in a variety of papers. The findings vary considerably with the type of building, type of heating, ventilating, and air-conditioning (HVAC) system, occupant density, and climate. For example, if minimum ventilation rates are increased from 5 L/s-occupant (10 cfm/occupant) to 10 L/s-occupant (20 cfm/occupant), the estimated increase in building HVAC energy used for fans, heating, and cooling, varies from less than 1% to approximately 50%. In office buildings with HVAC systems that have an economizer[26], increasing the average minimum ventilation rates to approximately 10 L/s-occupant (20 cfm/occupant) from 2.5 L/s-occupant (5 cfm/occupant) is likely to change building energy use by only a few percent to 10% (Eto and Meyer, 1988; Eto, 1990; Mudarri and Hall, 1993). The larger increases in energy use (e.g., 30% to 50%) are expected only in buildings with a high occupant density such as schools (Ventresca, 1991; Mudarri and Hall, 1996; Steele and Brown, 1990). Since workers' salaries in office buildings exceed total building energy use by a factor of approximately 100 (Woods, 1989), the cost of modest (e.g., 10%) increases in HVAC energy will be small compared to the potential savings cited above. However, to reduce adverse environmental impacts of energy use, energy efficient options for increasing ventilation (e.g., adding economizer systems where they are absent or venti-

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[26] To save energy, economizer systems automatically increase the rate of outside air supply above the minimum setpoint during mild weather.

lation with heat recovery) should be considered preferred options.

As an example of costs, we consider the results of analyses of Eto and Meyer (1988) involving a large 55,500 m^2 office building. Eto and Meyer (1988) do not indicate building occupancy; therefore, we will assume a default occupancy for offices of 7 persons per 100 m^2 (ASHRAE 1989) resulting in an estimated 3880 occupants. We will use results from the intermediate-severity climate of Washington D.C. Increasing the minimum ventilation rates from 2.5 L/s-person (5 cfm-person) to 10 L/s-occupant (20 cfm/occupant) increased the projected annual energy costs by $22,400 or $5.80 per person in 1993 prices ($20,400 in 1988 prices)[27]. The estimated incremental first cost of the HVAC system was $142,000 or 2.1% ($116,000 in 1988 prices)[28,29]. Spreading this first cost evenly over a 15-year period (an approximation) results in an additional annual cost of ~$9500; thus, the total estimated annual cost is ~$30,000 or $7.70 per person. The annual total compensation for the 3880 office workers in this building will be approximately $140 million (3880 persons x $36K per person). If the increased ventilation leads to a 10% reduction in respiratory infections, the days of lost work and reduced performance at work will decrease by 10%. Since respiratory infections cause workers to miss work about 1.4 days per year and to have 2.2 days of restricted activity, the annual value to the employer of the 10% reduction in respiratory disease would be $0.64 million[30] or twenty times the projected annual cost. Additionally, health care costs would be reduced by roughly $0.36 million annually[31]. If the increased ventilation decreases symptoms of SBS by 25% and SBS symptoms are responsible for a 1% drop in productivity, the associated annual productivity increase is $0.35 million (0.0025×3880 persons×$36K per person). Combining the three savings elements yields an annual savings of $1.4 million, 47 times the projected annual cost.

Improved Air Filtration. As discussed previously, improved air filtration has the potential to reduce disease transmission, allergies and asthma, and SBS symptoms. The first author of this paper has recently completed a field study that included installation of high-efficiency air filters in an office building. Product literature indicates that these filters remove 95% of particles with an aerodynamic diameter of 0.3 μm and a higher percentage of smaller and larger particles. Based on a preliminary review of data, the high-efficiency filters reduced the total indoor concentration of particles 0.3 μm and larger by a factor of 10 to 15. Many of these particles have an outdoor origin. The estimated reduction in the concentration of sub-micron indoor-generated particles is a factor of four. The annual cost of purchasing the high efficiency filters used in this study is approximately $23 per person, assuming the filters must be replaced annually[32]. The incremental cost of labor for installing an extra set of filters once per year is negligible compared to the cost of the filters. (We assume that low-efficiency prefilters are used to extend the life of the high-efficiency filters.) The increased airflow resistance of high-efficiency filters, compared to typical filters, can increase the required fan power if HVAC airflow rates are maintained unchanged. The increased cost of fan energy was estimated to be ~$1.00 per person-year using standard relationships between fan power requirements and airflow resistance, and assuming that the average airflow resistance increases by 60 Pa. However, in many retrofit applications the flow rate in the HVAC system can decrease substantially without adverse effects because existing flow rates are excessive. In these applications, installation of high-efficiency filters will actually save fan energy.

In the previous example, the estimated annual per-

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[27] Since the increased energy costs are dominated by electricity used for cooling, data on the price of electricity for commercial establishments were used to update costs (Table 8.11 of EIA, 1995).

[28] In many existing office buildings, there will be no incremental HVAC costs because oversized HVAC equipment will handle increased loads.

[29] Cost updated to 1994 using the ratio of the CPI (for all items) in 1994 to the CPI in 1988 which equals 1.25 (U.S. Department of Commerce, 1995)

[30] We assume a 25% reduction in productivity on restricted-activity days. We also scale the days in bed and restricted activity days reported by Dixon (1985) by the ratio of work days to total days.

[31] The direct health care costs of respiratory infection for the U.S. population were estimated to equal $15 billion in 1984 (Dixon, 1985). Adjusting to 1994 prices yields $28.9 billion. The incidence of acute respiratory conditions is approximately 74 per 100 for people of working age (18–64) and 104 per 100 for others (U.S. Department of Health and Human Services, 1994; U.S. Department of Commerce, 1995). Multiplying these ratios by the numbers of people in the workforce (130 million) and outside of the workforce (128 million) yields the total number of acute respiratory conditions per year (2.3×10^8). If health care costs per respiratory infection are approximately the same for workers and non-workers (relevant data were not identified), the annual health care cost per worker per respiratory illness is $126. Multiplying by the incidence of respiratory infections for workers yields an annual cost per worker of $93 or $0.36 million for 3880 workers.

[32] Calculations indicate that the high efficiency filters should have a lifetime of at least a year, before they need to be changed due to an increase in airflow resistance.

Table 1 Estimated potential productivity gains from improvements in indoor environments

Source of productivity gain	Strength of evidence	Potential U.S. annual savings or productivity gain (1993 $U.S.)
Reduced respiratory disease	Strong	$6–$19 billion
Reduced allergies and asthma	Moderate	$1–$4 billion
Reduced sick building syndrome symptoms	Moderate to Strong	$10–$20 billion
Improved worker performance:		$12–$125 billion
From changes in thermal environment	Strong	
From changes in lighting	Moderate	

person cost of improved air filtration is $24. We compare the filtration cost to the value of potential benefits. If the improved filtration resulted in a 10% reduction in respiratory disease, the annual savings would be $280 per worker (see sample calculation above for a 3880-person office). If the improved filtration reduced allergic symptoms experienced by the 20% of the workforce that have environmental allergies and this reduction in allergic symptoms resulted in a 1% increase in the productivity of allergic workers, the annual productivity gain would be $70 per person averaged over all workers (0.01×$36,000 annual compensation×0.2 of workers affected). If the improved filtration decreased the productivity loss from SBS symptoms from 1% to 0.75%, the annual productivity gain would be $90 per person. If all of these benefits were realized, the annual savings of ~$440 per worker would exceed the annual cost per worker by a factor of 18.

Conclusions

1. Based on a review of existing literature, there is strong evidence that characteristics of buildings and indoor environments significantly influence rates of respiratory disease, allergy and asthma symptoms, sick building symptoms, and worker performance.
2. There is strong theoretical evidence, and limited empirical data, indicating that existing technologies and procedures can improve indoor environments in a manner that increases health and productivity.
3. With existing data and knowledge, we can develop only crude estimates of the magnitude of productivity gains that may be obtained by providing better indoor environments; however, the projected gains are very large. For the U.S., the estimated potential annual savings plus productivity gains are $30 billion to $170 billion, with a breakdown as indicated in Table 1.
4. Sample calculations indicate that the potential financial benefits of improving indoor environments exceed costs by a large factor (e.g., a factor of 18 to 47).

Policy Implications

Very strong evidence that better indoor environments can cost-effectively increase health and productivity would justify changes in the components of building codes pertinent to indoor environmental quality, such as the prescribed minimum ventilation rates and minimum efficiencies of air filtration systems. Additionally, strong evidence of benefits would justify changes in company and institutional policies related to building design, operation, and maintenance. Health maintenance organizations and insurance companies might also be motivated to reduce rates charged to organizations that maintain superior indoor environments.

We do not at present have the specific and compelling cost-benefit data that are necessary to motivate these changes in building codes, designs, and operation and maintenance policies. The existing evidence of potential productivity gains of tens of billions of dollars per year is, however, clearly sufficient to justify a program of research designed to obtain these cost-benefit data. A research investment on the order of $10 million per year for five years would be sufficient to answer many of the key questions. The total cost of this multi-year program of research would be only 0.2% of our most conservative estimate of *annual* productivity gains.

The primary objectives of the research should be to develop more specific and accurate estimates of the benefits and costs of technologies and policies that improve indoor environments. Industry does not have the incentive to independently undertake this program of research because the required effort is very multidisciplinary and because the benefits of this research will be realized by the entire society. There are opportunities for government-industry partnerships; however, government leadership is necessary if society is to capitalize on this opportunity for large productivity increases. Wright and Rosenfeld (1996) describe the required program of research and identify research priorities.

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