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ABSTRACT

The goal of this paper was to critically review available evidence on relationships between indoor environmental quality (IEQ) in schools and student performance. Because available evidence from schools was limited, the review expanded to include studies on direct relationships between the performance of children and adults and the indoor environments in schools, workplaces, residences, and controlled laboratory settings. The most persuasive available evidence suggests that some aspects of IEQ, including low ventilation rate and less daylight or light, may reduce the performance of occupants, including students in schools. Other evidence identifies additional possible influences, such as pollen and some carpets. Substantial limitations in the quantity and quality of available research findings suggest many questions for future study. Sufficient evidence is available to justify (1) actions to safeguard IEQ in schools and (2) the conduct of focused, well-designed research to help guide future policies and actions regarding IEQ in schools.

INDEX TERMS: schools, students, performance, indoor environmental quality, indoor air quality

INTRODUCTION

There is widespread concern that indoor environments can affect occupants' health, comfort and performance (U.S. EPA, 2001). Indoor environments in schools are of particular public concern because:

1) Schools, relative to other kinds of buildings, are seen as particularly likely to have environmental deficiencies that could lead to poor indoor environmental quality (IEQ). In particular, chronic shortages of funding in schools contribute to inadequate operation and maintenance of facilities (GAO, 1995).
2) Children breathe higher volumes of air relative to their body weights and are actively growing. Thus, they have greater susceptibility to environmental pollutants than adults. Children also spend more time in school than in any other indoor environment outside the home. Adverse environmental impacts on the learning and performance of students in schools could have important immediate and lifelong effects, for the students and society.

The simple model in Figure 1 shows hypothesized influences of IEQ on the performance of students. Building characteristics [box A] can influence both indoor pollutant exposures and indoor physical parameters (collectively referred to in the paper as IEQ, or as *measured IEQ factors*). Indoor physical parameters can themselves influence indoor pollutant exposures, and both types of IEQ factors can influence health outcomes. Health outcomes can influence

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performance directly or through effects on attendance. Indoor physical conditions can also directly influence performance.

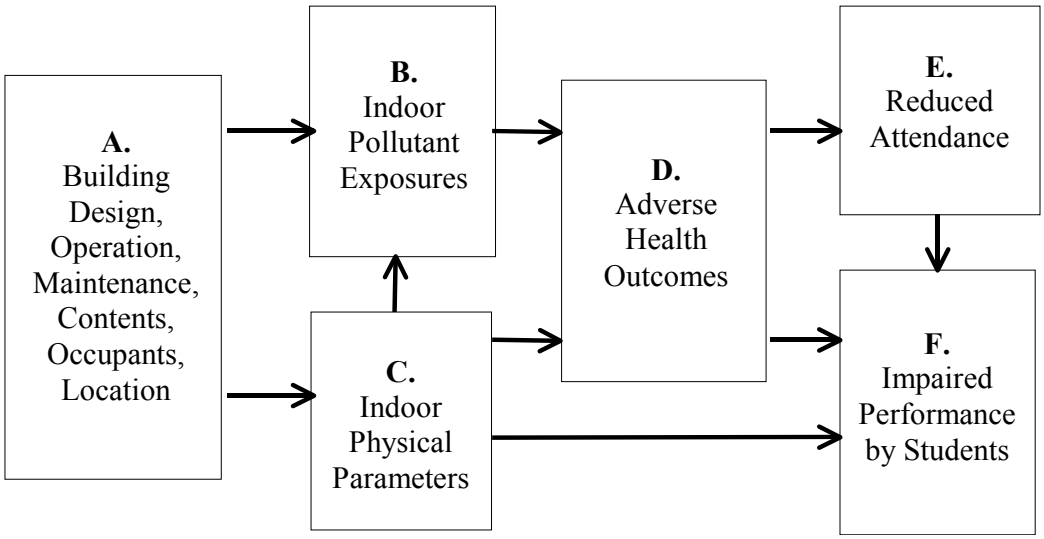

Figure 1. Links in hypothesized causal chains from building characteristics through indoor exposures and physical conditions in schools to student attendance and performance.

This paper summarizes the limited available evidence on direct associations between measured IEQ factors or building characteristics and the performance of building occupants. Although studied as direct associations, these influences are likely to occur through the links shown in Figure 1. Evidence on each of these links contributes to the plausibility of an overall influence of measured IEQ factors or building characteristics upon the performance of building occupants. A larger amount of information is available on these intermediate links; a future report by the same authors will evaluate this evidence.

The present review updates and extends previous reviews on IEQ-performance/productivity links, such as USEPA (2001), Bayer (2000), Fisk (2000), and Sensharma and Woods (1998). Because available evidence from schools was limited, the review included findings on a broader range of subjects and environments relevant to an understanding of IEQ effects on students in schools, e.g., potential adverse effects of school, day-care center, office, and home environments on their occupants. The environmental factors included in this review are: indoor environmental contaminants (including those of outdoor origin and excluding radon, lead, and asbestos); contaminant control processes (e.g., ventilation rate); indoor thermal parameters; and characteristics of buildings that can influence IEQ (e.g., presence of humidification or daylighting).

METHODS

We followed a search strategy similar to Sensharma and Woods (1998), electronically searching (through September 2001) the databases of PubMed, ERIC, Web of Science, Toxline, and the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE), and manually searching key relevant journals and conference proceedings.

Our review process included evaluation of the strength and consistency of current direct evidence on how IEQ in schools may influence learning or performance of students. We evaluated the strength of studies by evaluating their study designs and measurement methods. Studies with the strongest designs – well-designed experiments, quasi-experiments (e.g.,

controlled intervention studies), or prospective observational studies, with proper measurements of risks and outcomes and statistical analyses – were considered most persuasive. Studies with weaker designs or analyses, such as those lacking statistical control for potentially confounding variables, were considered less persuasive. Studies of particularly weak design, such as case studies, uncontrolled interventions, or crude comparisons of two groups, were omitted from the review unless they offered specific information of value. Non-peer-reviewed articles were included despite their usual brevity, lack of available detail, and preliminary nature.

RESULTS

This paper includes information on 21 articles or reports, listed in Tables 1a and 1b. Of these, 14 were peer-reviewed and 6 were considered of strong design. Only one study of the twelve in school settings had a strong design; five studies in other indoor environments had strong designs. This section and Tables 1a and 1b summarize research findings about direct relationships in schools or non-school indoor environments between *measured IEQ factors* and performance (Table 1a) and between *IEQ-related characteristics of buildings* and performance (Table 1b).

Table 1a. Findings from primary research on direct relationships between *measured IEQ factors* and *performance.*

PERFORMANCE OUTCOMES	STUDY FEATURES		MEASURED IEQ FACTORS						Reference
			POLLUTANT EXPOSURES AND CONTROL				PHYSICAL PARAMETERS		
	Setting/Subject	Design	Microbiologic	Chemical	Particles (outdoor source)	Low Ventilation Rate	Higher Temperature	Lower Relative Humidity	
subjective mental performance *	S, C	C-S,©	↓	↓		↓		↓	Smedje 1996
performance tests	L, A	E,©		○					Otto 1992
performance tests	L, A	E,©		○					Molhave 1985
telephone productivity	O, A	PC,©			↓				Burton 2001
reaction and performance tests *	S, C	Q-E,©				↓			Myhrvold 1996
simulated office tasks	O/L, C	E,©				↓			Wargocki 2000
learning efficiency	S/L, C	E,©					↓↑		Pepler 1968
typing	L, C	E,©					↓		Wyon 1974
performance tests	L, C	E,©					↓↑		Wyon 1979

LEGEND for Tables 1a, 1b

Assessed Relationships

- O no statistically significant or noteworthy relationship
- ↓ statistically significant or noteworthy relationship with adverse outcome
- ↑ statistically significant or noteworthy relationship with beneficial outcome
- finding from study of strong design

Settings/Subject

- **S** school
- **O** office or other non-school workplace
- **L** laboratory
- **C** children (~<18 yrs)
- **A** adults

Performance Outcomes

- * not peer-reviewed

Design

- **E** experiment
- **Q-E** quasi-experiment
- **PC** prospective cohort
- **C-S** cross-sectional
- **©** controlled or adjusted for key potential confounders

Table 1b. Findings from primary research on direct relationships between *IEQ-related characteristics of buildings* and *performance.*

PERFORMANCE OUTCOMES	STUDY FEATURES		IEQ-RELATED CHARACTERISTICS OF BUILDINGS										References
			Ventilation Features		Building Features				Interior Features				
	Setting/Subject	Design	Air-Conditioning	Personal Control	Better Facility Condition	Newer Building	Larger Building	Near Noise Source	Carpet	Daylighting	Type of Light Bulb		
achievement tests/ academic progress *	S, C	PC, C-S,©	↓	↑						▨↑			Heschong 1999
achievement tests	S, C	Q-E	↑										McNall 1967
performance tests	S/L, C	E,©	↑										Schoer 1973
achievement tests *	S, C	C-S	↑		O↑								Cash 1993
measured office work	O, A	Q-E,©		↑									Kroner 1994
achievement tests *	S, C	C-S, PC			↑								Lewis 2000
achievement tests *	S, C	C-S			↑								Earthman 1995
achievement tests *	S, C	C-S			↑								Berner 1993
subjective mental performance *	S, C	C-S,©				↓	↑						Smedje 1996
reading comprehension	S, C	C-S						↓					Haines 2001
simulated office tasks	O/L, C	E,©							▨↓				Wargocki 1999
simulated office tasks*	O/L, C	E,©							↓				Lagercrantz 2000
achievement tests	S, C	Q-E									↑↓		Hathaway 1995

Although the available evidence does not persuasively document relationships between performance and specific indoor pollutants, it suggests that lower outdoor air ventilation rates, known to cause generally higher concentrations of the pollutants produced indoors, were related to reduced performance among occupants (Table 1a – Wargocki, 2000; Smedje, 1996). One study documented that an outdoor air pollutant, pollen, can impair indoor performance of sensitized office workers (Table 1a – Burton, 2001). Two studies showed that the presence of a carpet (with uncharacterized emissions) taken from a

complaint building impaired performance of occupants (Table 1b – Wargocki, 1999; Lagercrantz 2000). One well-designed study found daylighting, or a related aspect of light in schools, to be related to increased learning by students (Table 1b – Heschong 1999). Insufficient consistent evidence was available to document relationships of indoor thermal parameters or noise to performance.

DISCUSSION

Because many risk factors and outcomes in the area of this review are not well defined, conducting strongly designed research studies has been challenging and the relationships explored here are far from documented causal links. Nevertheless, this review identifies useful scientific findings consistent with IEQ-performance links.

CONCLUSION AND IMPLICATIONS

These findings provide a basis for defining key future research questions and suggest that well-designed research has good prospects for documenting relationships between IEQ and performance in schools. However, since a primary goal of public health research is learning how to prevent adverse effects, effective public health actions do not always require or wait for documented causality; limited scientific evidence combined with common sense and public concern can justify early action. The results of this review may increase the justification for improving IEQ in schools.

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