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Do Indoor Environments in Schools Influence Student Performance? A Review of the Literature

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Abstract
Limited research is available on potential adverse effects of school environments on academic performance, despite strong public concern. We examine the scientific evidence relevant to this relationship by reviewing available research relating schools and other indoor environments to human performance or attendance. As a primary focus, we *critically review* evidence for direct relationships between indoor environmental quality (IEQ) in buildings and performance or attendance. As a secondary focus, we *summarize, without critique,* evidence on potential connections indirectly linking IEQ to performance or attendance: relationships between IEQ and health, between health and performance or attendance, and between attendance and performance. The most persuasive direct evidence showed increases in indoor concentrations of nitrogen dioxide and outdoor concentrations of several specific pollutants to be related to reduced school attendance. The most persuasive indirect evidence showed indoor dampness and microbiologic pollutants to be related to asthma and respiratory infections, which have in turn been related to reduced performance and attendance. Furthermore, a substantial scientific literature links poor IEQ (e.g., low ventilation rate, excess moisture or formaldehyde) with respiratory and other health effects in children and adults. Overall, evidence suggests that poor IEQ in schools can influence the performance and attendance of students, primarily through health effects from indoor pollutants. Also, inadequate IEQ in schools seems sufficiently common to merit strong public concern. Evidence is available to justify (1) immediate actions to protect IEQ in schools and (2) focused research on exposures, prevention, and causation, to better guide policies and actions on IEQ in schools.

Key Words: Indoor environment, Indoor air quality, Mold, Ventilation, Performance, Health, Schools

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Introduction

Public concern about adverse effects of indoor air has increased in recent decades, beginning with episodes during the 1970s in which occupants of residences and commercial and institutional buildings reported health problems associated with their buildings (Kreiss 1989). Among the commonly reported complaints in these episodes have been eye and upper respiratory tract irritation, headache, fatigue, and lethargy, and breathing difficulties or asthma. Reporting of new episodes has continued unabated, particularly in commercial buildings and schools. Wider recognition of this problem has also produced concern that health problems from poor indoor environments may reduce the performance of occupants in buildings, with potentially substantial adverse effects on workforce productivity (Fisk 2000; Mendell et al. 2002a).

Scientific evidence regarding adverse effects of indoor environments on health and performance has emerged slowly. Recent attention has focused on indoor environmental factors such as pollutants and thermal conditions, and on a range of adverse effects including recognized diseases, nonspecific health problems, and, to a limited extent, impaired performance.

Indoor environments in schools have been of particular public concern, for two primary reasons:

1) Schools, relative to other kinds of buildings, are seen as particularly likely to have environmental deficiencies because chronic shortages of funding contribute to inadequate operation and maintenance of facilities (U.S. General Accounting Office 1995).

2) Children have greater susceptibility to some environmental pollutants than adults, because they breathe higher volumes of air relative to their body weights and their tissues and organs are actively growing (Faustman et al. 2000; Landrigan 1998). Children also spend more time in school than in any indoor environment other than the home. Adverse environmental effects on the learning and performance of students in schools could have both immediate and lifelong consequences, for the students and for society.

This paper critically reviews available evidence on the relationship between indoor environments in schools (including measured environmental parameters as well as characteristics of the building and ventilation systems) and the learning and performance of students (see Figure 1). The term "indoor environmental quality" (IEQ) refers to *indoor pollutants* (including biological, chemical, or particulate pollutants) and *thermal conditions* (temperature and humidity), as well as noise, light, and odor (although the latter three are not included in this review).

There are many ways, direct and indirect, in which aspects of IEQ might influence the performance of building occupants. Figure 2 shows a variety of hypothesized causal links underlying the associations in Figure 1, through which poor IEQ could impair students' performance or attendance. First, the characteristics and conditions of HVAC systems and buildings strongly influence IEQ. IEQ factors in turn could influence health outcomes of students (or teachers), which could influence performance directly or through effects on attendance (or through impaired teaching). IEQ factors might also influence performance through discomfort or other physiologic processes.

Indoor environments in schools might cause health effects that directly impair concentration or memory – e.g., neurologic effects – or cause other health effects that indirectly affect learning. For instance, indoor pollutants might exacerbate diseases such as asthma or allergy that produce symptoms or absenteeism that in turn impair learning, or lead to use of medications that impair performance. Asthma is a principal cause of school absences from chronic illness, responsible for 20% of absences in elementary and high schools (Richards 1986). Indoor environments might also cause discomfort or distraction, through thermal, visual, acoustic, or olfactory effects that reduce performance.

There is little legal regulation in the U.S. regarding the IEQ experienced by the approximately 50 million U.S. schoolchildren in over 90,000 schools (U.S. Department of Education 2002a; b). Few states regulate IEQ in schools, and fewer still have minimum ventilation standards for schools. In the face of tight budgets, schools have little incentive or ability to protect children against poor indoor environments, particularly in the absence of clear documentation that poor IEQ poses risks to performance, attendance, or health of students. Perhaps inevitably, these circumstances have led to environmental deficiencies in the nation's schools. The U.S. General Accounting Office reported in 1995 that 63% of students in the U.S. attended schools where one or more building features was in need of extensive repair, overhaul, or replacement, or that contained environmentally unsatisfactory conditions (U.S. General Accounting Office 1995). Almost 14 million students attended school in buildings considered below standard or dangerous (U.S. General Accounting Office 1995). These estimates considered only the obvious physical conditions, not the less apparent deficiencies in IEQ such as inadequate ventilation found commonly in U.S. schools by other studies (e.g., Daisey (2003)).

Public demand to improve the educational achievement of children in the US is strong. Sufficient documentation of the adverse effects of poor IEQ in schools on student performance, however, has not been available to motivate protective environmental guidelines in schools as a strategy to increase student achievement. The present review evaluates the strength and consistency of current direct evidence that IEQ in schools influences students' performance or attendance. The review also goes beyond this to summarize evidence on other potential links connecting IEQ and performance. Finally, the review highlights key gaps in our knowledge about IEQ and its effects in schools and suggests priority topics and strategies for research.

Methods

The Methods section describes the scope of this review, details the strategies used to identify sources, and summarizes the criteria for inclusion of sources.

Scope of review

The central goal of this review is to assess evidence for relationships between *IEQ within classroom environments in schools and the academic performance of students through high school*. Because the availability of such evidence is limited, the review includes findings on a broader range of related environments and subjects of all ages: potential adverse effects of school, university, day-care center, office, and home environments on their occupants. The review also includes findings on other relationships that may provide causal links between IEQ and the performance of building occupants. These relationships include

- the influences of IEQ factors, measured or qualitative, on health

- the influence of adverse health on performance or attendance
- the influence of absenteeism on performance

This review will not assess effects of IEQ on discomfort or distraction, and consequent effects on performance, except insofar as thermal conditions have been shown to influence performance.

The *human outcomes* of primary interest in this review are performance and absenteeism. This review does not consider current controversies about the proper measurement of academic performance, but considers educational achievement tests and neurobehavioral performance tests to be relatively objective metrics of learning or performance that, whatever their limitations, are more accurate than subjective assessments of performance. Reduced attendance (i.e., absenteeism) also influences performance at school (or work). Reduced attendance may impair learning by decreasing class time for direct verbal and visual transfer of information from the teacher or by causing students to fall behind in their work. In addition, as school funding is often in part linked to attendance, reduced attendance could decrease school funding and thus impair a school's ability to provide a good learning environment, both physically and pedagogically.

Outcomes of secondary interest in this review include health effects, which may influence the primary outcomes of performance and absenteeism. Potential adverse health effects from indoor environments include asthma and allergy; respiratory infections including colds, flu, legionellosis, and sinus infections; lower or upper respiratory symptoms; and neurologic symptoms including headache, fatigue, or difficulty concentrating. These might in turn influence learning through direct physiologic effects, or indirectly through the effects of medication or reduced attendance.

The *environmental factors* of primary interest in this review are considered in two categories: (1) *measured IEQ factors*, including pollutants and thermal conditions and (2) *characteristics of heating, ventilation, and air-conditioning (HVAC) systems and buildings*. Pollutants considered here include biologic, chemical, and particulate, originating indoors or outdoors. Outdoor pollutants are included because characteristics of buildings, such as ventilation, design, and location, influence indoor exposures to pollutants entering from outdoors. The review excludes radon, lead, and asbestos, and also noise, light, and odor. The characteristics of HVAC systems and buildings considered here include pollution control practices such as ventilation or filtration that can reduce or dilute indoor contaminants, and the features or conditions of HVAC systems and buildings that can influence IEQ.

Search strategies

We searched electronic databases of scientific publications through July 2003, including Medline/PubMed, Educational Resources Information Center (ERIC), Web of Science, and the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE). Using a variety of search algorithms and combinations of key words, we sought publications related to indoor environments and either performance, absenteeism, or health, with separate searches for studies relating absenteeism to performance. In addition, we manually searched selected publications for relevant articles: the journal *Indoor Air* (1995 to the present); proceedings of the triennial International Conference on Indoor Air Quality and Climate ("Indoor Air '90" through "Indoor Air '02"); and the Healthy Buildings 1997 and 2000 conferences. We also used additional unpublished reports or bibliographies (Bayer 2000; Daisey and Angell 1998). Finally, we included other articles as appropriate to provide background information on current conditions in schools.

Selection and evaluation of studies
Articles considered of primary relevance assessed *direct* relationships between indoor environments and performance or attendance, in schools or other indoor environments. We reviewed these articles and provided methodological critiques. Articles considered of secondary relevance assessed relationships plausibly forming intermediate links between IEQ and performance or attendance (e.g., between IEQ and health, or attendance and performance). These secondary articles we summarized without methodological critique. We included only peer-reviewed articles and articles published in proceedings of scientific conferences. We mention literature reviews found, without evaluating or summarizing them.

References of primary relevance included either measurement of indoor pollutant concentrations or thermal conditions or characterization of HVAC systems or buildings, along with measures of performance or attendance. Our critique of these studies involved evaluating the strength of study designs and measurement methods (see Cook (1979), Rothman (1986), Mendell (1993)).

Studies with the strongest designs – well-designed experiments, quasi-experiments (e.g., controlled field intervention studies), or prospective observational studies, with proper measurements and statistical analyses – were considered most persuasive. Findings from especially persuasive studies of particularly strong design are noted in the text and tables. This designation required all of the following: a good experimental, quasi-experimental, prospective cohort, or case-control design; appropriate measurement of risks and outcomes; adequate control in the design or analysis of major potential confounders; absence of other key study flaws; and a sufficiently clear description of the study methods to assess the above features. This determination is finding-specific rather than study specific; for example, a strong experimental study may include less persuasive cross-sectional findings as well.

Among studies of primary relevance, studies with weaker designs or analyses, such as those lacking statistical control for key potential confounding variables, were considered less persuasive. We excluded studies of particularly weak design, such as case studies, uncontrolled interventions, or crude comparisons of two groups unless they offered specific information of value.

We also provide, for studies of primary relevance, reported estimates of the *magnitude* of effect for studied risks. Magnitude of effect (or strength of association) is generally reported as risk ratios (RRs) or odds ratios (ORs), accompanied by 95% confidence intervals (CIs) or p-values as indicators of statistical confidence. The RR and OR are measures of increased risk relative to a reference level of 1.0. (Subtracting 1.0 from the RR or OR and then multiplying by 100% gives the approximate relative increase found.) Unless stated otherwise, "significantly" increased risks reported here have p-values< 0.05.

The Results section describes and critiques available studies of primary relevance with respect to their strength and validity, as well as summarizing studies of secondary relevance. The Discussion section synthesizes findings by considering the overall evidence available on specific relationships, emphasizing strong or consistent research, and then evaluating applicability of this evidence to children in schools. Research findings on children, whether in schools or non-school settings, will be considered directly applicable if the exposures or risks studied are considered to also occur in schools.

We categorized overall evidence on relationships of specific aspects of IEQ to human response in four categories: (a) *persuasive evidence*, sufficient to document a causal relationship – this required at least several strongly designed studies with consistent findings relating measured indoor exposures to objectively measured performance or attendance outcomes, with the overall findings making alternate explanations unlikely; (b) *strongly suggestive evidence* of a relationship but insufficient to document a causal relationship – this required at least several strongly designed studies with consistent findings, but not necessarily with measured exposures or objectively measured outcomes, or, in the absence of contrary results, one strongly designed study relating indoor exposures or risk factors to objectively measured outcomes; (c) *suggestive evidence,* requiring more than one reasonably well-designed study relating indoor exposures or risk factors to outcomes; or (d) *sparse or no evidence or inconsistent evidence* of a relationship.

Results

The Results section summarizes and critiques research findings about direct relationships, in schools or non-school indoor environments, between:

- *pollutants* and performance or attendance (Table 1);
- *thermal conditions* and performance or attendance (Table 1);
- *characteristics of HVAC systems* and performance or attendance (Table 2);
- *characteristics of buildings* and performance or attendance (Table 2).

Within these sections on type of exposure or risk factor, findings on children are presented first, followed by findings on adults. Each section may include findings from schools, day-care centers, universities, offices, or controlled laboratory settings. The last part of the Results section briefly summarizes, without critique, findings on relationships between IEQ and health, health and attendance or performance, and attendance and performance. Supplemental materials available from the authors provide additional details and methodological critiques for studies discussed in this section and for literature reviews not mentioned here.

This review did not include relationships between noise, light, or odor and performance or attendance, although research and reviews are available on these topics. For reviews on light, see Tiller (2000), Fisk (2000); for a single study of potential importance, see Heschong Mahone Group (1999) and a reanalysis by Heschong (2002). For a review on noise, see Burt (2000); for single studies, see Bronzaft (1975), Evans (1997), and Evans (2000).

This review, from consideration of over 500 articles or reports, includes information on 36 references of primary relevance (Tables 1 and 2). Of these, 27 were peer-reviewed and 20 had findings considered to be from strong study designs. Fifteen articles reported studies of children in school settings, of which eight had strong study designs (although six of these assessed the relation of school absence to measured *outdoor* pollutants).

The reviewed studies assessed performance using educational achievement tests, neurobehavioral performance tests, psychological tests, simulated office tasks, electronically monitored job performance, or subjective assessments of performance. The studies assessed attendance using metrics such as absenteeism, illness-related absenteeism, or respiratory illness-related absence. Some studies used objective attendance data from school or work records, while others used subjective recall of absence, a measure that is more imprecise and susceptible to recall bias.

Tables 1 and 2 are constructed so that, for consistency, all upward-pointing arrows signify *increases in beneficial outcomes* of either performance or attendance. Downward-pointing arrows signify decreases in beneficial outcomes. This required reversing, for some studies, both the outcome metric and the direction of finding reported; e.g., reported increases in absenteeism are presented here as decreases in attendance.

|*Table 1 approximately here*|

Pollutants and performance or attendance
Table 1 includes studies that assessed relations between pollutants and the performance or attendance of occupants. This section discusses these studies in subsections on gases (volatile organic compounds and inorganic gases), microbiological materials, and particles. Two studies on performance and nine on attendance were conducted in schools with schoolchildren.

<u>Volatile organic compounds (VOCs)</u>
The one study providing evidence from a school setting (Smedje et al. 1996) reported an increased risk of subjectively reported impaired mental performance among Swedish students in association with higher indoor pollutant concentrations. ORs (and 95% CIs) were 1.2 (1.01-1.4) for each increase of 10μg/m^3 in total VOCs, and 2.9 (1.4-6.2) for each increase of 10μg/m^3 in formaldehyde. Although an apparently well-designed cross-sectional study with appropriate multivariate adjustment for potential confounding factors (only limited information was reported in a non-peer reviewed article in a conference proceeding), this study used a doubly subjective measure of performance (e.g., subjects were asked *how much they thought* their performance was reduced *by the indoor environment*). Also, this study estimated independent risks from many environmental factors, based on multivariate adjustments, but the role of correlation and potential confounding in this cross-sectional study further weakens the persuasiveness of the study's findings.

Gyntelberg (1994), in a cross sectional study of Danish office workers, found significant associations between concentration problems reported by workers and total concentrations of VOCs in the fibers from floor dust. The OR was 1.09 (1.05-1.13) for each additional VOC found at concentrations greater than 5 μg/g in the sample. This was a well-designed and analyzed cross-sectional study, although the outcome measure potentially related to performance was subjective.

A laboratory experiment with "sensitive" adults by Mølhave (1985) demonstrated that exposure to mixed VOCs caused impaired memory (for digits) on the digit span test (p-value <0.01, magnitude of change not reported). Subjectively assessed ability to concentrate was also impaired. However, the VOC concentrations used were much higher than generally found in indoor environments. A later laboratory experiment by Otto (1992), designed as a more rigorous replication of Mølhave (1985) but in subjects without known sensitivities, failed to find the effect found by Mølhave. Otto, however, did find increased subjectively assessed confusion and fatigue in subjects exposed to 25 mg/m^3 of VOCs: with exposure, confusion increased by 0.2 units from a mean level of 1.9 (p=0.03) and fatigue increased by 0.2 units from a mean level of 2.6 (p=0.4). The positive findings on objective tests only by Mølhave (1985) but not the study by Otto (1992) might be explained either by the use of sensitive subjects or by flaws in research design.

Inorganic gases

Table 1(b) summarizes evidence from one study (Pilotto et al. 1997) on the association between indoor pollution and children's attendance in schools. This strongly designed study on the effects of emissions from gas heaters in both school and home settings found significant, dose-response relations between indoor hourly peak concentrations of nitrogen dioxide greater than 80 parts per billion (ppb) and absences from school. In the high category of exposure (which was not above existing ambient standards), the adjusted absence rate increased from 0.014 to 0.024 (p=0.02), and the adjusted proportion absent increased from 0.47 to 0.63 (p=0.002). The OR (95% CI) for absenteeism at the higher exposure category was 1.92 (1.13-3.25). The reported dose-response relation strengthens the evidence for a cause/effect relationship even at these low levels.

Table 1(b) also summarizes evidence on five studies of strong prospective cohort design that assessed the relationships of measured *outdoor* pollutants to school absenteeism (Chen et al. 2000; Gilliland et al. 2001; Hwang et al. 2000; Park H et al. 2002; Romieu et al. 1992). Because these outdoor pollutants enter readily into the air indoors where children spend most of their time, it is likely that these study findings largely reflect effects from indoor exposures (although the role of exposures inside schools vs. homes is unclear). Findings were mixed for outdoor nitrogen oxides and absenteeism (Gilliland et al. 2001; Hwang et al. 2000; Park H et al. 2002). Hwang et al. (2000) found risk of illness absence to be significantly related to acute exposures to nitrogen dioxide – OR (95% CI) of 1.23 (1.1-1.4) per 10 unit increase in concentration – and more generally, to nitrogen oxides – OR (95% CI) of 1.11 (1.0-1.2) per 10 unit increase. H. Park et al. (2002) found a statistically nonsignificant increase in illness absence associated with a 15 part per billion (ppb) increase in nitrogen dioxide. Gilliland et al. (2001) found no relationship for nitrogen dioxide and absence.

Four studies suggested that absence from school increased with higher outdoor concentrations of ozone (Chen et al. 2000; Gilliland et al. 2001; Park H et al. 2002; Romieu et al. 1992). Chen et al. (2000) reported a 13% increase (95% CI, 3-23%) in total absenteeism for each additional 50 ppb of outdoor ozone. Gilliland et al. (2001) found, for each 20 ppb increase in outdoor ozone, increases of 63% (95% CI, 8-124%) for illness-related absence, 83% (4-222%) for respiratory illness-related absence, and 174% (91-292%) for lower respiratory illness-related absence with wet cough. Romieu et al. (1992) found that risk of absenteeism increased monotonically by exposure levels of ozone: at medium (0.13-0.22 ppb) and high (0.23-0.34 ppb) levels, RRs (95% CIs) were 1.4 (0.7-2.6) and 2.0 (0.9-4.1). H. Park et al. (2002) reported, for a 16 ppb increase in outdoor ozone, an RR (95% CI) of 1.08 (1.06-1.11) for illness absence. For carbon monoxide, one study found school absence increased by 3.8% (95% CI, 1-7%) in association with each 1 ppm increase in outdoor carbon monoxide concentration (Chen et al. 2000). H. Park et al. (2002) reported a *decrease* in illness absence associated with increased carbon monoxide: RR (95% CI), 0.96 (0.94-0.98). The one available study on sulfur dioxide reported, for a 6 ppb increase in sulfur dioxide, a RR (95% CI) for illness absence of 1.09 (1.07-1.12) (Park H et al. 2002).

Biologic pollutants

Table 1 (a) summarizes evidence from three studies on the association between biologic pollutants and performance, including one from schools (Burton et al. 2001; Gyntelberg et al. 1994; Smedje et al. 1996). Smedje et al. (1996) reported, from the previously described cross-sectional study in Swedish schools, significantly increased risks of subjectively assessed impaired mental performance with microbiologic exposures: ORs (95% CIs) were 4.3 (1.8-10.7) for each 10-fold increase in total bacteria and 2.9 (1.5-5.7) for each 10-fold increase in total fungi. Gyntelberg et al. (1994) reported from a cross-sectional study of office workers that an increased ability of floor dust to liberate histamine (a measure of allergenicity, likely related to the presence of biologic pollutants) was associated with subjectively assessed lack of concentration.

A prospective cohort study by Burton (2001) strongly documented impairment in measured performance of office work due to pollen exposures (of outdoor origin) during pollen season among allergic, but not among non-allergic, adults. Allergic workers were 10% less productive, during pollen season only; use of antihistamines reduced this decrement to 3%. Allergic workers had reduced odds of meeting two production standards: OR= 0.74 ($p \leq 0.0001$). While the relationship is clear, the role in this effect of indoor vs. outdoor exposures to pollen is unknown.

Particulate pollutants

Smedje et al. (1996) reported, from the previously described cross-sectional study in schools, a significantly increased risk of subjectively assessed impaired mental performance in students, with an OR (95% CI) of 1.9 (1.3-3.0) for each increase of 10 $\mu g/m^3$ in respirable dust.

Table 1(b) also summarizes evidence on four cohort studies, most of strong design, that assessed relations of outdoor particulate pollutants to school attendance (Chen et al. 2000; Gilliland et al. 2001; Makino 2000; Ransom and Pope 1992). Ransom and Pope (1992) reported that each 100 $\mu g/m^3$ increase in outdoor concentration of particles less than 10 micrometers in aerodynamic diameter (PM10) was associated with a 40% increase in school absenteeism, even at PM10 levels lower than 150 $\mu g/m^3$, the current legal ambient standard. Makino (2000) reported that higher mass concentrations of outdoor total suspended particulate matter (TSP) was associated with significantly increased school absence in one school, with OR (95% CI) for the highest concentration quintile of 1.19 (1.05-1.36) but nonsignificant increases in the other school studied. TSP would be a less sensitive metric for identifying effects of respirable particles, as it would be significantly influenced by nonrespirable particles. Furthermore, the reported analysis by Makino had numerous limitations. Gilliland et al. (2001), reported that PM10 was not associated with increases in illness absence from school. Chen et al. (2000) reported a *negative* relationship between school absenteeism and increased PM10, with overall daily absence *decreased* by 3% (95% CI, 1.3-4.7) for each 10 $\mu g/m^3$ increase in PM10. Because these outdoor particles, like outdoor gases, readily enter the air indoors where children spend most of their time, these study findings may largely reflect effects from indoor exposures, whether in schools or other settings.

Thermal conditions and performance or attendance
Table 1 summarizes 10 studies that assessed relations between thermal conditions and the performance (9 studies) or attendance (1 study) of occupants. This section discusses these studies in subsections on temperature and on humidity. (The findings on effects of temperature and humidity levels in buildings should be considered in conjunction with the findings, presented in a subsection below, on the presence of air-conditioning/cooling systems and of humidification systems in buildings.) A number of review articles are available on relationships between thermal conditions and performance or attendance (Green 1985; Levin 1995; Pilcher et al. 2002; Sensharma et al. 1998; Wyon 1993; 1996; 2000)**.**

<u>Temperature</u>
Table 1(a) summarizes evidence on relations between indoor temperature and performance from one study in a school setting (Schoer and Shaffran 1973) and seven studies (in eight reports) of adults in laboratory or office settings (Fang et al. 2002; Federspiel et al. 2002; Fisk et al. 2002; Mendell et al. 2002b; Pepler and Warner 1968; Wyon 1974; 1975; Wyon et al. 1979). Our review identified no research findings on the relationship of temperature and attendance.

Schoer and Schaffran (1973), in a set of well-designed experimental studies, assessed performance of students in a pair of classrooms set up as a laboratory, with one classroom cooled and one not. The study found a general advantage for performance tests in the cooled environment, with a consistent tendency for greater, statistically significant benefits for more complex performance tests. The number and variety of tests included in the three separate studies they reported precludes summary here of specific results. These were strongly designed studies with persuasive findings, although the differences found were not completely internally consistent.

Fisk et al. (2002) and Federspiel et al. (2002) reported findings from two analyses of a single, controlled, blinded quasi-experiment on ventilation rates and electronically monitored performance in a telephone call center. The study included real-time measurements of temperature (and relative humidity) and two kinds of multivariate analyses – within individuals and also across individuals over time. Performance was assessed as the measured time for completing two separate tasks – talk time on the telephone and wrap-up time after each call. The analysis of half-hour work periods (Fisk et al. 2002) found no relationship of performance to either thermal parameter, but was not intended or well-designed to see such relationships due to very small variation in temperature (half-hour averages were almost entirely within a 1° C range). The analysis of individual performance averaged over worker shifts of approximately 8 hours, including a broader range of temperatures (21 to greater than 26°C), showed effects only in the highest category of temperature (>25.4°C), where both measures of performance decreased, including a wrap-up time slowed by about 15% (Federspiel et al. 2002). This study and the analyses, nonetheless, were not strongly designed for assessing thermal effects.

Mendell et al. (2002b) reported, from a prospective cohort study of office workers, that higher temperatures within the conventional comfort range were associated with lower values on questionnaire measures of what the authors called "performance-related mental states." Three mental states were measured with two multi-question subscales from the Neurobehavioral Evaluation System related to mental confusion and fatigue and a single question on productivity (Baker et al. 1985). ((This study also included a-quasi-experimental intervention of particle removal, which will be described further below.) Each 1°C increase within the observed range of 22.2-25.6°C was associated with the following adverse changes relative to mean values: confusion, +7.9% (95% CI, 4.9 to 10.9%); fatigue, +7.7% (4.8 to 10.6%); and productivity, -4.1 (-1.9 to -6.4%). Pepler and Warner (1968) reported, from an experimental study of learning efficiency in a school laboratory, that as temperatures increased from 62°F to 80 °F, speed of work decreased by 7%, although effort decreased by 30% and error rates decreased by 17%, all with $p \leq 0.05$. Insufficient information was provided to clarify various inconsistencies in the findings. Wyon (1974) reported, from reanalyses of data from a previous experimental study by others, that male and female college students did substantially and significantly less typing work at 24°C than at 20°C. It was not feasible to extract and summarize magnitudes of effect from the article. Wyon (1975) reported, from an experimental chamber study in adult students, no differences in performance tests at different temperatures when subjects could adjust temperature as desired. Wyon et al. (1979) reported an experimental chamber study of the effects of rising temperatures between 20-29°C on mental performance in high school students. Although there was no consistent pattern of response on 10 aspects of performance, there was somewhat more evidence for adverse effects on performance from higher temperatures within the comfort range.

A strongly designed, controlled experimental trial on adults in a field laboratory by Fang et al. (2002) tested the effects of several temperature/RH combinations on the performance of simulated office tasks. Higher temperature/RH combinations (23°C/50% RH and 26°C/60% RH) were not associated with changes in task performance relative to 20°C/40% RH. However, because subjects were encouraged to adjust their clothing as needed to maintain thermal equilibrium, and succeeded in doing this, the results may not be comparable to most other research findings in which this is not the case, or generalizable to real-world building environments.

<u>Humidity</u>
Table 1(a) summarizes evidence on relationships between humidity and performance from one study (Smedje et al. 1996) from a school setting, two studies reported in three papers (Federspiel et al. 2002; Fisk et al. 2002; Mendell et al. 2002b) in office settings, and one from a field laboratory (Fang et al. 2002). Humidity is often measured and studied as RH, although use of this metric, strongly correlated with temperature, may make effects of these two parameters difficult to separate. Smedje et al. (1996) reported from a cross-sectional study, that higher RH was associated with increases in subjectively assessed impairment of mental ability among students (OR (95%CI) = 1.8 (1.2-2.7) for each 10% increase in RH); limitations of this study have been described previously. Mendell et al. (2002b) reported no relation, within a moderate range of humidities in an office setting, between humidity ratio (a measure of absolute humidity uncorrelated with temperature) and questionnaire measures of performance-related mental states.

Fisk et al. (2002) and Federspiel et al. (2002), in the previously described quasi-experimental study with real-time prospective measurements of thermal parameters, reported no association of RH with electronically monitored performance, although the observed variation in RH was apparently very narrow. Fang et al. (2002) in the previously described controlled experiment on thermal conditions, found no effect on performance tasks of higher relative humidities combined with higher temperatures (50% RH/23°C and 60% RH/26°C) relative to 40% RH/20°C.

Table 1(b) summarizes evidence from one study (Green 1974), in a school setting, on the link between indoor RH and attendance. Green (1974), from a prospective study of schools with or without humidification, reported consistent decreases in school absenteeism associated with indoor RH increased to between 20-40%. Magnitudes of effect could not be easily summarized from this report, but absenteeism in the reported sub-studies decreased by 3-9% for each percentage point increase in RH. Although the study design had limitations and statistical analyses were lacking, the flaws seem unlikely to have created this relationship spuriously.

Characteristics of HVAC Systems and Performance or Attendance
HVAC systems in buildings have two primary functions – to remove pollutants from indoor air and to control indoor thermal conditions. Specific HVAC features or operations can be related to either or both of these functions. This section also includes studies on two building features with HVAC functions: personal thermal control and operable windows. Studies may assess aspects of HVAC systems by the simple presence or absence of a specific feature (e.g., humidification systems), by numeric specifications (e.g., efficiency of a particle filter), or by quantification (e.g., flow rate of outdoor air delivered by ventilation).

Table 2 summarizes studies that assessed relations between characteristics of HVAC systems and the performance or attendance of occupants. This section discusses these studies in subsections on HVAC pollutant control and HVAC thermal control.

|Table 2 approximately here|

<u>HVAC pollutant controls</u>
Table 2 summarizes evidence from seven studies on relations between outdoor air ventilation rate and performance or attendance: two from schools (Myhrvold et al. 1996; Smedje et al. 1996), two from an office/laboratory (Fang et al. 2002; Wargocki et al. 2000), and three (in 4 articles) from offices (Federspiel et al. 2002; Fisk et al. 2002; Milton et al. 2000; Myatt et al. 2002). Smedje et al. (1996) reported a significantly increased decrement in subjectively assessed performance, OR (95% CI) = 0.7 (0.6-0.9), associated with each additional reduction in ventilation of 1 air exchange/hour. Limitations of this cross-sectional study are described above. Myhrvold et al. (1996) reported from a quasi-experimental study in schools that higher indoor carbon dioxide concentrations (indicating less outdoor air ventilation) were associated with lower scores on a computerized test of reaction time. Magnitude of the effects was not reported, but the correlation adjusted only for age was 0.11 (p=0.009). A published graph suggested an apparent (unadjusted) dose-response relation. Decreasing ventilation levels, corresponding to 0-999, 1000-1499, and 1500-4000 parts per million (ppm) of CO_2, were associated with mean performance indices of -0.08, 0.02, and 0.13, respectively (with negative scores representing better performance). Despite the objective quality of the outcome measure, this report

(Myhrvold et al. 1996) provided only very limited information in a brief, non-peer reviewed article and had numerous other substantial limitations.

A strongly designed experimental study (Wargocki et al. 2000) found, consistent with the two more limited studies described above, lower ventilation rates to be related to reduced performance among office occupants. Wargocki et al. (2000) reported that performance of four simulated office tasks improved monotonically with increasing ventilation rates, with a statistically significant trend for text typing ($p<0.03$), and similar patterns but larger p-values for addition ($p<0.06$) and proof-reading ($p<0.16$). On average, for each doubling of ventilation rate in the range between 3-30 L/sec per person, Wargocki et al. reported that work on specific office tasks increased from 1.1-2.1%. In contrast, Fang et al. (2002), in a simpler comparison of two ventilation rates using the same controlled environment, found no differences in task performance, an unexpected finding attributed by the authors to the limited data collected on this contrast.

Two reports of findings from a quasi-experimental study of changes in ventilation rate on performance in a telephone call center differed. Fisk et al. (2002) from multivariate analyses of performance times averaged over half-hour intervals throughout the call center, found no apparent effect over most of the range in ventilation rate (12 l/sec/person to 48 l/sec/person) except for a possible 2% improvement in worker performance at very high ventilation rates (less than 75 ppm difference between indoor and outdoor $CO_{2\ \text{concentrations}}$). In contrast, Federspiel et al. (2002), analyzing individual performance on two tasks averaged over work shifts, reported that talk tasks were performed fastest at the highest ventilation rates, but also increased at the lowest ventilation rates. There was no significant relationship between wrap-up performance and ventilation rate. Although most elements of the design and analyses of this call center study were strong, several limitations in the available data and their analyses, to the extent interpretable in these short publications from conference proceedings, limit the persuasiveness of the findings.

The well-designed and persuasive study in office buildings by Milton et al. (2000) found that ventilation rates substantially above current recommended levels were consistently associated with decreases of about one-third in short-term sick leave. The RR (95% CI) for short-term sick leave associated with lower ventilation rate (25 cfm/person vs. 50 cfm/person) was 1.5 (1.2-1.9). The authors suggested that this excess was likely to be due to respiratory disease and estimated that, if this relationship were causal, as much as 35% of short-term sick leave in these offices could be prevented by raising ventilation rates above currently recommended rates. The study design and analyses were strong, despite the rough estimation of ventilation rates used.

In contrast, Myatt et al. (2002), in a crossover, quasi-experimental study of ventilation rates and sick leave among office workers in two buildings, found no association. All ventilation levels studied, however, were relatively high, with a maximum indoor/outdoor CO_2 differential of 250 ppm, and an average less than half the 700 ppm maximum specified in ASHRAE standards.

Table 2 summarizes evidence from two studies, one from schools (Rosen and Richardson 1999) and one from an office building (Mendell et al. 2002b), on relations between particle removal in buildings and performance or attendance. Rosen and Richardson (1999) performed a quasi-experimental study in day-care centers that reduced indoor concentrations of small particles by

45-80% using negative ionization. They found the reduced concentration associated with significantly decreased absenteeism ($p<0.05$) among children. The study, conducted in only 2 facilities, was small and not well designed to separate effects of ionization from other possible explanations of findings. The study findings were not persuasive, as the 35-55% reductions in absenteeism associated with ionization the first year were not clearly different from a 36% reduction associated with a later period of no ionization. Mendell et al. (2002b) performed a double-blind, quasi-experimental crossover study of enhanced particle filtration in an office building. Questionnaire responses included three "performance-related mental states." The authors reported that enhanced filtration of small particles (which removed 95% of airborne particles between 0.3 and 0.5 micrometers) produced statistically significant improvement of 3.7% (95% CI, 0.9 to 6.5%) in the confusion scale and non-statistically significant improvement of 2.5% (-0.4 to 5.3%) on the fatigue scale and 2.1% (-0.1 to 4.4%) on the productivity question. This study had a strong design and analysis, although the outcomes were subjectively assessed.

Table 2 includes one study that assessed the relations between the presence of operable windows in offices and attendance. Preller et al. (1990) reported, from a large, apparently well-designed cross-sectional study of Dutch office buildings, a *decrease* in reported work absence attributed to symptoms in the building, associated with sealed (e.g., non-operable) windows (OR (95% CI) = 0.8 (0.7-1.0). These unexpected results are reported in a brief non-peer reviewed article providing few details of the study, and absenteeism was assessed only by subjective recall of workers.

<u>HVAC thermal control systems</u>
Table 2 summarizes evidence from six studies on relations between HVAC thermal control systems and performance or attendance: three in schools (Green 1974; McNall and Nevins 1967; Sale 1972) and three in office buildings (Kroner and Stark-Martin 1994; Milton et al. 2000; Preller et al. 1990).

One study assessed the relationship between the presence of air-conditioning in schools and student performance. McNall and Nevins (1967), in a quasi-experimental comparison between one air-conditioned school and several non-air-conditioned schools in Florida, found trends in favor of higher academic achievement in the air-conditioned school. Magnitude of findings cannot be easily summarized. The many limitations in design and analysis, particularly the inclusion of only one air-conditioned school, make these findings non-persuasive. This study also could not separate the presumably positive effects of *cooler* indoor temperatures in this hot-summer climate from other effects of the *presence* of the air-conditioning systems. In fact, numerous studies have found air-conditioning systems to be associated, even after statistical adjustment for differences in temperature, with *adverse* health effects in buildings, presumably due to production of contaminants (Mendell 1993; Mendell and Smith 1990; Seppanen and Fisk 2002). Findings on temperature and performance have been summarized in Section 3.2 above.

Green (1974) reported, from the previously described prospective study of schools, significantly lower absenteeism rates in humidified relative to non-humidified schools: for 10 years overall (4.6 vs. 5.1% ($p<0.05$)), and for yearly pair-wise comparisons over the 10 years ($p<0.01$). This study had multiple limitations in design and analysis, particularly in failing to control for potential confounding, but these seem unlikely to explain the association found. Sale (1972), from a cross-sectional study, found lower absenteeism associated with humidification in schools, and even lower absenteeism associated with humidification in both schools and homes. These findings were internally consistent, despite substantial limitations in design of the study, which included only one humidified school and scant statistical analysis. Milton et al. (2000), in the previously-described large, well-designed prospective study of office workers, found that presence of building humidification was associated with significantly increased absenteeism as determined from employer records: OR (95% CI) = 2.0 (1.2-3.1). This relationship was not estimated in the final statistical model reported, due to the small numbers of humidified buildings, but the preliminary statistical model in which it was contained was still credible. The degree to which this finding can be extrapolated to schools is uncertain, as it is not clear if illness affects absenteeism in schoolchildren equally as in adults.

Preller et al. (1990) reported, from the previously described cross-sectional study of offices, that workers in buildings without humidification systems, relative to those in buildings with humidification systems, reported decreased absenteeism related to symptoms in the building: OR (95% CI) = 0.7 (0.5-0.9). The results of this apparently well-designed and analyzed study, however, were reported only briefly in a non-peer-reviewed conference proceeding, and absenteeism was assessed only by subjective recall of workers.

The findings of Green (1974) and Sale (1972) in schools contrast with the findings by Milton et al. (2000) and Preller et al. (1990) in offices. The latter two studies were substantially more strongly designed, larger studies with less apparent risk of biased findings. The different findings may also reflect different effects among adults and children. A review by Green (1985) also reported consistent benefits of humidification among schoolchildren but inconsistent findings among adults. Inconsistent findings of benefits from higher indoor humidity may also be related to the previously reported potential adverse effects of humidification systems due to risk of contamination.

Kroner and Stark-Martin (1994) reported from a quasi-experiment in an office setting that personal thermal control was associated with a 2% increase in worker performance, but did not report performing statistical analyses. This finding, based on random, intermittent disabling of the personal thermal control mechanisms, is questionable. The study could not distinguish negative effects due to decreased comfort during periods without control from increased frustration during the periods the equipment was intermittently disabled. Preller et al. (1990) reported increased absenteeism from symptoms in office buildings associated with lack of personal thermal controls (OR (95%CI) = 1.4 (1.2-1.7)), but in a brief non-peer reviewed article providing few details of the study.

Characteristics of Buildings and Performance or Attendance

Table 2 summarizes five studies that assessed relations between characteristics of buildings and the performance of occupants: two in schools (Berner 1993; Smedje et al. 1996), two in office laboratories (Lagercrantz et al. 2000; Wargocki et al. 1999), and one in offices (Nilsen et al. 2002). One study was available on building characteristics and attendance (Nilsen et al. 2002).

<u>Facility conditions</u>

Berner (1993), from a cross-sectional study of schools, reported that poorer physical condition of school facilities, based on standardized facility inspection checklists, was associated with impaired performance on achievement tests. Average achievement scores increased 5.4 points ($p<0.05$) for each improved category of building condition (i.e., "poor" to "fair" to "excellent"). The design of this study had important limitations, such as limited control for major confounders like socioeconomic status that would be expected to exaggerate the associations found. However, the analysis was carefully done, and some reported analyses adjusting for level of parental economic input at the school (PTA budget per student) estimated an even stronger association (increased scores of 10.8 with each improvement of building condition category, $p< 0.005$). These findings, of positive relations between visible conditions of school facilities and objective measures of student performance, are suggestive, but it is not clear what causal agents the visible condition of school facilities represents, as the study did not consider IEQ or health effects.

Nilsen et al. (2002) reported findings from a year-long, controlled, blinded, 2-group, before-after quasi-experimental study of improved office cleaning, on two floors in a single building, with about 50 workers per group. The intervention led to a nonsignificant improvement in mental states potentially related to performance, but no improvement in performance assessed by tests. Sickness absence significantly improved (magnitude of 16.4% relative to the control group, with no data on precision provided), mostly from reduced short-term sick leave. Despite its generally strong design, this study in only two groups without crossover provides, by itself, suggestive (but not strongly suggestive) evidence for a relationship between increased office cleaning and reduced sickness absence.

Building structure/contents

Smedje et al. (1996) reported, from the previously described cross-sectional study of schools, that older buildings and buildings with more occupants were associated with decreased risk of subjectively assessed decrement in mental performance: OR (95% CI) = 0.8 (0.7-0.9) for each additional 10 years of building age and 0.8 (0.7-0.9) for each additional 10 school employees.

Wargocki et al. (1999) and Lagercrantz et al. (2000) performed similar studies in different office/laboratory spaces with completely controlled environments. The studies involved measurement of the performance of temporary office workers in conditions with and without the presence of a hidden carpet. The studies used pieces of the same carpet, taken from an office building with longstanding complaints, hung on hidden racks in the experimental office space. Both of these studies suggested that characteristics of the carpet used had detrimental effects on performance of some but not all tasks. Wargocki et al. (1999) reported that in the presence of the carpet, subjects typed 6.5% less text ($p=0.003$). Lagercrantz et al. (2000) reported that in the presence of the carpet, subjects typed less ($p<0.02$; a graph showed an approximate 1.5% reduction) and made more errors in adding ($p<0.02$; a graph showed an approximate 1.1% increase). Findings of the two studies, however, were not fully consistent, and odor-mediated effects could not be ruled out. Most important, because the emissions from the tested carpet were not characterized, the findings cannot be generalized to other carpets or indoor environments. This lack of generalizability is the key reason that, despite their careful design, we do not consider these studies to be strong. The study by Lagercrantz et al., in addition, reported only summary information in a short conference paper.

IEQ, health, and performance or attendance

Although limited research, particularly on children in schools, is available directly associating IEQ factors with performance or attendance, an extensive scientific literature exists on other relationships that are plausible links in causal chains connecting IEQ to performance or attendance (Figure 2). This section briefly summarizes, without critique, available evidence from primary studies or review articles on a number of these other relationships: between IEQ and health, between health and attendance or performance, and between attendance and performance. Material is not included on relationships between IEQ and comfort or physiologic responses, or between comfort or physiologic effects and performance.

<u>IEQ and health</u>

It is beyond the scope of this review to summarize and critique the large literature available on relationships between IEQ factors and health, although these relationships provide critical links in key hypothetical connections between IEQ and the performance or attendance of building occupants (Figure 2). The section first lists a number of recent articles that have extensively reviewed aspects of relationships between IEQ and health outcomes. The section next cites articles reporting primary research on health and a broad range of IEQ factors, from HVAC or building characteristics to measured pollutants or thermal conditions. The articles are grouped by types of health effect, and the health effects are roughly categorized by how strongly current evidence has associated them with effects on performance and absenteeism.

Review articles or chapters (none focusing specifically on children in schools, although mentioning articles on this topic) are available on the following topics:

- Respiratory infections and building environments (Fisk 2000)
- Dampness in buildings and health (Bornehag et al. 2001)
- Moisture and mold as risks for respiratory health effects (Peat et al. 1998)
- Indoor environments and asthma (Committee on the Assessment of Asthma and Indoor Air 2000), including a section on asthma and schools (pp. 321-323)
- Pets and asthma or allergies (Ahlbom 1998)
- HVAC system type and symptoms in buildings (Seppanen and Fisk 2002)
- Ventilation rates and health in buildings (Seppanen et al. 1999)
- Ventilation rates and type of system (Wargocki et al. 2002)
- Indoor environments and symptoms in offices (Mendell 1993)
- Many IEQ and health relationships, including indoor chemical and biologic pollutants, and effects including building-related illnesses, sensory irritation, eye irritation, and skin responses, in chapters within a comprehensive book (Spengler et al. 2000).

Respiratory infections and asthma are the health effects potentially associated with buildings for which the most evidence is available associating them directly with occupant performance. There are two likely mechanisms by which IEQ-related risk factors for asthma and respiratory disease could impair the performance of building occupants. First, respiratory infections and asthma are associated with increased absenteeism (Dixon 1985; Fowler et al. 1992; Smith DH et al. 1997; Weiss and Sullivan 1994), and this absenteeism seems likely, based on available evidence, to decrease performance among both students and workers (see section below on

"Attendance and performance"). In addition, these health outcomes seem likely, based on available evidence, to *directly* impair performance (see section below on "Health and performance or attendance"). Risk factors found in buildings for respiratory infections include nitrogen dioxide (Pilotto et al. 1997), moisture damage (Husman et al. 2002), concentration of specific or total molds (Jacob et al. 2002; Muller et al. 2002; Norback et al. 2002), renovation activities such as painting and flooring with associated emissions such as styrene and benzene (Diez et al. 2000), low ventilation rate (Fisk 2000; Menzies D et al. 2000; Milton et al. 2000), humidification (Milton et al. 2000), and also *lack* of humidification (Green 1985). Risk factors for either asthma or potentially related effects, such as increased pulmonary function variability, pulmonary hyper-responsiveness, or decreased pulmonary function, include fungi and bacteria (Garrett et al. 1998b; Garrett et al. 1998a; Hoffman et al. 1993; Seuri et al. 2000; Smedje et al. 1997), endotoxin (Michel et al. 2001; Michel et al. 1996), dust mites (Platts-Mills 2000), animal dander (Platts-Mills 2000; Smedje et al. 1997), formaldehyde (Rumchev et al. 2002; Smedje et al. 1997), chemicals in cleaning compounds (McCoach et al. 1999; Zock et al. 2001), outdoor pollutants (Guo et al. 1999; Steerenberg et al. 2001), dampness or water damage (Taskinen et al. 2000; Taskinen et al. 1997), carpets (Hansen 1987), and open shelves (Smedje et al. 1997).

A number of other health effects without demonstrated effects on absenteeism but with *potential* effects on performance have been associated with IEQ factors: allergic alveolitis, lung inflammation, bronchial obstruction, lower respiratory symptoms, atopy, and neurologic symptoms. Indoor risk factors for allergic alveolitis include dampness, water damage, or mold, in either buildings or HVAC systems (Hodgson et al. 1987; Kim et al. 2002; Kreiss 1989; Seuri et al. 2000; Thörn et al. 1996; Woodard et al. 1988). Indoor environmental risk factors for lung inflammation include endotoxin (Michel et al. 2001), formaldehyde (Franklin et al. 2000), and outdoor pollutants (Steerenberg et al. 2001). Risk factors for bronchial obstruction include PVC flooring (Jaakkola et al. 1999), textile wall materials (Jaakkola et al. 1999), and plasticizer-emitting materials (Oie 1997). Risk factors for asthmatic symptoms include moisture or dirt in HVAC systems (Mendell et al. 2003), moisture damaged surfaces (Bornehag et al. 2002; Park JH et al. 2002), plastic wall materials (Jaakkola et al. 2000), and outdoor pollutants (Ramadour et al. 2000). Risk factors for atopy include fungi (Garrett et al. 1998b; Muller et al. 2002), formaldehyde (Garrett et al. 1999), dampness or mold (Savilahti et al. 2001; Taskinen et al. 2000), and vehicle exhaust (Wyler et al. 2000). Risk factors for neurologic symptoms, such as headache, confusion, difficulty thinking, difficulty concentrating, or fatigue, include dust (Mølhave et al. 2000), VOCs (Mølhave et al. 1985; Otto et al. 1992), a used carpet taken from a complaint building (Lagercrantz et al. 2000; Wargocki et al. 1999), small particles (Mendell et al. 2002b), and higher temperatures within the comfort envelope (Mendell et al. 2002b).

Other health effects associated with indoor risk factors have uncertain connections with performance: nasal swelling, congestion, or inflammation (Norback et al. 2000b; Norback et al. 2000a; Pazdrak et al. 1993; Roponen et al. 2002; Sigsgaard et al. 2002; Steerenberg et al. 2001; Walinder et al. 1998; 1999; 2001); reduced lung function (Sigsgaard et al. 2002); irritant symptoms of nose, throat, eye, or skin (Mølhave et al. 2000; Nagda and Hodgson 2001; Rudblad et al. 1999; Ten Brinke et al. 1998; Walinder et al. 1998); increased mold-specific immunoglobulins (Hyvarinen et al. 2002); and nonspecific symptoms (Garrett et al. 1998b; Gyntelberg et al. 1994; Hodgson et al. 1991; Jaakkola and Heinonen 1989; Jaakkola et al. 1991; Kemp et al. 1998; Li et al. 1997; Meklin 2000; Mendell 1993; Mendell and Smith 1990; Menzies

R et al. 1993; Meyer et al. 1999; Meyer et al. 2002; Norback and Torgen 1989; Norback et al. 1990; Reinikainen et al. 1992; Rylander et al. 1992; Seppanen and Fisk 2002; Seppanen et al. 1999; Sieber et al. 1996; Skov et al. 1990; Taskinen et al. 2000; Wantke et al. 1996; Wyon 1992).

Health and performance or attendance

Absenteeism from viral respiratory infections is well recognized (Dixon 1985; Fisk 2000). Research has clearly documented that school absenteeism is more frequent among asthmatic children than well children, and that absenteeism increases with severity of the disease (Bussing et al. 1995; Diette et al. 2000; Fowler et al. 1992; McCowan et al. 1996; Parcel et al. 1979; Silverstein et al. 2001). The few available studies of a relationship between allergies and absenteeism have been positive, one in schools (McLoughlin et al. 1983) and one in offices (Preller et al. 1990).

Asthma has been associated, in many studies (Austin et al. 1998; Bussing et al. 1995; Diette et al. 2000; Fowler et al. 1992; Rietveld and Colland 1999) but not all (Gutstadt et al. 1989; Lindgren et al. 1992; Silverstein et al. 2001), with reduced performance among schoolchildren. Such a relationship for allergies has not been demonstrated among school children (McLoughlin et al. 1983), but has among allergic office workers during pollen season (Burton et al. 2001) and in controlled pollen exposures (Wilken et al. 2002). Various symptoms experienced in buildings have been associated with reduced performance among both school children (Diette et al. 2000; Landrus and Axcel 1990) and office workers (Hall et al. 1991; Nunes et al. 1993; Raw et al. 1990). Viral respiratory infections, according to a strong experimental study by Smith et al. (1990), adversely affect some aspects of performance.

Attendance and performance

Of 11 studies reviewed here, seven found increased school absences to be correlated with a measure of school performance (Douglas 1965; Ehrenberg et al. 1991; Marburger 2001; Rodgers 2001; Safer 1986; Silverstein et al. 2001; Ziomeck and Schoenberger 1983), three did not (Gutstadt et al. 1989; O'Brien et al. 1985; Port 1979), and one had mixed findings mixed (O'Neil et al. 1985). The two most strongly designed studies (Marburger 2001; Rodgers 2001) and one other of fairly strong design (Ziomeck and Schoenberger 1983) found statistically significant inverse relations between absence and performance. The overall picture from the 11 studies is of a clear *correlation* between school absenteeism and performance; while much of this correlation may result from mutually associated factors such as motivation or personal factors, some of the association, as best demonstrated by Rodgers (2001) and Marburger (2001), is likely to be causal. While the strongest studies thus suggest some direct relationship between increased absence and decreased short-term learning in school, it is not clear how much multiple reductions in short-term learning from absences aggregate to reduce long-term learning, or to what extent these effects, demonstrated most strongly to-date in studies of college classes, also occur in primary and secondary school classes.

Summary of findings

This review critiques and summarizes the limited available evidence on direct associations between measured IEQ factors or characteristics of HVAC systems and buildings and both the performance or attendance of building occupants. Although studied as direct associations, these influences are likely to occur through the links shown in Figure 2. This review more briefly summarizes the larger amount of available evidence on these separate links operating from IEQ through health effects to performance or attendance. Evidence on each of these specific links contributes to the plausibility of an overall influence of IEQ factors or HVAC/building characteristics upon the performance or attendance of building occupants.

Regarding relationships between IEQ (pollutants or thermal conditions) and performance or attendance, the review identified the following evidence:

- Strongly suggestive evidence linking higher indoor concentrations of nitrogen dioxide from indoor combustion sources to decreased attendance by children in schools (from one strong study).
- Strongly suggestive evidence linking higher concentrations of some gaseous pollutants – ozone and carbon monoxide, measured outdoors, but readily entering into buildings – to decreased attendance by children in schools, although the role of indoor exposures is not clear (from five strong studies).
- Strongly suggestive evidence that pollen exposure reduced performance of allergic adults, although the role of indoor exposures is not clear (from two strong studies).
- Weak, sparse, or inconsistent evidence on relationships between concentrations of VOCs, fungi, bacteria and respirable dust, and performance.
- Inconsistent evidence on concentrations of outdoor nitrogen dioxide or particles, and attendance among schoolchildren.
- Inconsistent evidence on temperature and performance, with more findings associating higher temperatures above the comfort envelope with decreased performance in adults and children (the potentially opposing effects of *benefits* from cooler temperatures and *risks* from contaminated air-conditioning systems might explain such inconsistencies).
- Inconsistent evidence on relative humidity and performance in offices and schools.
- Sparse evidence that increased relative humidity within the comfort envelope improves school attendance.

Regarding relationships between *characteristics of HVAC systems or buildings* and performance or attendance, the review identified the following evidence:

- Suggestive evidence linking presence of an old carpet taken from a complaint building to reduced performance by college students in controlled office/laboratories (from two strongly designed but difficult to generalize studies).
- Suggestive evidence from one fairly strong study that increased cleaning in offices can reduce illness absence in adults, but may not influence performance.
- Suggestive (but inconsistent) evidence linking inadequate outdoor air ventilation rates (known to allow build-up of pollutants produced indoors) to reduced attendance by adult workers in offices (from two strong studies).
- Inconsistent evidence linking inadequate outdoor air ventilation rates to reduced performance by adult workers in offices (two strong studies, and two others), and by students in schools (one potentially strong study with few details reported).
- Sparse or weak evidence that airborne particle removal increased performance and decreased absence in office workers.
- Sparse evidence that non-operable windows, personal thermal control, and lack of humidification decreased absence in office workers.

- Sparse or weak evidence that better physical facility conditions, larger buildings, older buildings, and presence of air-conditioning improved performance in schoolchildren.
- Conflicting evidence as to whether humidification increased or decreased absence in office workers or schoolchildren.

Regarding the relationships that may together provide the links between IEQ and performance or attendance – the relationships between IEQ and health effects, the separate relationships between these health effects and performance or attendance, and the relationship between attendance and performance – the review identified, without critique, the following evidence:

- Microbiological and chemical exposures from indoor sources, various building characteristics (such as moisture) associated with such exposures, and (possibly indoor) exposures to pollutants from outdoors have been related to respiratory infections and asthma, which are health outcomes documented to increase absenteeism and also likely to decrease performance.
- Indoor microbiological and chemical pollutants (including emissions from plastics) from indoor sources, and possibly some from outdoor sources, as well as a variety of HVAC and building characteristics, have been related to a broad range of additional health outcomes – allergic alveolitis, atopy, lung inflammation, bronchial obstruction, nasal swelling and inflammation, and a variety of respiratory, irritant, neurologic, and other symptoms – for which links to decreased performance or attendance are possible but have received little assessment.
- Fairly consistent correlations between reduced attendance and the performance of students that, due to findings in the strongest studies, seem to be at least partly causal.

Discussion

This section synthesizes and interprets the overall findings of the review, discusses limitations of the review, summarizes key existing data gaps and research questions, and suggests strategies for future research.

Synthesis of findings

We did not identify a set of findings sufficiently persuasive to establish specific causal relationships between IEQ in schools and the performance of students. We did identify several strongly suggestive or suggestive lines of evidence linking IEQ factors and the performance or attendance of building occupants through connections involving pollutant exposures. Strongly suggestive evidence linked higher concentrations of indoor nitrogen dioxide and outdoor ozone and carbon monoxide to decreased school attendance by children, and pollen concentrations to decreased office performance among allergic individuals. Suggestive evidence linked presence of (a specific) used carpet with reduced performance of office work. Inconsistent evidence linked lower outdoor air ventilation of buildings with decreased performance or attendance in offices and schools. Higher outdoor concentrations of ozone, carbon monoxide, and pollen are likely to cause higher indoor concentrations, and substantial proportions of exposures are likely to occur indoors. The relationships involving pollen, carpets, and ventilation, to the extent that they can be generalized to other offices, seem likely to apply to schools as well, assuming that the variety of relevant pollutant exposures is similar, and that children are at least as sensitive to them as adults.

We also found evidence supporting many individual links in a causal chain relating indoor environmental factors to occupant performance and attendance (Figure 2). A large body of evidence, much of it from studies of children, links a variety of IEQ exposures or building factors to health effects. Some of these health effects, such as respiratory infections and asthma, have demonstrated links to performance or attendance. While available evidence does not confirm links from IEQ through all documented IEQ-associated health effects to performance or attendance effects, the clear link between IEQ and a variety of health effects in children and adults by itself constitutes a substantial public health problem.

Other indirect evidence suggests a causal role of increased absence in reducing the performance of students. Decrements in teacher attendance or performance caused by poor IEQ may be an additional (but still undocumented) indirect cause of decreased performance among students.

Overall, the available evidence suggests that effects of IEQ on performance or attendance of occupants are likely to be mediated through biologic, chemical, or particulate pollutant exposures or through thermal conditions. Characteristics of HVAC systems, buildings, and occupied spaces, in ways not fully understood, influence IEQ exposures and conditions, which consequently may adversely affect the health, performance, and attendance of building occupants.

Limitations of review

This review has been most thorough in identifying and evaluating studies directly relating IEQ to the performance or attendance of building occupants. Identification of studies on other intermediate links was less thorough, and these reports, while subject to basic criteria for inclusion, did not receive methodological evaluation or critique. On the other hand, because many risk factors and outcomes in the area of this review are not well defined, conducting strongly designed research studies has been challenging. For this reason, the review used only moderately restrictive criteria, allowing inclusion of studies with substantial limitations and studies from conferences without formal peer review. The review did not include possible important effects of noise, light, or odor, nor did it include the relations of IEQ to discomfort or other physiological effects, and consequent effects on performance.

Since negative studies performed are less likely to be submitted or accepted for publication, they are less likely to be identified in literature reviews such as this, leading to a bias in reviews toward positive findings (Sterne and Egger 2001). The limited numbers of positive findings identified on any specific topic in this review prevents the use of available graphical checks for this bias. Therefore, the findings reported here may reflect findings skewed by publication bias toward the positive.

Key data gaps, research questions, and suggested research strategies

This review has identified several pathways through which school environments could reduce the performance and attendance of schoolchildren. Taken as a whole, findings from the available high-quality research supports links along several of these pathways. However, researchers have not yet identified the full range of environmental risks or exposures in school environments associated with performance or attendance; even for those initially identified, they have not adequately quantified the relationships or understood the biological processes involved in the adverse effects. Part of the difficulty in gathering this knowledge comes from limitations in the available techniques for measuring the risk factors, exposures, performance outcomes, and intermediate outcomes such as health effects. Thus, many critical gaps in our knowledge still exist.

A related gap in current knowledge is that little representative information is available to characterize the current IEQ that children in U.S. schools experience, in order to guide priority research or remedial actions. An exception is outdoor air ventilation rates, one of the best-documented risk factors for adverse effects on symptoms, if not on performance, in buildings. A broad range of studies, although not representative, suggests that ventilation rates are substantially below recommended levels in many US and European schools (Bartlett et al. 1999; Braganza et al. 2000; Corsi et al. 2002; Daisey et al.; Myhrvold et al. 1996; Norback et al. 2000b; Smedje and Norback 2000). Available studies have consistently associated inadequate ventilation rates in offices to increases in respiratory, irritant, and neurologic symptoms in adult workers. If the indoor exposures in school buildings that are controlled by ventilation are similar to the exposures in office buildings, and if children are at least as sensitive to these indoor exposures as adults are, then inadequate school ventilation is related to a substantial excess of preventable symptoms among U.S. school children, with uncertain other effects on health or performance. About other aspects of IEQ in current schools, little is known except that the state of repair and general physical conditions in schools are often poor (U.S. General Accounting Office 1995).

To justify improving school IEQ in order to improve performance or attendance of students, research in this area needs to better document valid and consistent associations between well-characterized environmental risks and performance or attendance, if possible clarifying the nature and mechanisms of any intermediate links (e.g., through health effects or discomfort). A primary goal of research on adverse effects of the environment is to produce evidence documenting cause-effect relationships, based on criteria such as study validity, strength and consistency of association, temporality, and biologic gradient (Hill 1965). For many of the IEQ/performance links reviewed here, however, sufficient evidence is not available even to document consistent statistical associations, much less causality.

More evidence is available of statistical associations between aspects of IEQ in buildings (for instance, related to moisture and ventilation rates) and the health of occupants, even if this evidence still fails to establish causal relationships. Thus, more justification exists now for improving IEQ in schools to reduce health risks to students than to reduce performance or attendance risks. However, since IEQ-performance or IEQ-absenteeism links ultimately identified are likely to operate largely through IEQ-health links, IEQ improvements that benefit the health of students are likely to have performance and attendance benefits as well.

A set of priority research recommendations for improving IEQ to benefit the health of *workers* in indoor environments, but readily applicable to students in schools, has recently been published (Mendell et al. 2002a). A similar set of prioritized research recommendations for improving IEQ to benefit the attendance and performance of students is beyond the scope of this review. To help fill the gaps in knowledge, however, we recommend as urgent research priorities:

- Document the prevalence in schools of exposures or conditions considered likely to have adverse effects on *performance, attendance, or health* (e.g., low ventilation rates; visible moisture or mold; and high concentrations of formaldehyde, nitrogen dioxide, or outdoor pollutants). Identify sites requiring immediate remediation.

- Document the consequences of these exposures or conditions for *performance, attendance, or health* using well-designed studies. Focus initially on exposures or conditions likely to be widespread, effects likely to be relatively widespread or serious, and situations relatively amenable to remedial or preventive actions.

- Document effective strategies to prevent or mitigate these exposures or conditions,

Research performed should use rigorous research strategies, strong study designs, the best feasible measures of exposures relevant to the human outcomes of interest, and objective physiologic/biologic measures of human outcomes. Results from available IEQ studies of strong research design demonstrate that rigorous design standards, although not now consistently applied, are possible to achieve, and suggests that well-designed research has good prospects for documenting existing IEQ-performance links in schools. Early research on preventive strategies is also important, even before specific causal exposures or mechanisms are fully understood, because this will accelerate public benefits. Finally, the design and conduct of research in this complex area requires multidisciplinary approaches, possibly including but not limited to educational research, social and behavioral research, exposure assessment science, microbiology, chemistry, building science, engineering, epidemiology, other medical or health science, and statistics.

An additional justification for urgent research and action is that a multi-billion dollar school construction program will occur in the U.S. within the next decade (Duke 1998), to provide classrooms for an expanding school-age population and replace deteriorating existing stock. This massive program may perpetuate the inadequate design and construction of current schools, and may include locations with high concentrations of outdoor pollutants, thus extending potential ill effects to new generations of children. Research is critical to clarify how indoor environments influence the performance and attendance of schoolchildren, so that current schools can be improved and new schools can be built that support the health and performance of the occupants.

Conclusions

The primary goal of this review was to summarize available knowledge relevant to indoor environments and the performance and attendance of children in school environments. The findings summarized here provide suggestive (and some strongly suggestive) evidence that certain conditions commonly found in U.S. schools, such as low ventilation rates, have adverse effects on the health and the academic performance of many of the more than 50 million U.S. schoolchildren (U.S. Department of Education 2002b). Effective public health actions do not always require or wait for documented causality. Thus these research findings make a strong case for immediate targeted actions of prevention and mitigation in school environments. These actions include ensuring, through the life of each existing and newly constructed school building, adequate outdoor ventilation, control of moisture, and avoidance of indoor exposures to commonly occurring microbiologic and chemical substances considered likely to have adverse effects. Furthermore, additional environmental health research in schools is needed to guide and motivate future actions.

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Table 1. Findings[a] from primary research on relationships between *pollutants* or *thermal conditions* and (a) *performance* or (b) *attendance*

OUTCOMES	STUDY FEATURES					IEQ EXPOSURES								REFERENCES
						Pollutants						Thermal Conditions		
	Setting	**Subject**	**Design**	**Key confounders controlled**	**Peer Reviewed?**	**VOCs**	**NO_2**	**Gases (outdoor source)**	**Biologicals**	**Particles**	**Particles (outdoor source)**	**Higher temperature**	**Lower relative humidity**	
(a) Performance														
performance tests	**L**	**A**	**E**	©	✔	▒								Molhave 1986
performance tests	**L**	**A**	**E**	©	✔	▒								Otto 1992
subjective mental performance	**S**	**C**	**cs**	©	**c**	↓			↓	↓			↑	Smedje 1996
Concentration, self-reported	**O**	**A**	**cs**	©	✔	↓			↓					Gyntelberg 1994
telephone job productivity	**O**	**A**	**C**	©	✔				▒					Burton 2001
performance tests	**S/L**	**C**	**E**	©	✔							▒ ○		Schoer 1973
telephone job speed	**O**	**A**	**C**	©	**c**							▒	○	Federspiel 2002
telephone job speed	**O**	**A**	**C**	©	**c**							○	○	Fisk 2002
simulated office tasks	**O/L**	**A**	**E**	©	**c**							▒	▒	Fang 2002
performance-related mental states	**O**	**A**	**C**	©	✔							↓	○	Mendell 2002
learning efficiency	**L**	**A**	**E**	©	✔							▒		Pepler 1968
typing tests	**L**	**A**	**E**	©	✔							↓		Wyon 1974
performance tests	**L**	**A**	**E**	©	✔							▒		Wyon 1975
performance tests	**L**	**A**	**E**	©	✔							▒		Wyon 1979
(b) Attendance														
attendance, parent-recall	**S**	**C**	**C**	©	✔		▒							Pilotto 1997
lack of illness absence	**S**	**C**	**C**	©	✔			▒						Romieu 1992

OUTCOMES	STUDY FEATURES					IEQ EXPOSURES								REFERENCES
						Pollutants						Thermal Conditions		
	Setting	Subject	Design	Key confounders controlled	Peer Reviewed?	VOCs	NO_2	Gases (outdoor source)	Biologicals	Particles	Particles (outdoor source)	Higher temperature	Lower relative humidity	
lack of illness absence	S	C	C	©	✓									Hwang 2000
lack of illness absence	S	C	C	©	✓									Park 2002
lack of illness absence, recorded and teacher recall	S	C	C	©	✓									Gilliland 2001
attendance	S	C	C	©	✓									Chen 2000
recorded attendance	S	C	C	©	✓						↓			Ransom 1992
recorded attendance	S	C	C	©	✓						↓			Makino 2000
attendance, recorded and parent recall	S	C	C		✓								↓	Green 1974

Table 2. Findings[a] from primary research on relationships between *HVAC system characteristics* or *building characteristics* and *(a) performance* or *(b) attendance*

OUTCOMES	STUDY FEATURES					HVAC AND BUILDING CHARACTERISTICS										REFERENCES
						HVAC Characteristics						Building Characteristics				
	Setting	Subject	Design	Key confounders controlled	Peer reviewed?	Lower ventilation rate	Airborne particle removal	Operable windows	Air-conditioning systems	Humidification systems	Personal thermal control	Better condition / cleaning	Newer building	Larger building	Carpet	
(a) Performance																
subjective mental performance	S	C	cs	©	c	↓							↓	↑		Smedje 1996
reaction/performance tests	S	C/A	qE	©	c	↓										Myhrvold 1996
simulated office tasks	O/L	A	E	©	✓	↓ (shaded)										Wargocki 2000
telephone job speed	O	A	qE	©	c	↓ ↑										Federspiel 2002
telephone job speed	O	A	qE	©	c	↓										Fisk 2002
simulated office tasks	O/L	A	E	©	c	(shaded)										Fang 2002
performance-related mental states	O	A	qE	©	✓		↑									Mendell 2002
academic achievement tests	S	C	qE		✓				↑ ○							McNall 1967
measured office work	O	A	qE	©	✓						↑					Kroner 1994
achievement tests	S	C	cs		✓							↑				Berner 1993
psychological tests of concentration	O	A	qE	©	c							(shaded)				Nilsen 2002
simulated office tasks	O/L	A	E	©	✓										↓	Wargocki 1999
simulated office tasks	O/L	A	E	©	c										↓	Lagercrantz 2000
(b) Attendance																
lack of sick days, records	O	A	qE	©	c	(shaded)										Myatt 2002
attendance	O	A	C	©	✓					↓						Milton 2000
attendance	DC	C	qE		✓		↑									Rosen 1999
lack of sick days, self-reported	O	A	cs	©	c			↑		↓	↑					Preller 1990
attendance, records and parental recall	S	C	cs		✓					↑						Green 1974
attendance, records	S	C	C		✓					↑						Sale 1972

OUTCOMES	STUDY FEATURES					HVAC AND BUILDING CHARACTERISTICS										REFERENCES
						HVAC Characteristics						Building Characteristics				
	Setting	Subject	Design	Key confounders controlled	Peer reviewed?	Lower ventilation rate	Airborne particle removal	Operable windows	Air-conditioning systems	Humidification systems	Personal thermal control	Better condition / cleaning	Newer building	Larger building	Carpet	
lack of sick days, records	**O**	**A**	**qE**	©	**c**											Nilsen 2002

LEGEND for Tables 1 and 2

Settings

- **S** school (indoor or outdoor)
- **DC** day care facility
- **O** office or other non-school workplace
- **R** residence
- **L** laboratory
- --- no specific setting

Subjects

- **C** children (age up to ~16 years)
- **A** adults (age over ~16 years)

Design

- **E** experiment
- **qE** quasi-experiment
- **C** cohort (prospective or retrospective)
- **cs** cross-sectional

Control for Confounding

- © controlled or adjusted for key potential confounders

Peer Review

- ✔ peer reviewed
- c in conference proceeding

Relationships found

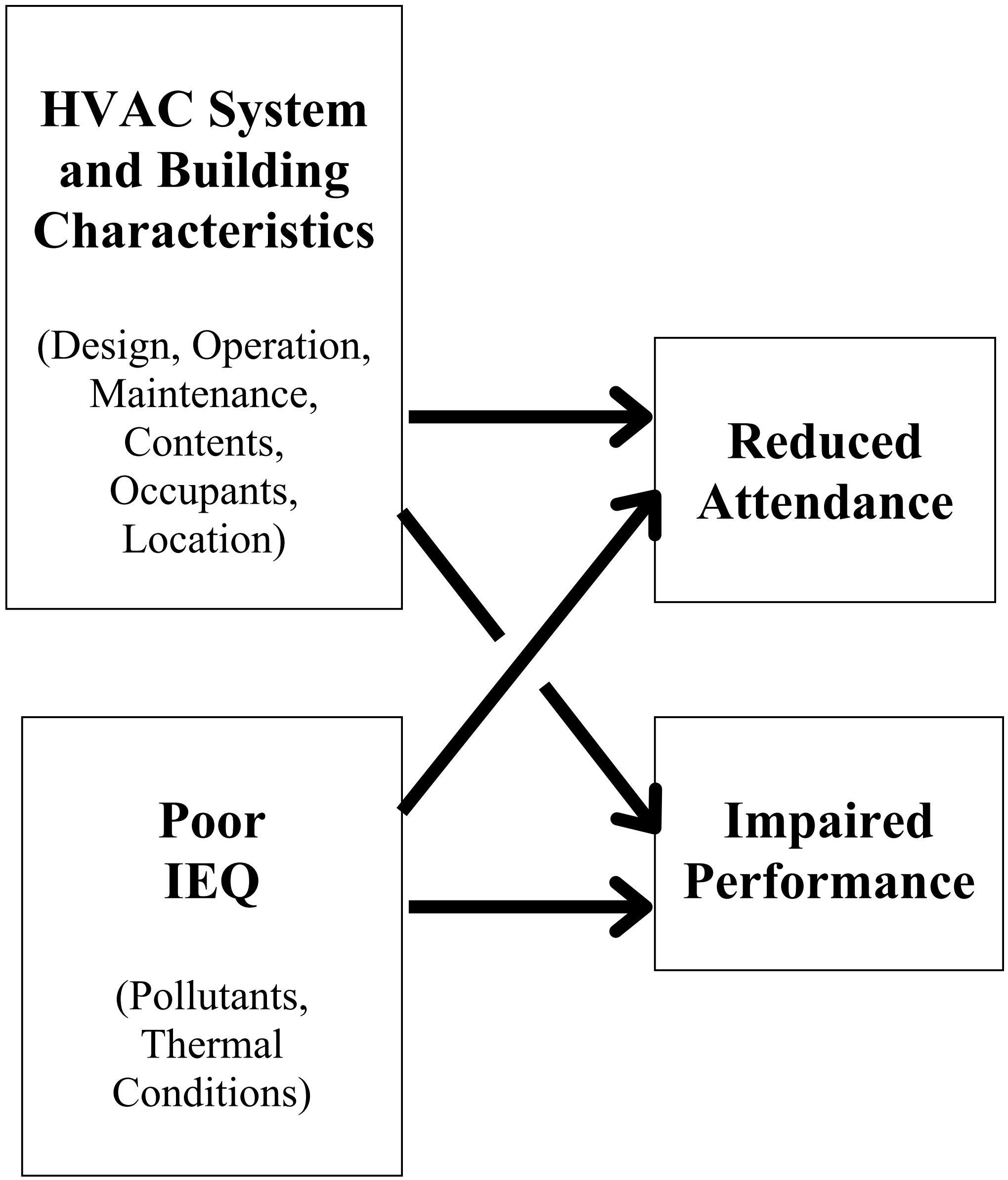
- O no statistically significant or noteworthy relationship
- 🡻 statistically significant or noteworthy *decrease* in beneficial outcome[a]
- 🡹 statistically significant or noteworthy *increase* in beneficial outcome[a]
- ▒ finding from study of strong design

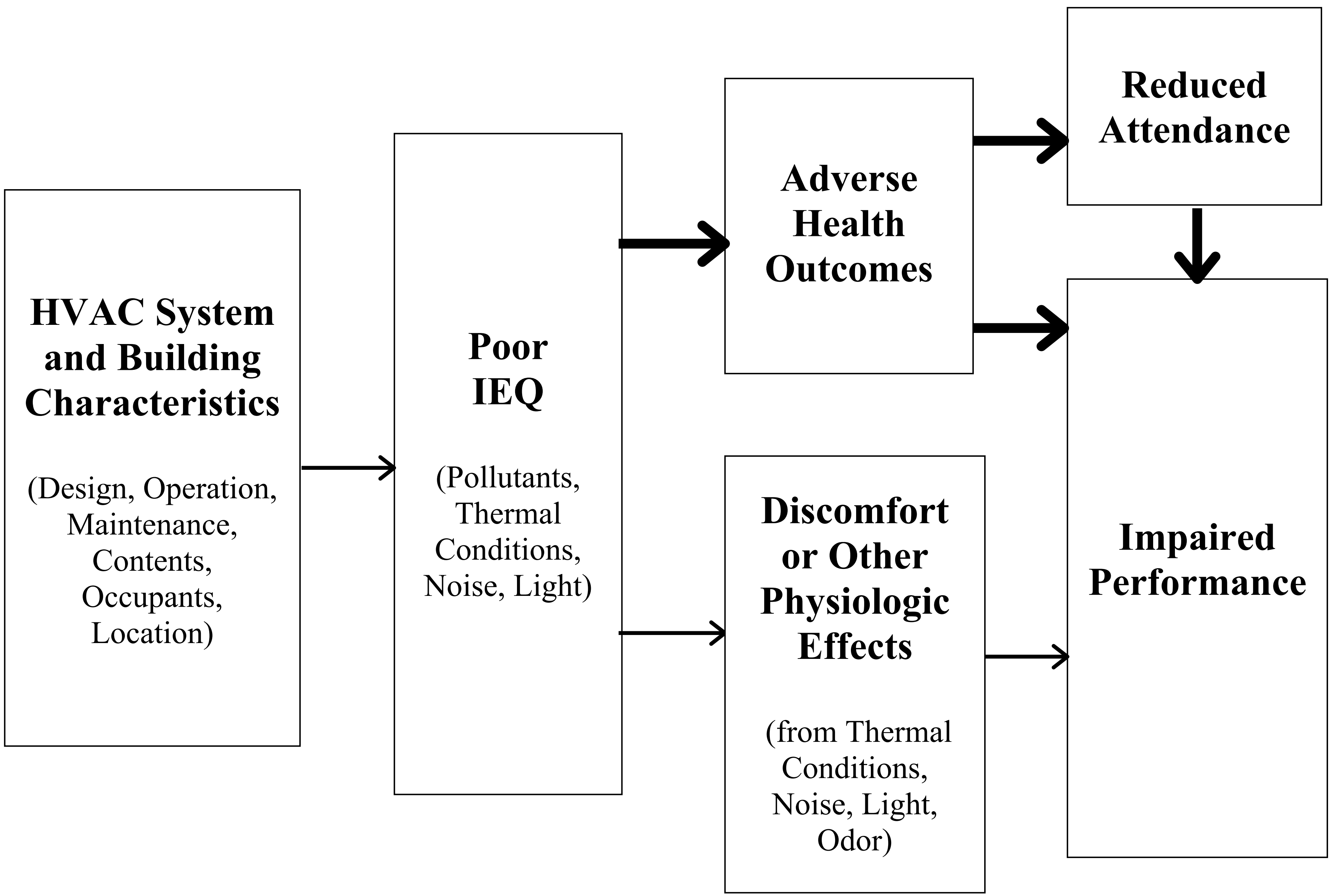
[a] As arrows represent the direction of specific findings, multiple arrows represent conflicting findings within a study. For consistency, upward-pointing arrows in these tables all represent positive effects. This required redefining outcomes for some reported studies; e.g., reported increases in illness absence, an adverse effect, are shown here as decreases in lack of illness absence.

Figure Titles

Figure 1. Primary associations reviewed

Figure 2. Hypothesized causal links relating indoor environmental quality (IEQ) in schools to attendance and performance of students (for primary associations reviewed, see Figure 1; **bold** arrows here indicate secondary associations summarized in review)


HVAC System and Building Characteristics
(Design, Operation, Maintenance, Contents, Occupants, Location)
Poor IEQ
(Pollutants, Thermal Conditions)
Reduced Attendance
Impaired Performance


HVAC System and Building Characteristics
(Design, Operation, Maintenance, Contents, Occupants, Location)
Poor IEQ
(Pollutants, Thermal Conditions, Noise, Light)
Adverse Health Outcomes
Discomfort or Other Physiologic Effects
(from Thermal Conditions, Noise, Light, Odor)
Reduced Attendance
Impaired Performance