DIDACTIC DAYLIGHT DESIGN FOR EDUCATION

by

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to Mom and Dad

Thank you for all of the years of encouragement and never letting me give up. No school or church, and few other parents, can teach the values and ethics you have instilled in me. For all of that and so much more, I am eternally grateful.

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to Beth Tauke, Ken MacKay, and Ed Steinfeld

Your continued guidance, care, and consideration for this thesis and all of my school works are an excellent indication of your character, dedication, and commitment. Your inspiration has proved to be extremely helpful for this thesis, and will prove to be invaluable to my future endeavors. Thank you.
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Abstract

STATEMENT OF ISSUE
This thesis investigates a modeling method for daylight design in the early design phase, as a means of promoting a positive and inclusive educational environment that allows for multiple modes of learning. Specifically, this study focuses on developing a tool for designers to study and apply daylighting methods in a rapid but informed manner. It also provides metrics to allow designers to analyze different daylighting design variables in relation to one another and against the lighting requirements of different modes of learning.

STATEMENT OF SIGNIFICANCE OF ISSUE
The design of learning environments is an important specialty within architectural practice, and encompasses “ever changing educational theories, the subtle spatial and psychological requirements of growing children and practical issues that are unique to these types of buildings.” (Dudek, 2000) It is argued that the architectural environment has a psychological effect on all humans, but can an inclusive, naturally well-lit environment presented to children aid in cognitive, spatial, and sensorial development? The significance of this topic lies in the fact that our first formal learning environments have the capability to influence the development of attitudes, knowledge, and skills throughout our lives. If all children experienced well-designed, inclusive environments, would they be more curious, creative, and open to new experiences, people, and places? Numerous studies have concluded that children experiencing naturally well-lit environments perform better on standard tests and that natural light promotes positive learning behaviors. Despite this, there seems to be few examples of naturally well-lit schools. This thesis proposes a tool designers can use to aid in the development of day lit schools and how can the lighting strategies be customized based on the different modes of learning?
METHOD OF INQUIRY
The method of inquiry includes a literature review of research on childhood psychology, elementary educational theory, behavioral design, and inclusive design with a specific emphasis on the effects of the architectural environment on children. It also includes extensive research on daylighting with an emphasis on its application to schools. The research includes daylighting design guidelines and case studies of daylighting strategies in schools. This research provides an evidence base for the development of a didactic daylighting design tool, metrics for its use, and theoretical designs it can produce. The daylight design tool takes the form of a scale model and drawings with metrics that utilize photographic and multimedia tools.

OUTCOME
This thesis provides research on the ways that daylighting can contribute to the development of educational environments that promote learning for a wider range of elementary school children. Preliminary work (research, experiments, and discussions) and a proposal for a didactic design tool complete with drawings, models, and corresponding data are included in the documentation, which is bound and submitted to the Faculty of the Graduate School of the University at Buffalo, State University of New York in partial fulfillment of the requirements for the degree of Master of Architecture.

COMMITTEE MEMBERS
Major Professor / Committee Chair: Beth Tauke
Committee Member: Kenneth MacKay
Committee Member: Edward Steinfeld
Introduction

In recent years, many advocates for the use of natural light in buildings, practices that design professionals refer to as “daylighting,” have emerged. Recent rise in the popularity of sustainable energy practices is a major contributor to the calls for natural light in the built environment. The so-called, “green” energy practice, when implemented properly, is often cited as a way of saving costs by reducing dependence on electric lighting as well as heating and air conditioning. This thesis posits that human factors, in addition to these green factors, are modified by natural light and cites studies in educational performance to demonstrate a need for daylighting in educational environments.

Architects are well aware that before the invention and popularization of electric lighting, many buildings were designed to take advantage of natural light. The reason was simple; people need light to do their jobs. Some architects simply flooded buildings with as much light as possible.
without concern for glare or heat gain. Others carefully factored in the sun’s altitude and azimuth and invented methods for daylighting that considered the tasks to be performed in a space. It was generally understood that factory workers worked better with better light conditions. Likewise, would it not stand to reason that students would learn better in improved light conditions?

The invention of electric lighting brought a slow decrease in the presence of architecture that acknowledged the benefits of daylighting. As buildings with effective daylighting aged, tenants and industries changed. Now, even buildings previously hailed for their excellent lighting were mismatched with new tenants with different lighting needs. This contributed to the growing perception of daylight as an aesthetic benefit rather than a functional necessity. The reconsideration of daylighting in buildings for green buildings reminds us of its functional attributes as well. This thesis focuses on the functional benefits of daylighting by presenting a list of educational activities and modes of learning, setting parameters for those educational activities, and quantitative evaluation criteria using false color rendition, a technique for applying a new spectrum of color to black-and-white images to make changes in brightness more apparent to the human eye.

This thesis offers research as evidence of the functional benefits of daylight in educational settings as a foundation for photographic studies of a didactic daylight study tool in the form of a physical model. The photographic studies are analyzed based on their relation to educational activities, and qualitative evaluation criteria mentioned above. The intention of this thesis is to develop didactic daylighting tools that combine metrics that have never been combined before, to aid in the design of sustainable and inclusive educational spaces. These tools include both a physical daylight model with assembly instructions; a set of instructions for performing photographic analysis in the form of false color renditions; and an example of how this tool may be used. The hope is that designers will use the tools provided to develop daylight solutions for their projects and in doing so, become more aware of the properties, behavior, and effects of daylight. Ideally, the same designers would become better designers, and begin to refine the tools to correct its flaws and better suit their individual needs.
Book Organization

This book is organized into five chapters. This chapter has introduced the thesis and will introduce a conceptual diagram that informs the organization of the project, and of the remaining chapters and subsections. Chapter two provides background information on the environmental variables studied, such as light, sound, and air issues in schools. This helps the reader to understand the basic concepts that have been introduced and that will be discussed further. It gives specifics on daylight and issues related to current daylighting practices. It describes specific problems with current lighting practices and offers research evidence of the impact of typical lighting and daylighting on learning. It gives a clear presentation of the relevance of the thesis in relation to human performance and more specifically, education.

Chapter three and four describe the method of inquiry and analysis; give a detailed description of a daylight study model using drawings and photographs. It couples the studies from previous daylight study models with evaluation criteria and metrics and describes how the criteria and metrics can be used as a design tool.

Chapter five summarizes the thesis research, findings, and provides a critical look at the project and design tools using the conceptual diagram introduced in this chapter.

Project Workflow

The conceptual diagram on the next page helps the reader visualize of the progression of the project from its inception. Each branch of the diagram is a different step in the decision-making process. Every effort has been made to ensure the terminology used in the diagram is consistent with terminology used throughout the book. The diagram on page 4 is supplemented by the text on page 5 which explains why each branch was pursued for this thesis. The chapters and subsections of this book are organized and labeled based on this diagram. The diagram will also reappear in the conclusion as a method for analysis.
Thesis Subject: Human Performance & Behavior in Education

Thesis Concept: Architectural Environment

Environmental Variables: Light, Air, Sound, Scent, Material, Comfort

Light Method Variables: Natural, Artificial, Nanotechnology

Control Variables: Early Design, Late Design, Perception, Sequence, Personal

Techniques: Physical Model, Digital Model, Physics, Case Studies

Design Variables:Orientation, Color, Materials

Light Entry, Geometry, Objects
This thesis asserts that differences in performance and behavior in the classroom are influenced by the environment. This thesis studies the architectural environment as the influence for performance and behavior, as opposed to studying social concepts such as teaching style, classroom crowding, and funding, which can also influence student performance and behavior.

Research presented in later chapters will show that architectural environmental variables have a significant impact on test scores and positive behaviors in the classroom. Lighting is one environmental variable that is related to multiple other aspects of design. Variables such as air, material, and comfort are also often addressed within light design.

The research also indicates positive improvement in test scores and behavior with light that has a more natural appearance, with the highest test scores and behavior in natural light. Views of the outdoors also contributes to better performance.

Despite the research, daylight is rarely effectively utilized in educational settings. Controlling the early design process by making daylight studies integral will allow designers to utilize and learn about daylight.

Physical modeling is more practical in the early design phase because it does not require specification of all of the design features, allowing the designer to control the level of model input. Digital modeling and physics equations require specific information before they can be useful, making them difficult to employ in the early design phases.

Allowing for the variables shown in the model will allow the designer to be as specific or as general as desired in the early design process. Controlling the level of input needed and the type of experiments performed will allow the designer to learn while using the model. It will also allow the same techniques to be used across multiple phases of the design process if needed, and in tandem with other techniques as they may become more appropriate as the design process progresses.
Overview

This chapter will discuss how environmental variables such as light, air, sound, scent, material, and comfort have an impact on performance and behavior in the classroom based on research and case studies. In particular, a special emphasis will be placed on light, as it is the main focus of this thesis. Air and sound have also been studied and researched as part of the project. Although no design has been developed to account for improving air and sound quality in the classroom, as the reader will see, the research strongly indicates that they have a significant impact on performance and behavior in the classroom as well.
Lighting has an impact on behavior in education environments in many different ways. This section will look at evidence of the impact of light on task performance using current research in addition to some background on the properties of light. It will address intensity, glare; and the differences between natural, full-spectrum, and cool-white fluorescent lights. It will also suggest solutions for improving classroom lighting.

**LIGHTING BASICS**

Light intensity can vary from eight to 1,000 foot-candles in a single room. (Gifford, 337) Generally, the eye can adjust to light changes quickly. Given enough transition time, students could read just as quickly with a very dim three foot-candles (32 lux) of light as they could at 53 foot-candles (570 lux), which is the standard classroom light intensity (cite). However, a study (Gifford, 337) showed that depending on placement in the room, and availability of natural lighting, This high variance within a room can create fluctuations of the eye causing strain on the eye. It also means that some students receive adequate light levels while others do not.

There are many reasons why daylight has the positive effects described above. One is the body’s circadian rhythm. The body’s internal clock is dependent on the daylight cycle to know when to release its hormones. Some of these hormones improve memory and others improve concentration. For example, it is recommended to study for a few hours after six in the evening because this is when a hormone that enhances long-term memory is released. Another hormone that improves concentration is released around ten in the morning. The presence of daylight allows the body to know when to release those hormones. In addition to hormone regularity, seasonal affective disorder (SAD) and depression is triggered by a lack of daylight. Children in windowless classrooms displayed symptoms of SAD including restlessness and irritability. SAD is believed to be a major contributor to absenteeism (Dudek, 35).

Despite the human body’s ability to adapt to light levels quickly, more natural light from windows results in 7-26% higher scores, and faster completion times on math and reading tests (Gifford, 339).
In addition, there is some indication that individual preferences may play a role in performance as well. Generally, students who preferred dim light performed better in dim light. Likewise, students who preferred more light, performed better in a more intense light (Gifford, 339).

**LIGHT SOURCES AND THEIR IMPACTS ON PERFORMANCE AND BEHAVIOR**

The type of light source is another important factor in performance. Many classrooms use fluorescent lighting that emit x-rays, radiation, and radio waves. These emissions decrease productivity, cause fatigue, confusion, eyestrain, irritability, depression, and hyperactivity (Rapp, 227). See the next section for more on issues that can arise from poor air quality. The noise emitted from ballasts can also be a distraction. See the section on Sound for more issues that can arise from noise. In addition, a small portion of the population may have sensitivity to fluorescent lighting. Known as photophobia, light sensitivity is usually a symptom of another condition such as corneal abrasion, uveitis, meningitis, retinal detachment, or others (Lee & Bailey). The studies suggest the need for better lighting conditions in the classroom.

One inexpensive way of reducing the need for fluorescent lights is the utilization of natural light. However, there are trade-offs which must be studied carefully, such as an increased glazing area that may increase unwanted heat loss or gain if not designed properly. When designed properly, this method is a more sustainable practice that can save energy and money. Another possible solution is the use of full-spectrum lighting. Full-spectrum lighting has color rendition that is much closer to natural light than fluorescent lighting. Although it cannot capture the complexity of the natural light spectrum, it spikes at each of the primary and secondary colors on the spectrum, as opposed to cool-white which gradually rises in the blue area of the spectrum. Germany has banned cool-white fluorescent lighting in all hospitals and schools. Studies also suggest that shielding lighting and the use of incandescent lighting can improve attention as well (Rapp, 228). Shielding also reduces glare, making reading and concentrating on other tasks easier.

In one study (Mayron, 441-448) of the differences between typical fluorescent lighting and full-spectrum lamps, 98 first-grade students in four classrooms were filmed during routine classroom activities. Each classroom was windowless, two had cool-white fluorescent lighting, and the other two had
full-spectrum florescent lighting. Full-spectrum students paid more attention and were less fidgety. Reading and other tests were inconclusive (Gifford, 338).

The study described above leaves the door open to other questions. Although the study has been confirmed by other studies, it fails to account for certain variables such as light intensity variations between rooms. In addition, behavior in the classrooms may have been determined by pre-existing social dynamics or differing teaching styles. Time also may have been a factor because restlessness can fluctuate throughout the day (increases just before lunch and recess). Other studies are needed to corroborate the imbalances of this one. One such study looked at a women’s college (Dalezman, et al.). It accounted for all of the shortcomings listed above, and even controlled reflections in the room. It too, concluded that basic information processing related to decision-making is better in full-spectrum lighting. Another study found that cool-white fluorescent lights are more physiologically arousing, and increase the hyperactive behavior of children already prone to autism and other psychological disturbances (Gifford, 338-339). Absenteeism is also reduced in schools with full-spectrum lighting (Gifford, 340).

One study found that classrooms with natural light or full-spectrum light caused two-month delays in the production of a stress hormone called cortisol, typically produced on spring mornings (Gifford, 340). This finding is significant because it demonstrates an actual chemical reaction to light that is based on natural biological processes. Whereas other studies measure instances of comfort and other subjective feelings about the space, this study focuses on chemical response and suggests that like plants, humans are chemically dependant on light to live a healthy life.

Another quantifiable statistic measuring the effects of lighting is the use of performance tests. The test gives sufficient evidence of the learning process and the effect light has on it. In a study of 21,000 students in the U.S., it was discovered that students in classrooms with the most daylight performed 20% faster on math tests and 26% better on reading tests. Rooms with larger window areas correlated with 15-23% improvement. Classrooms with skylights saw 20% faster rates of improvement. A separate study of 1,200 elementary school students found a 14% improvement in performance for students in classrooms with operable windows (Dudek, 34). Although it is pos-
sible that there are methodological flaws (e.g., socioeconomic factors may be influence test scores in wealthier school districts, that happen to be able to afford better quality architecture with more natural light), these studies are strong evidence in support of the use of natural day-lighting to illuminate spaces.

**GLARE**

Glare is an important issue. A study of teachers found that glare could lead to complaints of eye-strain, nausea, and headaches (Gifford, 340). This is in addition to other studies that show glare can have a negative impact on learning.

Because of the problems associated with glare, a consensus amongst authors is that glare should be reduced and that school environments should have a light reflectance value between 50 and 60 percent. There is also agreement that the brightness ratios should be uniform throughout the room (Brubacker, 148). As mentioned earlier, this will help achieve more uniform lighting and create equal opportunities for learning no matter where a student sits.

Glare, along with other factors, have at least one common problem, and that is the distraction of light. Colors and lighting patterns should always supplement learning; they should provide some stimulation, but not so much that it distracts. In general, materials and colors should be considered based on their light reflectance value. Floors should have a 20 to 30 percent reflectance (Brubacker, 148). Carpet is one way of reducing reflectance but it can cause problems in air quality and is difficult to maintain. Natural wood has a reflectance of 20-30% and could be considered. Other materials such as stone and concrete have varying reflectance making some of them suitable to be considered as an alternative to high-reflectance linoleum.

**DAYLIGHTING STRATEGIES**

Given this evidence of the benefits, both physical and mental, of natural light, several strategies have been developed over time to help achieve effective daylight infiltration. One method is to have a one-storey building oriented along the east-west axis. This allows diffuse north light to enter and for easily controlled south light. Another method is to place clearstory, skylight, or tall side windows
in the classrooms. It is also helpful to bring daylight in from multiple locations to help reduce the chances of glare. Classrooms should always use indirect lighting to reduce glare. Light shelves can also be used to bring light deeper into a room, and again, reduce glare (Dudek, 36).

The teaching walls, or the area where the teacher stands, should be the foreground, with remaining walls fading into the background. Teaching walls should have a slightly lower reflectance than the rest of the walls. Since color variation can be beneficial, this provides an opportunity to introduce a color in the form of an accent wall. Benefits of this accent wall include: relief of eye fatigue, focus of attention on the teacher, reduction in the overall glare reflected from white boards, and provide stimulation. It also reduces glare from natural light sources (Brubacker, 149). It should be noted that the focus of attention on the teacher by using an accent wall should work well in a traditional classroom using traditional teaching methods; however, classrooms with a focus on experimental learning may not require focus on the teacher, but instead encourage a group interaction.

Furniture, doors, and walls should have a reflectance value of 40 to 55 percent. The ceiling reflectance value should be 90 to 100 percent. Given these reflectance values, the reflective contrast ratio would be 2.5 to 1. The reflectance contrast ratio should never exceed 3 to 1. As a whole, the room average should be between 40 and 60 percent (Brubacker, 149). These values will help minimize distraction while providing clear and focused contrast between the background and the foreground. These values can be used in the design process. The photographic techniques discussed later in this book can use these values to determine if the light in a model will be suitable.

COLOR
It is important to consider that when choosing color to understand that colors affect the body differently at different ages so the selection of color should be based on the age of students that will occupy the space. Secondary grades should have a cool-colored background, which has been correlated to lowering heart and breathing rates (Brubacker, 149). One study of child-care centers suggests that rooms with varied colors increase cooperative behavior as opposed to single colored rooms (Gifford, 340).
The best approach to using color is to use a neutral color to allow the architecture to create the interest. Colors for accents should be chosen based on a scientific process and not taste and trends (Brubacker 149).

Warm colors are best in elementary schools as they have a diverting effect that “draws visual and emotional interest outward” (Brubacker, 149). Cool colors have a passive effect that elicits better concentration. Libraries and study halls, as well as other spaces where individual tasks are of importance should be painted in cool colors (Brubacker, 149).

It is important to note the correlation to light and air quality. Lights and computer monitors (particularly CRT displays), give off electromagnetic energy that attracts dust. Lights are often not cleaned because of their location. It is important to use compressed air to dust light fixtures when school is not in session, and prior to vacuuming (Rapp, 229).

**LIGHTING CONCLUSION**

Numerous studies have linked learning behavior and performance in the classroom, as well as chemical and biological fluctuations, to light quality. Many schools consider fluorescent lighting because they are generally the most cost effective, but considering the results of some of the studies, an increase in test scores by even five percent and in some cases, many more, may cause a school to see the value in effective lighting. The balance between the need for daylight, the need for ventilation, and the desire for a more sustainable environment can help influence school districts to embrace daylighting as necessary, rather than a frivolous detail. Even in existing schools, where daylighting may be impossible to add, changes from cool-white to full-spectrum fluorescent can be markedly beneficial. Choosing new light fixtures that reduce glare, enhance reflectance, and distribute light evenly, will be of great benefit. These studies have shown the benefits of something as simple as choosing proper colors and finishes for the next repainting, can be a good start in the right direction.

This research provides sufficient evidence that light, in particular, natural light has a positive impact on performance and behavior in the classroom. Since light also corresponds to color, air quality,
materials, and comfort, in addition to its sustainable benefits, it became the focus of the thesis. The following sections will demonstrate how other environmental variables such as air and sound also impact performance and behavior in the classroom, but since they are not the focus of this thesis, further evidence will be needed to determine how they can be effectively utilized. Chapter three and four will then describe how light can be controlled and planned for early in the design process using a physical model combined with metrics for evaluation.

NOTES


This section will explore the different types of air issues commonly found in the built environment and why it will offer evidence of the impact of air on performance. It will look at current research and give examples of the consequences of poor air quality as well as suggest solutions to air quality problems based on the available evidence.

AIR ISSUES AND THEIR IMPACT ON PERFORMANCE AND BEHAVIOR

In the past, many studies have tied comfort to performance, including performance in the classroom. The exact level of comfort is difficult to measure and therefore it may be difficult to establish how performance increases or decreases as the comfort level changes. It is possible that with too much comfort, one will become less productive. In fact, several studies refute the idea that the most comfortable setting produces optimal performance in the classroom. A study of British classrooms found that performance increased at temperatures slightly below optimal comfort. The study also concluded that performance increased when humidity was low with moderate air circulation. Work settings found similar results (Gifford, 341). Despite the specifics on exactly what level of comfort is necessary, the studies show that the environment does indeed have an impact on behavior and performance. Additional studies will show that the exact nature of that effect is dependant on several different aspects of the air, including quality and temperature, as well as other factors.

In recent years, support for research on the links between environmental dangers and health in children has been increasing. This is because health services researchers, environmental policy makers, and environmental economists have begun to notice the shortcomings of the lack of research (OECD, 80). Because of the amount of time children spend in educational facilities, the quality of the air in those facilities is of utmost importance. To illustrate the urgency of this issue, a 2005 study found that by improving air quality, absenteeism dropped by 15%, and test scores improved by 5%. Other studies have confirmed test score increases, reporting three to four percent increases (Lawson). The positive benefits of air control are impressive in their own right but consider the number of schools without air control measures in place. In fact, more than 350 separate reports gave schools less than a C grade for indoor air quality. This was consistent with an earlier report that
found that less than half of all schools had an indoor air quality program in place at all (Lewis). The U.S. Government Accountability Office reported that 14 million students (over 25%) in the U.S. attend schools with air quality that is below standard or dangerous and that the air in 15,000 schools is unfit to breathe (Lawson).

In 2003, the Organization for Economic Cooperation and Development (OECD) conducted a research project to evaluate the relationship between the environment and children’s health. From this research, they determined that children and adults have different health risks due to different exposures, susceptibility, as well as biological differences (OECD, 11). This means that when studying air quality problems, schools are an important place to consider.

The OECD determined that children are especially susceptible to environmental health risks. This is because children are more likely to be exposed to risks, more likely to be exposed to different risks than adults, and the risks they are exposed to will have a greater effect on them than on adults (OECD, 11). The different risks children are exposed to involve the nature of their interactions with the environment, their inexperience, and a general lack of understanding about risks. For example, a young child may crawl on the ground, exposing him or herself to dangers otherwise not threatening to adults. This part of risk exposure is not necessarily relevant to the air section of this thesis but can be helpful in understanding the environmental risks to children in the educational environment. It also brings attention to the need for advanced cleaning procedures and policy decisions that can help keep the learning environment a safer place. In addition to having an immune system that can only become more tolerant and capable of detoxifying pollutants with age, environmental hazards can have a greater impact on children than adults because of the total intake of pollutants per unit of body weight can be greater. For example, although children have smaller lungs, they breathe and circulate the contaminants of that air at a greater rate. Per unit of body weight, children require a greater percentage of food, water, and oxygen (OECD, 11). This means that by the time air quality is poor enough to warrant suspicion in adults, children already may have been feeling the effects. In addition, the symptoms can be less identifiable. Due to the qualitative differences between children through puberty and adults; and the OECD concludes that susceptibility differences are both substance specific and developmental stage specific (OECD, 42). Because children’s organs
are still developing, there also is a greater risk that damage resulting from toxins can be irreversible (OECD, 41).

**AIR POLLUTANTS**

To understand exactly what air quality problems put children at risk, we will now look at several common pollutants as well as their potential harmful effects and the solutions that can prevent those harmful effects. Many toxic, irritating, and/or carcinogenic gasses can be found in the air. In 1994, an indoor air quality crisis occurred at the University of Massachusetts at Boston. The cause of this crisis was the use of toxic agents in a poorly ventilated area. The chemicals were circulated through a heating system return grate and remained for a sustained period of time because the school had not used the fresh air intake system in years to save an estimated $600,000 in heating costs per year (May, 6). Indeed, this example demonstrates the need for awareness of the types of gasses that can be harmful.

One potentially hazardous gas is ozone (O3). Ozone is a gas made up of three oxygen atoms, as opposed to the two oxygen atoms (O2) that make up the oxygen molecules normally present in the atmosphere. It is created when electrical discharges split oxygen molecules into two separate atoms. Each of these atoms then bonds with another molecule, creating ozone. Air purifiers, laser printers, and photocopiers all can produce ozone. It is important to be sure ozone is kept below 0.1 parts per million because it can kill cells in the lungs, cause inflammation, and cause people with asthma to become symptomatic (May, 77-79).

Another harmful gas is carbon dioxide (CO2). In high concentrations (over 1,000 parts per million), it can cause drowsiness and affect one’s ability to focus on tasks. Because people exhale carbon dioxide, if the area is not properly ventilated, carbon dioxide concentrations can quickly rise to problematic levels. For example, an unventilated bedroom with doors and windows shut can reach 2,000 ppm overnight with only two people sleeping in it. An unventilated classroom with twenty students can quickly reach levels of over 3,000 ppm (May, 79-80). Adequate ventilation replenishes this stale air with oxygen, keeping students focused. Green plants can also have a small impact in
Not to be confused with carbon dioxide, carbon monoxide (CO), is a deadly, odorless gas that reduces the blood’s ability to carry oxygen to vital organs. It is a gas given off by vehicles and is the reason why a person should not leave a vehicle running indoors. Low-level concentrations of CO can cause heart problems, depression, and psychosis. A greater concentration (3,200 ppm) initially causes headache, dizziness, and nausea within ten minutes and unconsciousness and death in less than half an hour. Fresh air is the only way to prevent high carbon monoxide levels. Generally, faulty heating equipment usually is to blame for carbon monoxide poisoning, but it is possible that air intake vents located near parking garages can increase the level as well (May, 80-81).

Nitrogen dioxide (NO2) is the brown gas that mixes with ozone to form smog from combustion engines, notably, automobiles (May, 82). In 2005, a survey showed that increased concentrations of nitrogen dioxide reduced school attendance and that low ventilation rates are linked to reduced performance (Lawson).

Other combustible gasses such as methane, nitric oxide, formaldehyde, sulfur dioxide, and sulfurous acid can all be present in the air if combustion equipment such as heaters and stoves are not properly ventilated. In addition, research has shown that aggression, domestic disputes, and psychiatric disturbances increase with exposure to unpleasant odor and photochemical oxidants (Gifford, 303-304). Photochemical oxidants, hydrocarbons, ammonia, and amines are gasses given off by many cleaning products and must be used carefully, in well-ventilated areas. Generally, policy decisions can influence which cleaning chemicals are permitted in school buildings (May, 82-87). Most gas-related air quality problems can be solved if attention is paid to ensure proper equipment installation and maintenance. Ultimately, adequate ventilation is the best way to combat most air quality problems.

**ENVIRONMENTAL ALLERGENS**

Another problem with indoor air quality is related to living allergens. There are many causes of
indoor air quality problems relating to allergens such as mold in an HVAC system, bacteria, or fungi in carpeting. In 2001, the McKinley Elementary School in Connecticut was closed due to mold and fungus allergens present in some areas of up to 25 times greater than found in outside air. Immediately before closing, absentee rates had risen to over 25%. A combination of the problems that will be described below quickly exacerbated the situation, ultimately resulting in the school being permanently closed. Rather than remodeling the old school building for a cost of 3.5 million dollars, the district decided against renovating the old building, originally built in 1928, and instead build a new school for 21 million dollars (May 151-155). Some problem areas were in addition to the original school that was built in the 1970s. This is consistent with an EPA report that says mold increases are likely due to substandard construction practices of the 70s, 80s, and 90s. This example shows how simple allergenic organisms can have a disastrous effect on health and the economy if they are allowed to flourish. An understanding of what these organisms are and what conditions cause them to flourish is the first step to ensuring they do not.

Environmental allergens are hazardous for all people, and potentially deadly for people with asthma. Some studies have found an increase in the number of children with asthma in the past 20 to 30 years. In some countries the increase was slight, while in others, the number of instances has nearly tripled. In the United States, approximately 4.8 million school-age children have asthma, which amounts to one for every thirteen students. It is the leading cause of school absenteeism in the U.S (OECD, 80). It is important to point out that asthma can have other sources than air pollutants such as dietary allergens, which can account for some of the increase. The exact risk specifically due to air pollutants has yet to be determined (OECD, 52). It is however, safe to assume that regardless of the causes of asthma, the increase is cause for concern.

Carpeting is a nest for dust, mold, and microbial growth, the kind of environmental allergens that can cause or exacerbate asthmatic symptoms. In 2002, a study of Houston elementary schools found high levels of dust mites in 20% of rooms. Carpet placed on concrete slabs can be problematic if there is no moisture membrane because many schools are closed during the summer and left unventilated, dehumidified, and un-air-conditioned. Moisture can diffuse through the concrete and into the carpet. Depending on the relative humidity, mold and fungi will sprout in the carpet. Often,
carpets are cleaned during the summer, and reinstalled before completely drying as well. When placed back into an unventilated classroom, mold and fungi will grow (May, 143). The presence of a musty or stale odor is an indicator of the presence of mold. The best way to combat this is to not install carpet, but a well-ventilated room is always necessary. Fragrances to cover the musty, stale odor are not a substitute for an effective air handling system. They are often used in restrooms but sometimes employees use them to cover odor that may be an indicator of a greater problem. For example, a musty smell in the basement may be an indicator of mold in addition to being unpleasant. Covering the unpleasantness with a fragrance simply masks the odor but does nothing for occupant health. A more common misconception is the use of air purifiers. An air purifying system removes particle matter using a filter but the air itself is not clean of the environmental allergens (May, 151).

An often-overlooked aspect of air quality is pest control. A study of Baltimore schools found that 69% of the buildings contained measurable amounts of roach allergens in the dust. Kitchens could bring cockroaches and other pests. Aside from the bacteria and other problems caused by contact, roach allergen presence gives off allergens. About half of people with asthma are sensitive to those allergens (May, 141-142). Properly sealing the building and the implementation of proper policy can help curb this nuisance.

**VENTILATION**

Proper ventilation is the most obvious remedy for schoolrooms that are problematic when it comes to air quality. Science labs, machine shops, kitchens, and even administrative offices all have high potential for air quality problems. Proper space planning can help as well. Since ventilation of these areas will require more than the typical air handling system, by grouping these areas near each other, the same system can be used for all. Some of these methods for solving gaseous and living agitators of air quality will also help curb thermal discomforts. For example, operable windows are the best way to ensure adequate ventilation, as well as thermal comfort. In colder climates, a mechanical system is necessary for ventilation because of the need for thermal comfort.

**HEATING AND COOLING**

Temperature is the most-researched weather-related effect on people’s behavior. According to the
United States Riot Commission, all but one of 1967 riots started at temperatures above 80°F. The result of this study prompted another study that studied riots over a four-year period that concluded that riots did increase with temperature. Violent crimes such as assault, burglary, and rape occur more often when temperatures rise above 85°F and another study shows that baseball pitchers hit twice as many batters when temperatures rise above 90°F (Gifford, 303). From this evidence, it seems likely that if higher temperatures lead to higher aggression, learning environments will likewise be affected (Gifford, 303-304).

Ensuring schools are at the proper temperature and humidity can ensure the optimal learning environment. Studies have shown that elementary school children perform more poorly at language tasks in warmer temperatures. In schools without temperature control, a research study concluded that the temperature affected spelling, language, reading, and math abilities (Gifford, 342). Some suggest that occupant control is the best way to improve performance (Santamouris). However, in schools where 25 students may occupy a single classroom, it seems implausible to give each one individual control. It is also very plausible that students may not adjust temperature in the interest of what is best for learning. In addition, it becomes increasingly difficult to ensure proper air quality if the occupants are given control rather than allowing computerized control of the systems.

One study looked at temperature and gasses together. In 2000, that study showed that an increase the outdoor air flow rate from 1.3 to 11.5 l/s lowers asthmatic risks in school children. Another study found a significant correlation between measured room temperature, higher perceived temperature, lower air movement, more odor, and poorer air quality in computer classrooms. It was also noted that females were more likely to report indoor air quality dissatisfaction as well as related illness. The study concluded that computer classrooms must be air-conditioned with a significantly high ventilation flow (at least 10 l/s) and that CO2 levels must remain below 1000 ppm. It also concluded that there is a possible loss of learning ability resulting from poor indoor air quality (Norback). It is evident based on this that temperature, gasses, and allergens all have an effect on comfort, behavior, and learning ability in children.
AIR CONCLUSION

Both mechanical decisions and policy decisions can be used to improve indoor air quality, and presumably, comfort, behavior, and learning ability. These include: thorough and frequent cleaning and vacuuming, having a duct work cleaning schedule, replacing filters often, using only environmentally approved cleaners, reducing chemical use, keeping material data safety sheets (MSDS), using biological pest controls, and raising temperatures over 90°F, provided the indoor humidity levels are low, periodically when school is not in session to “bake-out” molds and chemicals. Some mechanical decisions include installing exhaust systems, ventilation systems, air-purification systems, dehumidifiers, and using natural ventilation (Rapp).

There have been many studies linking student performance and attendance to air quality. It has also been shown that many schools currently do not have adequate air quality. The most common air quality problems are related to carbon dioxide, and mold. It seems apparent that the best solutions to air quality problems are to increase ventilation. Schools should be designed with airflow and temperature in mind first, and materials should be carefully chosen to reduce mold presence. Finally, a program of policy decisions regarding cleaning and maintenance should be implemented to ensure continuing air quality. Further evidence is needed on what techniques are available for controlling air quality.

NOTES


Lawson, Scott H. “Why schools should breath easier: schools face a much wider variety of possible indoor air quality problems than typical adult workplaces. (Going Green).” New Hampshire Business Review, 30 (2008).
Sound

SOUND BASICS

Schools have many different types of spaces and they have different acoustic issues. It is best to avoid sharing spaces that require different acoustic needs. For example, a cafeteria or gymnasium requires sound damping, while an auditorium requires amplification (Grondzik, 844-846). One reason for the importance of acoustics in design is that the body perceives sound more quickly than other senses. Middle frequencies can be heard at three milliseconds. 160 milliseconds are required to react to touch (Dudek, 28). As people age, higher pitches become inaudible. Younger students can actually hear higher pitched noises that are inaudible to adults. This means that a high pitched noise emanating from a light ballast or HVAC system may be annoying and distracting to a student taking a test but the teacher may not even notice (Grondzik, 733). News outlets recently reported on cell-phone ringtones that are now available that are such a pitch audible to students but not teachers, preventing students from getting in trouble for having a ringing phone in class. Of course, this is not beneficial to the other students in class.
Sound and noise reduction are important issues in classroom design because of many different types of spaces in a school, the quick perception of sounds, and the wider range of pitch recognition in children. An inclusive environment facilitates these for everyone. If a person cannot see or hear because of a disability, it is of utmost importance to ensure the senses that are available to him or her are of the highest quality. A student who cannot see must rely solely on sound for instruction, so that sound must be free of distracting echoes, background noise, or noise from another room. This section will explore the basics of sound, and common sound problems in buildings. It will also suggest remedies to the common acoustical challenges.

**AIR-BORNE SOUND ISSUES, IMPACT, & SOLUTIONS**

Background noise accounts for the majority of sounds in the built environment: computers, HVAC systems, and lighting. Vehicles and wind can add to the noise, even with the windows closed. Sometimes, background noise is acceptable because, it blends into the background. If it is a constant tone, and if it is quiet enough, many can ignore it. A repetitive sound is different though. Constant clicking, or snoring are examples of a repetitive sounds. They are particularly irritating because the brain is constantly working to process them as information. For background noises, the brain has the ability to dismiss the constancy as unimportant, irrelevant information, whereas every time a repetitive noise reoccurs, the brain is again stimulated. This is similar to odor. For example, the brain tunes out the smell of one’s own cologne or perfume throughout the day. Likewise, light information is easy for the brain to adjust to. When entering a dark room, a person is first blinded, and then the brain and eye adjust, processing the information better with time. If the lights constantly flashed on and off, this would not happen.

To understand the reasons why sound has an impact on performance, we must examine what exactly sound is. Sound is created by small pressure changes in the air, similar to a water wave. The vibration of the air transfers through walls and eventually to the eardrum, which vibrates with the pressure changes. The brain then interprets these pressure changes as sound. Insulating materials will help deaden sound by absorbing the vibrations. The characteristics of sound include loudness, quality and pitch, similar to light’s characteristics of intensity, luminance, reflectance, and hue. Loudness is dependent on the energy of the sound and how far the eardrum moves in and out. This is like a large speaker with the volume turned up. As the volume increases, the vibration of
the speaker becomes more visible. The pitch determines how fast the eardrum moves. When pitch is so low that it is inaudible, it can actually cause mild stress, fatigue, and nausea (May, 69-71). In fact, sound energy can be deadly. 130 decibels is the equivalent of standing directly next to a jet engine and the vibrations are so intense that the body will be in pain. 150 decibels causes immediate loss of hearing (Grondzik, 748). The study of acoustics was actually popularized by the government looking for a weapon that would send an invisible concentrated wave of sound that would match the resonant frequency of human organs, causing death. Many are familiar with the collapse of the Tacoma Narrows Bridge in Washington on November 7, 1940. The fluctuations in the bridge were caused by wind matching the resonant frequency of the bridge. The theoretical weapon had the same principle in mind. The project was abandoned because there was no way to shield the resonant frequency from non-combatants, and because it would be considered too cruel (Battaglia). Obviously, these examples do not reflect dangers of school construction, but do represent the extreme nature that sound can have. Loud noises or even ultra-high or low frequency sounds can create unpleasant vibrations.

Two notes with close to identical pitches played at the same time creates a periodic change in amplitude that can cause stress. One such instance of this can be found in HVAC systems. Larger HVAC systems have two fans, one for blowing air and one for removing air. The noises generated by the fans are pure pitches. If the fans rotate at the same speed and the frequencies are close enough, a beat is produced that creates stress. The same effect can be produced with one source. If a noise is reflecting off surfaces, the sound waves behave similarly to two waves. This creates confusion for the listener because the brain is attempting to locate the sound. Since the sound is reflecting, one ear hears the sound, then the other, and they continue to alternate back in forth. The brain cannot locate the sound which can result in stress and headaches (May, 72). Sound can also trigger emotions as well as fluctuations in blood pressure and respiration rate (Dudek, 28). Think of an “energizing” song that gets a football player “pumped-up” before a big game. Fear, tranquility, and sadness are some emotions that may be elicited by sounds.

Aside from automatic body responses, noise can also have behavioral responses. Noise, as opposed to informative sound, is simply sound that interferes with the sound that is desired. Studies show that loud noise makes people walk faster and look straight ahead more. People were more
likely to give money to panhandlers at 72 decibels as opposed to 92 decibels outside of a construction site. The seriousness of a situation in which someone needs help is a factor as well. A study was conducted where a researcher dropped books and counted how many people helped. The experiment was conducted under normal sound background levels and again when a lawn mower was running nearby. The experiment was repeated another time when a cast was placed on the researcher. Twenty percent of passersby helped the cast-less stranger without noise. Only ten percent helped with noise. When the stranger wore a cast, eighty percent helped without noise, and only fifteen percent with noise. This might mean that although a greater percentage will help if the situation is more serious, the gap interval between helpers and non-helpers increases greatly in a more serious situation. The results documented by these tests assume the person recognizes the noise and understands that if he or she moves faster, the noise will end sooner (Gifford, 304-305). In the case of a building where noise is in the background with a student sitting at a desk, this would not be the case. Although, one could hypothesize that the student would attempt to rush through a test or reading faster to reduce the burden on the brain more quickly, but that is merely conjecture.

The most common noise problems in schools are reverberation within rooms and noise transfer between rooms. Insulating rooms and sealing gaps is the best way to prevent noise transmissions between rooms. Sealing gaps prevents “flanking paths” which are areas such as under doorways or the cracks around a light switch that allow sound to pass through directly regardless of the insulation of the wall.

Reverberation within a room is much more difficult to address, and like lighting, is best addressed in the early stages of design (Dudek, 28-29). Children generally enjoy a room with an acoustic design that matches the room’s function. For example, children are more likely to yell in a reverberant space and to be quiet in a room where sound is dampened. The creation of specific places for specific functions and acoustical requirements are the first step to effective acoustic planning. Secondly, speech recognition is improved if the source can be seen. This is because the lips and body language provide additional cues to words. Knowing the speaker can see the listener also encourages children not to converse either out of respect, or for fear of getting in trouble. Tiered seating, or a raised speaker is one way to achieve this. Sounds should be directed towards the listener from all directions. This means angling the ceiling and all walls toward the listener. Middle-range and high-
range frequency absorption can be accomplished by upholstered seating, carpets, curtains, and textured walls. Low-range frequencies can be absorbed using slotted boards. Absorbing materials should have a regular distribution. They should reduce reverberation time to 0.7 second for speech. This time will change for music rooms and for different sized rooms. Speech should be twice as loud as any background noise to be intelligible by most people. In addition, high ceilings help ensure adequate sound quality (Dudek, 29-30).

As mentioned above, the optimum reverberation time changes with room function. Elementary classrooms have an optimum time of 0.6 to 0.8 seconds. Lecture and conference rooms have an optimum rime of 0.9 to 1.1 seconds. Auditoriums and general-purpose rooms have a necessary time of 1.5 to 1.8 seconds (Grondzik, 776). Controlling reverberation often employs the use of absorptive materials in addition to room shape. Some absorptive materials include acoustic ceiling tiles, panel and cavity resistors, acoustic panel boards, acoustic plaster, sound baffles, carpeting, and drapery (Grondzik, 789-793).

Echoes are slightly different from reverberation. Echoes are produced when a reflected sound at high intensity reaches listeners 50 milliseconds after the direct sound is heard. Reverberation, on the other hand, has a lower intensity. Echoes are most commonly caused by ceiling and back wall reflections. Damping on the back wall reduces echoes. In addition, an angled ceiling in the back can lower the back wall height, and help direct sound waves in the right direction (Grondzik, 789-793).

**STRUCTURE-BORNE SOUND ISSUES, IMPACT, & SOLUTIONS**

Most of the sound measures discussed here are airborne sound related. Another, often overlooked aspect of noise reduction is structure-borne sound. The difference can be described using a cell phone as an analogy. A cell phone set to “vibrate” is often heard as well. The vibration agitates the airwaves, making a sound. When a person in a room is holding a vibrating cell-phone is his or her hand, the sound is less audible than if the phone were on a table. This is because the table is a better transmitter of sound than the air. The same is true with the building structure. A beam with a industrial blower on top will transmit the sound along the beam, which in turn will make the noise much more audible in rooms farther away. The most common structure-borne noise producers re components of HVAC such as, fans, compressors, cooling towers, condensers, duct work, damp-
ers, mixing boxes, induction units, and diffusers. Pipes and elevators are additional common noise producers. Floating floors, suspended ceilings, cavity absorbers, resilient pipe sealants, and cushioned floor tiles all aid in damping structure-borne sound transmission. To reduce machine noise, machines can be placed on vibration isolators that minimize the contact points between the machine and the floor. Baffles, board liners, and glass fiber honeycomb in ducts can reduce the noise air makes when passing through them (Grondzik, 832-837).

**SOUND CONCLUSION**

There are numerous studies in the field of acoustics, and many that link sound to negative behaviors. Many schools attempt to combine spaces that have opposite acoustic needs such as a cafeteria, which needs to absorb sound, and a concert space that needs to direct sound in specific ways. It is certain that there are better ways to arrange spaces that have the same financial benefits of combining spaces that are inappropriate to combine. Studies have shown the advantages of proper acoustic design and that schools are important because of the various and complex acoustic configurations of schools. Acoustic decisions should be based on calculations factoring in the complexities of every space individually to ensure the best possible condition. Further evidence is needed to determine which techniques for controlling early design of sound work best, and how to make common practices (such as insulating and installing HVAC systems) better for noise reduction.

**NOTES**


Other Environmental Variables

Other factors of the architectural environment that may play a role in influencing performance and behavior in the classroom include scent, color, materials, and comfort. Although all of these variables are factors in performance and behavior, this research thesis needs to be very specific in its study to be useful, and these other factors can be studied more in-depth by others at a different time.

Scent was briefly discussed in the section on air, and generally speaking, if one controls airflow, one can control odor. That is not to say that more pleasant, or bad odors do not have an influence on human performance and behavior, but in terms of built solutions, scent would be accommodated with air. Further studies may be conducted in fields other than architecture on the introduction of artificial scents to classroom environments. Likewise, color, unless determined by material, is applied after construction. The idea of modifying behavior through the introduction of pleasing or agitating colors has been studied by others and was not the focus of this thesis. In terms of built solutions, the only role color plays is in lighting, which is the topic of this thesis, and as such, it is included as a design variable for the physical model. Further research may need to be conducted to determine the exact relationship between color (as perceived independent of light), and performance and behavior in the classroom. Materiality is considered very important to architecture. Is it possible that materials, independent from their relationship to other environmental variables, have an impact on performance and behavior? Further studies would need to be conducted to determine an answer. With regard to light, materials are included as a design variable in the physical model because different materials may have different effects on the transmittance and reflectance of light. Finally, comfort is a broad category because it is dependent on all of the other environmental variables. It is known that comfort plays a role in determining performance and behavior, but as far as what specific interventions (cushioned chairs, etc.) can be a factor, further evidence is needed.

There may be more architectural environment variables that influence performance and behavior in addition to the ones discussed in this chapter. The remainder of the thesis looks specifically at natural lighting and how it can be controlled in the early design phase.
Overview

This chapter discusses different methods for controlling daylight, in particular, control in the early design process. It discusses techniques for controlling daylight in the early design process such as physical modeling, digital modeling, studying physics, and case studies. It takes a closer look at physical modeling and the early studies conducted to develop the latest model version used in the photographic studies.
Control Variables

There are many ways to control daylighting. The recent popularity of sustainability has made common daylighting practices more prevalent in the lexicon of the average person. Practices like installing light shelves, skylights, rooftop monitors, and other passive shading devices are well known in the sustainability community. It is the author’s assertion that their utilization does not often account for performance and behavior; rather, it often accompanies concerns for energy efficiency. The two do not always go hand-in-hand. Likewise, there is often no consideration for performance and behavior in determining which practice is used.

This thesis proposes a physical model that allows for the imperial study of each of the daylighting methods. The physical model also allows for studies on different sizes and placements of these methods. The light entry methods and other design variables will be discussed in further detail in chapter four.

It is important to recognize the different ways in which architects can control natural light. This thesis focuses on controlling the early design phase. By allowing light to be a factor before the building and classroom arrangement has been determined, and before form and materials have been set, they can all be chosen to effectively complement the daylighting method. Generally, controlling early design is accepted as better than adding features afterwards. This is true for most architectural interventions. For example, window shades are an example of a late design decision that are too generic to effectively distribute and control light in a specific way.

Other psychological controls are also plausible techniques that could have a significant impact. The idea of controlling one’s perception of light, or controlling the sequence in which one enters a space may be important. For example, a hallway painted black leading to a 50% grey classroom will make the classroom appear to be well lit. Whether this has a significant impact on performance and behavior or not remains to be seen. Perhaps it does for a short period but the eyes may soon readjust. Further evidence is needed. Other seemingly science-fiction types of personal control may have an impact as well. For example, body suits, integrated nanotechnology, and smart-sunglasses are
all technologies that are being studied in other fields, but may also have an impact on classroom performance and behavior.

Again, this thesis will be looking exclusively at techniques for controlling the early design phase but it is important to recognize control variables studied in other fields could also play an important role in shaping light perception as well as performance and behavior.

**Physical Modeling Technique**

**INCEPTION**
The physical modeling technique was determined to be the best technique for achieving the objectives discussed in chapter four. It was also determined to be the best technique for controlling the early design because it is a familiar tool to designers, especially in the early stages of design. This, in combination with the failures of the other techniques discussed later in this chapter, led to the decision to pursue it as the primary study technique.

**INITIAL MODELS**
The model images on the next page show the earliest concepts for the physical model. An earlier goal of this thesis was to design a space that was a “light space.” This was quickly determined to be ineffective based on research that indicated different education tasks require different lighting needs; no one space could be perfect.

It was then determined that in order to study the different techniques, a flexible model was needed. The initial flexible model pictured on the next page would prove to be too small for useful studies. Soon after, a larger flexible model was built. At this time, only light entry components were to be tested, but a matrix of possibilities was developed to demonstrate how many entry methods could be accounted for. After photographing, it was determined that a method of comparing one image to another was needed and that more design variables need to be accounted for in the model.
INITIAL MODEL USED FOR PHOTOGRAPHS
The matrix below illustrates the flexibility accounted for in the initial photographic model. The photographs on the following pages correspond to the times, dates, and positions indicated.

TIMES & DATES FOR ANALYSIS

<table>
<thead>
<tr>
<th>Time</th>
<th>September 1</th>
<th>December 21</th>
<th>July 1</th>
</tr>
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<tr>
<td>07:00 - 08:00 EST</td>
<td>A</td>
<td>D</td>
<td>G</td>
</tr>
<tr>
<td>12:00 EST</td>
<td>B</td>
<td>E</td>
<td>H</td>
</tr>
<tr>
<td>14:00 - 15:00 EST</td>
<td>C</td>
<td>F</td>
<td>J</td>
</tr>
</tbody>
</table>

POSSIBLE COMBINATIONS OF SIDES TO LIGHT

| South only | 1 | North & Top | 15 |
| East only  | 2 | South, East, & West | 16 |
| West only  | 3 | South, East, & North | 17 |
| North only | 4 | South, East, & Top   | 18 |
| Top lighting only | 5 | South, West, & Top   | 19 |
| South & East | 6 | South, North, & Top  | 20 |
| South & West | 7 | East, West, & North  | 21 |
| South & North | 8 | East, West, & Top    | 22 |
| South & Top | 9 | West, North, & Top   | 23 |
| East & West | 10 | South, East, West, & North | 24 |
| East & North | 11 | South, East, West, & Top | 25 |
| East & Top | 12 | East, West, North, & Top | 26 |
| West & North | 13 | All Sides | 27 |
| West & Top | 14 |             |       |

LIGHTING METHOD USED

<p>| Horizontal Bars | 0.1 | Vertical Bars | 0.4 |
| Light Shelf     | 0.2 | Partial Vertical Coverage | 0.5 |
| Windows         | 0.3 | Skylight      | 0.6 |</p>
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<th>Description</th>
<th>#</th>
<th>Example (bars at position #’s)</th>
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</thead>
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<td>1,2,3,4,5</td>
</tr>
<tr>
<td>Open at bottom / near side</td>
<td>1.b/6.b</td>
<td>6,7,8,9,10,11</td>
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<tr>
<td>Alt. open every other</td>
<td>1.c/6.c</td>
<td>1,3,5,7,9,11</td>
</tr>
<tr>
<td>Alt. open every 2</td>
<td>1.d/6.d</td>
<td>2,3,5,6,8,9,11</td>
</tr>
<tr>
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</tr>
<tr>
<td>Alt. open every 4</td>
<td>1.f/6.f</td>
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<td>5</td>
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<tr>
<td>Open center</td>
<td>1.h/6.h</td>
<td>1,2,3,4,6,7,8,9,10,11</td>
</tr>
<tr>
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<td>2,4,6,8,10</td>
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<tr>
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<td>1,s,6,11</td>
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<td>High positions</td>
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<tr>
<td>Mid. positions</td>
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</tr>
<tr>
<td>Alt. open mid. positions</td>
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<td>1,2,3,5,7,9,10,11</td>
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<td>4.a</td>
<td>1,2,3,4,5</td>
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<tr>
<td>Far side closed</td>
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</tr>
<tr>
<td>Alt. open</td>
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<td></td>
</tr>
<tr>
<td>Alt. closing top corner</td>
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</table>
TYPICAL STRIP OF SOUTH-FACING WINDOWS

12:00 15:00

DECEMBER 21

JUNE 28

SEPTEMBER 3
TYPICAL STRIP OF SOUTH-FACING WINDOWS WITH SKYLIGHT

12:00

15:00

DECEMBER 21

JUNE 28

SEPTEMBER 3
Digital Modeling Technique

As discussed earlier, the physical modeling technique was determined to be best for controlling daylight in the early design phase. This is because of some notable flaws with the digital modeling technique. When designing the “light space,” in addition to the model at the top of page 34, a digital model was developed. Because the specifics of this space were not known, there was not enough input for the computer to know how to render the space. The physical model allows the designer to select materials based on how they look to the human eye. Computer lighting software is best used for modeling a design once finished. It is difficult to use to quickly and accurately study different methods.

Physics of Light

Physics equations were also considered as a technique for determining how effective lighting will be. While it is true that a quick physics equation can determine how a space performs, it is much more difficult to account for more variables. As more variables are added, the equations become more complex. Physical modeling allows for the quick placement of desks, blackboards, and other objects and see the impact of light on these objects, and how the objects effect the light on the rest of the room. In addition, physics equations may require additional knowledge to use properly. The same is true with digital modeling.
Case Study

Case studies are invaluable to any architectural project. Daylighting projects are no different. However, they cannot give specifics on new designs. They can also provide useful ideas to test in the physical model. This section includes a case study of a daylight design in an elementary school. It does not prove the usefulness of the physical model presented in chapter four, but it does illustrate the connection between daylight and performance and behavior in the classroom.

SUTTON ELEMENTARY SCHOOL

The Sutton Elementary School in Sutton, MA has a framing system that produces 20 foot bays that allows for a consistent indirect lighting approach. The auditorium is lit from slots along the edges as opposed to classrooms that have roof monitors. This is because of the difference in activity that occurs in each space (Lam, 182-185).
CHAPTER FOUR
THE PHYSICAL MODEL

Overview

This chapter will establish the physical model objectives, describe the model’s process using its design variables, and give several example photographs of the pseudo color rendition technique. This chapter represents the main work of the thesis. This thesis asserts that the physical model, given its objectives, and in combination with pseudo color rendition, will aid in controlling the early design of natural lighting for educational environments in order to have a positive influence on student performance and behavior in the classroom.
Physical Model Objectives

FLEXIBILITY IN USE
The multiple design variables demonstrate the flexibility in the model’s use. This is important because the model must account for many variables. To be useful as a design tool, the model must allow the designer to be as flexible as possible.

SIMPLE & INTUITIVE USE
By not requiring full knowledge of the physics of light, or the knowledge of and specifications required by digital modeling, the familiar architectural language of the physical model renders it simple and intuitive. This, along with flexibility in use, are two of the seven principals of Inclusive Design.

ALLOW STUDY & COMPARISON BETWEEN DESIGN VARIABLES
The plug-in components of the model can be photographed and compared. The process of pseudo color rendering allows for easy comparison between design variables.

INFORM AND EDUCATE (DIDACTIC)
As design variables are studied and compared, a new understanding of light behavior will be gained allowing for quicker studies and experiments in the future and eventually leading to smarter design.
Process

STEP ONE: PROCESS FOR TESTING PREFABRICATED MODEL DESIGN VARIABLES

1.1: DETERMINE SCALE & DEVELOP DESIGN VARIABLES BASED ON NEED

After determining a base scale and site location, the designer develops wall components, roofs, desks, people, other items in the room, different colored panels, or other design variables that the designer wishes to explore. Below are images and drawings of example panels for the physical model.
MODEL PHOTOGRAPHS

Fuller Moore developed a similar model on page 171 of *Concepts and Practice of Architectural Daylighting*. He also discusses measurement methods on page 174 including the use of light meters.

1.2: PHOTOGRAPH DIFFERENT DESIGN VARIABLES

Using a manual camera, the designer photographs the model, positioning it at different times of day and year. He or she substitutes different panels one-at-a-time for a more empirical approach, or carefully combines panels. The designer must ensure the same sky conditions for each photograph, and ensure the same camera settings for each photograph. The same amount of light must enter the lens for each photograph to ensure photographs can be compared later.

See page 176 of *Concepts and Practice of Architectural Daylighting* for more specifics on camera position, exposure, and lenses. Note that this book only discusses analog photography. The pseudo color rendition process will require digital versions of the photographs. Whether using analog or digital photography, regardless of the settings, it is important to be sure that the camera is not automatically adjusting to light, and that the manual settings are consistent for every photograph.

Examples of these photographs along with pseudo color renditions can be found starting on page 50.
1.3: ANALYZE USING PSEUDO COLOR RENDITION

Using photo-editing software, the designer applies a new color table to the one already on the photograph. First, the photograph must be converted to black-and-white (not desaturated). This eliminates hue information but maintains lightness and saturation of the image. Now, the black to white spectrum is replaced with a new colored spectrum determined by the designer. This allows the designer to more clearly see otherwise subtle changes in light.

The designer can control the new color spectrum. With this method, lighter appearing colors such as yellow and cyan were given to areas where one would expect lighter conditions. It is more simple and intuitive. It is very possible to reverse this, assigning darker colors to lighter areas, though this is less intuitive. It is also possible to assign bands of a single color to certain values of grey. For example, a green band could be applied to an area that is good for a particular task and red applied areas too dark to perform said task to allow the designer to quickly see what areas are acceptable and which are not.

Using Adobe Photoshop CS3, use the following steps:

1: Image > Mode > Greyscale
2: Image > Mode > RGB Color
3: Image > Mode > Indexed Color, Click OK
4: Image > Mode > Color Table
5: Select a new color table such as spectrum, or create your own. Check the “Preview” box to see the changes while making them. To create your own table, simply select a shade of grey and then choose a new color. Or, select a range of grey shades to apply a new gradient. When selecting multiple colors, you will be prompted twice for a color. These will be the start and end points for the new gradient. When finished, you can save the color table file. Likewise, you can click “Load” to load a previously saved file. Click OK.
6: Image > Mode > RGB Color

See the examples of pseudo color rendition on the next page. Also, see the physical model analysis using pseudo color renditions on page 50.
The image on the left is an example of the full color spectrum applied to a black-and-white photograph. The center two images are tests of custom spectrums. The image on the right is an example of applying specific colors to specific values of brightness, rather than applying a gradient spectrum.
STEP TWO: USING THE TEST MODEL BASE TO TEST A CUSTOM MODEL

Once the designer has developed a set of design variable components that seem to work together based on the pseudo color renditions, he or she can then build a more precise scaled model that accounts for a greater number of other conditions.

Once this is complete, the model can be placed on the same base originally used for testing. Now the custom model can be photographed and rendered in pseudo color to ensure the results expected are actually present. The designer can then tweak the details of the custom model as needed.

STEP THREE: DESIGNING FOR THE ENTIRE BUILDING

The design used for one classroom will not work for all classrooms. The process must be repeated for classrooms with different functions, sizes, and solar orientation. It is important to remember that designing the building is not as easy as stacking each of these classroom blocks together. Some areas such as corners, or rooms off courtyards may require special considerations. As the designer assembles the classroom configuration, there may need to be changes to the original design. In this case, the change should be modeled and tested to see if it still accomplishes its initial goal.

It is also possible to use the solutions developed in the classroom to develop a concept for the rest of the building if desired. For example, a unique window treatment with vertical expressions could drive the facade materials and rhythm as well as set up an architectural language for the interior spaces.
Pseudo Color Renditions

TYPICAL WINDOW STRIP @ 12:00

- DECEMBER 21
- APRIL 18
- JUNE 28
- SEPTEMBER 3
TYPICAL WINDOW STRIP @ 15:00
Pseudo Color Renditions

TYPICAL THREE WINDOW CONFIGURATION @ 12:00

DECEMBER 21

APRIL 18

JUNE 28

SEPTEMBER 3
<table>
<thead>
<tr>
<th>Date</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 21</td>
<td>Light Distribution 1</td>
</tr>
<tr>
<td>April 18</td>
<td>Light Distribution 2</td>
</tr>
<tr>
<td>June 28</td>
<td>Light Distribution 3</td>
</tr>
<tr>
<td>September 3</td>
<td>Light Distribution 4</td>
</tr>
</tbody>
</table>
Pseudo Color Renditions

HALF EXPANDED METAL MESH SCREEN  @  12:00

DECEMBER 21

APRIL 18

JUNE 28

SEPTEMBER 3
HALF EXPANDED METAL MESH SCREEN  @  15:00
Pseudo Color Renditions

EXPANDED METAL MESH SCREEN @ 12:00

- DECEMBER 21
- APRIL 18
- JUNE 28
- SEPTEMBER 3
EXPANDED METAL MESH SCREEN @ 15:00
Pseudo Color Renditions

LIGHT SHELF WITH LOUVERS ABOVE HALF OF SHELF @ 12:00

- December 21
- April 18
- June 28
- September 3
LIGHT SHELF WITH LOUVERS ABOVE HALF OF SHELF @ 15:00
Pseudo Color Renditions

LIGHT SHELF WITH LOUVERS ABOVE HALF OF SHELF & MODIFIED ROOF @ 12:00

- December 21
- April 18
- June 28
- September 3
LIGHT SHELF WITH LOUVERS ABOVE HALF OF SHELF & MODIFIED ROOF  @  15:00
Pseudo Color Renditions

TESTING WITH DETAILED MODEL CHAIRS @ 16:00

REAL SPACE WITH & WITHOUT SUPPLEMENTAL FLUORESCENT LIGHTS @ 10:00
**ANALYSIS**

The pseudo color renditions on the previous pages clearly highlight changes in reflectance better than the black-and-white photographs. Although each of the interventions appears to look the same, upon closer inspection and comparison, changes based on time of day and year are evident, and as expected. The different design variables seem to have minimal impact on lighting; however, they do leave clues that allow the designer to infer potential changes to the design.

The studies shown were arranged as part of a sequence designed to mimic an imperial process of design. The first two configurations test typical classroom window arrangements. Then, a half screen is placed in the front of the room, the intention being to create a zone in the front of the room suitable for projection, while allowing adequate light on desktops for note taking. This not being successful, a full screen is tested, then a light shelf, then finally a new roof is added in tandem with a light shelf. This study showed that the angle chosen for projection is clearly unacceptable for said task. However, the designer can use information in the photographs to determine new solutions. For example, in the last experiment, darker areas are seen in the roof cavity, leading one to believe that by recessing areas, no matter how much light enters a room, a different zone can be created. One can then postulate that by recessing a projection area, perhaps this zone can be created. Then, this new design can be tested, along with another, and so forth.

Using the gradient charts on page 48, one can determine the brightness from the camera, assuming the camera is properly calibrated. Further evidence is needed to determine how once assures the brightness level displayed on screen is equal to that reflecting into the camera lens.

The real room studies should also be noted because they are evidence that the same technique can be used to study existing spaces.

Pseudo color rendition offers quantifiable metrics to analyze photographs of the physical model. However more evidence is needed to determine the specifics and validity of those metrics. This will be discussed further in the conclusion.
**Project Workflow Analysis**

This conclusion analyzes the project in relation to the project workflow conceptual diagram introduced in chapter one. It discusses what research has been supported, and which needs further evidence. It then analyzes the physical model objectives in a similar fashion. Finally, it lists resources for further reading in addition to the resources cited throughout the book.
Thesis Subject: Human Performance & Behavior in Education

Thesis Concept: Architectural Environment

Environment Variables: Light, Air, Sound, Scent, Material, Comfort

Light Method Variables: Natural, Artificial, Nanotechnology

Control Variables: Early Design, Late Design, Perception, Sequence, Personal

Techniques: Physical Model, Digital Model, Physics, Case Studies

Design Variables: Orientation, Color, Materials, Light Entry, Geometry, Objects
There is sufficient evidence to support the concept and suggest that the architectural environment does, in fact, have an impact on human performance and behavior in education. Further studies on each of the environment variables will help determine which variable has the largest effect, and which are more prudent to investigate.

There is sufficient evidence to suggest that lighting conditions are an aspect of the architectural environment that affect human performance and behavior in the classroom, as discussed in chapter two. There is also sufficient evidence to suggest that natural lighting is key to better performance and behavior.

Natural light improves performance and behavior, when compared to existing artificial light technologies. Further studies on artificial light, or other new technologies such as “smart building” systems are needed to determine if such technologies can exceed the positive results shown with natural light. Some artificial lighting such as full-spectrum have been shown to have a positive effect on performance and behavior but that effect is not yet greater than that of natural light.

Based on experimentation, it is clear that controlling the early design process can bring changes to how natural light is utilized and it is clear that it is better than adding natural light controls in the later design phases. Further evidence is needed to determine if the same results could be better achieved through psychological controls such as perception, sequencing, and personalization, as discussed in chapter two.

The physical model allows for sufficient manipulation of different design variables but each variable could be improved to a new degree of accuracy and usability. For example, objects such as people and desks need a better method of fastening to be simpler to use in the outdoor environment. A floor and objects with embedded magnets would help keep objects still when tilting the model, or using it in windy conditions. Although the model can account for a wide range of material studies, textured materials may behave differently in light at a smaller scale. Given unlimited resources, every design variable would ideally be tested to determine if it meets the physical model objectives, and every design variable would be machined to precisely fit together.
Physical Model Objectives Analysis

FLEXIBILITY IN USE
The model’s multiple design variables illustrate its flexibility in use. However, in order to achieve this flexibility, the model has many component parts, which reduces the effectiveness of the simple and intuitive objective. Further research is needed to determine if components could be combined to increase flexibility without sacrificing other objectives. For example, the camera positioning apparatus cannot be used with a different camera, or model scale. This would require a different camera apparatus. Although the base is flexible enough to allow for a different camera apparatus, the camera apparatus itself is not as flexible as it should be.

SIMPLE & INTUITIVE USE
The model’s flexibility objective sometimes competes with its simplicity and intuitiveness. The model is simple and easy to use, and explain. It also utilizes the concept of interchangeable parts, increasing its simplicity. Further evidence is needed by means of a focus group to determine its simplicity and usefulness for those unfamiliar with the project, and those of different demographics than the author.

ALLOW STUDY & COMPARISON BETWEEN DESIGN VARIABLES
Sufficient studies have been done to conclude that the model allows for study and comparison between design variables. Research also supports pseudo color rendition as a method for analysis. Further evidence is needed to test the reliability of the cross-media (analog to digital) method used and determine if there is a more accurate and/or more simplified cross-media method or a direct method.

INFORM & EDUCATE (DIDACTIC)
It is clear from use that the model is informative and it educates the user about daylight conditions. Further evidence is needed in the form of a study and/or focus group to determine the correlation between the information and education gained and the impact of that new knowledge on new designs.
Further Reading & References

This thesis is one step towards improving design in schools. It aims to improve design by providing a tool for designers that both aids in the design process, and teaches more inclusive and sustainable design. The conceptual diagram on page 66 identifies several other topics that require further study, both in architecture as well as other fields.

The following resources were useful for this thesis and contain a wealth of knowledge that cannot possibly be replaced by this thesis alone. This thesis is intended as a supplement to the existing knowledge in the field. Particularly useful sources have been highlighted.

Sources are formatted in MLA style.


Cuniff, Meghann M. “Air quality can be a difficult subject for schools: CdA officials scrub plan for class at district offices.” Spokesman-Review (2008).


