Review and Assessment of the Health and Productivity Benefits of Green Schools: An Interim Report

Committee to Review and Assess the Health and Productivity Benefits of Green Schools
Board on Infrastructure and the Constructed Environment
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
WASHINGTON, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by a Master Services Agreement between the National Academy of Sciences and the Massachusetts Technology Collaborative (awarded November 2004); Grant 1906 between the Barr Foundation and the National Academy of Sciences (awarded September 2004); and funding from the Connecticut Clean Energy Fund (awarded April 2005); the Kendall Foundation (awarded March 2005); and the U.S. Green Building Council (awarded February 2005). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-10120-4

Copies of this report are available from the Board on Infrastructure and the Constructed Environment, National Research Council, 500 Fifth Street, N.W., Room 943, Washington, DC 20001; (202) 334-3376.

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE TO REVIEW AND ASSESS THE HEALTH AND PRODUCTIVITY BENEFITS OF GREEN SCHOOLS

JOHN D. SPENGLER, Harvard University, *Chair*
VIVIAN E. LOFTNESS, Carnegie Mellon University, *Vice Chair*
CHARLENE W. BAYER, Georgia Institute of Technology
JOHN S. BRADLEY, National Research Council, Ottawa, Canada
GLEN I. EARTHMAN, Virginia Polytechnic Institute and State University
PEYTON A. EGGLESTON, Johns Hopkins University
PAUL FISETTE, University of Massachusetts, Amherst
CAROLINE BREESE HALL, University of Rochester
GARY T. HENRY, Georgia State University
CLIFFORD S. MITCHELL, Johns Hopkins University
MARK S. REA, Rensselaer Polytechnic Institute
HENRY SANOFF, North Carolina State University
CAROL H. WEISS, Harvard University
SUZANNE M. WILSON, Michigan State University

Staff

LYNDA STANLEY, Director, Board on Infrastructure and the Constructed Environment
KEVIN LEWIS, Program Officer
PAT WILLIAMS, Senior Project Assistant

BOARD ON INFRASTRUCTURE AND THE CONSTRUCTED ENVIRONMENT

HENRY J. HATCH, U.S. Army Corps of Engineers (retired), Oakton, Virginia, *Chair*
MASSOUD AMIN, University of Minnesota
REGINALD DesROCHES, Georgia Institute of Technology
DENNIS DUNNE, Consultant, Scottsdale, Arizona
PAUL FISETTE, University of Massachusetts, Amherst
LUCIA GARSYS, Hillsborough County, Florida
WILLIAM HANSMIRE, Parsons Brinckerhoff Quade & Douglas
THEODORE C. KENNEDY, BE&K, Inc.
SUE McNEIL, University of Delaware
DEREK PARKER, Anshen+Allen
HENRY G. SCHWARTZ, JR., Washington University
WILLIAM WALLACE, Rensselaer Polytechnic Institute
CRAIG ZIMRING, Georgia Institute of Technology

Staff

LYNDA STANLEY, Director
MICHAEL COHN, Program Officer
KEVIN LEWIS, Program Officer
DANA CAINES, Financial Associate
PAT WILLIAMS, Senior Project Assistant

Acknowledgment of Reviewers

This interim report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Karen Anderson, Florida Department of Health,
William J. Fisk, Lawrence Berkeley National Laboratory,
Robert E. Fullilove, Columbia University,
Martin Moeck, Pennsylvania State University, and
William Rose, University of Illinois at Urbana-Champaign.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Henry W. Riecken, University of Pennsylvania, Emeritus, and Richard N. Wright, National Institute of Standards and Technology, retired. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

BACKGROUND

At the request of the Massachusetts Technology Collaborative (MASSTECH), the Barr and Kendall Foundations, the Connecticut Clean Energy Fund, and the U.S. Green Building Council, the National Research Council (NRC), through the Board on Infrastructure and the Constructed Environment (BICE), appointed the Committee to Review and Assess the Health and Productivity Benefits of Green Schools. The committee's charge was to "review, assess, and synthesize the results of available studies on green schools and determine the theoretical and methodological basis for the effects of green schools on student learning and teacher productivity." In the course of the study, the committee was asked to do the following:

1. Review and assess existing empirical and theoretical studies regarding the possible connections between the characteristics of "green schools" and the health and productivity of students and teachers.
2. Develop an evaluation framework for assessing the relevance and validity of individual reports that considers the possible influence of such factors as error, bias, confounding, or chance on the reported results and that integrates the overall evidence within and between diverse types of studies.
3. Report the results of this effort in a manner that will facilitate the identification of causal relationships and the subsequent implementation of beneficial practices.
4. Identify avenues of research that represent potentially valuable opportunities to leverage existing knowledge into a better understanding of the relationships between green building technologies in schools and the performance of students and teachers.

The committee, appointed in January 2005, has held four meetings. A fifth meeting will be held in January 2006, and the committee will complete its final report by April 30, 2006. This interim report has been prepared at the request of MASSTECH. MASSTECH is preparing a legislative proposal for green school guidelines, to be submitted to the Massachusetts School Building Authority in December 2005. MASSTECH has requested a summary of the committee's findings and recommendations to date as guidance in finalizing its proposal.

Because this is an interim report, it is important to note that the committee has not yet fully addressed the statement of task. The committee has developed an evaluation framework (task 2) and has reviewed and assessed *some* of the empirical and theoretical studies that address some characteristics of green schools and their associations with the health and development of students and teachers (task 1). In this interim report, the committee has dealt with five characteristics of green schools—building envelope, ventilation, lighting, acoustics, and condition—and evaluated the scientific evidence for relationships/associations with various outcomes of health, learning, and productivity (task 3). The committee plans to review and assess additional characteristics of green schools and the evidence for associations with health and development and report the results of those assessments in its final report.

To fulfill the statement of task, the committee will also synthesize the results of all of the assessments (overall task) and identify avenues of research that represent opportunities to leverage existing knowledge into a better understanding of the relationships between green building technologies in schools and the performance of students and teachers (task 4).

COMPLEXITY OF THE TASK

The charge to this committee is to review and assess existing empirical and theoretical studies on the possible connections between characteristics of green schools and the health and performance of students and teachers. Such an evaluation would ideally be based on a generally accepted definition of green schools that would convey specific architectural features, systems, and operational practices. However, there is no single, accepted definition among educational professionals, architects, and others, of what constitutes a "green school." Instead, there are many definitions with varying levels of detail for green schools (sometimes referred to as "high-performance green schools" or "high-performance schools"). The definitions typically focus on environmental or other objectives to be achieved through "green" or sustainable design processes, features, and practices. Various sets of guidelines have been developed to suggest a multitude of ways in which the objectives can be achieved to some degree. Typically the guidelines move well beyond design and engineering criteria for school buildings to address land use, processes for construction and equipment installation, and operation and maintenance practices.

The committee's task is further complicated by the fact that green schools are not standardized in their design and there are relatively few schools considered as exemplifying green design. Adding to the complexity is the need to draw on literature from a wide array of professional disciplines, including medicine, education, architecture, and engineering. These disciplines have developed differing research methodologies and criteria for determining causality. The committee also recognizes that many factors in a school as well as in a community and individual households influence the educational achievement of individuals and schools systems. Those factors or variables can be difficult to control for or measure in evidence-based studies, which, in turn, limits the inferences that can be drawn. In addition, the effects of the built environment will necessarily appear to be small, given the number of variables.

COMMITTEE'S APPROACH

Given these complexities, the committee's approach was to identify those characteristics of green schools that are typically emphasized in the current definitions and guidelines and that differ from conventional new school construction norms. The committee also identified those characteristics that potentially have a level of importance for health and learning outcomes. In this interim report, the committee focuses on the following characteristics of green school buildings and their relationships to occupant health and productivity outcomes:

- Building envelope, moisture management, and health;
- Ventilation, pollutant source control, health, and productivity;
- Lighting, performance, and health;
- Acoustics, student learning, and teacher health; and
- Building condition and student achievement.

In evaluating the scientific literature related to these topics, the committee has relied on a hierarchy of evidence for scientific inference developed by the National Academies (Box ES.1) for use in health-related studies (IOM, 1991, 1993, 1994, 1996, 1999, 2003). This hierarchy has played an important role in the committee's deliberations.

Box ES.1 National Academies' Hierarchy of Evidence for Scientific Inference in Health-Related Studies

Sufficient Evidence of a Causal Relationship: Evidence is sufficient to conclude that a causal relationship exists between the agent and the outcome. That is, the evidence fulfills the criteria for sufficient proof of an association, and in addition, satisfies evaluation criteria such as strength of association, biologic gradient, consistency of association, biologic plausibility and coherence, and temporally correct association. The finding of sufficient evidence of a causal relationship between an exposure and a health outcome does not mean that the exposure would inevitably lead to that outcome. Rather it means that the exposure can cause the outcome, at least in some people under some circumstances.

Sufficient Evidence of an Association: Evidence is sufficient to conclude that there is an association. That is, an association between the agent and the outcome has been observed in studies in which chance, bias, and confounding can be ruled out with reasonable confidence.

Limited or Suggestive Evidence of an Association: Evidence is suggestive of an association between the agent and the outcome but is limited because chance, bias, and confounding could not be ruled out with confidence. For example, at least one high-quality study shows a positive association, but the results of other studies are inconsistent.

Inadequate or Insufficient Evidence to Determine Whether or Not an Association Exists: The available studies are of insufficient quality, consistency, or statistical power to permit a conclusion about the presence or absence of an association. Alternatively, no studies exist that examine the relationship.

Limited or Suggestive Evidence of No Association: Several adequate studies are consistent in not showing an association between the agent and the outcome. A conclusion of "no association" is inevitably limited to the conditions, magnitude of exposure, and length of observation covered by the available studies.

SOURCE: IOM, 2004.

FINDINGS AND RECOMMENDATIONS

Finding 1: In its review thus far, the committee has found the following:

- There are no well-designed, evidence-based studies concerning the overall effects of green schools on the health or development of students and teachers, in part because the concept of green schools is quite new. There are, however, a few well-designed studies that examine specific building features often emphasized in green school design and the effects of these components on health and learning.
- Given the level of interaction between people and their environments and other confounding factors, establishing cause-and-effect relationships between an attribute of a school building and its effect on students, teachers, and staff is difficult. The effects of the built environment will necessarily appear to be small, given the number of variables.
- Empirical measures do not, however, necessarily capture all relevant considerations that should be applied when evaluating research results. Qualitative aspects of the environment are also important. Thus, in the committee's collective judgment, there is value in attempting to identify design features and building processes and practices that may lead to improvements in learning, health, and productivity for students, teachers, and other school staff, even if empirical results are less than robust.

Finding 2: In regard to issues related to building envelope, moisture management, and health, the committee has found the following:

- There is sufficient evidence to establish an association between moisture problems in buildings (floods, visible dampness, leaks, mold growth in spaces or in heating, ventilation, and air-conditioning [HVAC] systems) and adverse health outcomes, particularly asthma and respiratory symptoms, among children and adults.
- Excessive moisture in a building can lead to structural damage, deterioration of the performance of building systems and components, and cosmetic damage, all of which can result in increased maintenance and repair costs.
- Guidelines for green schools typically do not adequately address the design detailing, construction, and long-term maintenance of building envelopes to ensure that allergen sources are controlled, moisture is controlled, and a building is kept dry over the long term.
- Well-designed, constructed, and maintained building envelopes are critical to the control and prevention of the excessive moisture and molds that have been associated with adverse health effects in children and adults. Designing for effective moisture management will likely have benefits for the building, including lower life-cycle costs. Excellent resources for proper moisture control design include *The Moisture Control Handbook, Principles and Practices for Residential and Small Commercial Buildings* by Joseph Lstiburek and John

Carmody (1994) and *The Building Foundation Design Handbook* (ORNL, 1988), published by Oak Ridge National Laboratory.

Recommendation 1: The control of excessive moisture, dampness, and molds to protect the health of children and adults in schools and to protect the structural integrity of a building should be a key objective for green schools. MASSTECH should develop guidelines that specifically address moisture control as it relates to the design, construction, operation, and maintenance of a school building's envelope (foundations, walls, windows, and roofs); ventilation systems; and related items such as siting, landscaping, and plumbing systems.

Finding 3: In regard to ventilation, pollutant source control, health, and performance, the committee has found the following:

- Numerous pollution sources and building system characteristics affect air quality in a school. The most important determinants of indoor air quality are (1) design and operation of the ventilation system to limit the buildup of pollutants and humidity and achieve thermal comfort, (2) control of indoor sources of pollutants, and (3) control of outdoor sources of pollutants.
- There is a robust body of evidence indicating that the health of children and adults can be affected by air quality in a school.
- A growing body of evidence suggests that teacher productivity and student learning, as measured by absenteeism, may be affected by indoor air quality as well.
- Indoor pollutants and allergens from house dust mites, pet dander, cockroaches, and rodents also contribute to increased respiratory and asthma symptoms among children and adults.
- The reduction of pollutant loads, both sensory and not, has been shown to reduce the occurrence of building-associated symptoms and to improve the health and comfort of people occupying the buildings.
- Although compliance with the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) standards for ventilation rates may be the minimal acceptable standard for green schools, there is good evidence that increasing the ventilation rate beyond the ASHRAE standard will further improve comfort and productivity. However, an upper limit on the ventilation rates, indicating when the benefits of outside air begin to decline, has not been established.

The committee will address additional issues related to heating, ventilation, air-conditioning, and their associations with health and productivity outcomes in its final report. Until this review is completed and the results are synthesized, the committee will defer making specific recommendations.

Finding 4: In regard to lighting, performance, and health, the committee has found the following:

- Daylight is a special light source because it may provide a view (through a window), high light levels, and good color rendering, and it is ever-changing. Direct and reflected sunlight can create significant visual problems if windows, skylights, and clerestories allow in too much or too little light. However, such problems can be controlled with manual blinds and other types of window treatments.
- There is good evidence from studies of adult populations that the visual conditions in schools resulting from both electric lighting and daylighting are adequate for most children and adults.
- There is, however, concern that a significant percentage of students in classrooms do not have properly corrected eyesight, and thus, the general lighting conditions suitable for visual functioning by the average student may be inadequate for those students without properly corrected eyesight. It could be hypothesized that daylight may benefit these children by providing higher light levels and better geometries than would otherwise be present from electric lighting alone. However, the potential advantages of daylight in classrooms for improving visual performance of children with or without properly corrected eyesight has not been systematically studied.
- Because of inconsistent results and the small number of well-designed studies, there is insufficient evidence at this time to determine whether or not an association exists between daylighting and student performance.
- A growing body of evidence suggests that lighting may play an important nonvisual role in human health and well-being through the circadian system. However, the effect of light on health through circadian regulation of sleep, depression, and cell cycle has not been directly studied in children.

Recommendation 2: To determine the potential and actual performance of a lighting system, the entire system should be assessed because total performance cannot be effectively evaluated based solely on the source of illumination or on the individual components needed to create the entire lighting system.

Recommendation 3: For green schools in which the lighting strategy is to use daylight extensively, control systems that can be easily operated, such as manual blinds or other types of window treatments, should be specified in order to control excessive sunlight or glare.

Finding 5: In regard to noise, acoustics, student learning, and teacher health, the committee has found the following:

- Sufficient evidence exists to conclude that there is an association between decreased noise levels in schools and improvement in student achievement.
- Although there is strong evidence that reduced noise levels are most important for younger children because they are still developing speech discrimination, additional research is required to more precisely define possible needs for control of reverberant sound for younger children.

- Some available evidence indicates that teacher health, in regard to voice impairment, may be adversely affected by noisier environments, although the magnitude of the effect cannot currently be estimated as a function of exposure to noise.

Recommendation 4: To facilitate student learning, guidelines for green schools should include requirements to meet American National Standards Institute (ANSI) Standard S12.60, "Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools."

Finding 6: In regard to building condition and student achievement, the committee has found the following:

- The body of available research is suggestive of an association between the condition of a school building and student achievement. All of the studies analyzed by the committee found that student test scores improved as the physical condition of school buildings improved. The degree of improvement of students' test scores varied across the studies, but in all cases students in buildings in better condition scored higher than students in buildings in poor condition.

Recommendation 5: Guidelines for green schools should place significant emphasis on operations and maintenance practices if potential health and productivity benefits are to be achieved and maintained over the lifetime of a building.

1

Introduction

The charge to the Committee to Review and Assess the Health and Productivity Benefits of Green Schools is to review and assess existing empirical and theoretical studies concerning the possible connections between characteristics of "green schools" and the health and performance of students and teachers. Ideally, such an evaluation would be based on a generally accepted definition of green schools that would convey specific architectural features, systems, and operational practices. However, among educational professionals, architects, engineers, and others, there is no single, accepted definition of a green school (sometimes referred to as "high-performance green schools" or "high-performance schools"). Instead, there are many definitions with varying levels of detail. The definitions typically focus on environmental or other objectives to be achieved by building in a "green" or sustainable manner. MASSTECH, for example, defines a green school as having the following three distinct attributes:

- Less costly to operate than a conventional school,
- Designed to enhance the learning and working environment, and
- Conserves important resources such as energy and water.

The Collaborative High Performance Schools Web site notes that green schools are defined by the following 13 attributes: healthy, comfortable, energy efficient, material efficient, water efficient, easy to maintain and operate, commissioned, environmentally responsive site, a building that teaches, safe and secure, community resource, stimulating architecture, and adaptable to changing needs (CHPS, 2005). Other definitions abound.

The definitions often are put into operation through various sets of guidelines for constructing green schools. The guidelines typically identify a number of ways in which the objectives can be achieved to some degree. Such guidelines have been issued by California (CHPS, 2004) and Washington state (WSBE, 2005) and are in developmental stages in Massachusetts. These guidelines move well beyond design and engineering criteria for school buildings to address land use, processes for construction and equipment installation, and operation and maintenance practices. Guidelines may include design and engineering goals such as locating schools near public transportation to reduce pollution and land development impacts; placing a building on a site to minimize its environmental impact and optimize daylighting and solar gain; designing irrigation systems and indoor plumbing systems to conserve water; designing energy and lighting systems to conserve fossil fuels and maximize the use of renewable resources; selecting materials that are nontoxic, biodegradable, and easily recycled, and that minimize the impacts on landfills and otherwise reduce waste; and creating an indoor environment that provides occupants with thermal comfort and acoustic, visual, and air quality.

Guidelines for green schools also include construction goals such as the appropriate storage of materials on construction sites to avoid water damage, the reduction of waste materials and appropriate disposal to reduce resource depletion, and the introduction of commissioning practices[1] to ensure the performance of integrated building systems. To address the life-cycle performance of schools, guidelines for operation and maintenance practices are also included, such as using nontoxic cleaning products, replacing air filters in ventilation systems on a regular schedule, and establishing a long-term indoor environmental management plan.

GREEN SCHOOLS VERSUS CONVENTIONAL NEW SCHOOLS

Given the lack of a generally accepted definition of green schools, the committee focused on differentiating land use, building design/engineering, construction, and operations and maintenance practices that are often highlighted in the green school literature and not likely to be introduced in conventional new school construction. The committee then identified research in the literature looking at the relationships between these characteristics and a performance outcome (health, learning, productivity) in students or teachers. A complicating factor is that building systems and characteristics operate in an integrated fashion to effectively deliver (or not) overall building performance in regard to thermal comfort; air, visual, acoustic, and spatial quality; and long-term building integrity. Further, this performance will be affected by the operation and maintenance of these integrated systems over time and by the occupants of buildings and their activities. Thus there is a need to synthesize the results so that potential trade-offs between certain features and practices can be identified.

The committee's approach then was to identify those building characteristics that are emphasized in available definitions and guidelines as constituting green school design and differ from conventional new school construction norms. The committee also identified those elements that potentially have a level of importance for health and learning outcomes. In this interim report, the committee has focused on the following characteristics of green school buildings and their relationship to occupant health and productivity outcomes:

- Building envelope, moisture management, and health;
- Ventilation, pollutant source control, health, and productivity;
- Lighting, performance, and health;
- Acoustics, student learning, and teacher health; and
- Building condition and student achievement.

THE ELEMENT OF TIME

The design and construction of a new school or the renovation of an existing one require a substantial commitment of resources—time, dollars, materials, expertise—by a community. Typically, once built, a school is used for educational purposes for 30 years or

[1] Commissioning is "a quality-focused process for enhancing the delivery of a project. The process focuses on verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated to meet the Owner's Project Requirements" (ANSI, 2004).

longer. While the building is in service, the investment made in its operation, maintenance, and repair will be six to eight times greater than the initial cost of construction.[2]

School buildings are composed of materials and components that wear out at differing rates and that vary in their complexity and operations and in the costs to maintain them. So, although a building's foundations and walls may last for 50 to 100 years, the roof will likely wear out after 20 years and the air-conditioning system in 15 years. The level of maintenance undertaken, the timeliness and quality of the maintenance, the climate, and other factors will also affect the service lives of various systems and components.

Some design changes in green schools may increase the complexity of building systems. No matter how positive the design/engineering and construction gains are for green schools, their ongoing maintenance will be critical to the outcomes for health, learning, and productivity. Thus, the process of creating a green school does not end at the ribbon cutting.

MODELING THE EFFECTS OF GREEN SCHOOLS

Green schools have two complementary, but not identical, goals: (1) to support the development (physical, social, and intellectual) of students, teachers, and staff by providing a healthy, safe, comfortable, and productive physical environment and (2) to have positive environmental and community attributes. Thus, research on green schools might be conceptualized with two quite different sets of outcome measures: improved student and staff health and development, or improved environment and community. In line with its charge, the committee is focusing on outcomes associated with student and teacher health and performance.

An assessment of the outcomes of the quality of a school building on student and teacher health and performance must be set in context. First, time spent in school is, at most, 40 to 50 hours per week, and other environments could equally affect health and performance, including home, neighborhood, recreational, cultural, and religious settings. Even if outcomes could be tied specifically to the quality of the school setting, the influence of other educational factors might be far greater, including quality of curriculum, teacher education/preparation, parental support, peer support, background of student, prior health of student, quality of the administration, and educational standards. For example, research on teaching suggests that student learning is affected by teacher quality (variously defined as teacher experience, teacher knowledge, etc.), and research on learning suggests that student learning may also be affected by the quality of instructional materials, including curriculum, texts, and laboratory equipment. Policy researchers suggest that teaching and learning might be shaped by various state policies regarding teacher education, licensing, hiring, and professional development (Darling-Hammond, 1999), national policies such as the No Child Left Behind Act, and their implementation.

To help inform the committee of mechanisms by which the physical environment might affect student learning, teacher productivity, or the health of students, teachers, and staff, the committee developed a conceptual model for evaluating the research related to such links (Figure 1.1).

---

[2] The annual operation and maintenance costs of a building, however, will be only a fraction of the annual costs to operate an educational institution, which includes the salaries and benefits of teachers, administrators, and support staff; educational equipment and supplies; food service; and other expenses.

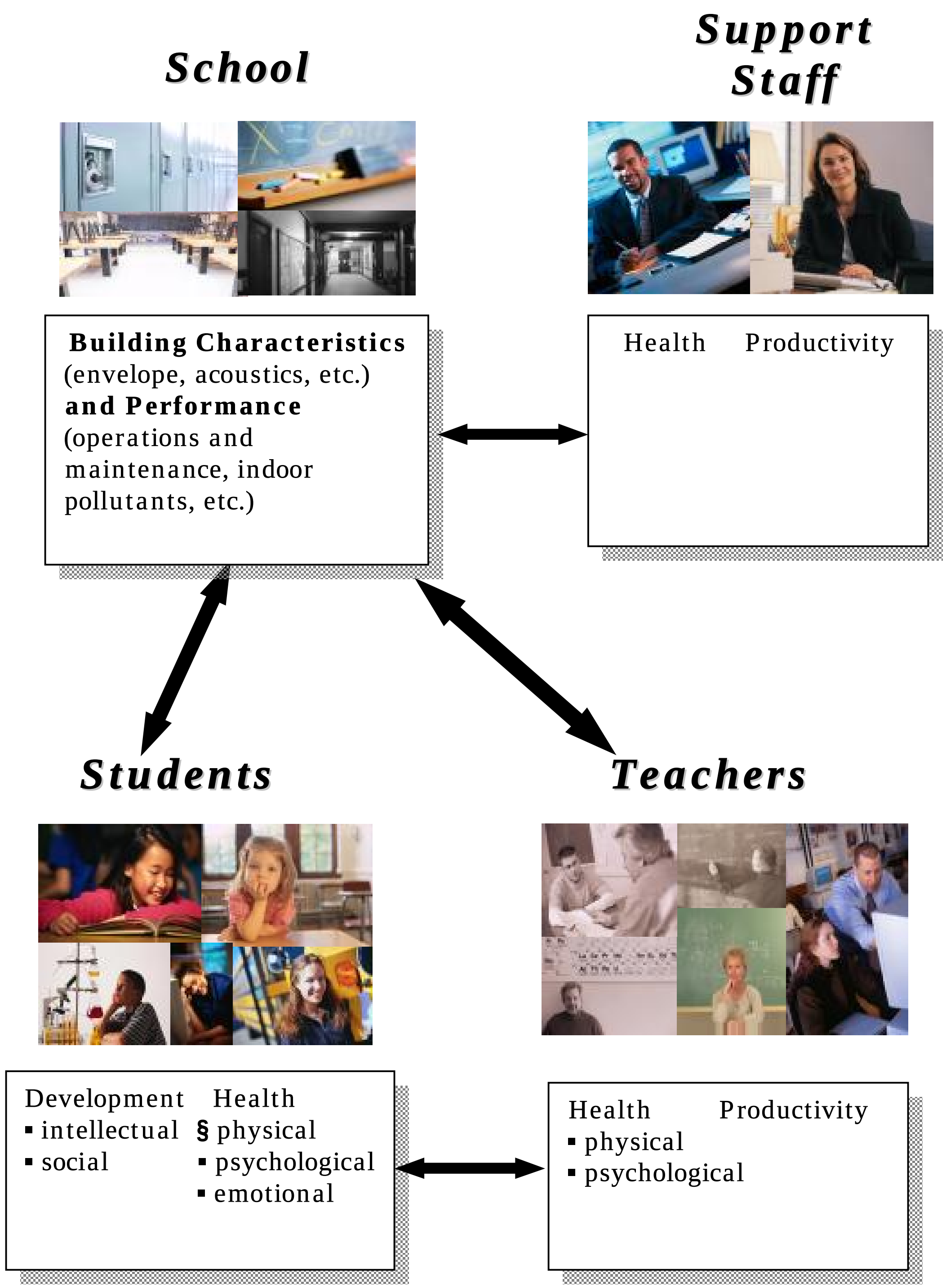

FIGURE 1.1 Conceptual model for evaluating links between school buildings, learning, and health.

School Building Characteristics and Human Response

In the conceptual model, a school building's physical characteristics (envelope, acoustics, lighting) affect an individual by providing an environment with appropriate (or inappropriate) light, sound, temperature, air, spatial condition, and other qualities. The *performance* of a school building and the quality of the environment provided will change by season (e.g., airborne pollen) and over time (e.g., mold growth from chronic water leakage) and will be affected by operational, maintenance, and repair practices and procedures.

Despite the individual nature of systems in school buildings, whether conventional or green, the interactions among systems can determine the overall performance of a building. Ventilation, for example, affects other environmental factors such as temperature, humidity, noise, vibration, and air quality factors of moisture control and microbial contamination. The mechanical ventilation system may also play a role in the transmission of infectious diseases or chemical emissions from materials and products. The location of air intakes, the efficiency of ventilation filters, and the operation of the system all will affect the amount and quality of outdoor air used to ventilate the indoor environment. The quality of a ventilation system's performance will depend on nonmechanical factors such as the level and timeliness of maintenance and repair, the training of maintenance staff, and management and operational practices. How a school is used (for educational purposes only or for community and other activities) and how intensely it is used (9 or 12 months of the year, by how many people) will also affect the overall performance of its systems.

The physical and psychological health of teachers may be affected by a school building's characteristics and conditions. When teachers' well-being suffers, so too might their instruction and their participation in school activities. In that sense, teachers can be seen as both an outcome of building conditions (they might be healthier or not, more motivated or not) and a mediating variable (they might teach differently or interact with students differently depending on their health and well-being) in explaining students' experiences. They may also positively or negatively alter a school's physical setting by adjusting the temperature of a room, opening or closing windows, and other actions.

A second population affected by building characteristics is students. Primary outcomes of interest are student learning and health. Student outcomes might be directly or indirectly related to a school building's condition: If there is high absenteeism at a school among teachers because of poor air quality, the content of instruction may suffer. If students are absent because of poor air quality, there is less opportunity to receive instruction. And, just as teachers can alter the school setting, so too can students.

A third population that can affect and be affected by a school's environment is the administrators (principals, financial staff, counselors, librarians) and support staff (building operations, maintenance, cleaning crews, and kitchen workers). These groups may spend as much time in a school building as teachers and students and sometimes at different times of the day (before and after classes, on weekends, during school breaks and summer vacation). The quality of the support staff training may be of particular significance in the performance of building systems, the timeliness and quality of maintenance and repair, and cleaning and sanitation practices.

Outcomes of Human Responses

It is impossible for researchers to directly access an individual's personal experiences. Instead, access to those experiences is gained indirectly by measuring outcomes such as learning, productivity, or attendance or by revealed preference (surveys). It becomes quite complicated to draw firm inferences about a cause-and-effect relationship between the physical environment and health and performance outcomes for individuals. Often multiple converging lines of research are needed for establishing "scientific fact." In addition, differing populations may have differing responses to features or attributes of the built environment.

In studying the relationships between building characteristics and condition and related teacher and student outcomes, researchers use indicators or surrogates for the relevant variables (Table 1.1). In the studies reviewed by the committee, multiple and quite varied measures were used for both the independent and the dependent variables. One measure, absenteeism, was used as a surrogate measure for student health, teacher health, student learning, and teacher productivity. (The committee plans to discuss outcome indicators in greater detail in its final report.)

TABLE 1.1 Illustrative Example of Indicators Used to Measure Relevant Outcomes

	Student	Teacher
Health	Asthma Allergies Cold/flu and other respiratory diseases Headaches Eye fatigue	Asthma Allergies Cold/flu and other respiratory diseases Vocal fatigue Headaches Eye fatigue
Development (learning and productivity)	Standardized test scores Working memory Prospective memory Sustained attention Reading comprehension Verbal comprehension Demonstration of concepts Graduation rates College enrollment rates Disciplinary incidents	Turnover/retention Attitude/motivation Teaching behaviors/methods Years of experience Knowledge Educational preparation Certification/licensure Teacher examination scores

COMPLEXITY OF THE TASK

The committee has been asked to consider the possible influence of confounding, bias, error, and chance in the relevant literature. Confounding, in particular, poses a major challenge to researchers and those evaluating their work. Confounding occurs when the exposure-adverse event association is biased as a result of a third factor that is capable of causing the adverse event and is statistically associated with the exposure. For example, in any epidemiological study comparing an exposed with a nonexposed group, a simple comparison of the groups may either exaggerate or hide the true difference, because it is likely that the two groups will differ with respect to factors that are also associated with the risk of the outcome of interest, such as socioeconomic status. Said differently, a simple comparison of the incidence of health outcomes among exposed and nonexposed groups may exaggerate an apparent difference because socioeconomic status is also thought to influence the incidence of several health problems.

A variety of confounding factors will be present in any study that attempts to link features of school buildings with student and teacher health and development. Age differences among students will influence the outcomes of research into health and learning: Young children have a higher relative volume of breathing per weight than teenagers; their tissues and organs are actively growing; they are still developing language and cognitive skills; and they spend more time in school than anywhere but home.

Research studies that include the use of any measure of student performance in making comparisons to other variables must try to control extraneous variables that influence the performance of students. For instance, when comparing student achievement test scores with the condition of the physical environment, a researcher would normally attempt to control other influences or variables that affect outcomes. They may include socioeconomic status, the community background of a student or a teacher, or the curriculum. Student test scores will also be influenced by conditions in the classroom on the day of the test and other factors.

Another confounding factor is that school buildings themselves are not standardized, making direct comparisons between school environments problematic. Unlike tract housing developments, most schools are designed by architects as unique structures, whose features depend on the resources available, construction methods, teaching methods, and building codes in effect at the time. They may have one or multiple stories, accommodate a hundred or several thousand students, and may be 5 or 100 years old; all of these factors could potentially influence health and performance outcomes.

The condition of school buildings is also a factor to be considered. School conditions are widely divergent across the country or even within localities. Those school systems with less financial ability and a greater percentage of students from low-income households seem to have school buildings in worse condition than those school systems that have a high tax base and the financial and leadership ability to solve the problems of providing good school buildings for students. Compounding these difficulties is the collection of data about school buildings: The Educational Writers Association (1989) found that few states had sufficient capability to properly evaluate school buildings because the department of education either had few or no personnel to conduct such services. Consequently, the collection of data was erratic.

The Variability and Quality of Research

Gaps in the research literature are also of concern. For example, much of what is known about the impact of the physical environment on health, well-being, and performance is based on studies of adult populations. Some research is quite narrow—in an effort to control for all possible extraneous variables. Other research is so broad that confounding variables are possible, if not likely. In general, much less is known about the impact of the school environment—green or otherwise—on the health and performance of children as compared with the impact of workplace environments on adults. Extrapolating from studies of adults to conclusions about a much younger population can be suspect. For example, environmental factors in the school may interact with genetic factors to determine the degree to which a child develops language skills or displays asthma symptoms. The physical environment could potentially have acute as well as lifelong effects on children's health and performance.

The line of reasoning inherent in this study's task—mapping connections from physical environments to student and teacher outcomes—poses significant challenges concerning cause-and-effect relationships. One challenge is that of directionality of relationships. Green schools might have positive effects on student health, but it might also be that students who live in communities inclined to build green schools are healthier to begin with. Another challenge is that in a conceptual model such as the one used here, the effects of physical environments might be "trumped" in some ways by other forces—teacher quality or parent involvement or financial resources. With outcomes as complex as student health and development—influenced as they are by many school, family, and community factors—it might be impossible to design research that controls for all potentially confounding variables.

A third challenge concerns the variability in the characteristics and standards used by different disciplines to conduct research. For example, medical research may employ clinical trials and intervention studies in which various factors can be controlled for and their results directly evaluated using established protocols. Often clinical trials of drugs include placebos administered according to the same protocol as the drug of interest. Epidemiological studies often rely on statistical significance as a quantitative measure of the extent to which chance or sampling variation might be responsible for an observed association between an exposure and an adverse event. In these studies, quantitative estimation is firmly founded in statistical theory on the basis of repeated sampling.

Studies linking the built environment with the behaviors of its occupants, in contrast, cannot set up strictly controlled trials or easily manipulate variables to test for statistical significance. Studies attempting to link students' and teachers' development with school environments cannot control for the effects of the environments in which students and teachers live during the times when they are in nonschool venues. In addition, there are no standard protocols for conducting building-related research, although some studies have used similar methodologies or evaluation methods, including multiple regression analyses and measures of statistical significance.

Measuring Student Learning and Teacher Productivity

Education is the transferring of knowledge and skills to students and is difficult to measure directly. To measure whether and how well students are learning, indicators or surrogate measures are often used to determine whether cognitive skills are indeed being transferred. Such surrogates include standardized test scores, demonstration of concepts, and graduation rates.

Productivity for an individual or an organization has been defined as the ability to enhance work output through increases in either the quantity and/or the quality of the product or service to be delivered (Boyce et al., 2003). Productivity is influenced both by the individual and the system within which he or she works. Increasing evidence is available to indicate that the built environment can influence both individual and organizational productivity. It can be measured in the number of units manufactured or in the number of words typed correctly in a given amount of time. Absence is often used as a surrogate, the rationale being that people who are absent are less productive than people who are on the job.

For other kinds of work, including teaching, productivity is more difficult to define and measure. Productivity is closely linked to the "quality" of teachers, both individually and collectively. Researchers have used various measures such as years of service, educational preparation, certification/licensure, and scores on teacher examinations (Praxis) in an attempt to obtain a measure of objectivity in determining the quality of the teaching staff. These measures can be quantified to a certain extent and therefore are used quite efficiently in research studies. These measures of quality have not been tested sufficiently, however, to enable a great deal of confidence in their effectiveness. The years of experience a teacher has is to a degree a measure of quality because the teacher is usually evaluated for the decision of granting tenure. To that extent, the quality of the teacher is high enough that the administration decides to retain the teacher because in its judgment the teacher has performed satisfactorily in the years before being considered for tenure. Conversely, there is no guarantee that gaining tenure is anything more than meeting the minimum standards.

For those reasons and because of the multiplicity of variables that can influence learning, evaluations of educational interventions do not often find a significant change in student achievement outcomes. Intensive in-service education for teachers, major revisions of curriculum, and addition of curricular units on substance abuse prevention or economics tend to show small gains at best. Thus, if certain building characteristics or operation practices also are shown to yield only a small gain, at best, in student achievement, such an outcome is not unexpected.

COMMITTEE'S APPROACH

The committee's initial review of the literature focused specifically on those studies that purport to address the connections between sustainable or green building design, student learning and health, and teacher productivity and health. No well-designed, evidence-based studies concerning the overall effects of green schools on the health or development of students and teachers were identified. However, a few studies examined specific building features often emphasized in green school design and the effects of these features on health and performance. Among those are a series of studies on daylighting and student achievement produced by the Heschong-Mahone Group between 1999 and 2003. These studies are discussed in Chapter 4. For the most part, however, the literature on green schools, health, and productivity consists of anecdotal information and case studies of varying quality. The committee also did not identify any evidence-based studies that analyze whether green schools are actually different from conventional schools in regard to the health and productivity of occupants. This lack of well-designed, evidence-based studies specifically related to green schools is understandable, because the concept of green schools is relatively new and evidence-based studies require a significant commitment of time and resources.

A much more robust body of scientific evidence is available that looks at the characteristics emphasized in green school design—building envelope, mechanical and engineering systems, lighting, acoustics—and their relationships to occupant health, development, and productivity. Typically, those studies look at a single system or at a very limited number of variables, and the quality of the studies varies. For example, a literature review of the available evidence on building characteristics, dampness, and health effects identified 590 epidemiological studies addressing these topics. Of these, only 61 met standards for a strong study design and the provision of useful information (NORDAMP, 2002). Relatively few studies look at the interrelationships of two or three building systems and their effects, for example, ventilation, acoustics, learning, and health. With these caveats in mind, the committee determined it should review the scientific literature relating to those characteristics of green schools that are typically emphasized in definitions and guidelines and that differ from conventional school building practices.

However, a review of all research literature that touches on some aspect of buildings and their potential impacts on occupant health, learning, or productivity is an undertaking beyond the resources of this study. In cases in which rigorous reviews of a particular aspect of interest have been conducted by the National Research Council or other organizations or researchers, the committee relies on that work (e.g., IOM, 2004; Mendell and Heath, 2004). In those areas in which the research is fairly limited but important to the study, the committee is conducting its own review. In all cases, the committee describes the source of the literature reviewed, the research methodology used in the studies reviewed, and the basis for the committee's conclusions. Ultimately, the determination of the scope of the literature review must be based on the committee's collective judgment in regard to where its efforts should be concentrated to best address the task statement and meet the sponsors' requirements.

In evaluating the literature, the committee has relied on a hierarchy of evidence for scientific inference developed by the National Academies (Box 1.1) for use in health-related studies (IOM, 1991, 1993, 1994, 1996, 1999, 2003). This hierarchy has played an important role in the committee's deliberations.

Given the level of interaction between people and their environments and other confounding factors, it may never be possible to categorically establish a causal relationship between an attribute of a school building and its effect on students, teachers, and staff. The effects of the built environment will necessarily appear to be small, given the number of variables. Nor may it be possible to quantify the effects of one feature, such as acoustics, on student learning. The committee used its collective best judgment with regard to evaluating the plausibility of the published research and possible explanations of physiological mechanisms, and then integrated the results of those studies found to be useful (if flawed) into its findings, conclusions, and recommendations.

Box 1.1 National Academies' Hierarchy of Evidence for Scientific Inference in Health-Related Studies

Sufficient Evidence of a Causal Relationship: Evidence is sufficient to conclude that a causal relationship exists between the agent and the outcome. That is, the evidence fulfills the criteria for sufficient proof of an association, and in addition, satisfies evaluation criteria such as strength of association, biologic gradient, consistency of association, biologic plausibility and coherence, and temporally correct association. The finding of sufficient evidence of a causal relationship between an exposure and a health outcome does not mean that the exposure would inevitably lead to that outcome. Rather it means that the exposure can cause the outcome, at least in some people under some circumstances.

Sufficient Evidence of an Association: Evidence is sufficient to conclude that there is an association. That is, an association between the agent and the outcome has been observed in studies in which chance, bias, and confounding can be ruled out with reasonable confidence.

Limited or Suggestive Evidence of an Association: Evidence is suggestive of an association between the agent and the outcome but is limited because chance, bias, and confounding could not be ruled out with confidence. For example, at least one high-quality study shows a positive association, but the results of other studies are inconsistent.

Inadequate or Insufficient Evidence to Determine Whether or Not an Association Exists: The available studies are of insufficient quality, consistency, or statistical power to permit a conclusion about the presence or absence of an association. Alternatively, no studies exist that examine the relationship.

Limited or Suggestive Evidence of No Association: Several adequate studies are consistent in not showing an association between the agent and the outcome. A conclusion of "no association" is inevitably limited to the conditions, magnitude of exposure, and length of observation covered by the available studies.

SOURCE: IOM, 2004.

Empirical measures do not, however, necessarily capture all relevant considerations that should be applied when evaluating research results. Qualitative aspects of the environment are also important. Thus, in the committee's collective judgment, there is value in attempting to identify design features and building processes and practices that may lead to improvements in learning, health, and productivity for students, teachers, and other school staff, even if empirical results are less than robust.

Chapters 2 through 6 of this interim report present the committee's findings and recommendations related to building envelope, moisture management, and health; ventilation, pollutant source control, health, and productivity; lighting, performance, and health; acoustics, student learning, and teacher health; and building condition and student achievement. As noted previously, additional topic areas, findings, and recommendations will be included in the committee's final report.

FINDINGS

Finding 1: In its review thus far, the committee has found the following:

- There are no well-designed, evidence-based studies concerning the overall effects of green schools on the health or development of students and teachers, in part because the concept of green schools is quite new. There are, however, a few well-designed studies that examine specific building features often emphasized in green school design and the effects of these components on health and learning.
- Given the level of interaction between people and their environments and other confounding factors, establishing cause-and-effect relationships between an attribute of a school building and its effect on students, teachers, and staff is difficult. The effects of the built environment will necessarily appear to be small, given the number of variables.
- Empirical measures do not, however, necessarily capture all relevant considerations that should be applied when evaluating research results. Qualitative aspects of the environment are also important. Thus, in the committee's collective judgment, there is value in attempting to identify design features and building processes and practices that may lead to improvements in learning, health, and productivity for students, teachers, and other school staff, even if empirical results are less than robust.

2

Building Envelope, Moisture Management, and Health

The foundation, walls, windows, and roof of a building make up an "envelope" intended to shelter people and equipment from the weather, and from natural and man-made hazards. Windows and doors allow outside air, light, people, equipment, and supplies to enter or exit a building. Skylights allow in daylight. Building envelopes can be designed for natural ventilation or for mechanically conditioned air or hybrid systems. Whether planned or not, buildings have openings that allow the penetration and internal movement of air, water, and contaminants.

Typically, guidelines for green schools address building envelope issues concerning siting, glazing, natural ventilation, and materials. Typically, the conservation of water, both outside and inside the building, is addressed through landscaping-related efforts such as irrigation, and plumbing-related features, such as restrooms. Existing guidelines are silent for the most part about building envelope per se except in reference to roofs and sound attenuation of outside noise. The committee believes that the design, construction, and maintenance of the building envelope are critical to green schools and therefore should have a more prominent place in any set of green school guidelines, for the reasons outlined below.

BUILDING ENVELOPE AND MOISTURE MANAGEMENT

It is popularly thought that green buildings are those buildings that are constructed using specific materials, systems, and technologies. However, it may not be as obvious that "dry" is a primary design objective for a green school building. Moisture ranks as a leading cause of structural damage, and excess moisture in a building has been associated with a variety of health problems in children and adults (IOM, 2004).

Water-related issues in buildings originate from many sources: groundwater, plumbing failures, construction materials, occupants, and the external environment. As long as a building is properly designed, sited, constructed, operated, and maintained, water can be managed effectively. However, excess water or moisture in a building can lead to structural failures and health-related problems when materials stay wet long enough for microbial growth, physical deterioration, or chemical reactions to occur (IOM, 2004). A complex set of moisture-transport processes related to climate, building design, construction, operation, and maintenance determine whether a building will have a moisture problem that could influence the health of the occupants.

Well-designed moisture control considers the potential damage and degree of risk associated with each of the following four transport mechanisms (from most to least potent):

1. Bulk transport,
2. Capillary transport,

3. Air transport, and
4. Vapor diffusion.

Bulk transport, or leakage of rain, melting snow, and groundwater through the building envelope, is orders of magnitude more destructive than any other force. Capillary movement of water from the outside of the building into the building through porous surfaces and the movement of air-transported water vapor are second and third in the rank order of transport mechanisms. Both represent a significant threat and require dedicated attention during design and construction. Vapor diffusion is a relatively weak force but also requires careful detailing and execution of building assemblies. Excellent resources for proper moisture control design include *The Moisture Control Handbook, Principles and Practices for Residential and Small Commercial Buildings* by Joseph Lstiburek and John Carmody (1994) and *The Building Foundation Design Handbook* (ORNL, 1988).

EXCESSIVE MOISTURE AND HEALTH

Recently there has been concern that indoor moisture "dampness" and mold growth can lead to a variety of health problems in adults and children. The most consistent and convincing associations relate to respiratory disease, especially asthma. Asthma is a disorder of airflow obstruction. People with asthma are subject to episodic wheezing, coughing, and shortness of breath. Although these symptoms are common clinical features of asthma, they are common symptoms of other respiratory illnesses as well. Finding a widely accepted definition of this disease has proved problematic, and the following has been offered as the most acceptable:

> Asthma is understood to be a chronic disease of the airways characterized by an inflammatory response involving many cell types. Both genetic and environmental factors appear to play important roles in the initiation and continuation of the inflammation. Although the inflammatory response may vary from one patient to another, the symptoms are often episodic and usually include wheezing, breathlessness, chest tightness, and coughing. Symptoms may occur at any time of the day, but are more commonly seen at night. These symptoms are associated with widespread airflow obstruction that is at least partially reversible with pharmacologic agent or time. Many persons with asthma also have varying degrees of bronchial hyperresponsiveness. Research has shown that after long periods of time this inflammation may cause a gradual alteration or remodeling of the architecture of the lungs that cannot be reversed with therapy. (IOM, 2000, pp. 23-24)

Asthma affects 8 percent to 10 percent of the population and even larger proportions of children in certain cities or poor urban populations. It is a common reason that children are absent from school and one of the most common causes of work absences as well; 14 million days of school loss were recorded in 1994-1996, 3.4 days per child with asthma (Cox-Ganser et al., 2005).

Indoor environments are an important factor in chronic asthma symptoms and morbidity, whether these environments are in the home or in the school. The Institute of

Medicine (IOM) has issued two reports on the association of excessive moisture or "dampness," mold growth, and respiratory illness in building occupants, *Clearing the Air: Asthma and Indoor Air Exposures* (IOM, 2000) and *Damp Indoor Spaces and Health* (IOM, 2004). Both concluded that damp, moldy buildings were associated with respiratory symptoms both in people with asthma and in the general population. To the extent that they might affect indoor dampness, green school designs might affect students' health and productivity. If school buildings can be designed to minimize the contribution to asthma morbidity, they can have a positive impact on health and performance.

The report *Damp Indoor Spaces and Health* considered separately the common respiratory symptoms (wheeze, cough, shortness of breath) and the diagnosis of asthma (usually based on reported physician diagnosis, reversible obstruction measured by lung function tests, or use of appropriate medication by the respondent). In addition, the report distinguished asthma development (the appearance of asthma for the first time) from asthma exacerbations (asthma symptoms in persons with a diagnosis of chronic asthma).

Using the National Academies' hierarchy of evidence for scientific inference (see Box 1.1), the report found ***sufficient evidence of an association*** between indoor dampness and several respiratory health outcomes, although the evidence was not strong enough to say there was a causal relationship. In the case of asthma, the association was found in people with asthma in general.

There are at least two distinct variants of asthma: an extrinsic, allergic variant that occurs in the context of immunoglobulin E (IgE)-mediated sensitization to environmental allergens and an intrinsic, nonallergic variant with no detectable sensitization and low IgE concentrations. In both variants, the airways are strikingly hyperresponsive, and symptoms may also be mediated by irritant responses. In those studies that evaluated asthmatic patients for IgE-mediated sensitization, the association was stronger in sensitized individuals; thus the IOM study concluded that the association was strongest in sensitized individuals. In addition, an association between dampness and mold and the symptoms of cough or wheeze was consistently found in studies of the general population. Because asthma has been diagnosed in only 8 percent to 10 percent of the population, it was unlikely that this relationship could be accounted for in these studies by asthma alone. Thus, the 2004 IOM study concluded that moisture and mold were associated with cough and wheeze in the general population.

The existing evidence was considered to be insufficient to support an association between dampness and mold and asthma ***development*** because fewer studies were available. Of the 10 studies available, only 1 (Jaakola et al., 2002) found that the association was insignificant. The others found an association with moisture, mold, or both. Particularly important were the three birth cohort studies (Belanger et al., 2003; Slezak et al., 1998; Maier et al., 1997) in which infants and children who were genetically at risk to develop asthma were observed for several years. Stark et al. (2003) reported on a birth cohort of 849 infants less than 1 year old who had at least one sibling with physician-diagnosed asthma; they found that wheeze and persistent cough were associated with measured airborne concentrations of *Penicillium* and *Cladosporium*, two types of mold commonly found in indoor air samples.

Finally, upper respiratory symptoms (nasal congestion, sneezing, runny or itchy nose) were associated with damp indoor environments and mold. Like asthma, chronic rhinitis has an allergic and a nonallergic variant. The allergic variant occurs in the context of IgE-mediated sensitization to environmental allergens. In the studies included in the 2004 IOM report, upper respiratory symptoms were associated with dampness and mold in persons with self-identified allergic rhinitis, as well as in the general population. Other studies reported that the frequency of “colds,” that is, acute viral infectious rhinitis, was associated with dampness and mold. Because the cause of upper respiratory symptoms could not be identified, the committee concluded that the symptoms, but not a specific illness, were associated.

The mechanisms by which damp indoor spaces and mold are associated with respiratory illness are not clear, but there are several possibilities. First, many people with asthma demonstrate IgE-mediated sensitization to mold, so the possibility exists that symptoms are related to specific immune mechanisms. Mold produces a number of materials such as peptidoglycans and polysaccharides that induce inflammation through the innate immune pathways; other materials such as volatile organic compounds[3] and toxins may have direct effects because asthmatic airways have a characteristic hyperresponsiveness and are excessively responsive to exposures to irritants. Other organisms such as gram-negative or gram-positive bacteria might coexist with mold in damp environments; endotoxin or lipoteichoic acid from these organisms might induce airway symptoms. Finally, the interaction of moisture and mold with building materials may produce metabolites that have direct irritant effects on asthmatic airways. The multiplicity of possible mechanisms illustrates that the pathways to respiratory effects will be complex, but all of these mechanisms are plausible consequences of excessive indoor moisture. Maintaining structures that are dry (i.e., without excessive moisture) potentially could prevent all of these effects.

The findings of key relevance to this interim report from *Damp Indoor Spaces and Health* are summarized in Box 2.1.

[3] Volatile organic compounds (VOCs) are emitted as gases from certain solids or liquids. VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects.

Box 2.1 Findings from the Institute of Medicine Relevant to This Study

Sufficient Evidence of an Association Between Dampness and Respiratory Health

- Asthma symptoms in sensitized persons
- Cough
- Wheeze
- Upper respiratory (nasal and throat) tract symptoms

Limited or Suggestive Evidence of an Association

- Asthma development
- Dyspnea (shortness of breath)
- Lower respiratory illness in otherwise healthy children

Sufficient Evidence of an Association Between Mold or Other Agents and Respiratory Health

- Asthma symptoms in sensitized persons
- Cough
- Wheeze
- Upper respiratory (nose and throat) tract symptoms
- Hypersensitivity pneumonitis in susceptible individuals

Limited or Suggestive Evidence of an Association

- Lower respiratory illness in otherwise healthy children

SOURCE: IOM, 2004.

In addition to potential health benefits, designing for effective moisture management will likely have benefits for the building as well. The more durable a building is, the longer its components will last (Deal et al., 1998). The materials in long-lived building assemblies are replaced less frequently than in nondurable structures. This makes dry structures resource and energy efficient, because new replacement materials are not harvested, mined, and produced, nor is energy used to make, transport, and assemble the replacement components. Dry buildings also require fewer resources and money to repair and maintain. For example, damp surfaces cause stains and peeling paint that require frequent repainting and cleaning. For these reasons, dry buildings may have lower life-cycle costs associated with them.

FINDINGS AND RECOMMENDATION

Finding 2: In regard to issues related to building envelope, moisture management, and health, the committee has found the following:

- There is sufficient evidence to establish an association between moisture problems in buildings (floods, visible dampness, leaks, mold growth in spaces or in heating, ventilation, and air-conditioning [HVAC] systems) and adverse health outcomes, particularly asthma and respiratory symptoms, among children and adults.
- Excessive moisture in a building can lead to structural damage, deterioration of the performance of building systems and components, and cosmetic damage, all of which can result in increased maintenance and repair costs.
- Guidelines for green schools typically do not adequately address the design detailing, construction, and long-term maintenance of building envelopes to ensure that allergen sources are controlled, moisture is controlled, and a building is kept dry over the long term.
- Well-designed, constructed, and maintained building envelopes are critical to the control and prevention of the excessive moisture and molds that have been associated with adverse health effects in children and adults. Designing for effective moisture management will likely have benefits for the building, including lower life-cycle costs. Excellent resources for proper moisture control design include *The Moisture Control Handbook*, *Principles and Practices for Residential and Small Commercial Buildings* by Joseph Lstiburek and John Carmody (1994) and *The Building Foundation Design Handbook* (ORNL, 1988).

Recommendation 1: The control of excessive moisture, dampness, and molds to protect the health of children and adults in schools and to protect the structural integrity of a building should be a key objective for green schools. MASSTECH should develop guidelines that specifically address moisture control as it relates to the design, construction, operation, and maintenance of a school building’s envelope (foundations, walls, windows, and roofs) and ventilation systems, and related items such as siting, landscaping, and plumbing systems.

3

Ventilation, Pollutant Source Control, Health, and Performance

The primary purpose of a building's heating, ventilation, and air-conditioning (HVAC) system is to provide comfort for the occupants by meeting thermal requirements and diluting contaminants. HVAC systems accomplish this through the conditioning of outside air coming into occupied spaces and the removal of irritants and pollutants. The principal standards and guidelines for HVAC system design and operation include (1) American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 62.1-2004, "Ventilation for Acceptable Indoor Air Quality"; (2) American National Standards Institute (ANSI)/ASHRAE Standard 55-2004, "Thermal Environmental Conditions for Human Occupancy"; (3) the Department of Energy EnergySmart Schools guidelines; and (4) individual state codes, some of which are based on or reference other codes such as the International Building Code.

Green school guidelines typically address HVAC systems as they relate to energy efficiency, indoor air quality (ventilation), moisture control, filter efficiencies and maintenance, and the elimination of CFC-based refrigerants.

In a comprehensive review of the literature related to indoor air quality, ventilation, and health symptoms in schools, Daisey et al. (2003) found the following:

- Reported ventilation and carbon dioxide (CO_2) levels indicated that a significant proportion of classrooms did not meet the (then) ASHRAE standard 62-1999 for minimum ventilation rate;[4]
- A variety of volatile organic compounds (VOCs) and bioaerosols (primarily molds and fungi, dust mites, and animal antigens) could be found in school environments; and
- Although there were a number of studies in which typical building-related symptoms[5] were measured, there was a relative paucity of literature in which specific building conditions or measured pollutants were then linked to specific symptoms.

The following sections address some aspects of indoor air quality and pollutant source control, ventilation rates, and moisture management in HVAC systems. The committee plans to address additional issues related to HVAC systems, including temperature and humidity, in its final report.

[4] The ASHRAE standard has since been revised.

[5] Building-related symptoms, frequently referred to as "sick building syndrome," have been defined as a set of symptoms reported subjectively by occupants of a building that may improve when they leave the building. Symptoms include eye, nose, and throat irritations; headaches; fatigue; difficulty breathing; itching; and dry, irritated skin (FFC, 2005).

INDOOR AIR QUALITY AND POLLUTANT SOURCE CONTROL

There are many sources of exposure to pollutants internal and external to a school. Internal sources include stationary and (potentially) mobile combustion sources; building materials and equipment; educational materials; cleaning products; biological agents; and human activity. External sources include combustion sources (stationary and mobile); biological material; and soil gases (e.g., radon, VOCs from municipal waste sites) particulate matter, and ozone entering through air intakes and the building envelope.

Outdoor Sources

Outdoor sources of air pollution can affect the health of children and adults in two ways. First, students, teachers, and administrative and support staff are exposed to outdoor pollutants before they enter a building, which can lead to increased respiratory symptoms (Schwartz, 2004). Second, outdoor sources of pollution can contribute to indoor air pollutant concentrations through several routes: outdoor air is drawn into a school building by the ventilation system through air intakes located at the rooftop, at ground level, or from below-grade "wells." Outside air also enters the building through doors and windows and through leaks in the building envelope. People themselves can carry viruses, bacteria, pollen, and pollutants, such as dust mites and pet dander, into a school on their shoes and clothing.

Mendell and Heath (2004) found that "a substantial literature of strongly designed cohort studies is available on associations between outdoor pollutants and attendance of children at school" (p. 9). They concluded that there was strongly suggestive evidence that absence from school increased with exposure to ozone at higher concentrations. However, the findings were mixed on associations of school absence with exposure to outdoor nitrogen oxides, carbon dioxide, and particles <10 µ in aerodynamic diameter.

Pollen Exposure

Other significant sources of pollutants outside schools are plant-derived materials, or biomass, which can generate bioaerosols, including molds, fungi, and pollen. The 2000 IOM study *Clearing the Air* found as follows:

> Although there is sufficient evidence to conclude that pollen exposure is associated with exacerbation of existing asthma in sensitized individuals, and pollen allergens have been documented in both dust and indoor air, there is inadequate or insufficient information to determine whether indoor air exposure to pollen is associated with exacerbation of asthma. (p. 8)

The study also noted that "there is relatively little information on the impact of ventilation and air cleaning measures on indoor pollen levels, although it is clear that shutting windows and other measures that limit the entry rate of unfiltered air can be effective" (p. 14).

Indoor Sources

There are numerous pollutants in a school building. These pollutants include particulate matter, chemicals, and biological particles or organisms. Sources include building materials (e.g., structural materials such as particleboard, adhesives, insulation); furnishings (carpets, paints, furniture); products used in the building (cleaning materials, pesticides, markers, art supplies); and in some cases the occupants themselves (CO_2, pet hair).

There are a limited number of studies in which source reduction or control methods in schools have been related to pollutant exposures. Smedje and Norbäck (2001) observed that classrooms with more frequent cleaning had lower concentrations of cat and dog antigen in settled dust. However, few studies have looked systematically at changes in exposure, health effects, or productivity based on changes in building materials or products used in schools.

The literature on source reduction and control in homes, particularly with asthmatic children, is more extensive (Takaro et al., 2004). Integrated pest management techniques have been shown to be effective in reducing antigen levels in homes (Phipatanakul et al., 2004) and have been shown to reduce pesticide levels in schools (Williams et al., 2005). However, whether they result in better health outcomes or productivity in schools has not been determined (Phipatanakul et al., 2004; Williams et al., 2005). A recent review by Shendell and others (2004a) examined the various sources and types of controls available for these sources. The committee will address those issues in greater detail in its final report.

INDOOR AIR QUALITY AND VENTILATION RATES

Ventilation rate is based on the outdoor air requirements of a ventilation system. A number of studies have reviewed the effect of ventilation rates on health, productivity, and airborne pollutant control. Although the majority of these studies have been in environments other than schools, there have been several more recent studies and reviews either specifically on schools or including schools in the overall study. Typically, these studies also look at a second variable, such as temperature or humidity, components of thermal comfort, to identify any confounding or synergistic effects.

School-Related Studies

Mendell and Heath (2004) looked at the literature and found

- Suggestive, although not fully consistent, evidence linking low outdoor ventilation rates in buildings to decreased performance in children and adults, and
- Suggestive but inconsistent evidence linking lower ventilation rates with decreased attendance among adults.

Wargocki et al. (2005) conducted a field intervention experiment in two classes of 10-year-old children. Average air temperatures were reduced from 23.6°C to 20°C, and outdoor air supply rates were increased from 5.2 to 9.6 liters per second (l/s) per person in a 2 x 2 crossover design, each condition lasting a week. Tasks representing eight different aspects of schoolwork, from reading to mathematics, were performed during appropriate lessons, and the children marked visual-analogue scales each week to indicate building-related symptom intensity. Increased ventilation rate increased work rate in addition, multiplication, number checking ($p < .05$), and subtraction ($p < .06$). Reduced temperature increased work rate in subtraction and reading ($p < .001$), and reduced errors in checking a transcript against a recorded voice reading aloud ($p < .07$). Reduced temperature at increased ventilation rate increased work rate in a test of logical thinking ($p < .03$). Their experimental data indicated that increasing ventilation rates from 5.4 to 9.6 l/s per person and decreasing temperatures from 24^{o}C to 20^{o}C potentially would improve the performance of schoolwork by children.

Smedje et al. (2000) investigated the impact of improving the ventilation systems in schools on allergies, asthma, and asthma symptoms in schoolchildren. They issued questionnaires to 1,476 children in 39 schools (mixed primary and secondary schools) during the 1993-1995 period. Various exposure factors were measured during this time period in 100 classrooms. In 12 percent of the classrooms, new ventilation systems were installed, increasing the air-exchange rate and reducing the humidity levels in the schools. The air pollutant levels in these schools were lowered with the installation of the new ventilation systems as compared with the levels in the classrooms without the new ventilation systems. Also, the incidence of asthma symptoms, but not allergies, was reduced in the classrooms with the new ventilation systems. Their results indicated an improvement in the children's health in the classrooms with increased ventilation, lower humidity levels, and reduced airborne pollutant levels.

Shendell et al. (2004b) explored the association between student absences and indoor CO_2 levels. These researchers noted that "since measuring the actual ventilation rate is expensive and potentially problematic, the indoor concentration of carbon dioxide (CO_2) has often been used as a surrogate for the ventilation rate per occupant, including in schools." They measured the short-term (5 min) CO_2 levels in 409 traditional and 25 portable classrooms from 22 schools in Washington state. Attendance data were collected from school records. Their results indicated that a 1,000-ppm increase above the outdoor concentration of CO_2 was associated with statistically significant 10 percent to 20 percent increases in student absences. Although student absences are not a direct measurement of student performance, an increased number of absences may contribute to poorer student performance.

Studies of Offices and Other Building Types

In a study of 3,720 hourly employees of a large Massachusetts manufacturer in 40 buildings with 115 independently ventilated working areas, Milton et al. (2000) analyzed the relationship between the rate at which outdoor air was supplied for ventilation and the amount of sick leave taken. The researchers found "consistent associations of increased sick leave with lower levels of outdoor air supply and IEQ [indoor environmental quality] complaints" (p. 212). Seppanen and Fisk (2004) further developed a quantitative relationship by fitting the data from these epidemiological studies by using the Wells-Riley model of airborne disease transmission to predict the relationship. The model predicted that there would be a decrease in illness over time with increasing ventilation rates.

Seppanen et al. (1999) reviewed the literature on the association of ventilation rates in nonresidential and nonindustrial buildings (primarily offices) with health and performance outcomes. The review included 20 studies investigating the association of ventilation rates with human responses and 21 studies investigating the association of CO_2 levels with human responses. A majority of studies found that ventilation rates of less than 10 l/s per person were associated in all building types with a statistically significant worsening in one or more health or perceived air quality outcomes. Some studies found that increasing ventilation rates up to 20 l/s per person was associated with significant decreases in the prevalence of building-related symptoms or with further significant improvements in perceived air quality. The ventilation rate studies reported relative risks of 1.1 to 6 for building-related symptoms for low compared to high ventilation rates.

VENTILATION AND HEALTH

Ventilation and health in nonindustrial indoor environments were the subjects of a European Multidisciplinary Scientific Consensus Meeting (EUROVEN) review of the scientific literature on the effects of ventilation on health, comfort, and productivity in offices, schools, homes, and other nonindustrial environments (Wargocki et al., 2002). The group reviewed 105 papers and judged 30 as being conclusive, providing sufficient evidence on ventilation, health effects, data processing, and reporting. The EUROVEN group agreed that ventilation is strongly associated with comfort (perceived air quality) and health (building-related symptoms, inflammation, infections, asthma, allergy, short-term sick leave) and found an association between ventilation and productivity (performance of office work). They concluded that increasing outdoor air supply rates in nonindustrial environments improves the perceived air quality, and that outdoor air supply rates of less than 25 l/s per person increase the risk of building-related symptoms, increase short-term sick leave, and decrease productivity among occupants of office buildings.

Seppanen and Fisk (2005) reviewed the scientific literature regarding the effects of ventilation on indoor air quality and health, focusing on office-type buildings. Overall their literature review indicated that ventilation has a significant impact on several important user outcomes, including:

- Communicable respiratory illnesses,
- Building-related symptoms,
- Task performance and productivity,
- Perceived air quality among occupants and sensory panels, and
- Respiratory allergies and asthma.

The literature review also indicated that better hygiene, commissioning, operation, and maintenance of air handling systems may be particularly important for reducing the negative effects of HVAC systems. Ventilation may also have harmful effects on indoor air quality and climate if not properly designed, installed, maintained, and operated. The committee will address the literature on ventilation and health in greater detail in its final report.

VENTILATION AND COMFORT

Fang et al. (1998) and Toftum et al. (1998) showed that perceived air quality is strongly influenced by the humidity and the temperature of inhaled air even when the chemical composition of the air is constant and the thermal sensation for the entire body is kept neutral. These findings address the importance of the second purpose of ventilation systems, which is to condition the air to comfortable levels of temperature and humidity. There is a robust literature on the effects of temperature and humidity on both comfort and productivity, although it is based primarily on studies in office buildings (Fanger, 2000; Seppanen and Fisk, 2005; Wyon, 2004). Studies show that productivity declines if temperatures go too high (Federspiel et al., 2004). The committee will address the literature on temperature, health, and performance in greater detail in its final report.

Quantifying Relationships Among Ventilation, Health, and Productivity

Although there is good evidence that HVAC system characteristics can and do affect occupant health and comfort, including in schools, until recently there have been few studies that attempted to measure the magnitude of either the health or productivity effects. Several recent reviews, however, have attempted to quantify the relationship of ventilation rate and pollutant transport to the health and productivity of people indoors.

Wyon (2004) investigated the productivity of office workers based on reducing indoor air pollutant loads by source removal or increasing ventilation rate. Wyon showed that during realistic experimental exposures lasting up to 5 hours, the performance of simulated office work was significantly increased (by approximately 6 percent to 9 percent) by the removal of common indoor sources of air pollution, such as floor-coverings, old supply air filters, and personal computers, or by keeping the sources in place while increasing the clean air ventilation rate from 3 to 30 l/s per person. Wyon then went on to confirm these laboratory findings in a field investigation during an 8-week period. A reduction in pollutant loads in buildings can be expected to reduce building-related symptoms.

Seppanen and Fisk (2005) used previous studies (primarily in office buildings) to develop a model relating building ventilation rates, perceived air quality, and temperature to occupant symptoms and productivity. They estimated that increasing the average ventilation rate from 0.45 to 1.0 exchanges per hour would decrease the sick leave prevalence in an office from 2 percent (5 days per year) to 1.6 percent (3.9 days per year).

MOISTURE MANAGEMENT IN HEATING, VENTILATION, AND AIR-CONDITIONING SYSTEMS

Several findings in the 2004 IOM study *Damp Indoor Spaces and Health* pertain specifically to the design and operation of HVAC systems as a critical factor in the control of moisture in buildings:

- Although relatively little attention has been directed to dampness and mold growth in HVAC systems, there is evidence of associated health effects (p. 42).

- Liquid water is often present at several locations in or near commercial-building HVAC systems, facilitating the growth of microorganisms that may contribute to symptoms or illnesses (p. 42).
- Microbial contamination of HVAC systems has been reported in many case studies and investigated in a few multibuilding efforts (p. 43).
- Sites of reported contamination include outside air louvers, mixing boxes (where outside air mixes with recirculated air), filters, cooling coils, cooling coil drain pans, humidifiers, and duct surfaces (p. 43).
- Bioaerosols from contaminated sites in an HVAC system may be transported to occupants and deposited on previously clean surfaces, making microbial contamination of HVAC systems a potential risk factor for adverse health effects (p. 43).
- Menzies study of ultraviolet germicidal radiation of drip pans and cooling coils shows that limiting microbial contamination of HVAC systems may yield health benefits, and follow-up research is recommended (p. 44).

In addition to moisture and mold, other allergens and irritants found in school buildings may affect a substantial minority of students, teachers, and staff through the same pathways described above. Indoor environments contain varying quantities of allergens from a variety of sources: house dust mites, cat and dog dander, cockroaches, rodents, and seasonal pollens. Indoor concentrations of particulates and various gaseous pollutants (ozone, NO_2, VOCs) may be higher than those found in outside air. The strength of the association of each of these agents was summarized in *Clearing the Air: Asthma and Indoor Air Exposures* (IOM, 2000), and many of them were found to be more strongly related to asthmatic symptoms than were moisture and mold. Through proper design and maintenance practices, green schools can minimize the effects of these exposures. This may involve simple measures such as closing the windows during pollen season or prohibiting furry pets in a school. In other cases, more subtle design considerations may be needed, for example, limiting food preparation, vending, and eating to certain areas with structural and finish features that allow easy pest control.

Taken together, these findings indicate the significant role that HVAC system design and operation play in controlling moisture and pollutants inside buildings.

FINDINGS

Finding 3: In regard to ventilation, pollutant source control, health, and performance, the committee has found the following:

- Numerous pollution sources and building system characteristics affect air quality in a school. The most important determinants of indoor air quality are (1) design and operation of the ventilation system to limit the buildup of pollutants and humidity and achieve thermal comfort, (2) control of indoor sources of pollutants, and (3) control of outdoor sources of pollutants.
- There is a robust body of evidence indicating that the health of children and adults can be affected by air quality in a school.

- A growing body of evidence suggests that teacher productivity and student learning, as measured by absenteeism, may be affected by indoor air quality as well.
- Indoor pollutants and allergens from house dust mites, pet dander, cockroaches, and rodents also contribute to increased respiratory and asthma symptoms among children and adults.
- The reduction of pollutant loads, both sensory and not, has been shown to reduce the occurrence of building-associated symptoms and to improve the health and comfort of people occupying the buildings.
- Although compliance with the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) standards for ventilation rates may be the minimal acceptable standard for green schools, there is good evidence that increasing the ventilation rate beyond the ASHRAE standard will further improve comfort and productivity. However, an upper limit on the ventilation rates, indicating when the benefits of outside air begin to decline, has not been established.

The committee will address additional issues related to heating, ventilation, and air-conditioning systems and their associations with health and productivity in its final report. Until this review is completed and the results are synthesized, the committee will defer making specific recommendations.

4

Lighting, Performance, and Health

Typically, when addressing lighting requirements, guidelines for green schools focus on energy-efficient lighting systems and the use of daylighting to further conserve energy. They also encourage access to views through the installation of windows.

For purposes of learning, performance, and productivity, lighting in a school building should allow people to see to read, to see others with whom they are communicating, and to perform other visual tasks associated with learning, teaching, and school administration. Lighting can be provided by electric sources or by daylight through windows, clerestories, and skylights. Typically, school buildings use a combination of electric lighting and daylight.

Electric lighting systems are made up of a series of components: luminaires, lamps (incandescent, fluorescent, high-intensity discharge [HID]), ballasts (except when using incandescent lamps), and controls. Electric lighting systems differ in the amount of power they require to operate and in the amount and direction of light they are able to generate for the design objectives. They also vary in their initial cost, ease of maintenance and commissioning, and expected life. Also important, electric lighting systems vary in their ability to provide good color rendering, low glare, low flicker, and low noise.

Fluorescent lighting systems are the most prevalent sources of general illumination in schools. Modern fluorescent systems (T8 and T5 lamps with electronic ballasts) can provide low cost, long life, high efficacy, good color, low noise, and low flicker. Other sources of illumination, including incandescent and HID, can be specified in schools to best accomplish specific design objectives, from outdoor applications such as sports fields to illuminating pictures or works of art (Rea and Bullough, 2001).

Windows are an important part of the school design.[6] First and foremost, windows provide a view to the outside. They also provide high light levels and, when properly located, ideal eye-task-lighting geometries for reflective visual tasks (i.e., those other than self-luminous displays, such as computer screens, and audio visual presentations). Skylights and clerestories can also be beneficial sources of illumination even though they do not provide a view.

A key difference between designs with electric light and/or daylight is that electric light is almost always static, whereas daylight is ever changing over the course of a day, with weather conditions, and with season. Daylight will also be different from one school to another, depending on building orientation and site, local climate, and latitude, so a "cookie cutter" building design will rarely provide ideal lighting conditions. The dynamic nature of daylight, together with its wide range of intensities and geometries, demands a dedicated understanding of its interactions with the building and its spaces. In some circumstances it may be desirable to conduct detailed lighting, heating, and cooling simulations in order to gain such an understanding. The potential benefits of higher lighting levels, excellent color

[6] This discussion is restricted to the lighting effects of windows.

and form rendition, views, and the temporal lighting qualities may justify this careful design requirement and additional analyses.

LIGHTING AND ITS IMPACT ON THE VISUAL AND CIRCADIAN SYSTEMS

When evaluating the performance of any lighting system, electric or daylight, its impact on two biological systems—the visual and the circadian—needs to be considered together with the physical attributes of light that differentially affect these systems (Figure 4.1).

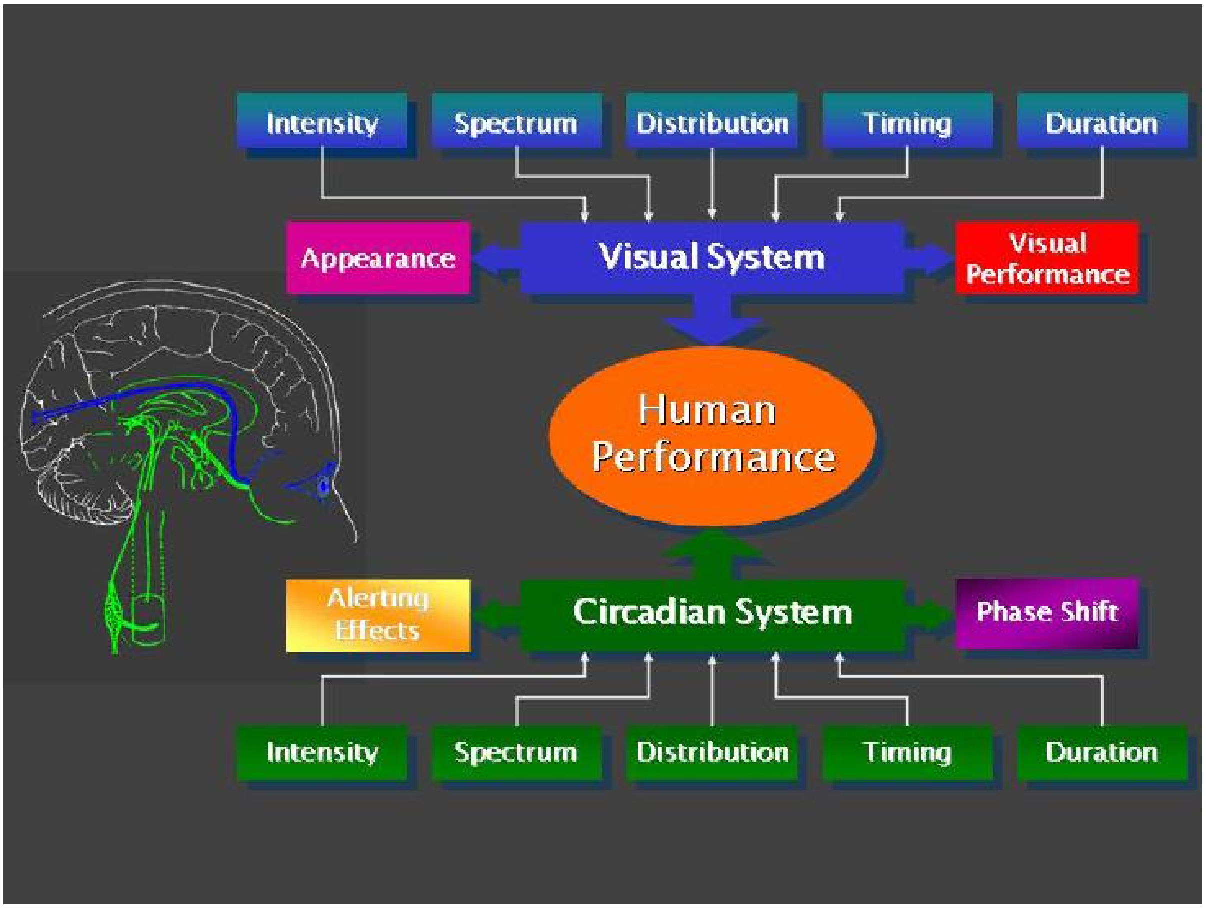

FIGURE 4.1 Light as it affects human performance and health through the visual and circadian systems. SOURCE: Lighting Research Center.

The Visual System

The visual system functions as a very quick remote-sensing mechanism that alerts us to changes in the environment and enables us to identify threats and opportunities around us. The visual system is fairly well understood for normal adult populations in regard to the effects of light on both appearance (what things look like) and visual performance (how well visual information is processed). For example, there is a complete model of visual performance available for predicting the impact of background luminance (light level), target contrast, target size, and observer age from 18 to 65 years (Rea and Ouellette, 1991). Presumably, most school-age students should behave like 18-year-olds in regard to visual performance, but this has not been systematically studied. In general, given the characteristics of the visual response functions, it can probably be concluded that most lighting and task conditions are adequate for normal student visual performance. Going the next step, however, is more tenuous because there is no evidence that the quality or quantity of light directly affects student learning performance (Larson, 1965; Demos et al., 1967; Boyce et al., 2003).

Lighting for Visual Performance

The performance of any lighting design cannot be effectively evaluated solely on the basis of the source of illumination or the individual components needed to create the entire lighting system. Instead, lighting performance should be evaluated within the integrated system of enclosure design and controls, space geometry and finish, and fixture components in relation to the task requirements.

For a large majority of the people working in buildings, lighting for vision during the day is quite adequate, in part because people have very flexible visual systems and adjust their posture in response to the available lighting conditions. For example, the dimmer the light, the closer one holds the reading materials to maintain a constant ability to read. Experiments in the laboratory show that people will systematically adjust the eye-to-task geometry to maintain good task visibility, either by moving closer to the visual task or shifting posture to avoid reflected glare (Rea et al., 1985). A flexible visual system combined with a flexible body provides most people with the ability to adapt to less than ideal lighting environments.

A significant minority of the school-age population may not have properly corrected eyesight, however. Students without properly corrected eyesight may not be able to take full advantage of adaptive strategies to see learning materials in the classroom. In a large study using the 1996-1997 National Health Interview Survey, Kemper et al. (2004) determined that approximately 25 percent of school-age children in the United States have corrective lenses. They showed that the prevalence of corrective lenses is related to several population factors such as age (older children are more likely to wear corrective lenses), ethnicity (black and Hispanic children are less likely to wear corrective lenses), income (poorer children are less likely to wear corrective lenses), and gender (girls are more likely to wear corrective lenses than boys). Of particular note, insurance coverage appears to be a major factor in the prevalence of corrective lenses in school-age children. The actual percentage of corrective lenses probably underestimates the number of children who need them. Moreover, it is unknown whether students' corrective lenses actually have the proper refraction. Because lighting and task variables (e.g., particularly task target contrast and size) as well as proper refraction determine visual performance, it seems likely that at least some students are not able to adequately see learning materials in the classroom.

Within the context of the school environment, then, adequate lighting for the majority of the students may be insufficient for some fraction of school-age children. It could be hypothesized that for those students who do not have the proper refraction, daylight may offer a significant advantage by providing higher light levels and better geometries than would otherwise be present from electric lighting alone. However, the potential advantage of daylight in classrooms for improving visual performance of children with or without properly corrected eyesight has not been systematically studied.

The adult (teaching and administrative) population will also likely have problems with refractive errors. Normal aging involves a continuous loss of visual accommodative ability, known as presbyopia, from about 20 years of age to approximately 65 years (Weale, 1992). Until about age 45 the gradual loss in ability to focus on near objects is hardly noticed, but after this approximate age nearly everyone begins to adopt new strategies to see small targets. Instead of getting closer to an object to see it as they did when they were younger, people with presbyopia actually move the object further away from their eyes, or they place the object under a bright light, usually provided by a window or skylight. Eventually, everyone seeks optical aids, such as bifocals or reading glasses, to see normal print, but use of bright light from the right direction will continue to be a strategy employed by older people to see small targets throughout their lives.

Glare and Visual Performance

In regard to glare, there is much less certainty in predicting visual comfort, even in adults, than in predicting visual performance (Rea, 2000; Boyce, 2003). A clear distinction is made between glare that reduces visual performance (disability glare) and glare that does ***not*** (discomfort glare). Disability glare can be precisely predicted for a given individual and for the general population. As would be expected, disability glare becomes more problematic with age owing to changes in the optical media of the eye, particularly from scattering of light within the eye by the crystalline lens (Weale, 1963).

Windows are the largest sources of glare in a classroom. However, glare can be controlled by using fixed overhangs in conjunction with blinds or window treatments that can be manually operated. Methods to control light from skylights and clerestories are also needed because of ever-changing lighting geometries and light levels as the day progresses.

Formulas do exist for calculating discomfort glare, and these are often used to characterize the lighting layout for a space using commonly available lighting software. However, collective understanding of the mechanisms underlying discomfort glare is rather poor (Boyce, 2003). It appears that psychological phenomena contribute significantly to discomfort glare so that, for example, bright flashing lights in an office are highly uncomfortable, but the same lights can be highly desirable in a night club for dancing. Therefore, although disability glare is the same in both applications, discomfort glare is not. In this context, and given the strong psychological component to discomfort glare, predicting visual comfort in school-age children is an area that requires more research.

DAYLIGHTING AND STUDENT LEARNING

Several well-designed studies investigating the effect of daylighting on student performance were conducted by the Heschong-Mahone Group between 1999 and 2003. In the 1999 study, data were obtained from three elementary school districts located in Orange

County, California; Seattle, Washington; and Fort Collins, Colorado (Heschong-Mahone, 1999). The study looked for a correlation between the amount of daylight provided by each student's classroom environment and test scores. Test results for more than 21,000 students in these districts were analyzed. Demographic data sets, architectural plans, aerial photographs, the presence of skylights, maintenance records, and daylighting conditions for more than 2,000 classrooms were among the factors reviewed.

The study developed a regression model for approximately 150 independent variables (e.g., teacher salaries, grade level, attendance), including available daylight represented by five different levels, or "daylight codes." Although the regression analysis leads to a prediction that an increase in the value of the daylight code can increase scores in both math and English by more than 20 percent, a closer examination of the results shows that only 0.3 percent of the variance in the regression model is explained by daylight code (Boyce, 2004). This is a very small effect and one that cannot be justified as reliable. As noted below, these results could not be replicated in a subsequent study.

A reanalysis of the Capistrano and the Seattle school districts' data was undertaken in 2001 to look at additional variables that might have a confounding influence, including teacher assignments (Heschong-Mahone, 2001). In 2003 a third study was undertaken to see whether the original methodology and findings would hold when data came from a school district with a different climate and curriculum. The Fresno California school district was used. The preliminary statistical analyses replicated the structures of the models used in previous studies. In the Fresno study, the holistic variable called the Daylight Code "was not significant in predicting student performance. It had the least explanatory power of the variables considered, and the lowest significance level" (Heschong-Mahone, 2003, p. viii).

The authors proceeded with more detailed multilinear regression (statistical) analysis to see whether they could gain some insight into why the Daylight Code was not significant in Fresno as it had been in earlier studies. Among the authors' conclusions were that sources of glare negatively affect student learning; direct sun penetration into classrooms, especially through unshaded east or south facing windows, is associated with negative student performance, likely causing both glare and thermal discomfort; blinds or curtains allow teachers to control the intermittent sources of glare or visual distraction through their windows; when teachers do not have control of their windows, student performance is negatively affected (Heschong-Mahone, 2003, p. ix). They summarized that

> Characteristics describing windows were generally quite stable in their association with better or worse student performance. Variables describing a better view out of windows always entered the equations as positive and highly significant, while variables describing glare, sun penetration, and lack of visual control always entered the models as negative. (Heschong-Mahone, 2003, p. viii)

Because of the inconsistent results of this limited number of well-designed studies, there is insufficient evidence at this time to determine whether or not an association exists between daylighting and student learning.

LIGHTING AND THE CIRCADIAN SYSTEM

The circadian system involves biological rhythms that repeat at approximately 24-hour intervals. The behavior of all terrestrial species, including humans, is driven by an internal clock synchronized to the solar light-dark cycle. Indeed, light is the primary stimulus to the internal clock. The circadian system regulates not only overt daily patterns of behavior such as activity and rest, but also our bodies at the cellular level, regulating functions such as the cell cycle (Moore, 1997).

Current lighting technologies and lighting standards are designed exclusively for providing visual sensation. However, light affects the visual system very differently than it affects the circadian system. Relative to the visual system that underlies conventional photometry and all lighting standards, the circadian system needs a much higher light level on the retina for activation (McIntyre et al., 1989a,b); it has a peak spectral sensitivity to much shorter wavelengths (Brainard et al., 2001; Thapan et al., 2001); it has greater sensitivity to light in the inferior retina (viewing the sky) than in the superior retina (Glickman et al., 2003); it requires much longer exposures for activation (McIntyre et al., 1989a,b; Rea et al., 2002); and, most important, it is differentially sensitive to light depending on the time of day (Jewett et al., 1997).

There is a growing body of literature indicating that the effect of light on circadian regulation can affect productivity as well as health. Seasonal affective disorder (SAD), or the "winter blues," is recognized by the medical community as a psychiatric disorder. Apparently, seasonal reductions in the amount of daylight available in the winter at extreme northern (and southern) latitudes can induce depression (Rosen et al., 1990). Light treatment, typically provided with bright light from electric lighting systems, is recognized by the medical community as the preferred method of treating SAD (Rosenthal et al., 1985).

The incidence of SAD, or winter blues, in school-age children is poorly documented, although it has been reported that adults who experience SAD also experienced it as a child. It seems too that postpubescent young women are more likely to experience SAD (Rosenthal, 1998). Depending upon latitude, between 4 percent and 30 percent of the adult population, usually women, experience some symptoms of seasonal depression (Rosenthal, 1998), which in turn, might affect teachers. Less learning might be expected from those children who experience symptoms of seasonal depression, so lighting may play a very important role in the design of a green school at northern latitudes during the winter months. Systematic attempts to alleviate seasonal depression in children through lighting design have not been undertaken, but these early findings suggest a reconsideration of the role that light, particularly daylight, plays in the classroom.

Nearly half the population experiences some form of sleep disorder (National Sleep Foundation, 2005). Poor sleep directly affects a person's ability to perform tasks and learn new tasks (Jennings et al., 2003; Heuer et al., 2004). Light and dark have a dramatic impact on sleep quality (Turek and Zee, 1999; Reid and Zee, 2004). Adolescents in particular commonly go to sleep late (after midnight) and have difficulty getting up early (before 7:00 a.m.) to go to school (Carskadon et al., 1998). In extreme cases this difficulty in falling asleep early and getting up early is diagnosed as delayed sleep phase syndrome (DSPS). Many students with DSPS must get special training or even repeat grades because of poor attendance and poor performance. Light is a recognized treatment for this disorder, and a regular light-dark cycle may have broader implications for sleep quality in a larger group of children.

Recent research at the other end of the age spectrum shows that light treatment can consolidate sleep and increase sleep efficiency during the night in older people (Satlin et al., 1992; Fetveit et al., 2003; van Someren et al., 1997; Figueiro and Rea, 2005). A regimen of bright light at school during the day, together with dark nights at home, may increase student attendance and performance. Here again, however, there have been no systematic studies in school-age children.

DAYLIGHTING, VIEW, PERFORMANCE, AND HEALTH

Studies have been conducted using subjective ratings from adults providing evidence that people like views from windows (Markus, 1967; Jackson and Holmes, 1973; Ne'eman and Longmore, 1973; Collins, 1975; Ludlow, 1976; Cuttle, 1983; Heerwagen and Heerwagen, 1986; Leslie and Hartleb, 1990, 1991; Boubekri et al., 1991) and that real estate prices are higher for architectural spaces with a view from windows (Boyce et al., 2003). Kuller and Lindsten (1992) studied children's health and behavior in classrooms with and without windows for an entire academic year. At the end of the study, they concluded that work in classrooms without windows affected the basic pattern of the hormone cortisol, which is associated with stress. The authors concluded that windowless classrooms could have a negative effect on children's health and concentration. This finding is strictly suggestive, however, because no direct relationship between cortisol levels and student performance and health was established (Rusak et al., 1997).

FINDINGS AND RECOMMENDATIONS

Finding 4: In regard to lighting, performance, and health, the committee has found the following:

- Daylight is a special light source because it may provide a view (through a window), high light levels, and good color rendering, and it is ever-changing. Direct and reflected sunlight can create significant visual problems if windows, skylights, and clerestories allow in too much or too little light. However, such problems can be controlled with manual blinds and other types of window treatments.
- There is good evidence from studies of adult populations that the visual conditions in schools resulting from both electric lighting and daylighting are adequate for most children and adults.
- There is, however, concern that a significant percentage of students in classrooms do not have properly corrected eyesight, and thus, the general lighting conditions suitable for visual functioning by the average student may be inadequate for those students without properly corrected eyesight. It could be hypothesized that daylight may benefit these children by providing higher light levels and better geometries than would otherwise be present from electric lighting alone.

However, the potential advantages of daylight in classrooms for improving visual performance of children with or without properly corrected eyesight has not been systematically studied.

- Because of inconsistent results and the small number of well-designed studies, there is insufficient evidence at this time to determine whether or not an association exists between daylighting and student performance.
- A growing body of evidence suggests that lighting may play an important nonvisual role in human health and well-being through the circadian system. However, the effect of light on health through circadian regulation of sleep, depression, and cell cycle has not been directly studied in children.

Recommendation 2: To determine the potential and actual performance of a lighting system, the entire system should be assessed because the total performance cannot be effectively evaluated based solely on the source of illumination or on the individual components needed to create the entire lighting system.

Recommendation 3: For green schools in which the lighting strategy is to use daylight extensively, control systems that can be easily operated, such as manual blinds or other types of window treatments, should be specified in order to control excessive sunlight or glare.

5

Noise, Acoustics, Student Learning, and Teacher Health

Various studies show that noise exposure affects educational outcomes, and other research provides evidence of mechanisms to explain these effects of noise on learning. Speech intelligibility studies have found that students' ability to recognize speech sounds is decreased by even modest levels of ambient noise, and this effect is magnified for younger children. This problem may not be appreciated by adults, who are better able to recognize speech in the presence of noise.

Most learning in school classrooms involves speaking and listening as the primary communication modes: Students learn by listening to the teacher and to each other (Goodland, 1983). Excessive background noise or reverberation (i.e., many delayed reflections of the original sound) can interfere with speech perception and, consequently, can impair educational outcomes. Careful attention to acoustical design requirements is essential for creating an effective learning environment. Nonetheless, a 1995 report of the U.S. General Accounting Office estimated that approximately 22,000 U.S. schools attended by 11 million students had unsatisfactory acoustics for noise control: 28 percent of the schools in the survey reported unsatisfactory or very unsatisfactory environments related to acoustics for noise control (GAO, 1995a).

In 2002, the American National Standards Institute (ANSI) issued voluntary standard S12.60, "Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools," which calls for a maximum ambient noise level of 35 dB(A) and includes recommendations for the required sound isolation between classrooms and adjacent spaces or the outdoors (ANSI, 2002). Many classrooms currently do not meet the recommendations of this standard, but at least one state, Connecticut, has already adopted the use of ANSI S12.60 for its schools.

People's ability to understand speech is influenced largely by the level of speech sounds relative to the level of ambient or background noise. Reverberant sound causes one word to smear into the next and can decrease the intelligibility of speech. Acoustical design involves designing to control sound to facilitate improvement in the perception of speech sounds. Controlling sound should focus primarily on reducing unwanted noise, and secondarily on controlling excessive reverberation. Good acoustical design can allow for more accurate verbal interaction and less repetition among teachers and students because spoken words are clearly understood, and as a consequence, it can facilitate learning. There is also evidence that good acoustical design may have a health benefit for teachers, by reducing the incidence of voice impairment.

Excessive noise can also interfere with learning by affecting memory (Hygge, 2003) and acting as a distraction that impairs a student's ability to pay attention. The ability to pay attention is most important when students are engaged in tasks that demand higher mental processes, such as learning new concepts or when teachers are verbally presenting new or complex information (Hartman, 1946). (See also Anderson, 2004, for a review of the effects of noise on children and classroom acoustics issues.)

Excessive background noise in a classroom can originate from outside the building (aircraft and traffic noise, lawnmowers and leaf blowing) or from within the building (heating, ventilation, air-conditioning, plumbing systems, noise from adjacent classrooms or hallways, gymnasiums or music rooms) or noise from the students themselves. However, it is important to note that the level of residual noise from the students is strongly related to the general level of ambient noise in the room. That is, student chatter will increase as the general level of ambient noise increases, an example of the Lombard effect (Junqua, 1996).

Speech perception studies have investigated how interference from noise and reverberation influences the perception of syllables, words, or sentences in classrooms. The importance of ambient noise levels is mostly related to speech-to-noise ratios. Kindergarten and first and second grades are the primary years in which children learn to break down written words into their phonetic components and acquire the ability to read. This requires careful listening to develop the ability to discriminate among minor differences in words such as pet, pit, pot, put, and pat (Anderson, 2004). Such differences can be lost in a noisy environment, and hence younger children require higher signal-to-noise ratios corresponding to quieter conditions.

The impacts of excessive noise vary according to the age of the students because

> the ability to focus on speech is a developmental skill that evolves with maturation of the brain and mastery of language. Because the auditory mechanism does not fully mature until age 13 to 15 years, young children . . . require better acoustical environments than do adult listeners to achieve equivalent word recognition scores. (Anderson, 2004, p. 119)

For that reason, a student’s difficulty in understanding speech in noisy situations may not be recognized by teachers, building designers, or other adults. Said another way, adults cannot recognize the level of children’s difficulty by using their own ability to perceive speech under the same adverse listening conditions. Elliott et al. (1979) found that the ability to recognize sentences in noisy environments improves systematically with age for children ages 7, 9, 11, 13, 15, and 17 years. This has recently been shown in extensive studies in actual classrooms (Bradley and Sato, 2004).

There are also studies suggesting that the negative effects of excessive reverberation are more acute for younger listeners (Náběleк and Robinson, 1982), but the requirements for children of various ages have not been determined. Although most standards (e.g., ANSI S12.60) recommend approximately a 0.6-s reverberation time, some studies have suggested that much shorter reverberation times would be better (Nábělek and Picket, 1974). However, some of these studies are flawed and their results cannot be relied upon. These experimental results are incomplete because they include only the negative effects of increased reverberation but not the positive benefits (i.e., increased speech levels). Further research is required to more precisely confirm optimum reverberation times for children of various ages.

NOISE AND STUDENT ACHIEVEMENT

Since the 1970s, a number of studies have been conducted that compare the reading skills of students in schools exposed to transportation noise with the reading skills of students in schools in quieter areas. A study in the early 1970s looked at the performance of children in a New York school that was parallel to the tracks of an elevated train. During a 3-year time period, a comparison of aggregate scores for students in grades two, four, and six was made between students on the noisy side and students on the nonnoisy side of the school. Students on the noisy side lagged behind in reading an average of 3 to 4 months compared with students on the quieter side. After the train tracks were treated to abate the noise, reading levels of children on what had been the noisier side of the building improved (Bronzaft and McCarthy, 1975; Bronzaft, 1981).

A 1982 study of students in New York schools under and not under flight paths matched the students for socioeconomic status, race, gender, hearing loss, mother's education level, and English as a second language (Green et al., 1982). The study found that high levels of environmental noise were inversely related to reading ability in elementary school children. A later study of students in New York matched students/schools for low socioeconomic status, student absentee rates, and teacher experience and then analyzed reading achievement test scores for grades two through six (Evans and Maxwell, 1997). The analysis found that a higher percentage of students in noisy schools were reading 1 to 2 years below their grade level.

A study of schools near Munich Airport looked at the cognitive effects on children when the airport was in operation and then after the airport was moved to a new location. The study found impaired reading comprehension in third and fourth grade children in schools located near the airport. Children from noisy communities had significantly more errors on a standardized reading test when compared with students from quieter communities. Further, reading comprehension deteriorated in children in schools near the new airport (Hygge et al., 1996).

A 1997 study comparing students from two schools near Heathrow Airport found a significant association between noise and reading comprehension that could not be accounted for by annoyance, social class, or other factors (Haines et al., 2001a,b).

In one of the most comprehensive and rigorous studies to date, Stansfeld et al. (2005) conducted a cross-national, cross-sectional study to assess the effect of exposure to aircraft and road traffic noise on cognitive performance (reading comprehension) and health in children. The study assessed 2,844 children ages 9 to 10 in 89 schools located in the United Kingdom, Spain, and the Netherlands in 2002. Schools in all three countries were selected on the basis of increasing levels of exposure to aircraft and traffic noise. The selected schools were matched by students' socioeconomic status, the primary language spoken at home, and other factors. External noise was measured, and reading comprehension was assessed using standardized and normalized tests routinely used in each country.

Tests were also conducted to measure students' recognition and recall (episodic memory), sustained attention, working memory, and prospective memory. Socioeconomic characteristics were assessed as potential confounding factors, and pilot studies were conducted to assess the feasibility, reliability, validity, and psychometric properties of the cognitive tests to be used. The pooled data gathered through the study were analyzed statistically using multilevel modeling, and the final results were adjusted for a number of factors including children's long-standing illness, parental support for schoolwork, and home ownership. The authors noted that the study's limitations were that it was cross-sectional, not longitudinal; was restricted to 9- and 10-year olds; did not focus on noise exposure in the students' homes; and used different noise assessment techniques in the three countries.

This study found that chronic exposure to aircraft noise "was associated with a significant impairment in reading comprehension. . . . [A] 5-decibel difference in aircraft noise was equivalent to a 2-month reading delay in the United Kingdom and a 1-month delay in the Netherlands" (Stansfeld et al., 2005, p. 1946). This outcome was consistent with findings from other studies on the effects of aircraft noise on reading comprehension. Because it was a cross-sectional study, the effect of long-term noise exposure to aircraft noise could not be measured. Socioeconomic status was not found to be a factor in the size of the effect, a finding that differs from findings of other studies. The study also found that aircraft noise was "not associated with impairment in working memory, prospective memory, or sustained attention" (Stansfeld et al., 2005, p. 1946).

Stansfeld et al. (2005) also looked at the effect of traffic noise on the children. The authors noted linear exposure-effect associations between exposure to road traffic noise and increased functioning of episodic memory, in regard to information and conceptual recall (Stansfeld et al., 2005, p. 1947).

NOISE AND TEACHERS' HEALTH

Teachers who work in noisy classrooms must constantly raise their voices to be heard over various other sounds. Over time, this can lead to vocal fatigue and other voice problems. One study published in 1993 found that four out of five teachers who participated in the study indicated some problems with vocal fatigue (Gotaas and Starr, 1993). A 1995 study of populations in the U.S. workforce that rely on voice as a primary tool of their trade found that teachers constitute more than 20 percent of the voice-clinic load or five times the number expected by their prevalence in this segment of the workforce (Titze et al., 1996).

FINDINGS AND RECOMMENDATION

Finding 5: In regard to noise, acoustics, student learning, and teacher health, the committee has found the following:

- Sufficient evidence exists to conclude that there is an association between decreased noise levels in schools and improvement in student achievement.
- Although there is strong evidence that reduced noise levels are most important for younger children because they are still developing speech discrimination, additional research is required to more precisely define possible needs for control of reverberant sound for younger children.
- Some available evidence indicates that teacher health, in regard to voice impairment, may be adversely affected by noisier environments, although the magnitude of the effect cannot currently be estimated as a function of exposure to noise.

Recommendation 4: To facilitate student learning, guidelines for green schools should include requirements to meet American National Standards Institute (ANSI) Standard S12.60, "Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools."

6

Building Condition and Student Achievement

For more than two decades, professional organizations and governmental agencies have been reporting on the condition of the nation's schools (AASA, 1983; Council of Great City Schools, 1987; Educational Writers' Association, 1989; GAO, 1995a,b; NEA, 2000).[7] These reports have consistently found that a substantial portion of the school-age population was being educated in substandard buildings. And schools with the highest concentrations of students from low-income households were more likely to be in substandard condition.

In *School Facilities: Condition of America's Schools*, the U.S. General Accounting Office estimated that approximately 14 million students (30 percent of all students) attended schools that needed extensive repairs or replacement (one-third of the school inventory) (GAO, 1995a). Approximately 28 million students attended schools that needed extensive repairs on one or more major building systems. The building components or features most often identified as needing attention in substandard schools were proper thermal control (temperature and humidity), ventilation, plumbing, roofs, exterior walls, finishes, windows, doors, electrical power, electrical lighting, life safety (fire suppression), and interior finishes and trims. The cost to make necessary repairs was estimated at more than $100 billion (1995 dollars). The state of Massachusetts was included in this survey, and the condition of the school buildings in that state reflected the condition of schools nationwide.

A second GAO report, ***School Facilities: America's Schools Not Designed or Equipped for 21st Century,*** found that approximately 40 percent of the schools surveyed could not meet the functional requirements of laboratory science or large-group instruction (GAO, 1995b). About two-thirds of the schools reported that they could not support educational reform measures such as a private space for counseling and testing, parental support activities, social/health care, day care, and before- and after-school care.

In 2000 the U.S. National Center for Educational Statistics reported that at least 29 percent of the nation's schools had problems with heating, ventilation, and air-conditioning; 25 percent had plumbing problems; 24 percent reported problems with exterior walls, finishes, windows, and doors; and about 20 percent had less than adequate conditions for life safety, roofs, and electrical power. About 11 million students attended school in the school districts reporting buildings with less than adequate condition. Of these students, approximately 3.5 million students attended schools in which the condition was rated as poor, replacement was needed, or significant substandard performance was apparent (NCES, 2000).

The National Education Association (NEA) has estimated it would cost $322 billion to repair, modernize, retrofit for new technology, and make major improvements to existing school buildings (NEA, 2000). This figure also included new construction and additions to

[7] Note: The studies referred to in this chapter use building condition as a qualitative and quantitative measure of a variety of systems and components. In some cases, these conditions included problems related to moisture in buildings, acoustics, lighting, and so forth. Thus, building condition is not necessarily separate from the issues discussed in Chapters 2 through 5.

existing buildings, which explains the disparity with earlier estimates. For the state of Massachusetts, the cost to improve all existing buildings is estimated to range from $8.9 billion to $9.9 billion.

Implicit in these reports is the underlying assumption that school condition and functionality can influence student learning, either positively or negatively. Although most school buildings start out meeting current codes, standards, and functional design, over time physical conditions deteriorate if building components and systems are not properly operated and maintained or repaired in a timely manner.

SCHOOL BUILDING CONDITION AND STUDENT ACHIEVEMENT

The committee identified seven studies that investigated the relationship between the condition of school buildings and at least two student variables. The one consistent variable was student achievement as measured by some form of standardized or normed test or examination administered to all students in the schools. Four of the seven studies focused on high school students, one focused on third and fifth graders, and two included students at elementary, middle, and high school levels. A description of each of the studies, the methodology used, the reported findings, and the committee's conclusions follow.

Edwards (1992) investigated the relationship between parental involvement, school building condition, and student achievement in the schools of Washington, D.C. She hypothesized that the condition of public school buildings is affected by parental involvement and that the condition of the school building further affects student achievement. She analyzed these relationships by evaluating the condition of school buildings, determining the extent of parental involvement and the amount of funds parents raised for the local school, and compared the results with student achievement scores, as measured using average test scores on the Comprehensive Test of Basic Skills (CTBS).

Edwards found that building condition did have an effect on student achievement scores. The analysis indicated that as a school moves up from one condition category to another (e.g., from poor to fair), the achievement scores can be expected to increase by 5 percent. If the school moves up two categories, such as from poor to excellent, the average achievement scores can be expected to increase by 11 percent.

In a similar study, Cash (1993) investigated the relationship between certain school building conditions, student achievement, and student behavior in rural high schools in Virginia. Basically, the same hypothesis that Edwards employed was used in conducting this study. The condition of the building in this study, however, was the independent variable, and student achievement and behavior served as dependent variables.

The condition of the school building was determined through evaluation by local school system personnel. Cash developed a building evaluation instrument, the Commonwealth Assessment of Physical Environment (CAPE), to be used by local school personnel to determine the classification of the building. The CAPE was derived from previous studies that showed a positive relationship between a particular building condition and student achievement and behavior, including air-conditioning, classroom illumination, temperature control, classroom color, graffiti, science equipment and utilities, paint schedules, roof adequacy, classroom windows, floor type, building age, supporting facilities, condition of school grounds, and furniture condition. The presence or absence of these factors determined the overall condition of the building: substandard, standard, and above standard.

Student achievement was measured by use of scaled scores of students taking the Test of Academic Proficiency (TAP), which was administered to all 11th grade students in Virginia. The ratio of students receiving free and reduced lunches was used to control for socioeconomic status of the school attendance area, and the Virginia Composite Index was used as a measure of local fiscal capacity, to control for the wealth of the school jurisdiction.

The data analysis was done by comparing achievement score means of building condition ratings using analysis of covariance to adjust the means. The percentage of students who did not qualify for free or reduced lunch was the covariant. The adjusted mean scale scores in achievement and the behavior ratios for each building were compared across the three levels of building condition and between the three levels of overall, cosmetic, and structural categories. Cash found significant differences between the achievement scores of students in poor buildings and those in above-standard buildings when the overall condition of the building was used as a measure. She also found a larger number of differences in scores of students when the cosmetic features of a building were used as a measure of comparison. She observed that apparently students were more aware of the cosmetic than the structural condition of a building. The difference between test scores of students in poor and above-standard buildings ranged from 2 to 5 percentile points, depending on the subtest.

Earthman et al. (1996) used a similar methodology to conduct a study in North Dakota that included all 199 high school buildings in the state. North Dakota was selected for the study because traditionally students as a whole score among the highest in the nation on the Scholastic Aptitude Test. North Dakota students also scored third highest in the International Comparison of 8th Grade Math scores in 1992, behind only Asia and Japan (Leadership News, 1994). The state has a relatively homogeneous, mostly rural population.

Although the differences in the composite score were exactly the same as for the Cash study, there are some notable differences. The CTBS has additional subtests that the TAP does not have, such as reading, vocabulary, mathematics concepts, and spelling. The differences in reading, vocabulary, and spelling are rather high, considering the differences in other subtests. The North Dakota study does support the findings of both the Edwards and the Cash studies. Both of these researchers found at least a 5 percent difference in composite achievement scores in their population. The North Dakota study found a similar difference in percentile rankings in student achievement scores.

Hines (1996) used the same methodology and data-gathering instrument as Cash to study large urban high schools in Virginia. His results in comparing building condition and student achievement were basically the same. The range of differences between substandard and above-standard buildings, however, was greater than what was found in the study of rural high schools and in the North Dakota high schools study. In the Hines study, differences in test scores for students in above-standard schools ranged from 9 points higher for writing and science, to 15 points higher for reading, and 17 points higher for mathematics compared with the test scores of students in substandard buildings. This compares favorably with the results Edwards obtained in her comparison between the worst and best school buildings. Edwards stated that the difference in mean achievement scores for her study population was as much as 10.9 percent between school buildings in the substandard and above-standard categories (p. 24).

Lanham (1999) completed a study of the relationship between classroom conditions and student achievement in the elementary schools of Virginia that housed both third- and fifth-grade students. The researcher used the same general approach to investigating this relationship as Cash (1993) did on the high school level. From a total of 989 elementary schools, a random sample of 299 schools was drawn. Responses were received from 197 schools, representing a 66 participation rate. Lanham concluded that although certain school building and cosmetic components and features have a part in explaining the variance in student achievement scores, the socioeconomic status of the student as represented by participation in the free and reduced lunch program accounts for the most variance.

Schneider (2002) investigated the relationship between the condition of school buildings and student achievement scores in two large urban school districts, Washington, D.C., and Chicago, Illinois. In testing for the relationship between student achievement and building condition, the researcher used the results of the reading and on math scores on the Stanford Achievement Test in Washington, D.C., and the Iowa Test of Basic Skills in Chicago.

In Washington the difference in achievement scores was reported as the percent of students performing above the basic level of achievement for the grade. In Chicago the difference was reported as the percent of students performing at grade level. After controlling for factors such as poverty, ethnicity, and school size, the researcher was able to report a difference in both cities of between 3 to 4 percentage points in performance between students in poor buildings and those in good buildings. In other words, the students in schools with good conditions were performing from 3 to 4 percentage points better than students in buildings with poor conditions. In Washington, the difference was 3 percent in both reading and math between students in good and poor buildings. In Chicago, the difference was 3 percent for reading and 4 percent for math scores. These differences are well within the range of differences reported by other researchers.

Lewis (2000) conducted a study in the Milwaukee public schools comparing building condition with student achievement scores. The school system had approximately 139 elementary, middle, and high school buildings. All buildings were evaluated for both condition and adequacy. The Wisconsin Student Assessment System (WSAS) was used to measure student achievement. The WSAS consisted of three sets of standardized tests administered in the fourth, eighth, and tenth grades. Students were assessed in reading, mathematics, language arts and writing, science, and social studies. Scores on these examinations were reported as a percentage of students in each school building who were achieving at or above the level defined as proficient in the subject. These percentages were converted to standardized scores with a mean of 100 for analysis purposes. WSAS scores for 1996, 1997, and 1998 were used. Data were also gathered on student demographics, race, attendance, truancy, suspensions, mobility, and participation in school lunch programs. Multiple regression analyses were conducted. The overall hypothesis of the study was that as the condition of the school building increased, student test scores would also increase.

The study demonstrated several significant relationships, yet the findings were not consistent. Based on these results, Lewis (2000) concluded that the "significant relationships for facility measurements typically explain about 10 to 15 percent of the differences in scores across schools when the influences of the other variables were statistically controlled" (p. 11). When comparing student demographic indicators such as mobility rates, eligibility for free/reduced lunches, attendance, and suspensions, only 9 estimates out of 48 were found to be significant. Thus those indicators that were significant explained between 8 and 28 percent of the difference between test scores when other variables were controlled.

SCHOOL BUILDING FUNCTIONALITY AND STUDENT ACHIEVEMENT

Eleven studies were identified that investigated the relationship between school building functionality and student achievement. In each study, the age of the school building was used as a surrogate for functionality. The age of a building may not in and of itself be a direct negative factor in student achievement, but what qualities the building does not have might provide a direct relationship to student achievement. Building age might also serve as a surrogate for a number of specific variables such as condition of the building, thermal control, proper lighting, acoustical control, support facilities, condition of laboratories, aesthetic condition, among others.

Under the variable of school building age, McGuffey (1982) reviewed seven studies (Thomas, 1962; Burkhead et al., 1967; Michelson, 1970; Guthrie et al., 1971; McGuffey and Brown, 1978; Plumley, 1978; and Chan, 1979). In all cases, increasing building age was significant as a factor detrimental to student achievement and behavior; i.e., as building age increased, student achievement decreased.

McGuffey and Brown (1978) studied 188 school districts in Georgia to explore the relationship between building age and student achievement. They used the scores on the Iowa Test of Basic Skills for the fourth and eighth grade students and the Test of Academic Progress for eleventh grade students. In comparing student test scores with the age of the building, the statistical analyses indicated that building age could account for 0.5 percent to 2.6 percent of the variance among fourth grade students, 0 percent to 2.6 percent of the variance among eighth grade students, and 1.4 percent to 3.3 percent of the variance among eleventh graders.

In addition to the studies above, Garrett (1981), Chan (1982), Bowers and Burkett (1989), and Phillips (1997) conducted similar studies using age of the building as an independent variable and student achievement test scores as dependent variables. Their findings substantiated those of previous studies.

Students in the new school building significantly outperformed the students in the older building in reading, listening, language, and arithmetic. Further, faculty in the new building reported fewer disciplinary incidents and health problems than did faculty in the old building. Attendance likewise was better for students in the new building than for students in the old school. Researchers conducting these studies concluded that a relationship did exist between the physical environment and student achievement, health, attendance, and behavior.

In all of the studies cited above, the range of difference between the test scores of students in substandard and standard school buildings was between 1 and 17 percentile points. In almost all cases there was a positive difference for students in the better buildings. These findings are of particular importance because of the large number of school buildings across the United States that are in substandard condition.

All of these studies raise the important question, If students are housed in poor buildings for a number of years, will the negative effect on achievement be multiplied the longer a student is in these buildings? The research cited here is simply a snapshot of conditions and relationships at one period of time, not over successive periods of time. There is a reasonable basis to believe, however, that the harmful effect of poor school buildings on student test scores may be cumulative and may continue to worsen the longer the student is in school.

The condition of existing buildings results from the amount of attention to maintenance that the buildings have had over the years. Assuming the original building is constructed of quality materials with good workmanship applied, the normal life of a well-built school is at least 30 years. During this period of time proper maintenance is required to keep the building in as good a condition as when it was initially constructed. Lack of attention to maintaining the building in good condition results in deterioration of the structure and all of its systems, and the life expectancy of the building is reduced.

LIMITATIONS OF THE CURRENT STUDIES

One factor that can have an influence on the results of a research study devoted to the investigation of the relationship between school building condition and student achievement is the method used to evaluate the condition of a building. There is no statistical evidence to indicate that using one kind of building assessment method or instrument is better than using another. Nevertheless, the studies that have used instruments designed to gauge maintenance and its effects have not been as successful in finding relationships as those studies that have used instruments designed to study the performance of occupants. This leads one to believe that a focus on assessment of a building does limit the results of some studies.

The studies that used the age of a building or the condition of a school building as an independent variable in comparing student achievement test scores have the same limitations as cited above. As in almost all studies using student achievement scores, there is the limitation of not being able to control all of the variables associated with student learning. Variables such as the quality of the teaching staff, the curriculum, the viability of the student test measures, and, most important, the background of the student are all virtually impossible to completely control. For this reason the evidence found in these studies concerning the relationship between school building age and student achievement must be considered as a suggestive association.

FINDING AND RECOMMENDATION

Finding 6: In regard to building condition and student achievement, the committee found the following:

- The body of available research is suggestive of an association between the condition of a school building and student achievement. All of the studies analyzed by the committee found that student test scores improved as the physical condition of school buildings improved. The degree of improvement of students' test scores varied across the studies, but in all cases students in buildings in better condition scored higher than students in buildings in poor condition.

Recommendation 5: Guidelines for green schools should place significant emphasis on operations and maintenance practices if potential health and productivity benefits are to be achieved and maintained over the lifetime of a building.

References

AASA (American Association of School Administrators). 1983. The Maintenance Gap: Deferred Repair and Renovation in the Nation's Elementary and Secondary Schools. Arlington, VA: AASA.

Anderson, K. 2004. The problem of classroom acoustics: The typical classroom soundscape is a barrier to learning. Semin. Hearing 25:117-129.

ANSI (American National Standards Institute). 2002. Standard S12.60. Acoustical Performance Criteria, Design Requirements and Guidelines for Schools. Washington, DC: ANSI.

ANSI (American National Standards Institute). 2004. Building Commissioning. Washington, DC: ANSI.

ANSI/ASHRAE. 2004. Standard 55-2004. Thermal Environmental Conditions for Human Occupancy. Washington, DC: ANSI.

ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers). 2004. Standard 62.1. Ventilation for Acceptable Indoor Air Quality. Washington, DC: ASHRAE.

Belanger, K., Beckett, W., Triche, E., Bracken, M.B., Holford, T., Ren, P., McSharry, J.E., Gold, D.R., Platts-Mills, T.A., and Leaderer, B.P. 2003. Symptoms of wheeze and persistent cough in the first year of life: Associations with indoor allergens, air contaminants and maternal history of asthma. Am. J. Epidemiol. 158:195-202.

Bloom, B., and Tonthat, L. 2002. Summary health statistics for U.S. children: National health interview survey, 1997. Vital Health Stat. Series 10, 203:1-46.

Boubekri, M., Hull, R.B., and Boyer, L.L. 1991. Impact of window size and sunlight penetration on office workers' mood and satisfaction: A novel way of assessing sunlight. Environment and Behavior 23(4):474-493.

Bowers, J.H., and Burkett, C.W. 1989. Effects of physical and school environment on students and faculty. Educational Facility Planner 27(1):28-29.

Boyce, P.R. 2003. Human Factors in Lighting, 2nd Edition. London and New York: Taylor and Francis.

Boyce, P.R. 2004. Reviews of Technical Reports on Daylight and Productivity. Troy, NY: Lighting Research Center. Available at www.daylightdividends.org.

Boyce, P.R., Hunter, C., and Howlett, O. 2003. The benefits of daylight through windows. Report submitted to Capturing the Daylight Dividends Program. Troy, NY: Lighting Research Center. Available at www.daylightdividends.org.

Bradley, J.S., and Sato, H. 2004. Speech intelligibility test results for grades 1, 3 and 6. Children in Real Classrooms. Paper Tu4B1.2. Proceedings of the 18th International Congress on Acoustics. Kyoto, Japan.

Brainard, G.C., Hanifin, J.P., Greeson, J.M., Byrne, B., Glickman, G., Gerner, E., and Rollag, M.D. 2001. Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor. J. Neurosci. 21(16):6405-6412.

Bronzaft, A.L. 1981. The effect of a noise abatement program on reading ability. J. Environ. Psychol. 1:215-222.

Bronzaft, A.L., and McCarthy, D.P. 1975. The effect of elevated train noise on reading ability. J. Environ. Behav. 7:517-528.

Burkhead, J., Fox, T., and Holland, J.W. 1967. Input and Output in Large-City High Schools. Syracuse, NY: Syracuse University Press.

Carskadon, M.A., Wolfson, A.R., Acebo, C., Tzischinsky, O., and Seifer, R. 1998. Adolescent sleep patterns, circadian timing, and sleepiness at a transition to early school days. Sleep 21(8):871-881.

Cash, C.S. 1993. Building condition and student achievement and behavior. Unpublished doctoral dissertation. Blacksburg, VA: Virginia Polytechnic Institute and State University.

CDC (Centers for Disease Control and Prevention). 2004. Asthma Prevalence, Health Care Use and Mortality, 2002. Hyattsville, MD: U.S. Department of Health and Human Services.

Chan, T.C. 1979. The impact of school building age on the achievement of eighth-grade pupils from the public schools in the state of Georgia. Unpublished doctoral dissertation. Athens, GA: University of Georgia.

Chan, T.C. 1982. A comparative study of pupil attitudes toward new and old school buildings. Greenville, SC: Greenville County School District. ERIC Document Reproduction Service No. ED 222 981.

CHPS (Collaborative for High Performance Schools). 2004. Best Practices Manual. Volumes 1-4. Available at www.chps.net.

CHPS. 2005. Web site at www.chps.net. Accessed October 31, 2005.

Collins, B.L. 1975. Windows and People: A Literature Survey: Psychological Reaction to Environments with and Without Windows. National Bureau of Standards Building Science Series 70. Washington, DC: U.S. Department of Commerce.

Council of Great City Schools. 1987. Report on Deferred Maintenance to the Council of the Great City Schools. Washington, DC: Council of Great City Schools.

Cox-Ganser, J.M., White, S.K, Jones, R., Hilsbos, K., Storey, E., Enright, P.L., Rao, C.Y., and Kreiss, K. 2005. Respiratory morbidity in office workers in a water damaged building. Environ. Health Perspect. 113:485-490.

Cuttle, K. 1983. People and windows in workplaces. Pp. 203-212 in Proceedings of the People and Physical Environment Research Conference. Wellington, New Zealand.

Daisey, J.M., Angell, W.J., and Apte, M.G. 2003. Indoor air quality, ventilation, and health symptoms in schools: An analysis of existing information. Indoor Air 13:53-64.

Darling-Hammond, L. 1999. Teacher Quality and Student Achievement: A Review of State Policy Evidence. Seattle, WA: University of Washington.

Deal, B.M., Rose, W., and Riley, S.E. 1998. Commissioning for humidified buildings. USACERL Technical Report 99/03. Champaign, IL: U.S. Army Corps of Engineers Construction Engineering Research Laboratories.

Demos, G.D., Davis, S., and Zuwaylif, F.F. 1967. Controlled physical environments. Building Research 4:60-62.

Earthman, G.I., Cash, C.S., and Van Berkum, D. 1996. Student achievement and behavior and school building condition. J. School Business Management 8(3):26-37.

Educational Writers Association. 1989. Wolves at the Schoolhouse Door: An Investigation of the Conditions of Public School Buildings. Washington, DC: Educational Writers Association.

Edwards, M.M. 1992. Building conditions, parental involvement and student achievement in the D.C. public school system. Unpublished master's thesis. Washington, DC: Georgetown University.

Elliott, L., Connors, S., Kille, E., Levin, S., Ball, K., and Katz, D. 1979. Children's understanding of monosyllabic nouns in quiet and in noise. J. Acoust. Soc. Am. 66:12-21.

Evans, G.W., and Maxwell, L. 1997. Chronic noise exposure and reading deficits. J. Environ. Behav. 29(5):638-656.

Fang, L., Clausen, G., and Fanger, P.O. 1998. Impact of temperature and humidity on the perception of indoor air quality. Indoor Air 8:80-90.

Fanger, P.O. 2000. Indoor air quality in the 21st century: The search for excellence. Indoor Air 10:68-73.

Federspiel, C.C., Fisk, W.J., Price, P.N., Liu, G., Faulkner, D., Dibartolomeo, D.L., Sullivan, D.P., and Lahiff, M. 2004. Worker performance and ventilation in a call center: Analyses of work performance data for registered nurses. Indoor Air 14(Suppl 8):41-50.

Fetveit, A., Skjerve, A., and Bjorvatn, B. 2003. Bright light treatment improves sleep in institutionalized elderly—An open trial. Int. J. Geriatr. Psychiatry 18(6):520-526.

FFC (Federal Facilities Council). 2005. Implementing Health-Protective Features and Practices in Buildings. Washington, DC: The National Academies Press.

Figueiro, M.G., and Rea, M.S. 2005. LEDs: Improving the sleep quality of older adults. Proceedings of the CIE Midterm Meeting and International Lighting Congress. Leon, Spain, May 18-21.

GAO (General Accounting Office). 1995a. School Facilities: Condition of America's Schools. GAO/HEHS-95-61.Washington, DC: GAO.

GAO. 1995b. School Facilities: America's Schools Not Designed or Equipped for 21st Century. GAO/HEHS-955-95. Washington, DC: GAO.

Garrett, D.M. 1981. The impact of school building age on the academic achievement of high school pupils in the state of Georgia. Unpublished doctoral dissertation. Athens, GA: University of Georgia.

Glickman, G., Hanifin, J.P., Rollag, M.D., Wang, J., Cooper, H., and Brainard, G.C. 2003. Inferior retinal light exposure is more effective than superior retinal exposure in suppressing melatonin in humans. J. Biol. Rhythms 18(1):71-79.

Goodland, J. 1983. A Place Called School. Prospects for the Future. New York: McGraw-Hill.

Gotaas, C., and Starr, C.C. 1993. Vocal fatigue among teachers. Folia Phoniatr. (Basel) 45:120-129.

Green, K.B., Pasternack, B.S., and Shore, R.E. 1982. Effects of aircraft noise on reading ability of school-age children. Arch. Environ. Health 37:24-31.

Guthrie, J.W., Kleindorfer, G.B., Levin, H.M., and Stout, R.T. 1971. Schools and Inequity. Cambridge, MA: MIT Press.

Haines, M.M., Stansfeld, S.A., and Brentnall, S. 2001a. The West London School Study: The effects of chronic aircraft noise exposure on child health. Psychol. Med. 3:1385-1396.

Haines, M.M., Stansfeld, S.A., Job, R., Berglund, B., and Hea, J. 2001b. Chronic noise exposure, stress responses, mental health and cognitive performance in schools. Psychol. Med. 31:265-277.

Hartman, G. 1946. The effects of noise on children. J. Educ. Psychol. 37:149-161.

Heerwagen, J., and Heerwagen, D. 1986. Lighting and psychological comfort. Lighting Design and Application 6:47-51.

Heschong-Mahone Group. 1999. Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance. Fair Oaks, CA: Heschong-Mahone Group.

Heschong-Mahone Group. 2001. Daylighting in Schools: Reanalysis Report. Technical Report P500-03-082-A-3. Sacramento, CA: California Energy Commission.

Heschong-Mahone Group. 2003. Windows and Classrooms: A Study of Student Performance and the Indoor Environment. P500-03-082-A-7. Fair Oaks, CA: Heschong-Mahone Group.

Heuer, H., Kleinsorge, T., Klein, W., and Kohlisch, O. 2004. Total sleep deprivation increases the costs of shifting between simple cognitive tasks. Acta Psychol. (Amst.) 117(1):29-64.

Hines, E.C. 1996. Building condition and student achievement and behavior. Unpublished doctoral dissertation. Blacksburg, VA: Virginia Polytechnic Institute and State University.

Hygge, S. 2003. Classroom experiments on the effects of different noise sources and sound levels on long-term recall and recognition in children. Appl. Cognit. Psychol. 17:895-914.

Hygge, S., Evans, G.W., and Bullinger, M. 1996. The Munich Airport noise study: Cognitive effects on children from before to after the change of airports. Proceedings of Internoise ’96 5:2189-2194. Liverpool.

IOM (Institute of Medicine). 1991. Adverse Effects of Pertussis and Rubella Vaccines. Washington, DC: National Academy Press.

IOM. 1993. Adverse Events Associated with Childhood Vaccines: Evidence Bearing on Causality. Stratton, K.R., Howe, C.J., and Johnston, R.B., eds. Washington, DC: National Academy Press.

IOM. 1994. Veterans and Agent Orange: Health Effects of Herbicides Used in Vietnam. Washington, DC: National Academy Press.

IOM. 1996. Veterans and Agent Orange. Update 1996. Washington, DC: National Academy Press.

IOM. 1999. Veterans and Agent Orange. Update 1998. Washington, DC: National Academy Press.

IOM. 2000. Clearing the Air: Asthma and Indoor Air Exposures. Washington, DC: National Academy Press.

IOM. 2003. Veterans and Agent Orange. Update 2002. Washington, DC: The National Academies Press.

IOM. 2004. Damp Indoor Spaces and Health. Washington, DC: The National Academies Press.

Jaakola, M.S., Nordman, H., Piipari, R., Uitti, J., Laitinen, J., and Karjalainen, A. 2002. Indoor dampness and molds and development of adult-onset asthma: A population-based incident study. Environ. Health Perspect. 110:543-547.

Jackson, G.J., and Holmes, J.G. 1973. Let's keep it simple—What we want from daylight. Light and Lighting 12:80-82.

Jennings, J.R., Monk, T.H., and van der Molen, M.W. 2003. Sleep deprivation influences some but not all processes of supervisory attention. Psychol. Sci. 14(5):473-479.

Jewett, M., Rimmer, D.W., Duffy, J.F., Klerman, E.B., Kronauer, R., and Czeisler, C.A. 1997. Human circadian pacemaker is sensitive to light throughout subjective day without evidence of transients. Am. J. Physiol. 273:R1800-R1809.

Junqua, J.C. 1996. The influence of acoustics on speech production: A noise-induced stress phenomenon known as the Lombard reflex. Speech Commun. 20:13-22.

Kemper, A.R., Bruckman, D., and Freed, G.L. 2004. Prevalence and distribution of corrective lenses among school-age children. Optom. Vis. Sci. 81(1):7-10.

Kuller, R., and Lindsten, C. 1992. Health and behavior of children in classrooms with and without windows. J. Environ. Psychol. 12:305-317.

Lanham III, J.W. 1999. Relating building and classroom conditions to student achievement in Virginia's elementary schools. Unpublished doctoral dissertation. Blacksburg, VA: Virginia Polytechnic Institute and State University.

Larson, C.T. 1965. The effect of windowless classrooms on elementary school children. Architectural Research Laboratory, Department of Architecture, University of Michigan, Ann Arbor.

Leadership News. 1994. Performance-Based Funds to Finance Educational Reforms. August 15, p. 4.

Leslie, R., and Hartleb, S. 1990. Windows, variability, and human response. Proceedings of the International Daylighting Conference. Moscow.

Leslie, R., and Hartleb, S. 1991. Some effects of the sequential experience of windows on human response. J. Illuminating Engineering Society, Winter, pp. 91-99.

Lewis, M.G. 2000. Facility Condition and Student Test Performance in the Milwaukee Public Schools. ED 459 593. Scottsdale, AZ: Council of Educational Facility Planners, International.

Lstiburek, J., and Carmody, J. 1994. The Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings. New York: John Wiley & Sons.

Ludlow, A.M. 1976. The functions of windows in buildings. Lighting Research and Technology 6(2):57-68.

Maier, W.C., Arrighi, H.M., Murray, B., Llewellyn, and Redding, G.C. 1997. Indoor risk factors for asthma and wheezing among school children. Environ. Health Perspect. 105:208-214.

Maniccia, D., Rutledge, B., Rea, M., and Narendran, N. 1998. A field study of lighting controls. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY.

Mannino, D., Homa, D., Akinbami, L., Moorman, J., Gwynn, C., and Redd, S. Centers for Disease Control and Prevention. Surveillance for asthma prevalence-United States 1980-1999.

Markus, T.A. 1965. The function of windows: A reappraisal. Building Science 2:97-121.

McGuffey, C.W. 1982. *Facilities*. Chapter 10. Pp. 237-288 in W. Herbert, ed., Improving Educational Standards and Productivity. Berkeley, CA: McCutchan Publishing Corp.

McGuffey, C.W., and Brown, C.L. 1978. The impact of school building age on school achievement in Georgia. CEFP Journal 16:6-9.

McIntyre, I.M., Norman, T.R., Burrows, G.D., and Armstrong, S.M. 1989a. Human melatonin suppression by light is intensity dependent. J. Pineal Res. 6(2):149-156.

McIntyre, I.M., Norman, T.R., Burrows, G.D., and Armstrong, S.M. 1989b. Quantal melatonin suppression by exposure to low intensity light in man. Life Sci. 45(4):327-332.

Mendell, M.J., and Heath, G.A. 2004. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. Indoor Air 15:27-52.

Michelson, S. 1970. The Association of Teacher Resourcefulness with Children's Characteristics. Do Teachers Make a Difference? A Report on Recent Research on Pupil

Achievement. U.S. Office of Education Report OE-58042. Washington, DC: U.S. Government Printing Office.

Milton, K., Glenross, P., and Walters, M. 2000. Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaint. Int. J. Indoor Air Quality and Climate 10:211-221.

Moore, R.Y. 1997. Circadian rhythms: Basic neurobiology and clinical applications. Annu. Rev. Med. 48:253-266.

Nábělek, A.K., and Pickett, J.M. 1974. Reception of consonants in a classroom as affected by monaural and binaural listening, noise, reverberation, and hearing aids. J. Acoust. Soc. Am. 56(2):628-639.

Nábělek, A.K., and Robinson, P.K. 1982. Monaural and binaural speech perception in reverberation for listeners of various ages. J. Acoust. Soc. Am. 71(5):1242-1248.

National Sleep Foundation. 2005. Sleep in America Poll. Available at http://www.sleepfoundation.org/_content/hottopics/2005_summary_of_findings.pdf. Accessed September 20, 2005.

NCES (National Center for Education Statistics). 2000. Condition of America's Public School Facilities: 1999. NCES2000-032. Washington, DC: U.S. Department of Education.

NEA (National Education Association). 2000. Modernizing Our Schools: What Will It Cost? Washington, DC: NEA.

Ne'eman, E., and Longmore, J. 1973. Physical aspects of windows: Integration of daylight with artificial light. Proceedings of CIE Conference on Windows and Their Function in Architectural Design. Istanbul.

NORDAMP (Nordic Interdisciplinary Review of the Scientific Evidence on Associations Between Exposure to "Dampness" in Buildings and Health Effects). 2002. Indoor Air 15(10):7-16.

ORNL (Oak Ridge National Laboratory). 1988. The Building Foundation Design Handbook. ORNL/SUB/86-724143/1. Oak Ridge, TN: ORNL.

Phillips, R.W. 1997. Educational facility age and the academic achievement and attendance of upper elementary school students. Unpublished doctoral dissertation. Athens, GA: University of Georgia.

Phipatanakul, W., Cronin, B., Wood, R.A., Eggleston, P.A., Shih, M.C., Song, L., Tachdjian, R., and Oettgen, H.C. 2004. Effect of environmental intervention on mouse allergen levels in homes of inner-city Boston children with asthma. Ann. Allergy Asthma Immunol. 92(4):420-425.

Plumley, J.P., Jr. 1978. The impact of school building age on the academic achievement of pupils from selected schools in the state of Georgia. Unpublished doctoral dissertation. Athens, GA: University of Georgia.

Rea, M.S., ed. 2000. IESNA Lighting Handbook: Reference and Application. 9th edition. New York: Illuminating Engineering Society of North America.

Rea, M.S., and Bullough, J.D. 2001. Application efficacy. J. Illuminating Engineering Society 30(2):73-96.

Rea, M.S., and Ouellette, M.J. 1991. Relative visual performance: A basis for application. Light. Res. Technol. 23(3):135-144.

Rea, M.S., Ouellette, M.J., and Kennedy, M.E. 1985. Lighting and task parameters affecting posture, performance, and subjective ratings. J. Illuminating Engineering Society 15(1):231-238.

Rea, M.S., Figueiro, M.G., and Bullough, J.D. 2002. Circadian photobiology: An emerging framework for lighting practice and research. Light. Res. Technol. 34(3):177-190.

Reid, K.J., and Zee, P.C. 2004. Circadian rhythm disorders. Semin. Neurol. 24(3):315-325.

Rosen, L.N., Targum, S.D., Terman, M., Bryant, M.J., Hoffman, H., Kasper, S.F., Hamovit, J.R., Docherty, J.P., Welch, B., and Rosenthal, N.E. 1990. Prevalence of seasonal affective disorder at four latitudes. Psychiatry Res. 31(2):131-144.

Rosenthal, N. 1998. Winter Blues. Seasonal Affective Disorder. What It Is and How to Overcome It. New York and London: Guilford Press.

Rosenthal, N., Sack, D., Parry, B., Mendelsom, W., Tamarkin, L., and Wehr, T. 1985. Seasonal affective disorder and phototherapy. Ann. N.Y. Acad. Sci. 453:260.

Rusak, B., Eskes, G.A., and Shaw, S.R. 1997. Lighting and Human Health: A Review of the Literature. Ottawa: Canada Mortgage and Housing Corporation.

Satlin, A., Volicer, L., Ross, V., Herz, L., and Campbell, S. 1992. Bright light treatment of behavioral and sleep disturbances in patients with Alzheimer's disease. Am. J. Psychiatry 149:1028-1032.

Schneider, M. 2002. Public school facilities and teaching: Washington, DC, and Chicago. Available at www.edfacilities.org.

Schwartz, J. 2004. Air pollution and children's health. Pediatrics 113:1037-1043.

Seppanen, O.A., and Fisk, W.J. 2004. A model to estimate the cost effectiveness of indoor environment improvements in office work. Berkeley, CA: Lawrence Berkeley Laboratory.

Seppanen, O.A., and Fisk, W.J. 2005. Some quantitative relations between indoor environmental quality and work performance or health. Proceedings of Indoor Air 2005. Beijing, China.

Seppanen, O.A., Fisk, W.J., and Mendell, M.J. 1999. Association of ventilation rates and CO_2 concentrations with health and other human responses in commercial and institutional buildings. Indoor Air 9:226-252.

Shendell, D.G., Barnett, C., and Boese, S. 2004a. Science-based recommendations to prevent or reduce potential exposure to biological, chemical, and physical agents in schools. J. School Health 74(10):390-396.

Shendell, D.G., Prill, R., Fisk, W.J., Apte, M.G., Blake, O., and Faulkner, D. 2004b. Associations between classrooms' CO_2 concentrations and student attendance in Washington and Idaho. Indoor Air 14:333-341.

Slezak, J.A., Persky, V.W., Kuiz, F.J., and Byers, C. 1998. Asthama prevalence and risk factors in selected Head Start sites in Chicago, IL. J. Asthma 35:203-212.

Smedje, G., and Norbäck, D. 2000. New ventilation systems at select schools in Sweden—Effects on asthma and exposure. Arch. Environ. Health 55:18-25.

Stansfeld, S.A., Berglund, B., Clark., C., Lopez-Barrio, I., Fischer, P., Ohrstrom, E., Haines, M.M., Head, J., Hygge, S., van Kamp, I., and Berry, B.F. 2005. Aircraft and road traffic noise and children's cognition and health: A cross-national study. Lancet 365:1942-1949.

Stark, P.C., Burge, H.A., Ryan, L.M., Milton, D.K., and Gold, D.R. 2003. Fungal levels in the home and lower respiratory tract illnesses in the first year of life. Am. J. Resp. Crit. Care Med. 168:232-237.

Takaro, T.K., Krieger, J.W., and Song, L. 2004. Effect of environmental interventions to reduce exposure to asthma triggers in homes of low-income children in Seattle. J. Exposure Analysis Environ. Epidemiol. 14:S133-S143.

Thapan, K., Arendt, J., and Skene, D.J. 2001. An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. J. Physiol. 535:261-267.

Thomas, J.A. 1962. Efficiency in education: A study of the relationship between selected inputs and mean test scores in a sample of senior high schools. Unpublished doctoral dissertation. Palo Alto, CA: Stanford University.

Titze, I.R., Lemke, J., and Montequin, D. 1996. Populations in the U.S. workforce who rely on voice as a primary tool of trade. NCVS Status Progress Report 10:127-132.

Toftum, J., Jorgensen, A.S., and Fanger, P.O., 1998. Upper limits for air humidity to prevent warm respiratory discomfort. Energy and Buildings 28:15-23.

Turek, F.W., and Zee, P.C. 1999. Introduction to sleep and circadian rhythms. Pp. 1-17 in Turek, F.W., and Zee, P.C., eds., Regulation of Sleep and Circadian Rhythm. New York: Marcel Dekker.

Van Someren, E.J., Kessler, A., Mirmirann, M., and Swaab, D.F. 1997. Indirect bright light improves circadian rest-activity rhythm disturbances in demented patients. Biol. Psychiatry 41:955-963.

Wargocki, P., Sundell, J., Bischof, J., Brundrett, G., Fanger, P.O., Gyntelberg, F., Hanssen, O., Harrison, P., Pickering, A., Seppanen, O.A., and Wouters, P. 2002. Ventilation and health in non-industrial indoor environments: Report from European Multidisciplinary Scientific Consensus Meeting (EUROVEN). Indoor Air 12:113-128.

Wargocki, P., Wyon, D.P., Matysiak, B., and Irgens, S. 2005. The effects of classroom air temperature and outdoor air supply rate on the performance of school work by children. Proceedings of Indoor Air 2005. Beijing, China.

Weale, R.A. 1963. The Ageing Eye. London: HK Lewis and Company.

Weale, R.A. 1992. The Senescence of Human Vision. Oxford: Oxford University Press.

Williams, G.M., Linker, H.M., Waldvogel, M.G., Leidy, R.B., and Schal, C. 2005. Comparison of conventional and integrated pest management programs in public schools. J. Econ. Entomol. 98(4):1275-1283.

WSBE (Washington State Board of Education). 2005. Washington High Performance School Buildings: Report to the Legislature. Seattle, WA: Paladino and Company.

Wyon, D.P. 2004. The effects of indoor air quality on performance and productivity. Indoor Air 14(Suppl 7):92-101.

Appendix A

Biographies of Committee Members

John D. Spengler, Chair, is the Akira Yamaguchi Professor of Environmental Health and Human Habitation in the Department of Environmental Health at Harvard University's School of Public Health. He has conducted research in the areas of personal monitoring, air pollution health effects, aerosol characterization, indoor air pollution, and air pollution meteorology. More recently, he has been involved in research that includes the integration of knowledge about indoor and outdoor air pollution as well as other risk factors into the design of housing, buildings, and communities. He uses the tools of life-cycle analysis, risk assessment, and activity-based costing as indicators to measure the sustainable attributes of alternative designs, practices, and community development. He serves as adviser to the World Health Organization on indoor air pollution, personal exposure, and air pollution epidemiology, and he has served as either a member or consultant on various U.S. EPA Science Advisory Board committees. He received a B.S. in physics from the University of Notre Dame, an M.S. in environmental health sciences from Harvard University, and a Ph.D. in atmospheric sciences from the State University of New York-Albany.

Vivian E. Loftness, Vice Chair, is a professor of architecture at Carnegie Mellon University. She is an international energy and building performance consultant for commercial and residential building design and has researched and written extensively on energy conservation, passive solar design, climate, and regionalism in architecture. Professor Loftness has worked for many years with the Architectural and Building Sciences Division of Public Works Canada, researching and developing the issues of total building performance and the field of building diagnostics. Through the Advanced Building Systems Integration Consortium, she has been actively researching and designing high-performance office environments. Professor Loftness is a member of the advisory board at Johnson Controls and Owens-Corning Fiberglass Construction. She has been involved in international organizations including as resident, Executive Interchange Canada Architecture and Building Sciences, Department of Public Works Canada (October 1982 to June 1985) and as principal investigator, World Meteorological Organization, for Climate/Energy Graphics, and she has previously served on NRC committees. She holds a B.S. in architecture and a master's of architecture from the Massachusetts Institute of Technology.

Charlene W. Bayer is the Research Institute Branch head, principal research scientist, and adjunct professor at the Georgia Institute of Technology. A reviewer for the *Journal of Chromatographic Science, Indoor Air,* and *Analytical and Bioanalytical Chemistry,* and periodically for a variety of other peer-reviewed journals and conference proceedings, she has expertise in indoor environments, air quality, and related health concerns. Dr. Bayer is a past member of the ASHRAE Environmental Health Committee and serves on numerous other review committees for Underwriters' Laboratories, the U.S. Environmental Protection

Agency, Oak Ridge National Laboratory, and the American Chemical Society. Dr. Bayer was a semifinalist in *Discovery Magazine* awards for Innovative Technology of Importance in 1999 and holds numerous patents for materials and devices for monitoring and improving air quality. Her current research includes a project to develop a personal monitoring vest able to monitor a variety of pollutants that are suspected as being asthmatic aggravators while linking these with pulmonary function tests sponsored by the Department of Housing and Urban Development. She holds a B.S. in chemistry form Baylor University and an M.S. and a Ph.D. in organic chemistry from Emory University.

John S. Bradley is a principal research officer at the National Research Council of Canada's Institute for Research in Construction. Dr. Bradley is involved in the design of efficient procedures for making advanced acoustical measurements in rooms for speech and music, and the use of these quantities to evaluate such spaces more scientifically; measuring techniques for predicting and evaluating speech intelligibility in rooms, including school classrooms; noise control related to buildings, including for outdoor noises; and relationships between physical and subjective assessments of annoyance caused by noise from various sources. He is a fellow in the Acoustical Society of America, past president of the Canadian Acoustical Association, and a member of the Acoustical Society of America Technical Committee on Architectural Acoustics and the editorial board of the Audio Engineering Society. He has served on ANSI and ISO standards committees as well as the WHO working group for community noise guidelines. He holds a B.S. in physics and a master's in physics/acoustics from the University of Western Ontario, and a Ph.D. in physics/acoustics from Imperial College, University of London.

Glen I. Earthman is professor emeritus of educational administration at Virginia Polytechnic Institute and State University. His research interests extend to all phases of school facilities, with a concentration on exploring the relationship between school building condition and student achievement. Dr. Earthman has 40 years of experience in the field of education, serving as a teacher, principal, and executive director for school facility planning in the Philadelphia public schools, where he directed a staff of 250 professional planners and architects engaged in all activities associated with planning school facilities and monitoring the construction and evaluation of the resultant buildings. He is a member and past officer of the International Society for Educational Planning and the Council of Educational Facility Planners, International (CEFPI). He received the CEFPI President's Award for planning activities in 1992 and the Planner of the Year Award in 1994. He holds a B.A. and a master's degree from the University of Denver and a Ph.D. from the University of Northern Colorado, where he served as a graduate fellow in the School Planning Laboratory.

Peyton A. Eggleston is the director of the Center for Children's Environmental Health at Johns Hopkins University, a center of excellence sponsored by the National Institute of Environmental Health Sciences and one of EPA's National Centers for Environmental Research. He is also a professor of pediatrics at the Johns Hopkins School of Medicine. His research focus is environmental allergens—their role in respiratory diseases (in particular, asthma), risk factors for sensitization, means of avoidance, and methods and effectiveness of indoor environmental control. He is credited with more than 190 publications and serves on the editorial board of the *Journal of Allergy and Clinical Immunology*. He has served as a member of the Board of Allergy and Immunology and is an active member of the Academy of Asthma, Allergy, and Immunology. Dr. Eggleston received his medical degree from the University of Virginia and training in pediatrics and allergy-immunology at the University of Washington.

Paul Fisette is the director and an associate professor of building materials and wood technology and an associate professor of architecture at the University of Massachusetts, Amherst. Professor Fisette's research and professional focus involve the performance of building systems, energy-efficient construction, sustainable building practices, and the performance of building materials. He has developed an innovative Web service that provides technical advice on the performance, specification, and use of building materials. Professor Fisette has written more than 200 published works on building science and construction technology. Previous to his current position, he owned and operated a general contracting business and was a senior editor with *Custom Builder Magazine,* covering technical information and innovations of interest to small- and medium-sized residential building firms. Professor Fisette is a member of the National Research Council's Board on Infrastructure and the Constructed Environment (BICE) and a contributing editor for the *Journal of Light Construction,* and he has served on a variety of editorial and professional advisory boards. He holds B.S. and M.S. degrees in wood science and technology from the University of Massachusetts.

Caroline Breese Hall, M.D., is a professor of pediatrics and medicine in infectious diseases at the University of Rochester School of Medicine. At Rochester her research has focused on virology, especially respiratory syncytial virus, human herpes virus 6, and vaccines, resulting in more than 500 published articles. Among the national positions Dr. Hall has held are president of the Pediatric Infectious Diseases Society; member of the Red Book Committee for 8 years and chairman for 4 years; and member of the CDC's Advisory Committee of Immunization Practices, the Board of Scientific Counselors for the National Center of Infectious Diseases, committees for the Institute of Medicine, the American Board for Pediatric Infectious Diseases, and the Subboard for Pediatric Infectious Diseases. Among the awards she has received are the Pediatric Infectious Diseases Society Distinguished Physician Award and the Clinical Virology Award from the Pan American Society of Virology, as well as being named among the best doctors in America and among the top 20 women physicians in America. She graduated from Wellesely College and Rochester Medical School and did her subsequent residency training at Yale, followed by fellowships first in pediatric infectious diseases and then allergy and immunology in the Department of Medicine at Yale University.

Gary T. Henry is a professor of policy studies in the Andrew Young School of Policy Studies at Georgia State University, where he specializes in educational policy, school accountability, and program evaluation. He previously served as the director of evaluation and learning services for the David and Lucile Packard Foundation. Dr. Henry has evaluated a variety of policies and programs, including pre-K and the HOPE Scholarship program in Georgia as well as school reforms and accountability systems. He has served as the director of the university's Applied Research Center. He is the author of *Practical Sampling* (Sage 1990) and *Graphing Data* (Sage 1995) and co-author of *Evaluation: An Integrated Framework for Understanding, Guiding, and Improving Policies and Programs* (Jossey-Bass

2000), and he has published extensively in the field of evaluation and policy analysis. In addition, he served as deputy secretary of education for the Commonwealth of Virginia and chief methodologist with the Joint Legislative Audit and Review Commission for the Virginia General Assembly. He received the Evaluation of the Year Award from the American Evaluation Association in 1998 for his work with Georgia's Council for School Performance and the Joseph Wholey Distinguished Scholarship Award in 2001 from the American Society for Public Administration and the Center for Accountability and Performance. He received his Ph.D. from the University of Wisconsin.

Clifford S. Mitchell is an associate professor and director of the Occupational Medicine Residency Program at the Johns Hopkins Bloomberg School of Public Health. His research interests include indoor air quality and its effects on human health in schools and in office buildings. He holds a B.A. from Williams College, an M.S. from the Massachusetts Institute of Technology, an M.D. from Case Western Reserve, and an M.P.H. from Johns Hopkins University School of Public Health.

Mark S. Rea is the director of the Lighting Research Center at Rensselaer Polytechnic Institute (RPI), a position he has held since 1988. He is also a professor at the School of Architecture and in the Department of Philosophy, Psychology, and Cognitive Science at RPI. Prior to RPI he was the manager of the Indoor Environment Program, Building Performance Section at the National Research Council of Canada. He also has been a visiting scientist at the Electricity Council Research Centre, Capenhurst, United Kingdom. He is a fellow of the Illuminating Engineering Society of North America and of the Society of Light and Lighting (United Kingdom). He is on the international editorial advisory board of the *Lighting Research and Technology Journal* and is editor-in-chief of the *Illuminating Engineering Society of North America Lighting Handbook* (8th and 9th editions). He received the William H. Wiley Distinguished Faculty Award from RPI and the Gold Medal from the Illuminating Engineering Society of North America. Dr. Rea received a B.S. in psychology and an M.S. and a Ph.D. in biophysics from Ohio State University.

Henry Sanoff is professor emeritus of architecture at the North Carolina State University College of Design. He came to the College of Design in 1966 from the University of California, Berkeley, where he was an assistant professor. He is a member of the Academy of Outstanding Teachers and has been designated an Alumni Distinguished Graduate Professor. Mr. Sanoff teaches courses related to community participation, social architecture, design research, design methodology, and design programming. He has been a visiting lecturer and scholar at more than 85 institutions in the United States and abroad. He is the U.S. editor of *The Journal of Design Studies* and a member of the editorial board of the *Journal of Architecture and Planning Research.* Professor Sanoff is also recognized as one of the founders of the Environmental Design Research Association (EDRA) in 1969. His research has concentrated on the areas of social housing, children's environments, community arts, aging populations, and community participation. Professor Sanoff received a bachelor of architecture and a master of architecture from Pratt Institute.

Carol H. Weiss is the Beatrice B. Whiting Professor of Education at the Harvard Graduate School of Education, where she teaches in the areas of administration, planning, and social policy. Her courses include evaluation methods, research methods, use of research as a strategy for change, and organizational decision making. She has published 11 books, 3 of which are on evaluation and 5 on the uses of research and evaluation in policy making. Her recent work is about the influences on educational policy making exerted by information, ideology, interests, information, and institutional constraints. She has been a fellow at the Center for Advanced Study in the Behavioral Sciences, a guest scholar at the Brookings Institution, a congressional fellow under the sponsorship of the American Sociological Association, a senior fellow at the U.S. Department of Education, and a member of seven panels of the National Academy of Sciences. She is on editorial boards for the *Teachers College Record*, *Journal of Educational Change, Journal of Comparative Policy Analysis, Asia-Pacific Journal of Teacher Education and Development, American Behavioral Scientist*, and others. She holds a Ph.D. in sociology from Columbia University.

Suzanne M. Wilson is a professor of teacher education in the Department of Teacher Education Michigan State University. She is an educational psychologist with an interest in teacher learning and teacher knowledge. Her studies include the capacities and commitment of exemplary secondary school history and mathematics teachers, and she has written extensively on the knowledge base of teaching. She recently concluded a longitudinal study of the relationship between educational policy and teaching practice by examining efforts to reform mathematics teaching in California. She is also the director of the Center for the Scholarship of Teaching. Her areas of expertise include curriculum policy, history of teachers and teaching, mathematics reform, teacher assessment, teacher education and learning, and teaching history. Dr. Wilson earned her Ph.D. from Stanford University.

Role of the Board on Infrastructure and the Constructed Environment

The Board on Infrastructure and the Constructed Environment (BICE) was established by the National Research Council (NRC) in 1946 as the Building Research Advisory Board. BICE and its predecessor organizations have been the principal units of the NRC concerned with the relationship between the constructed and natural environments and their interaction with human activities. Principal areas of focus include:

- Human factors and the built environment,
- Project management methods,
- Construction methods and materials,
- Security of facilities and critical infrastructure,
- Multihazard mitigation methods,
- Construction and utilization of underground space, and
- Infrastructure and community building.

The BICE brings together experts from a wide range of scientific, engineering, and social science disciplines to discuss potential studies of interest; develop and frame study tasks; ensure proper project planning; suggest possible reviewers for reports produced by fully independent ad hoc study committees; and convene meetings to examine strategic issues. The board members listed in the front of this document were not asked to endorse the committee's conclusions or recommendations, nor did they see the final draft of this report before its release.

Additional information about the BICE can be obtained online at http://www.nationalacademies.org/bice.