ILLUMINATING EDUCATION:
COMPOSITION AND USE OF LIGHTING IN PUBLIC K-12 CLASSROOMS

by

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Submitted to the Department of Architecture in partial fulfillment of the requirements for the degree of

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ABSTRACT

Despite ample research on light's effect on the human body (and particularly its effect on student and teacher health and performance), understanding of light's role in operational energy consumption, and advancement made in architectural design to address these impacts, little is known about actual use patterns and occupant exposure to light in classroom settings. Through the measurement of lighting conditions and an examination of occupant behavior under both electric and natural lighting systems in K-12 schools of Southern California, this research aims to bridge gaps between knowledge of light's impact on the human body and results of human exposure to various light as well as our understanding of occupant use and the current architectural design of schools. An analysis of illuminance and color temperature measurements across 21 classrooms, observations, and questionnaire responses from 27 teachers reveals muted daylight availability and low and warm color electric lighting conditions in the classroom that consistently falls below recommended illuminance and light levels, as well as lighting controls, installations, and design that may not allow for adequate control within these rooms by occupants. The work presented informs future design choices and assumptions made by architects of K-12 schools, and may provide context for research on and estimates of light's biological impact on students.

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INTRODUCTION

"There is no area of our mental and bodily functioning that the sun does not influence. Our bodies were designed to receive and use it in a wide range of ways. We were not designed to hide from it in houses, offices, factories and schools. Sunshine, reaching us through our eyes and our skin, exercises a subtle control over us from birth to death, from head to tail." — Downing, 1988

As the world becomes more urbanized, humans are spending more time indoors and, by extension, under artificial lighting. In these indoor spaces, especially those in which humans spend much of their productive time such as offices and schools, light is needed not only to carry out basic tasks but is also needed to execute biological functions which drive our wellbeing. As a result, the effects of daylight and various electric lighting systems on the human body have been well documented.

In particular, lighting has been shown to influence, amongst other biochemical reactions, the circadian rhythm, hormone levels, and vitamin D production of humans and through them, mental health, vision and eye development, risk of disease, dental health, fatigue, alertness and physical growth. Many of these biological effects have a large impact on the health of developing children in the United States, or at the very least may have long-term consequences for student occupants as, over 13 years of compulsory education, children spend approximately 8 hours a day, 180 days of the year sitting in classrooms which may often times lack occupant choice in movement and building use. In addition to its effect on human health, light has also been linked to the performance and productivity of students in schools.

Research that addresses the effects of light on human aspects has, in current times, translated to an emphasis on student wellbeing, satisfaction and performance over financial and environmental efficiency in classroom and school building design. School design more often than before aims to address effective daylighting and electric lighting system design solutions for student and teacher occupants.

Despite the advancements made in understanding the effect of light on the human body and building efficiency, and through this knowledge design solutions which provide effective lighting for classrooms and their occupants, little research has been made on the actual use and intake of light by students and teachers in classrooms.

The purpose of this research is to study the actual use of and exposure to artificial and natural lighting in K-12 public classrooms in order to bridge gaps between the known effects of lighting on the human body and sustainable design, and actual use and intake by classroom occupants. Put more simply, the research is interested in knowing *how* occupants actually interact with lighting systems (as opposed to the expected use by designers) and *how much* light occupants are receiving (in comparison to research which describes the benefits and detriments of exposure to light at various levels and spectrums).

The thesis aims to answer: How do students and teachers use and operate light on a day-to-day basis? To how much and what composition of light are students exposed? Are there differences in use and light quality between schools of different age groups, subjects, or other social variances? What are the gaps between design or expected occupant behavior and actual use of lighting systems in schools?

In approaching these questions, two primary sets of data will be collected from classrooms in participating public elementary, middle and high schools in the Orange County-Los Angeles area. Quantitative data on light composition and levels – including illuminance provided by natural daylight, illuminance provided by electric lighting, and color spectrums of artificial lighting – will be collected in each classroom independently of data on human use – including the manipulation of blinds, manipulation of switches and occupant perception. Data collected regarding human use will require the approval of MIT's Committee on the Use of Humans as Experimental Subjects (COUHES) as occupants will be observed and teachers will be surveyed on the use of lighting in their classrooms.

Data collected will ultimately inform the design of healthy and active classroom spaces and provide an estimate on the levels and composition of radiation school-aged children are exposed to in relation to the estimated benefits of healthy lighting.

The following proposal is organized into four sections. Below, a literature review is provided discussing light, its effect on humans, its subsequent effects on design and efforts made to quantify light use in classrooms in more depth. The proposal additionally includes a more detailed discussion of the problem and objectives of this thesis, an outline of research methodologies, and a timeline surrounding the development of the thesis.

BACKGROUND

LIGHT AND HUMANS

As the world becomes more urbanized, people are spending far less time outdoors and far more time indoors, be that in school or at the work place. Effectively, people are spending more time under artificial lighting, and while artificial lighting may provide enough illumination for humans to perform certain activities, it can only simulate natural lighting to certain degrees. Electric lighting often provides illuminance levels between 215 – 1,600 lux in comparison to the 2,700 – 100,000 lux provided by the natural environment between twilight and noon, likewise, electric lighting cannot provide the same range of light wavelengths as does the sun, sometimes lacking the blue color of our natural environment or ultraviolet light (Hathaway 1995). This high discrepancy between the amount and quality of light being received by humans and the natural outdoor light levels to which our bodies have adapted has raised concerns regarding human health, and by extension the health of school-aged children as light may heavily impact the development of the human body during this age. As such, research studying the effects of quantity, composition and intake of light on the human body has been conducted; a summary of those explored in this proposal is presented in Table 1.

Table 1. Summary of the effects of lighting on human/student health

HUMAN ASPECT	CONTRIBUTOR	SUMMARY OF FINDINGS
Vision	Amount	Minimum light levels are required in order for occupants to complete basic tasks, office/school spaces require about 300 lux for reading. (Rea 2000; "Best Practices Manual" 2002)
Eye Development	Amount	High lighting levels, 10,000 lux, promote dopamine production and protect the eye from deformation and near-sightedness (Dolgin 2015)
Sleeping Patterns	Wavelength Composition [Blue light]	Light composition affects circadian rhythm, blue light is needed during the day to promote healthy sleep patterns (Figueiro and Rea 2010)
Student Attendance	Wavelength Composition [Full Spectrum]	Students exposed to full-spectrum light are likely to have higher attendance (approximately 3.2 more days) (Hathaway 1995)
Student Performance	Wavelength Composition [Full Spectrum]	Students exposed to full-spectrum light mimicking natural lighting are more likely to have higher standardized test scores (Hathaway 1995)
Physical Growth	Wavelength Composition [Full Spectrum / UV]	Developing students exposed to full-spectrum lights with UV are more likely to have greater gains in mass and height (Hathaway 1995)
Dental Health	Wavelength Composition [UV light]	Developing students exposed to lights with UV supplements are at less risk of developing dental cavities (about 20% less likely) (Hathaway 1995)
Satisfaction	Exposure to Nature	Window views to the nature have been shown to provide humans with a connection to the outdoors, improving wellbeing (Gilchrist et al 2015)

A study conducted by Hathaway in 1995 aimed to study the effects of lighting types and metric quality on the nonvisual effects of developing school age children. Studies prior to this work demonstrated positive effects of UV light on human health, including Vitamin D production, calcium intake, reduced tooth decay, and cleaner surfaces (UV light kills bacteria more effectively); light was also shown to relate to improved working ability, academic performance, vision, resistance to fatigue, and increased weight and growth. Additionally, studies had demonstrated the color spectrum of lights affected human lethargy, perception, and blood pressure. Working off previous studies, Hathaway analyzed the effect of different artificial lighting types in the classroom – traditional, full-spectrum fluorescent lamps, full-spectrum lamps with UV supplements, and cool-white fluorescent lamps – on the rate of students' dental cavities, attendance, achievement, and general growth and development over a two year period (fourth grade through sixth grade). The study found that the type and qualities of artificial lighting provided in classrooms did indeed had nonvisual effects on the students. Students exposed to the UV supplement developed significantly less dental cavities than students not exposed to UV lights. Students who were exposed to full-spectrum fluorescent lights additionally demonstrated higher scores on standardized tests and higher attendance rates (about 3.2 days more per student) despite having no collective significant differences prior to the experimental study. Students exposed to full-spectrum lighting with UV supplements likewise had the greatest growth in height and weight over the two years, as compared to students who were not exposed to UV or full-spectrum lighting. (Hathaway 1995)

Table 2. Summary of Hathaway, 1995 findings

FACTOR	**SITE**			
	1	2	3/4	5
COLOR CHARACTERISTICS	Golden	Bluish	Bluish + UV	Yellow-Green
COLOR TEMPERATURE (K) (>5000 = DAYLIGHT)	2100	5500	5500	4250
COLOR RENDERING INDEX (CRI) (100 = DAYLIGHT)	21	91	91	62
	EFFECTS ON STUDENTS			
REDUCTION IN CAVITIES	-	-	+	na^b
ATTENDANCE RATIOS	-	+	+	
ONSET OF MENARCHE	-	+	+	
GAINS IN HEIGHT	-		+	+
GAINS IN WEIGHT			+	-
GAINS IN BODY FAT	+	+	+	-
ACADEMIC ACHIEVEMENT	-	+	+	+

With regards to lighting's effect on sleep, studies conducted by Figueiro and Rea at Rensselaer Polytechnic Institute (RPI) concluded that school-aged students exposed to daylighting were also exposed to more short-wave or blue light, affecting the natural circadian cycle on those students by allowing them to have healthier and more regulated sleeping patterns; in contrast when short-wavelength light was artificially removed for five-days from young students' exposure in school, dim light melatonin onset was significantly delayed (Figueiro and Rea 2010).

Likewise, the amount of light humans are exposed to during growth affects eye development and risk of near-sightedness, or *myopia*. Originally thought to be a genetic problem and then associated to academics and excessive use of electronic screens, steep rises in childhood myopia – in the United States alone about half of young adults are near-sighted, twice as many than fifty years ago – has prompted new research into the causes of near-sightedness. Researchers have found childhood development of near-sightedness to be inversely linked to hours spent outdoors independent of the activity conducted, as opposed to hours spent reading or on the computer. In other words, children who are exposed to more natural light are less likely to develop myopia, regardless of whether they are physically active; those who read outside receive the same benefits as those who played outside. Further research demonstrates that high levels of illumination, natural or electric, slows the development of myopia in animals, such as baby chicks, by about 60% as compared to indoor light levels. One hypothesis is that light increases dopamine in the retina which effectively protects the eye from elongating during development. Specifically, researchers at the Australian National University in Canberra estimate that children need three hours of outdoor light at 10,000 lux on a daily basis in order to protect themselves against myopia – for comparison, a well-lit classroom typically exhibits light levels of about 500 lux. (Dolgin 2015)

Though not necessarily tied directly to the metric quantification of light in buildings, research suggests that views to the outdoors are related to the satisfaction and wellbeing of occupants, especially when views include natural features such as grass and trees. In particular, research by Gilchrist et al suggests that views to the outdoors and the presence of natural features may have a deeper impact on occupant wellbeing than time spent outdoors during breaks (Gilchrist, Brown, and Montarzino 2015).

The effects light has on human wellbeing potentially bleeds into the productivity of users. In the office setting, the 'happy-productive-worker hypothesis' suggests that wellbeing and job satisfaction are closely related to job performance, productivity, and civic behavior; this relationship is strongest amongst people undergoing complex or cognitive work (Harter, Schmidt, and Keyes 2003; Judge et al. 2001).

LIGHT, CULTURE, AND SPACIAL EXPERIENCE

In addition to the biological and psychological effect light has over the human body, light is also a vital aspect of our culture and our human experience within spaces. Despite the range of ways which light may stimulate our senses, experiences, and thoughts, buildings today are constructed to provide standardized light, temperature, and humidity. To quote Lisa Heschong's *Thermal Delight in Architecture*:

"A parallel might be drawn to the provision of out nutritional needs. Food is as basic to our survival as is our thermal environment. Just as thermal needs have been studied, so scientists have also studied the basic nutritional requirements of human beings. Our level of understanding makes it theoretically possible to provide for all of our nutritional needs with a few pills and injections. However, while eating is a basic physiological necessity, on one would overlook the fact that it also plays a profound role in cultural life of a people. A few tubes of an astronaut's nutritious goop are no substitute for a gourmet meal. They lack sensuality – taste, aroma, texture, temperature, color. They are disconnected from all the customs that have developed around eating – the specific types of food and social setting associated with breakfast, with family dinner, with a sweet treat... A proper gourmet meal has a wide variety of tastes – salty, sweet, spicy, savory – so that the taste buds can be renewed and experience each flavor afresh. This renewal mechanism seems to be especially active for the thermal sense when we experience a temperature change within the basic comfort zone. There is an extra delight in the delicious comfort of a balmy spring day as I walk beneath a row of trees and sense the alternating warmth and coolness of sun and shade.

"We all love having our world full of colors, every color in the rainbow and then some. Even though studies have shown blue to be the most restful color, I doubt that anyone would put forth an argument for a monochromatic world. And yet a steady-state thermal environment is the prevailing standard for office buildings, schools, and homes across the United States" (Heschong 1979, 17 – 20).

A similar parallel can be drawn for light. Light is as vital to our human experience and poetic thoughts as experiencing the sense of taste, touch, and sound. Yet in our spaces, we fail to provide sensual stimulation through light and connections to the outdoors; stimulation which may prove to educate, enlighten, and enhance the daily lives of occupants just as we also introduce new sounds, instruments, tastes, and sensations to young learners.

THE ROLE OF LIGHT IN CLASSROOM DESIGN

As a result of the human needs for light and environmental and financial efficiency concerns, light has affected the development of policy, design and use in public classrooms over the past two centuries.

As early as the nineteenth century, daylighting in schools had been a topic of interest and had influenced architectural design. One of the first design guides for educational facilities, *School architecture: being practical remarks on the planning, designing, building, and furnishing of school houses,* by Robson was published in 1874. With regards to lighting, the book suggested classrooms should have a 20% glazing area, and north or north-east facing windows in order to minimize glare and heating. These guidelines deeply influenced the design of schools in the United Kingdom in the 1800s. (Wu and Ng 2003)

Likewise, several trends, attitudes towards education and advancements in research affected policy and design solutions in classrooms between 1900 and the present. In the midst of the open-air school system boom in the early 1900s, the Illuminating Engineering Society pushed for the use of reflected or diffused lighting in order to improve reading light in classrooms. Post-World War II, innovation in construction and scientific studies – which quantified metrics of lighting – influenced the adoption of school building regulations in the UK which recommended a minimum of 2% daylight factor and 5% where possible but neglected the effects of glare and heating. In the 60s and 70s, the integration of air-conditioning and fluorescent lighting as well as the oil crisis primarily influenced the design of classrooms; in particular, occupants desired the environmental uniformity which electric lights and air-conditioning could provide indoors, but needed to make the systems as "efficient" as possible in order conserve energy sources during the shortage. As a result classrooms were designed to maximize the use of electric lights and air-conditioning and minimize the use of windows which allowed heat to transfer in and out of the building, sometimes even resulting in windowless classrooms. As a result of a series of studies between 1970 and into the 1990s that emphasized the effect of lights on human psychology and health, designers once again began to consider human performance and satisfaction as central to the classroom environment. (Wu and Ng 2003)

Today, ASHRAE provides a guidebook for the energy design of K-12 School Buildings, which aims mainly to reduce operational energy consumption in the schools by 50% as compared to baseline schools. The guidebook also makes note of the benefits of effective daylighting on student and teacher productivity, pointing to studies conducted by Figueiro and Rea. In its guidebook ASHRAE indicates that designers should implement daylighting early into the design scheme, implement daylighting that provides controlled quality lighting by eliminating uncontrolled direct radiation onto the working plane, implement lighting that provides a higher quality of light than electric lighting 60% of the time so that occupants do not default to turning on the lights, and implement lighting that does not add superfluous solar radiation to the classroom during peak cooling times. ASHRAE also provides various specific design strategies in order to meet these objectives, including placing daylighting windows above 7 feet or 2 meters, minimizing view windows in addition to minimizing east and west facing glass, and not installing operable shades or blinds to minimize the risk of unused windows. Most importantly, the guidebook distinguishes *View Windows*, which provide a connection to the outdoors and in many cases are used as display areas in schools which render the windows useless, from *Daylighting Windows*, which are more efficient in directing light. ("Daylighting" 2011)

Another guidebook which provides guidelines on the design of classroom spaces is the Collaborative for High Performance Schools' *Best Practices Manual,* which sites the benefits of high performance schools as "higher test scores, increased average daily attendance, reduced operating costs, increased teacher satisfaction and retention, reduced liability exposure, and reduced environmental impact." These guidelines focus design strategies on the benefits of student performance and sustainability as opposed to health. Some guidelines include preventing direct sunlight penetrations, avoiding glare, the use of gentle and uniform lighting, and integrated lighting controls. ("Best Practices Manual" 2002)

QUANTIFYING LIGHT

Both the Collaborative for High Performance Schools in California (CHPS) and the Illuminating Engineering Society of North America (IESNA) provide guidelines for minimum illuminance levels. For classroom activities, light levels of about 30 – 250 foot-candles, approximately 300 – 2700 lux, are recommended ("Best Practices Manual" 2002; Rea 2000). A summary of recommended illuminance levels from IESNA and CHIPS accompanied by reference spaces and activities (Allen and Iano 2006, 156) is provided in Table 3.

Table 3. Summary of recommended illumination

	RECOMMENDED ILLUMINANCE LEVELS AT WORKING PLANE			
			RECOMMENDED ILLUMINANCE	
	SOURCE	**DESCRIPTION**	**(fc)**	**lux**
ORIENT	IESNA	Orientation in public spaces	3	30
	IESNA	Orientation for short visits	5	55
	IESNA	Simple visual tasks	10	110
CLASSROOM TASKS	CHPS	Screen Lecture	15	160
	IESNA	Kitchen, Conference Room (high contrast, large size tasks)	30	325
	CHPS	Lecture	30 (min) 45	325 485
	CHPS	Reading, Artwork, Social Time	30 (min) 45	325 485
	IESNA	Classrooms, Clerical Work (medium contrast tasks)	50	540
SPECIAL	IESNA	Laboratories (low contrast, small size tasks)	100	1075
	IESNA	Surgery (highly specialized tasks)	300 (min) 1000	3230 10750

In addition to illuminance which measures incident light at any given point in time, other metrics exist to determine if a space is naturally daylit such that electric lighting is minimally needed. Though the metric does not account for glare, useful illumination, and in some cases excess of light, the daylight factor is one of the simplest metrics to qualify daylit spaces and equals the fraction of illumination outdoors under overcast conditions available at the working plane indoors, or DF = 100 x horizontal illumination outdoors/horizontal illumination indoors ("Daylight Factor | Daylighting Pattern Guide" 2016). The metric is used under overcast sky conditions, on the basis that overcast skies are the "worst case scenario" for natural daylighting (Reinhart 2012) and best represents lighting conditions in overcast regions such as London (Kensek and Suk 2011). Daylight availability calculated under actual sky conditions, including clear skies may better represent sunny environments such as Los Angeles (Kensek and Suk 2011). As a rule of thumb, daylight factors between 2 – 5 are considered to be daylit, while those below 2 are underlit and those above 5 are overlit ("Daylight Factor | Daylighting Pattern Guide" 2016).

BEHAVIORAL PATTERNS AND LIGHT USE IN THE GENERAL POPULATION

Research that explores human interaction with electric lighting systems and blinds exists, especially within the realm of the office space. Overall, field studies demonstrate that "switching behavior" or use of controls of lighting by individuals are conscious and consistent choices in the office environment. The data collected by these studies suggest that individual control and behavior are partly tied to patterns that are related to the external stimuli on individuals, including temperature and lighting levels. However, while patterns may be identifiable on the level of the individual, these patterns vary within groups of subjects. Some variables that affect these patterns include activity use, age, fatigue, and culture. (Reinhart and Voss 2003)

Within the scope of individuals in the office space, these field studies point to specific behavioral patterns. With regards to light switching, Love observed two human scenarios: people either switch on the lights and keep them on even when temporarily absent, or people only use electric lighting when illuminance levels are too low (Love 1998). Hunt additionally observed that all lights are either switched on or off simultaneously; switching primarily occurs when occupants are entering or leaving a space, and switching lights on is strongly correlated to minimum daylight illuminances on the working plane (Hunt 1979; Hunt 1980).

With regards to the operation of blinds, Rubin found that people consciously set their blinds in a position over a long period of time (weeks and months) as opposed to operating blinds on a daily basis, In this study Rubin additionally found that blinds were more often kept open than closed (Rubin, Collins, and Tibott 1978). Continuing with Rubin's work, Rea concluded that humans have long-term perception of solar radiation and found that occupants close blinds in order to reduce solar penetration (Rea 1984). Inoue additionally found that blinds are operated based on a threshold level of solar radiation (50 W/m^2), and that operation is proportional to the penetration depth or solar radiation (Inoue et al. 1988). Lindsay, who contrastingly found regular blind operation in some offices, speculated that blinds are generally operated to avoid glare as opposed to heat (Lindsay and Littlefair 1993).

In 2001, Reinhart and Voss conducted research on the manual control of lighting and blinds in connection with integrated control systems – primarily the use of automatic dimmers and automated blind systems based on light levels, which could be overridden by occupants. The research served primarily to reproduce and test "previously identified switching patterns" for the systems, and to understand these switching patterns in the context of manual lighting control in the presence of automatic controls. Findings generally supported the previous literature on switching behavior, with regards to both electric lighting and blind systems. Approximately 88% of "switch-on" events occurred upon arrival of the occupant; however, with the dimmer installed, "switch-off" events occurred much less frequently than in previous field work as occupants sometimes failed to notice when the lights were dimmed and not off. In the presence of automatic blind controls, the researchers found that half of all manual adjustments were corrections to automatic blind adjustments, supporting the argument that occupants consciously set their blinds; of these corrections, 88% of users manually opened the blinds after the system had closed them, additionally supporting the notion that people often leave blinds open as opposed to closed. Overall, blinds were open approximately 80% of the time. (Reinhart and Voss 2003)

BEHAVIORAL PATTERNS AND LIGHT USE IN CLASSROOMS

While occupant behavior and manipulation of lighting systems have been largely studied in the context of office spaces, little research has gone into studying the behavior of occupants in classroom settings. In 2009, Sze's thesis for the Harvard Graduate School of Design set out to study the types of lighting, temperature, air quality controls, and technologies in use in New York City public schools, their use and occupant satisfaction. The purpose of this study was to ultimately inform strategies for improving occupant comfort, reduce energy use and enhance occupant satisfaction. (Sze 2009)

With regards to lighting use, Sze collected data on natural and electric lighting levels in the classrooms with an illuminance meter and collected information on lightbulb types, teacher satisfaction, perception of glare, the adjustability of shading devices, and the adjustability of light levels through paper surveys administered during staff meetings. (Sze 2009)

With regards to satisfaction, the thesis found about 70% of teachers in New York City public schools rated the overall lighting quality in their classrooms as excellent or good; according to survey results, glare from electric lighting was rarely a concern. Additionally, 85% of teachers did not perceive the lighting system as providing multiple lighting levels in the room, even though controls allowed for multiple levels of lighting. The majority of teacher discontent came from the operability of shading devices which the teachers perceived as difficult to operate, broken, or too fragile. (Sze 2009)

As a result, about one third of teachers never adjusted the shading devices, and classroom lights were always on at full capacity regardless of whether there is enough daylight in the room. About 50% of teachers claimed to turn the lights on upon arrival and only turn them off at the end of the day; 5% of teachers reported never turning the lights off. These claims were supported by field observations in which rooms were fully lit even when unoccupied. (Sze 2009) These findings seem to correspond with similar findings in the office setting. The study additionally found that the classrooms each had three to four rows of fluorescent light fixtures, most with three T-12 fluorescent tubes and either baffles or diffusers and some with T-8 tubes. (Sze 2009)

As the study's focus was to provide efficient lighting for school systems in New York City, the conclusions were directed at design strategies for the district. Lighting levels were found to meet the minimum illumination levels required to complete school tasks. Strategies suggested included the implementation of automatic dimmers to account for the contribution of natural daylight and counteract the use of lights at full capacity. (Sze 2009)

Though the guidelines do not make reference to data or research on use patterns, the ASHRAE guidebook for K-12 schools also makes certain assertions on occupant behavior in classrooms: teachers may often use windows below 2 meters in height as display walls as there is limited wall space, and occupants in schools "tend to adjust blinds for the long term" as they "are motivated to close blinds" by glare and heat sources "but not to reopen them" as electric lighting is provided ("Daylighting" 2011).

PROBLEM

With regards to light and education, research has largely focused on light's impact on human health and the environment, and this research has in turn influenced the design of classroom spaces to better address human needs, performance and sustainability. The importance of both natural and artificial light in the classroom cannot be understated as developing children spend a large portion of their time in the educational system without much control over environmental conditions. It is also important to note that, in addition to daylight, artificial lighting has varying benefits and detriments to the human body depending on the composition and levels of light provided to occupants.

Despite the advancements in research and understanding, design strategies are largely based on assumptions, anecdotal observations on occupant behavior, or observations adopted from settings outside of the classroom; likewise, while researchers know of effects of light on human health, estimates on actual exposure to light and color temperature are needed in order to assess quantifiable effects of light on the broader population. In essence, despite the abundance of research on and understanding of light's effect on the human body, and particularly its effect on student and teacher health and performance, knowledge of light's role in operational energy consumption in school buildings, and advancements made in design to address these impacts, little is known about the actual use patterns and occupant exposure to light in classroom settings. Research related to this topic has discussed use patterns in office settings, touched upon possible use patterns in the classroom setting – though this research was largely influenced by building flaws in the district – and discussed lighting system controls and technologies available to classroom occupants in pockets of the United States.

OBJECTIVE

The purpose of this research is to further study the use of and exposure to artificial and natural lighting in K-12 public classrooms in Southern California in order to bridge gaps between the known effects of lighting on the human body and sustainable design, and actual use and intake by classroom occupants. The research is interested in knowing ***how*** occupants actually interact with lighting systems (as opposed to the expected use by designers) and ***how much*** light occupants are receiving (in comparison to research which describes the benefits and detriments of exposure to light at various levels and spectra). The ultimate goal of this research is to inform classroom design strategies and to complement research on light's role in human health by providing knowledge on use patterns and light intake.

The thesis aims to answer the questions:

- *How do students and teachers use and operate light on a day-to-day basis?*
- *How much and what composition of light are students exposed to?*

- *Are there differences in use and light quality between schools of different age groups, socio-economic standing or other social variances?*
- *What are the gaps between design or expected occupant behavior and actual use of lighting systems in schools?*

METHODOLOGY

In order to effectively address the objectives of this thesis and provide a large enough data set of information, data was collected from multiple K-12 classrooms in Orange County, California during the month of January, 2015. As a native of Southern California and alum of schools in the area, the author chose this region for research because connections to local school teachers and administrators had the potential to streamline the process and make it and more comfortable for school administrators to approve research on their campuses. These regions are additionally more likely to be regular in weather on a day to day basis, and may provide more stability in the data collection of light. A total of 21 classrooms participated in quantitative data collection and observations and 27 teachers were surveyed across five schools and two districts. Of these schools, two were elementary schools and three were high schools; no middle schools chose to participate.

Data was additionally collected under two categories: ***qualitative data related to behavioral use of light*** and ***quantitative data related to light quality and quantity***. This separation of data serves dual purposes: (1) separation of data corresponds to the two objectives of the research – ***use of*** and ***exposure to*** light, respectively – and (2) separation of data related to human subjects from data relating to quantity of light aided in streamlining the review of research involving human subjects from MIT's Committee on the Use of Humans as Experimental Subjects (COUHES). Approval for the study was granted by COUHES (Appendix F) as well as school districts if they required research review boards prior to commencing data collection.

QUANTITATIVE DATA COLLECTION – LIGHT EXPOSURE

Quantitative data collected for each participating classroom included:

a) Illuminance measurements (lux) at the working plane within the classroom

b) Color temperature (kelvin) within the classroom

c) Illuminance measurements (lux) in the unshaded outdoors (an illuminance logger was placed on the roof of a car parked near participant schools)

d) High-Dynamic Range (HDR) photographs within the classroom

Sets of measurements were collected twice in each classroom: once before or at the start of the school-day and once during or after lunch. These metrics provide basic information on light levels and color temperature changes throughout the day in comparison to outdoor light levels. However, due to variations in classroom availability and bell schedules between high schools, elementary schools, and schools at different districts, the time at which measurements were taken varied; the bulk of morning measurements were taken anytime between 7 am – 9 am, and afternoon measurements were taken anytime between 11:30 am – 2:30 pm. During each set of measurements, three or more illuminance and color temperature measurements were taken at student desks, near the center of the classroom. Photographs were additionally shot in order to reference the location of measurements taken and to document lighting conditions within the classroom. Simultaneously, an illuminance logger collected values from an unshaded spot near the school once every minute.

A *Luxi for All* diffusion dome coupled with calibrated *Cine Meter II* software for the iPhone 5 was used for collecting illuminance and color temperature measurements. This software was calibrated with, and readings were compared to those of a trusted Skekonic color meter and illuminance meter. The accuracy of *Cine Meter II* for the iPhone in comparison to trusted color meters from Minolta, Sekonic, and Asensetek, has additionally been documented and reliably lies within 10% of trusted color temperature averages when calibrated (Wilt 2016). The instrument was chosen because of its ability to dually display illuminance and color temperature readings in real time – which saved the need for both a color meter and illuminance meter, its affordability, and its ability to log information with timestamps quickly – which saved time from writing values manually.

QUALITATIVE DATA COLLECTION – HUMAN USE

Qualitative data relating to human use of lighting systems included:

a) 15-minute survey for teachers on their perception of classroom lighting

b) Observations on classroom behavior

All observations were conducted during regular scheduled class hours with minimal interruption to classroom procedures and instruction. Surveys were administered both physically to participating teachers and electronically via email in order to allow for flexibility in participation. The questionnaire asked questions related to teacher's perception of their own use of lighting in the classroom and was estimated to take approximately 15 minutes to complete. Teachers were informed of their right to not complete the questionnaire or to end their participation at any time. A copy of the survey administered is provided in Appendix H.

Observational data was additionally collected during a time-span of approximately 40 – 60 minutes for each participating classroom as notes in a physical notebook. The observational periods aligned with classroom periods for high schools, but given the more fluid nature of schedules for younger students did not overlap with significant benchmarks of time at elementary schools. Observations included lighting conditions at the beginning of class time or the observational period, any changes in the use of lighting systems including how often subjects turned on and off lights or opened and closed shades, as well as the teaching methods employed and tools used during teaching.

Unlike the quantitative data, qualitative data involved using humans as research subjects, and in particular involved minors who are considered a vulnerable population. As a result, the methods covered in this section of the research were submitted for approval from COUHES.

Table 4. Data collected

HUMAN USE DATA	LIGHT LEVEL + COMPOSITION DATA
SURVEYS + OBSERVATION	DATA COLLECTION
How often lights are turned on/off When lights are turned on/off How often shading devices are used When shading devices are used Perception of lighting quality and glare Reasons for switching behavior Obstructions to daylight Perception of views to the outdoors	Daylight illuminance levels in rooms (lux) Electric illuminance levels in rooms (lux) Color Temperature of lighting (K) Types of lightbulbs used Number and placement of lightbulbs used Window to wall ratios Square footage of room

NOTE ON PARTICIPANT SELECTION

A total of 21 classrooms participated in quantitative data collection and observations and 27 teachers were surveyed across 5 schools and 2 districts. Of these schools, two were elementary schools and three were high schools; no middle schools chose to participate.

Administrators of schools were contacted to request participation in December of 2015 and January of 2016. If administrators agreed to participate, teachers were asked to participate in the survey and observation of their classroom, as well as to open their doors to quantitative data collection. Teachers and administrators were informed of the option to participate in some, all, or none of the forms of the study, to advise changes to protocol based on their school's interest, or to reject the offer all together. Where administrators presented the opportunity for the researchers to reach out to teachers, teachers were selected on the basis of covering as many types of classrooms or school subjects (English, art, math, science, history, etc.) in order to obtain data that more accurately depicted an average school day.

No parent permission forms were sent to students being observed. In accordance with COUHES procedures, the institutional review board (IRB) waived consent from parents for student observations primarily because observation posed minimal risks to subjects, the waiver would not contradict the rights and welfare of the subjects as described in the Family Educational Rights and Privacy Act (FERPA) (as no data on individual identity, identifiable records or educational records were collected) and the Protection of Pupil Rights Amendment (PPRA) (as no survey was conducted on minor students and no students were exposed to instructional materials outside of those already in place by the school system), and the participation of all students in a classroom was needed in order to sit in and adequately study group behavior.

FINDINGS

LIGHT EXPOSURE

1. Color temperature

Analysis of color temperature averages within in classrooms reveals stark differences between lighting conditions in classrooms when naturally lit and when electrically lit.

On average, when lights were turned off and classrooms that had windows were solely lit by daylight, the rooms offered color temperatures comparable to those of the natural environment – approximately 5000 K. While classrooms which have windows provided for natural color levels on average, color temperature varied widely in the naturally lit rooms, with color temperatures ranging anywhere between 3200 K (comparable to standard electric lighting) and upwards of 7000 K excluding one outlier measured at 12,000 K (potentially more blue than the sky on a given day). The data likewise reveals that a majority of classrooms experience color temperatures below the average of 5000 K. This data excludes classrooms which do not have a window of any size, and which are thus constrained by electric lighting output alone.

Unsurprisingly, when lights were turned on, electric lighting combined with natural lighting provided for incredibly uniform color temperatures averaging 3400 K with deviations of no more than 1000 K. When visualized these data points appear as tight clusters, compared to the dispersion under solely naturally lit conditions (Figure 1). The uniformity under electric lighting consistently exposes occupants to color temperatures 1500 K below both daylighting levels and target levels of 5000 K which represents direct sunlight at about mid-day. The difference between color temperatures under electric and natural lighting is even greater when compared to morning color temperatures which are bluer.

The graphs accompanying Figure 1 contain data points representative of classroom averages when the lights are on in the morning, on in the afternoon, off in the morning, and off in the afternoon as read from left to right. Total averages for each set of data are represented as white bars within the graph. Common color temperatures of other light sources are provided alongside the graph for reference ("Entry & Foyer Lighting Planner: Color Temperature" 2016; Konica Minolta, 14). Data is additionally summarized in Table 5 and a full data set of averages for each classroom is provided for reference in Appendix C.

Table 5. Summary of average color temperatures.
Average color temperature with lights on, compared to when only daylit and to static target.

	MORNING			**AFTERNOON**		
	DAYLIGHTING	**ELECTRIC LIGHTING**	**DIFFERENCE**	**DAYLIGHTING**	**ELECTRIC LIGHTING**	**DIFFERENCE**
AVERAGE	5213	3390	-1823	4741	3430	-1311
TARGET COMPARISON	5000 (static target)	--	-1610	5000 (static target)	--	-1570

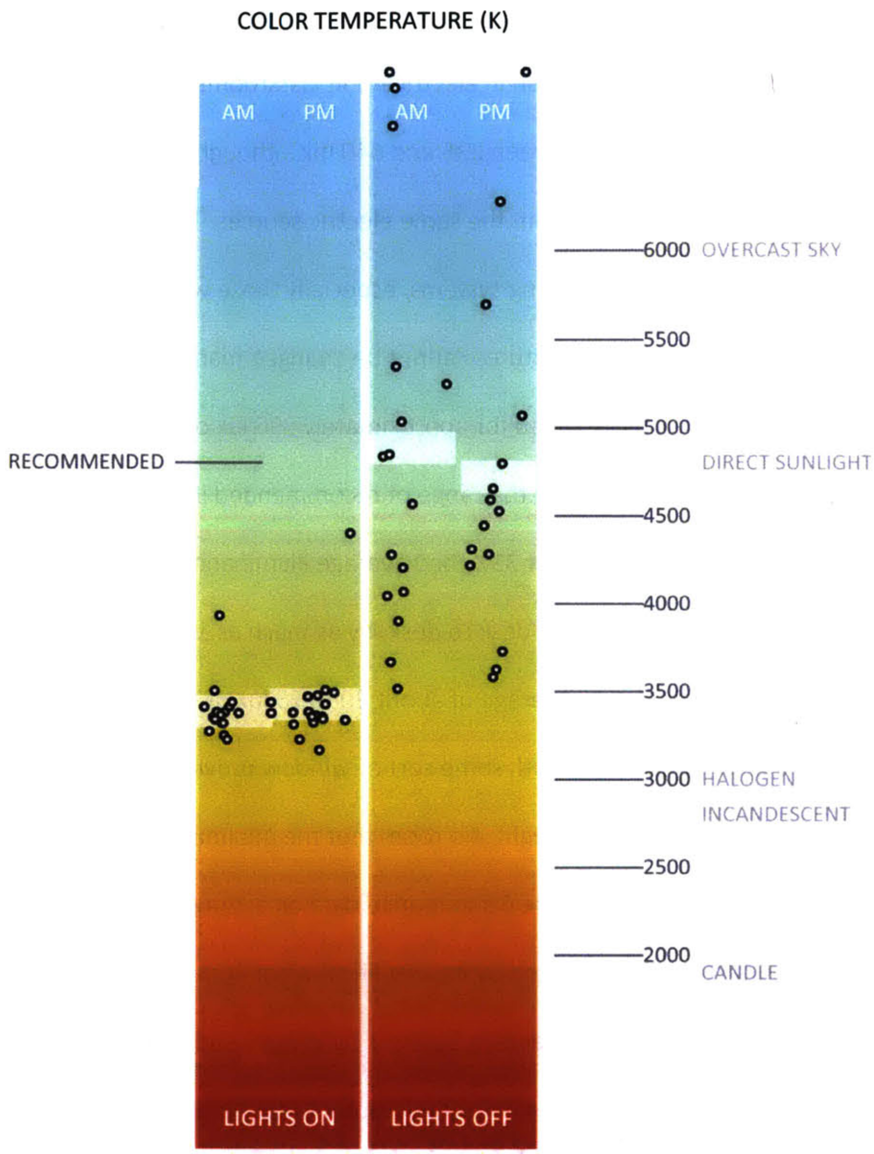


Figure 1. Color temperature (K) in.
Column 1: lights on, morning/afternoon.
Column 2: lights off,morning/afternoon.

2. Illuminance

Illuminance measurements taken in electrically lit classrooms also provided fairly uniform lighting conditions – lighting levels ranged between 235 and 640 lux – though this uniformity was not as concentrated as color temperatures from the same electric sources. This may be attributed to personal choices made by teachers on how lighting systems, especially those with multi-switches, are kept on; while color temperature provided by fixtures cannot be changed manually, illuminance output can.

On average, classrooms provided for approximately 390 lux of illumination – about 90 lux above minimum recommendations and within the range of recommended lighting levels. Despite this average, about 7 of the 21 classrooms studied, or 33%, had average illuminance values below recommended levels of 300 lux. Illuminance also varied from desk to desk, by as much as 100 – 200 lux. When lights were off, natural lighting only provided for an average of about 20 to 25 lux of illumination within the classrooms. 47%, or nearly half of the classrooms with some sort of window provided natural illuminance values of under 5 lux which is comparable to twilight. No room met the minimum recommendation of 300 lux with natural lighting alone. Figure 3 and Table 6 summarize data on average illumination within classrooms.

The daylight factor is limited both by its simplification of light availability to the percentage of light entering the room from light available in outdoor conditions and by its tie to the overcast sky condition, therefore the specific analysis of daylight factor is not possible. However, a similar analysis may provide insight on daylighting within the classrooms. Consistent with findings on illuminance levels which revealed that no room was adequately lit for high contrast or medium contrast tasks under natural lighting alone, nearly all rooms had indoor illuminance to outdoor illuminance ratios under 1%. It is important to note that the values were derived from measurements taken under clear sky conditions.

It is worthy to note that, in both the case of illuminance and color temperature, measurements were taken on clear days in winter, when sun angles are lowest and direct light may be maximized.

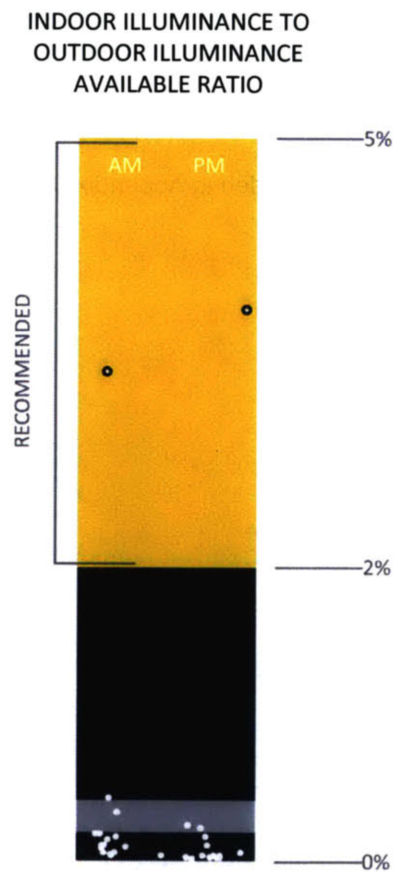


Figure 2. Indoor:Outdoor Illuminance.
Taken under clear sky conditions.

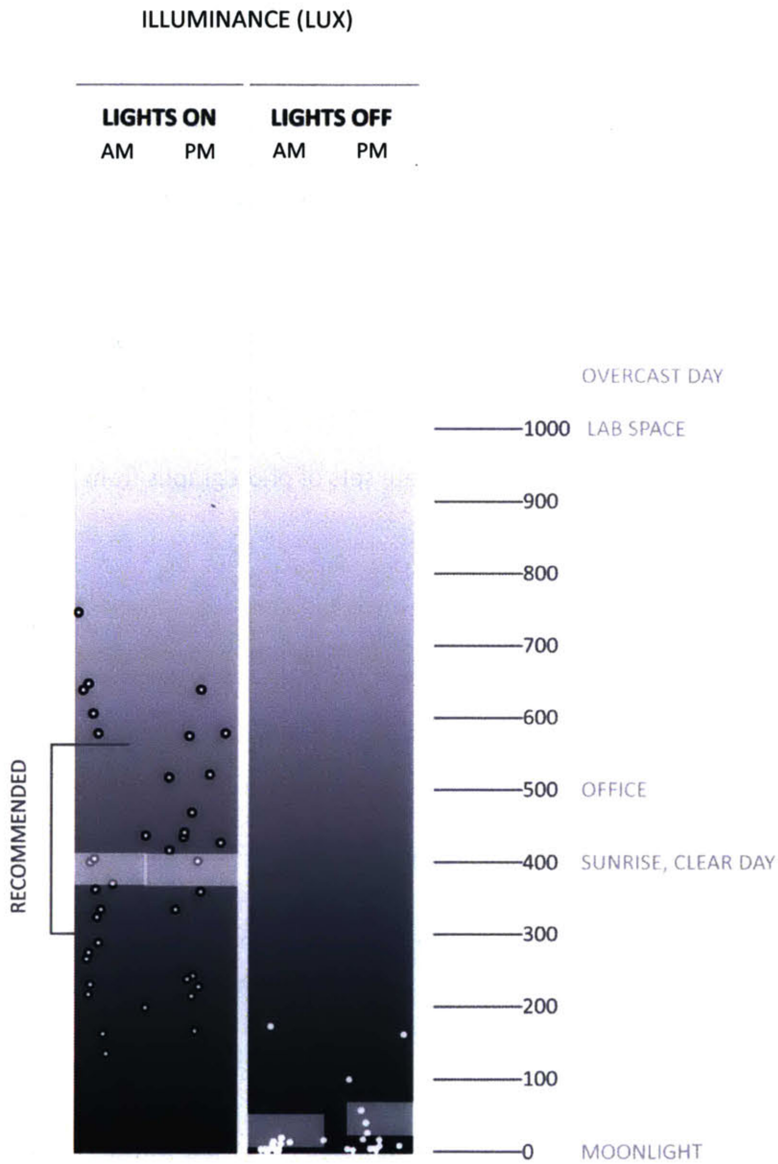


Figure 3. Measured illuminance (lux).
Column 1: lights on, morning/afternoon.
Column 2: lights off, morning/afternoon.

Table 6. Summary of illuminance measurements and findings

	MORNING			AFTERNOON		
	DAYLIGHTING	ELECTRIC LIGHTING	DAYLIGHT FACTOR	DAYLIGHTING	ELECTRIC LIGHTING	DAYLIGHT FACTOR
AVERAGE	17	390	0.33%	28	389	0.29%
RANGE	2 – 173	135 – 647	0 – 3.38%	2 – 161	166 – 639	0 – 3.81%

These abstract values – illuminance and color temperature – can additionally be visualized within the participating classroom. Figure 4 - Figure 6 on the next pages provide sets of photographs taken within some classrooms to demonstrate the stark differences between measurements taken when lights are on and when lights are off. Most notably, the photos demonstrate a clear visual difference between color temperatures. Photos on the top, or those taken when electric lights are on, are visually "yellow" or "orange" tinted, while photos presented on the bottom, or those taken when electric lights are off, are more "blue". These photographs were taken at the same white balance and at exposure values of 0, or EV 0 within each classroom. Complete sets of photographs from all classrooms are provided in Appendix D.

Figure 4. Classroom 4.1

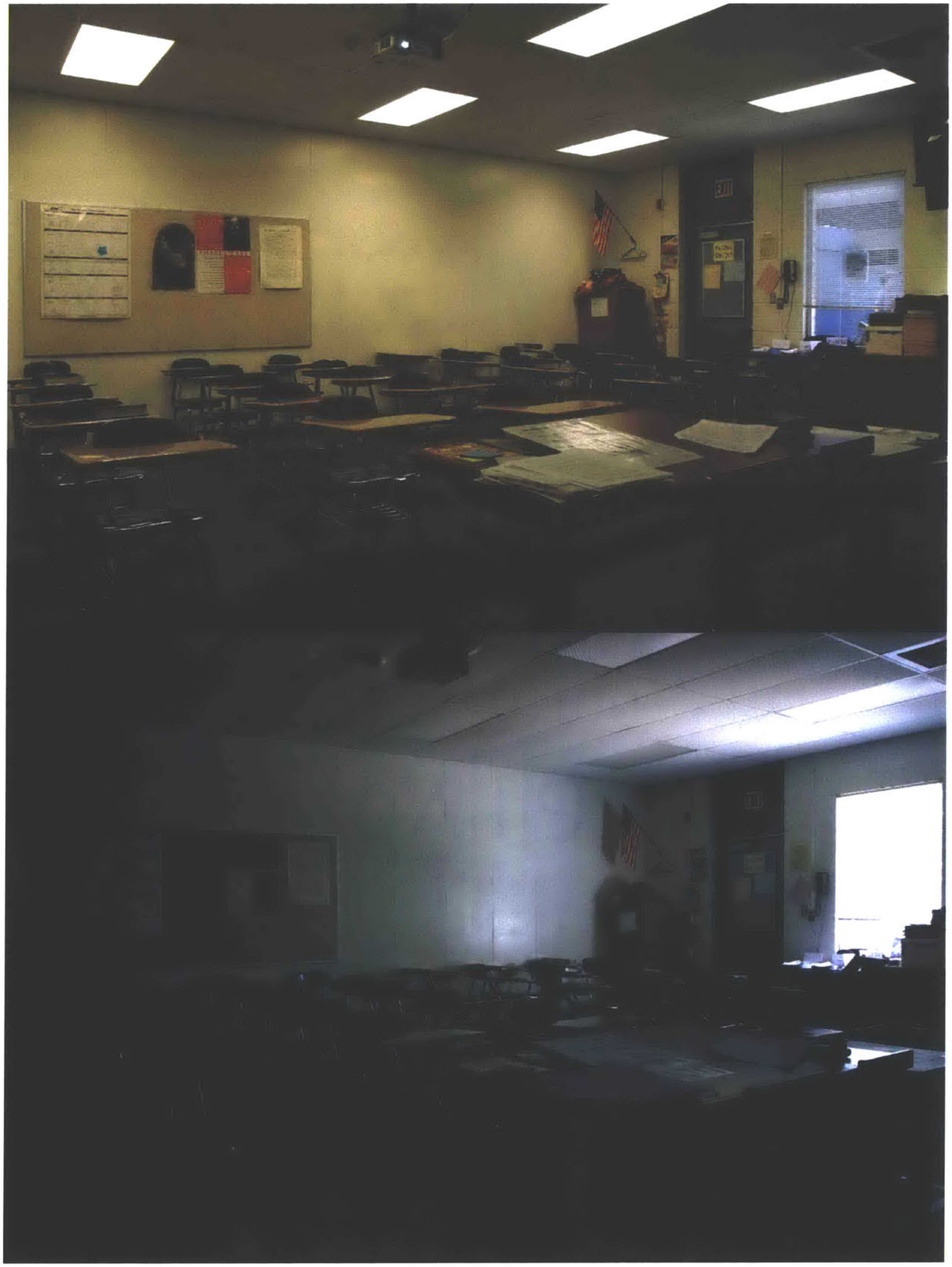


Figure 5. Classroom 2.4

Figure 6. Classroom 3.1

USE OF LIGHTING SYSTEMS[1]

1. ELECTRIC LIGHTING

As a whole, available controls and switching behavior were found to have an impact on how often lights were on and off in classrooms; for the most part, lights are kept on most of the time.

Though controls available in the classroom were diverse across both elementary and high schools, high schools were more likely to be equipped with multi-switches while teachers at elementary schools were more likely to report having one manual on-off switch and occupancy sensors (Figure 7). Nearly all controls were located at the entrance of classrooms.

Though most were satisfied with the controls made available in the classroom, participants unsurprisingly reported varied levels of control over lighting in correspondence with controls available. Those with dimmers reported having the highest level of control over lighting (Figure 8), a feeling that echoes the voice of a handful of teachers who actively volunteered their desire for dimmers in the classroom. The relationship and importance between controls and classroom use is made evident by the fact that approximately one third of participants who had access to multi-switches reported keeping only a fraction of lights on at a time.

[1] This section provides a summary of data collected, and some accompanying figures that may be most relevant. Where noted, figures in the appendix which may be relevant to the text but are not immediately provided are noted in the format (Appendix 'X', Figure 'Y'). A full compilation of accompanying charts and graphs is provided in Appendix E.

Figure 7. Reported lighting controls

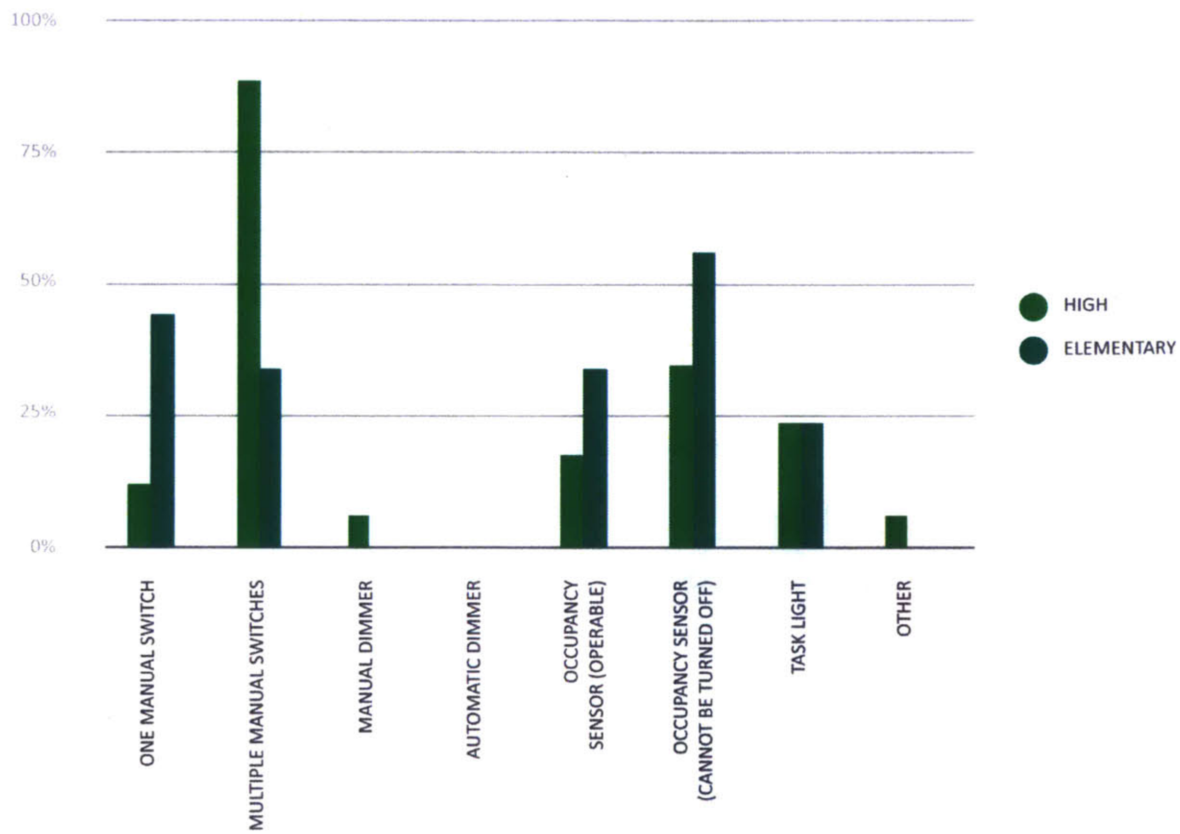
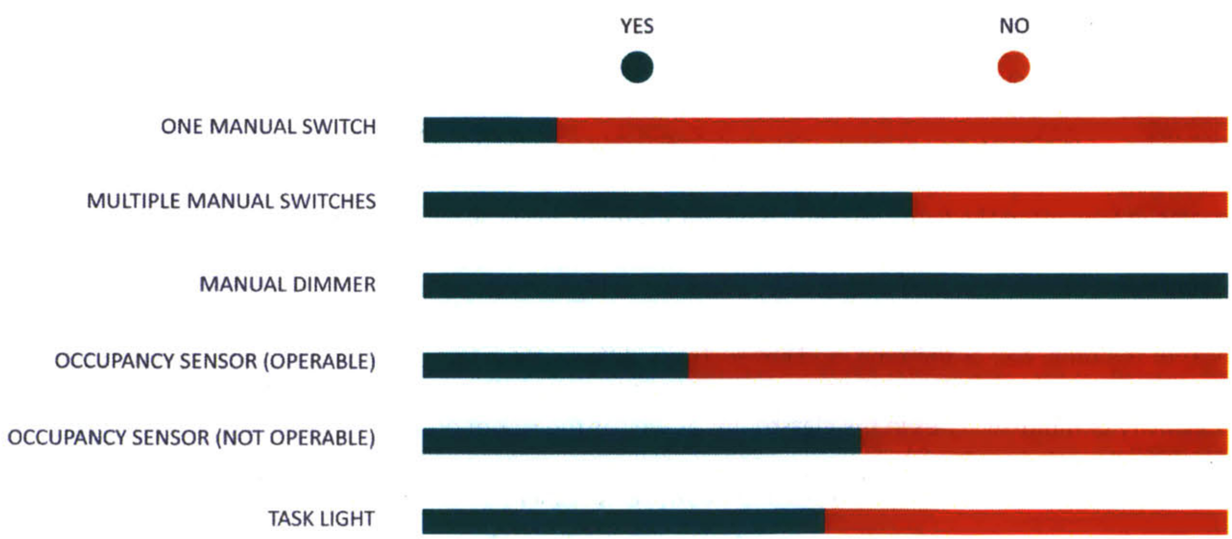
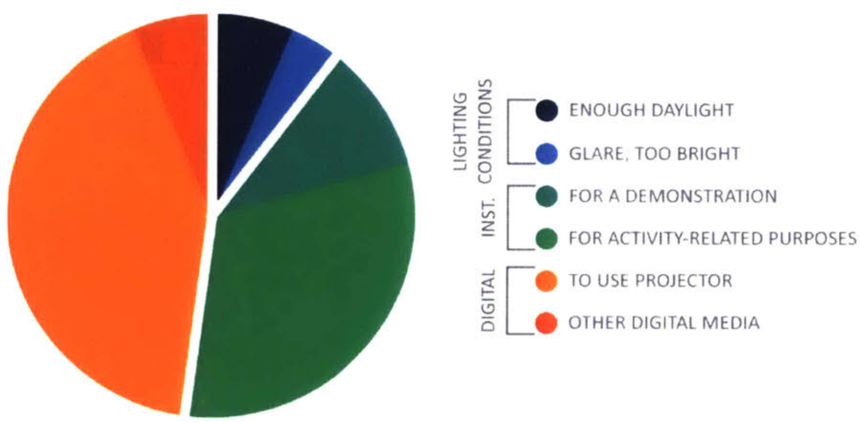


Figure 8. Do you feel your controls allow you to reach multiple levels of lighting?



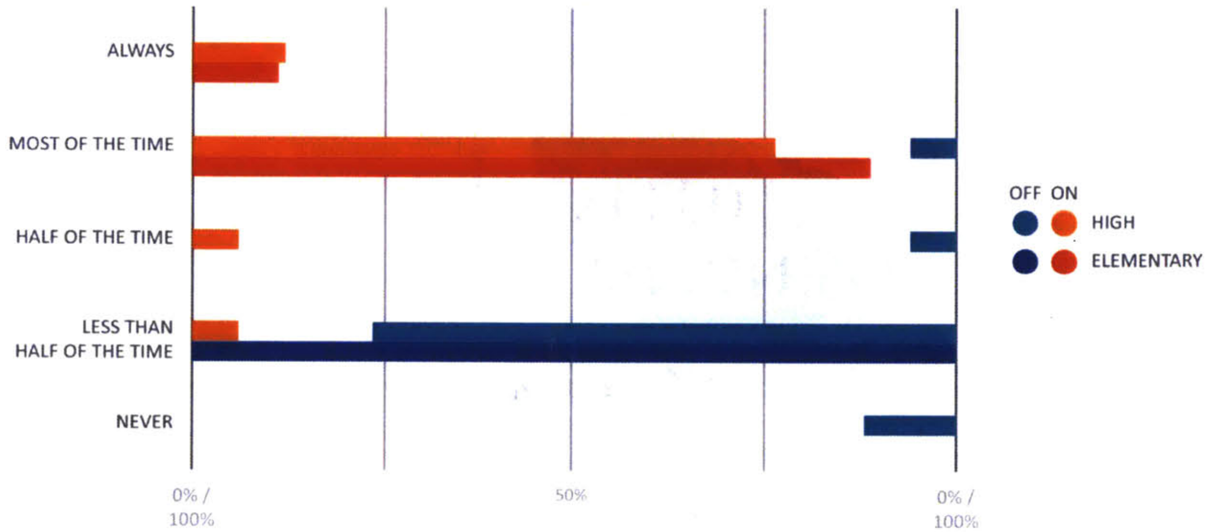
Overall, a majority of participants reported actively switching lights on or off for instructional purposes as needed, while relatively few reported leaving lights on for whole school days (Appendix E, Figure 21). Correspondingly, only 20% of participants reported turning lights off because of environmental lighting conditions, such as daylight availability or glare. These conditions only accounted for 10% of all reported reasons for switching behavior in classrooms, while the use of presentations, digital media, and other demonstrations and activities accounted for the majority of light switching (Figure 9).

Figure 9. Reasons teachers turn lights off



The differences in lighting controls between elementary and high schools, which predominantly give more control over lighting conditions to high school teachers than elementary school teachers, inform how often lights are on in the classroom. Figure 10 revels that high school classrooms are more diverse in how often the lights are turned on; for example, while all elementary participants reported having lights off less than half of the time, a handful of high school participants reported having lights off most of the time, half of the time, and never. These differences in use patterns may be related to the availability of multi-switches in the classrooms as well as the lack of occupancy sensors which may reduce control. These differences may also be muffled by the fact that nearly all participants, regardless of their demographic, primarily switch lights on or off for instructional purposes as opposed to environmental conditions, as described previously. We may expect to see more diversity in use patterns if environmental factors play a greater role in switching behavior. On average, approximately 80% of participants reported having the lights on "most of the time" (Figure 10).

Figure 10. Lights are turned on/off...

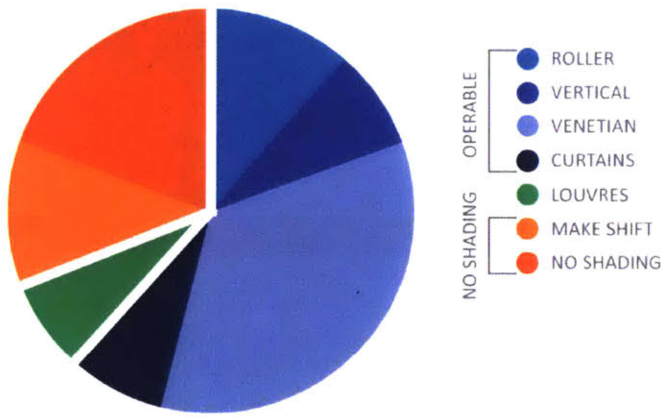


In addition to the reported use of shades, most participant schools were found to have tinted windows. Some teachers and staff members volunteered information that the tinted windows are a security and privacy feature for the schools and prevent potential criminals from viewing into classrooms during lockdown situations. At one school, staff suggested tinted windows *or* closed shades were required in order to protect the students during such events. However, it is unclear if tinted windows are used for security at all participating schools, are primarily to prevent solar gains, or a combination of both.

2. DAYLIGHTING

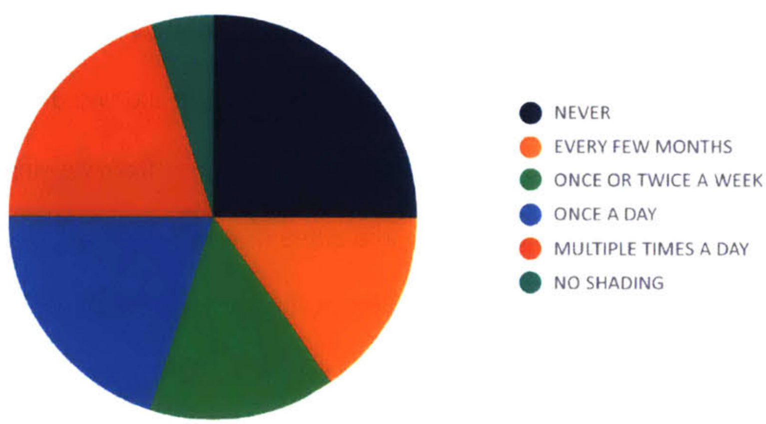
Much as for electric lighting, participant elementary school classrooms were more likely to have less control over shading in the classrooms (Appendix E, Figure 22). Approximately one third or 31% of participants reported having either no shading devices or make-shift forms of shading in their classroom, of which a majority were elementary school participants (Figure 11). Especially at elementary schools, but also in high schools, the mass use of windows as poster space for projects and assignments was observed.

Figure 11. Reported shading devices



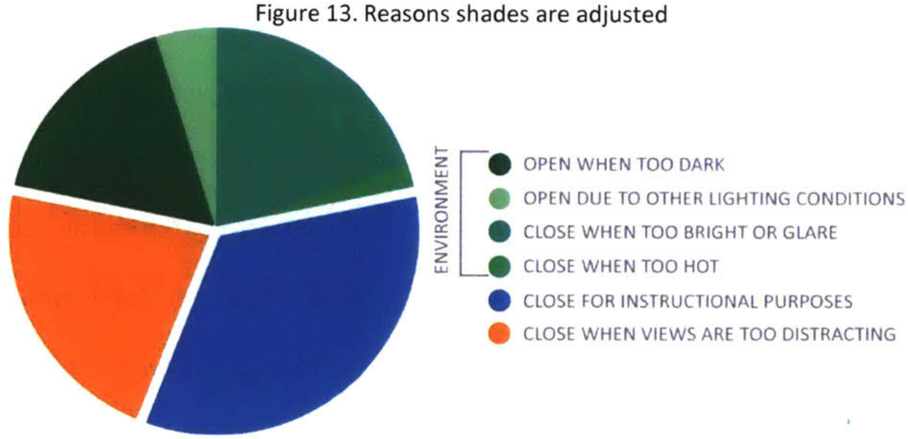
However, unlike in electric lighting, large diversity existed in how often shades were adjusted, though a quarter still report never adjusting shades (Figure 12).

Figure 12. How often shades are adjusted



Shades are also more likely to be adjusted due to environmental conditions such as excessive heat, glare, or darkness in the classroom (Figure 13). Shades are reportedly mostly closed or mostly open just about as equally between different classrooms, though differences between responses to the question "How often is the shading system mostly closed to daylight?" and "How often is the shading system mostly open to daylight?" reveals the influence of human perception (Appendix E, Figure 23).

Figure 13. Reasons shades are adjusted



3. PERCEPTION OF ELECTRIC AND DAYLIGHTING CONTROL

About two-thirds of participants reported glare in their classrooms "sometimes", though few reported glare being a consistent problem (Appendix E, Figure 24).

In keeping with the measured illuminance values of naturally lit classrooms, a majority of participants reported that daylight alone did not provide for "enough" light either in the winter or summer. As expected, even dimmer lighting conditions were reported for the summer than the winter, as sun angles are higher and direct light is less likely to penetrate into classrooms. (Appendix E, Figure 25; Figure 26). Most participants also reported having "more than enough" light overall, including electric and natural light (Appendix E, Figure 27), though these perceptions do not align with presented illuminance measurements. One reason for the difference between measured illuminance values and the reported lighting conditions may be in the way electric lighting is perceived by occupants. A common complaint among participants was that that electric lights were too bright and contributed to the development of headaches or migraines. It is possible that this perception of "harsh" lighting may be more closely related to direct lighting which can cause discomfort through glare and high lighting contrasts in the room, or even to color temperature.

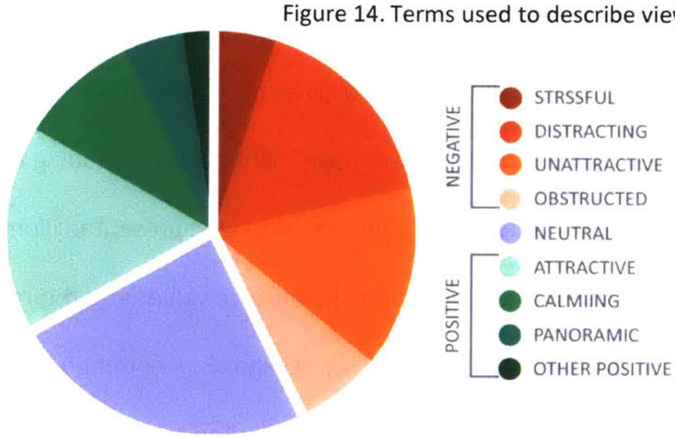
More participants also expressed satisfaction with electric lighting controls than with shading systems available (Appendix E, Figure 28; Figure 29).

4. VIEWS TO THE OUTDOORS

Across the five participant schools, teachers were asked to categorize the views from their windows. Views that predominantly contained plant life or social features were reported about as equally as views which were predominantly of other buildings or streets, and views which had an equal balance of plant life and urban features. The greatest categorization, about 30%, was that view contained an equal combination of buildings and plants. Meanwhile, almost about a quarter reported views of "only buildings within a few feet from the window" (Appendix E, Figure 30). It is interesting to note that the high schools sampled tended to report more views of buildings and streets than the elementary schools which were more likely to report greater levels of plant life and social environments (Appendix E, Figure 31).

Though those surveyed used negative, positive, and neutral labels to characterize their views almost equally, negative terms were used slightly more often (Figure 14).

Figure 14. Terms used to describe views



Unsurprisingly, views which contained plant life or social features were much more likely to be labeled in a positive manner, while views which were predominantly urban were more likely to be perceived negatively (Figure 15, Table 7). Unexpectedly, neither those who reported having views to social areas nor those who reported having unattractive views were anymore more likely than the others to describe their views as "distracting".

Figure 15. Views and descriptors/terms

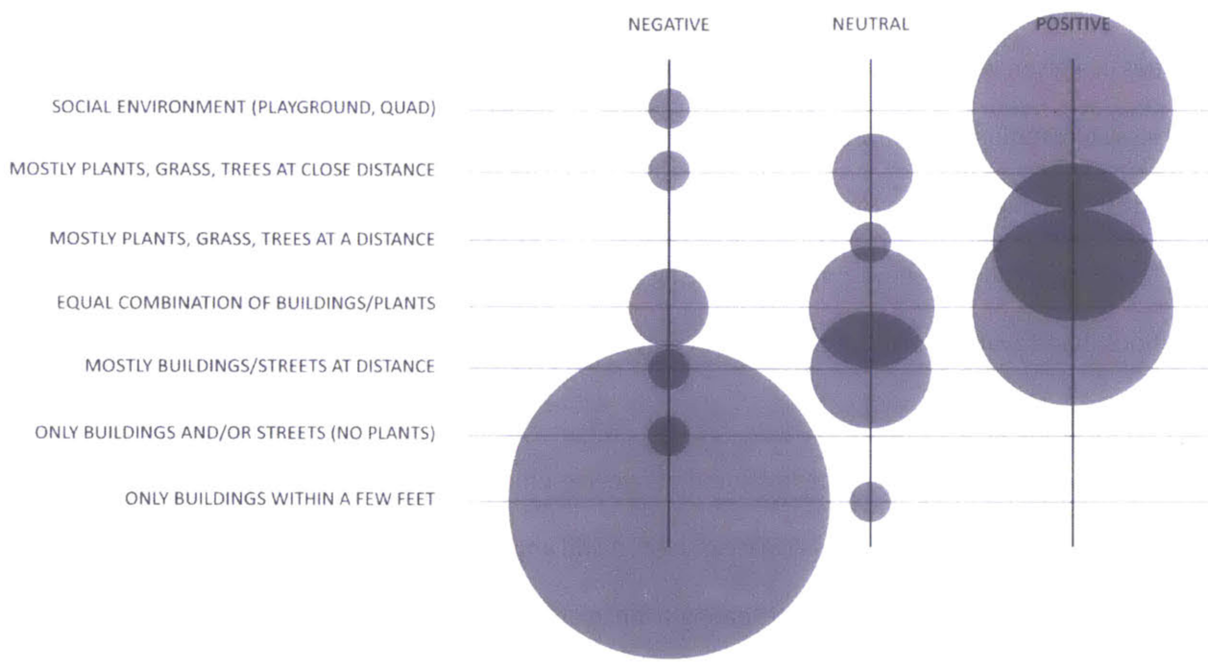


Table 7. Number of times negative, neutral, and positive terms were mentioned

	NEGATIVE	NEUTRAL	POSITIVE
SOCIAL ENVIRONMENT (PLAYGROUND, QUAD)	1	0	5
MOSTLY PLANTS, GRASS, TREES AT CLOSE DISTANCE	1	2	0
MOSTLY PLANTS, GRASS, TREES AT A DISTANCE	0	1	4
EQUAL COMBINATION OF BUILDINGS/PLANTS	2	3	5
MOSTLY BUILDINGS/STREETS AT DISTANCE	1	3	0
ONLY BUILDINGS AND/OR STREETS (NO PLANTS)	1	0	0
ONLY BUILDINGS WITHIN A FEW FEET	8	1	0

5. DIFFERENCES IN LIGHTING CONDITIONS AND USE BETWEEN DEMOGRAPHICS

Some differences between lighting controls, uses, and conditions have already been presented in this section: high school occupants are more likely to have greater control over electric lighting and shading, elementary schools are more likely to be static in terms of how often lights are turned on possibly because of available controls, and elementary schools are more likely to have views with more plant and social life. While some factors that play into these differences have already been explored, it is notable also to point out that elementary school participants have naturally also reported implementing a wider variety of teaching methods than high school teachers, and are more likely to implement outdoor activities in a given week (Appendix E, Figure 32). Overall, large scale, high contrast tasks – which may need less illumination to comfortably complete – composed a greater fraction of all reported teaching methods than in high schools (Appendix E, Figure 33). These differences in teaching methods may play a large factor in switching behavior and available lighting controls and may also be influenced by lighting conditions made available. Future studies with greater participant sample sizes may more accurately describe this relationship.

In addition to the differences explored between elementary and high schools, differences in use and lighting conditions between participating science and engineering classes and classes of other subjects are notable. In particular, participating science and engineering classes were found to be the only classes which reported having lights "always" on (Figure 16), alongside visual arts, were the only classes to report "never" adjusting the shades (Figure 17), and were the most likely to report having shades either "always" or "never" closed in an absolute fashion – about two thirds of science or engineering classes reported so (Figure 18). Not all science and engineering classes fit this exact pattern, but the pattern may reveal use and teaching methods associated with the subject that affect what type of light is needed for instruction in these types of classroom. Overall, special consideration is needed for the design of science and engineering classrooms, as well as visual art classrooms, which may require light for specialized visual tasks that differ from instruction in humanities and math subjects.

Figure 16. How often lights are on by subject

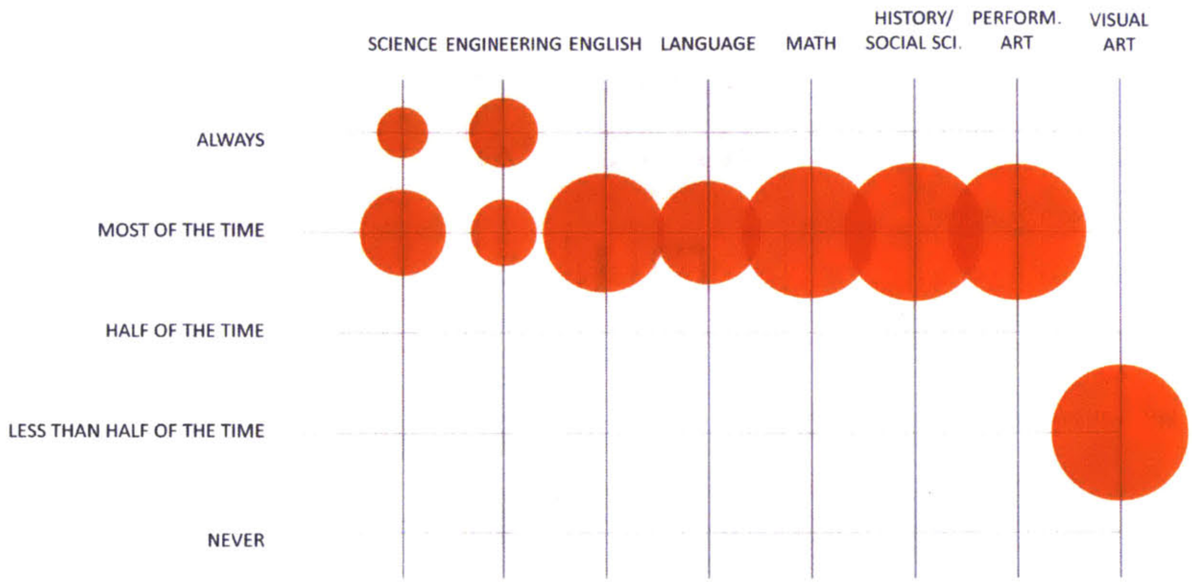


Figure 17. How often shades are adjusted by subject

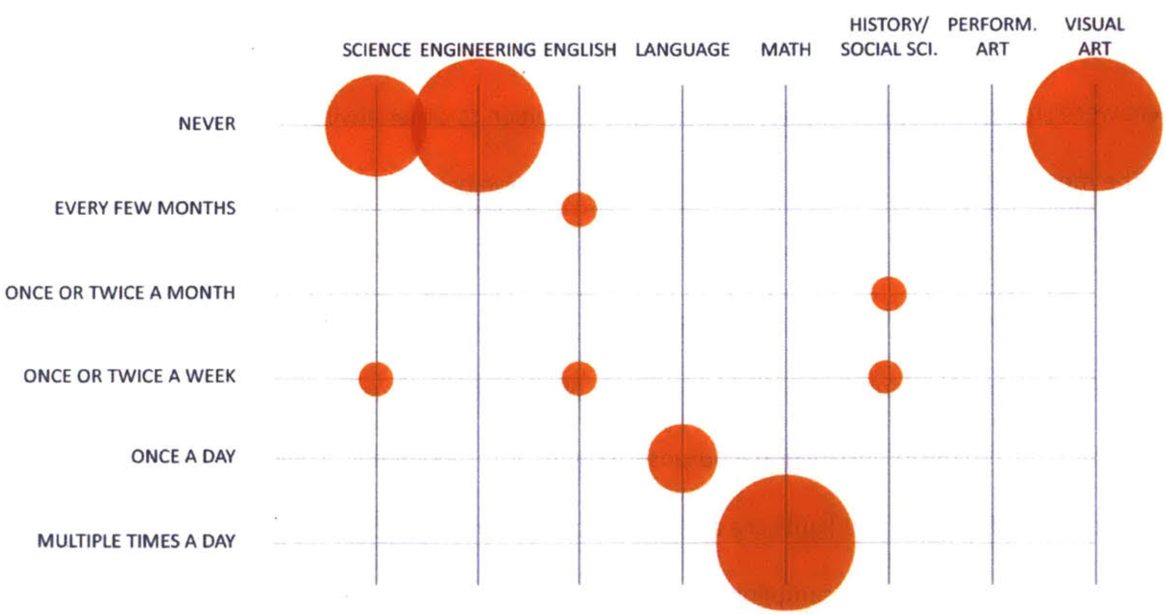
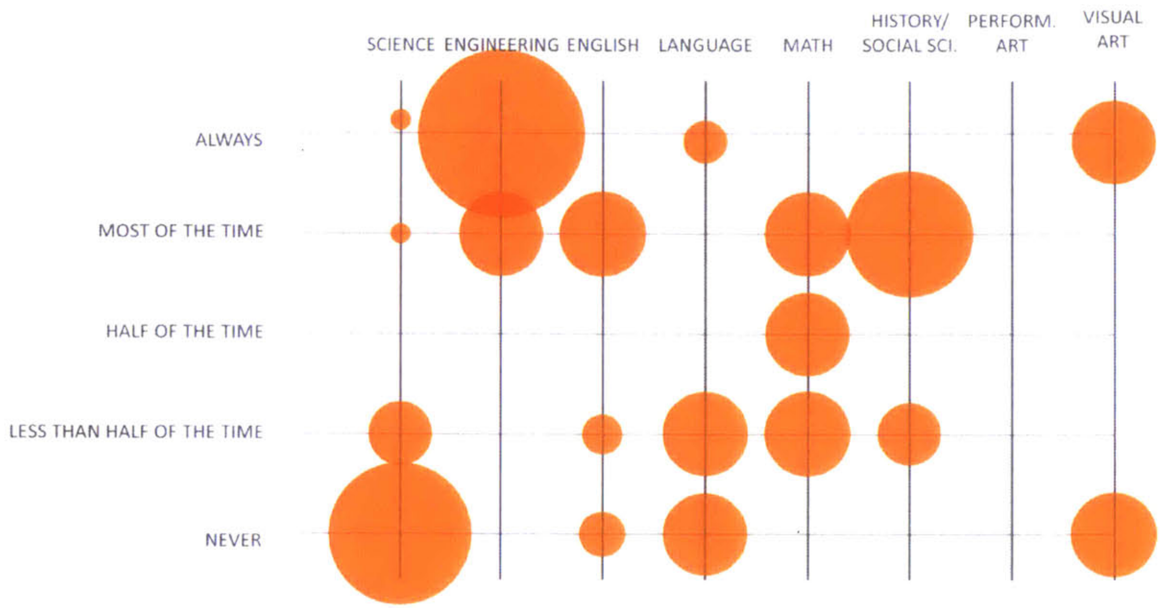


Figure 18. How often shades are closed by subject



COMPARISON TO LITERATURE FINDINGS

Overall, the data collected in this study and the subsequent findings closely align to those of Sze's 2009 "Indoor Environmental Conditions In New York City Public School Classrooms" Survey in which 183 teachers were surveyed on similar lighting conditions in addition to other environmental factors (Sze 2009). The most similar findings between the two studies involve occupant interaction with shading devices; both studies reveled varied use patterns in shade adjusting in addition to reveling a similar percentage of teachers that had no shading (Figure 19). In contrast, occupant interaction with electric system differed in that Sze found occupants were more likely to leave lights on all day as opposed to switching them on and off for instructional purposes (Figure 20). Though this analysis differs, Sze's results support findings in this study that lights are always or mostly on in classrooms. Differences may be attributed to site climate, culture, sampling size, and increased use of digital media over the past seven years since 2009.

While Sze found illuminance levels to meet minimum standards in New York schools, use patterns of classroom occupants closely correspond to findings presented in the previous sections. These similarities support the findings described in previous sections, though the differences may contain findings to Southern California schools and schools similar in typology of participating schools.

Figure 19. Comparison of reported shade adjusting behaviors (Sze, 2009)

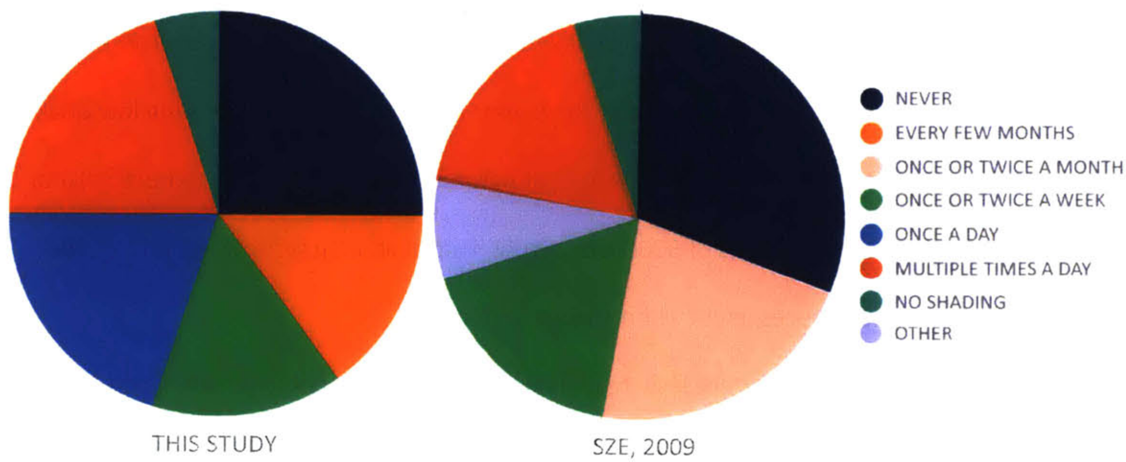
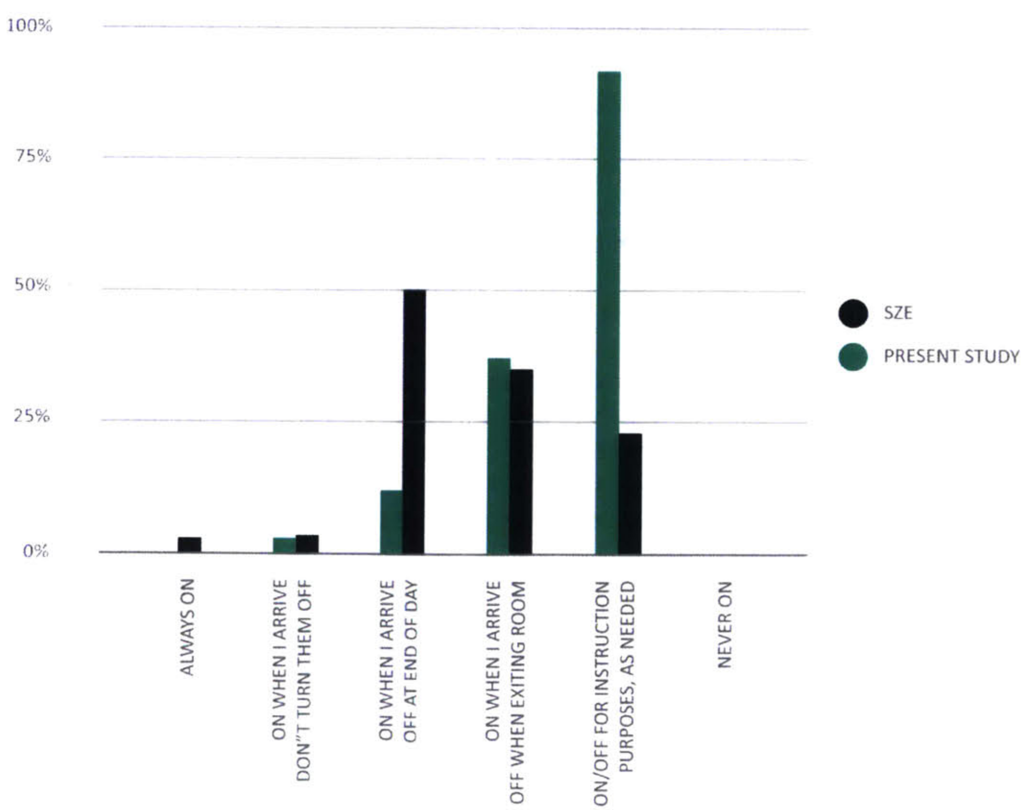


Figure 20. Comparison of reported switching behaviors (Sze, 2009)



DISCUSSION

OCCUPANT EXPOSURE TO LIGHT AND HEALTH

Overall, classrooms exhibit inadequate lighting conditions in terms of both illuminance and color temperature. While the classrooms on average meet minimum recommended illuminance levels of 300 lux, about one third of classrooms exhibit illuminance levels below 300 lux. Moreover, classrooms which do meet recommended illuminance levels only meet the lowest baseline standard, revealing low quality lighting. Likewise, classroom lighting fails to provide light at natural color temperatures; where natural lighting typically emits color temperatures of 5000 K or higher, indoor lighting systems currently only provide for 3500 K color temperatures, even when shades are open.

Overall these lighting conditions are less than ideal and potentially unhealthy when compared to light's biological influence over developing human bodies and adult human bodies alike. When compared to existing literature, for example, the low quantities of light exhibited by participant classrooms impair vision and eye development in occupants and especially children. Likewise, the warm color temperatures provided within these classrooms impair the natural circadian rhythms of classroom occupants, primarily affecting sleeping patterns, alertness, and other linked biological functions. This is especially true when considering high school bell schedules which include early zero periods that begin at 7 am or earlier; lack of access to natural outdoor color temperature impact students circadian rhythm early in the day.

The work likewise reveals the implementation of rigid controls which are often ill-suited to promote the use of natural daylight, do not respond to program and use patterns within both high schools and elementary schools, and fail to provide for nuanced control over classroom spaces as a whole. In particular, participant elementary schools are given less control over lighting in classroom spaces despite a wider range of activities implemented in these classrooms, while science and engineering classrooms are afforded the same controls as other high school subjects despite presumably having particular task-related needs. This lack of control not only fails to promote natural daylighting but in fact promotes the use of electrical lighting such that teachers must have lights on "most of the time" if not "all of the time".

While modern buildings stress uniformity and the standardization of light across occupied spaces through the emphasis placed on electric lighting fixtures over daylighting techniques, a renewed emphasis on daylight and window use is needed in order to properly supplement existing electrical light with natural and energy efficient power from the sun and provide for natural color temperatures that better suit the human biology. An emphasis on natural lighting additionally provides diverse stimulation that enhances the human experience and enlightens occupants through differences in light, color, and illumination. Though these unquantifiable effects of light on the human experience differ from the quantifiable and biological effects explored in previous sections, they are not incompatible with the science behind the light measurements and standards that impact our biology; the sun itself provides humans with these diverse experiences, yet also provides quantifiable levels of illuminance and color temperature to which our bodies naturally and healthily react.

Despite this need to better integrate natural daylighting solutions, proper electric lighting which not only provides for greater amounts of illuminance but also provides for quality lighting must also be promoted in conjunction. In particular, new design and policy should promote higher output lighting fixtures that provide for diffuse lighting conditions and cooler color temperatures as well as controls which allow for proper lighting where natural daylight needs to be supplemented and for varied use within classroom spaces. The promotion of these diffuse systems would allow occupants to reach higher levels of illumination to reduce eye strain by addressing occupant perception of "harsh" lighting and by providing healthier lighting conditions in terms of illuminance and color temperature. The integration of greater nuance in controls would also allow electric systems to work together with natural daylighting systems by providing light only where supplemental light is needed in the case of new buildings.

Given the differences between results from Sze's 2009 work and results from this study, these findings may be contextualized to schools in climates similar to that of Southern California that have been built with similar typologies – generally, buildings with generally small to midsized windows at the working plane, and schools with portable classroom additions.

IMPLICATIONS FOR CURRENT AND FUTURE LIGHTING DESIGN

Simple and affordable measures can be taken in existing classrooms in order to better promote the integration of healthy lighting in terms of both natural daylight and electrical systems. In order to better promote the use of the window through which natural daylight can illuminate the room and provide cooler color temperatures, fixed external shading can be provided to minimize direct light and glare (especially in north-south facing classrooms), and internal shading devices may be removed given that fixed shading provides for comfortable lighting conditions; these conditions would promote the use of the window to let in more daylight. The implementation of lightbulbs which provide for higher output and cooler color temperatures may also improve healthy lighting conditions in existing classrooms.

In both the case of new design and retrofits, up-lighting fixtures are also recommended in order to reduce visual discomfort and glare. Up-lighting may not only reduce contrasts that are perceived as "harsh" and allow for higher illumination that is not perceived as "too bright", but may also diffuse light more evenly across classroom spaces and provide for greater consistency of illumination from desk to desk.

In both existing and new classroom buildings, window lighting systems can also jointly address security concerns and natural lighting concerns. Where tinted windows may currently be used in order to provide for privacy, new design and retrofits must consider how the need for privacy and daylight interact. In existing buildings, this may mean using tinted windows to provide for both diffuse light and privacy, while in new buildings the implementation of high windows placed above seven feet or two meters in height may hinder outsiders from peering in while still providing for great levels of outdoor illumination. The balance between security and light is also indicative of concerns which must be addressed by future classroom design in the United States.

In new construction, an emphasis on high windows places above seven feet or two meters in addition to any separate windows at the working plane is highly recommended. When combined with proper fixed shading techniques that minimize direct solar gains, these windows promote the use of natural daylight on various levels. For one, windows above this height are out of the reach of occupants and are not likely to be adjusted or covered in make-shift shades or classroom projects. The height of these windows as stated previously, additionally provide for the greatest amount of daylight penetration, as light coming from any angle can reach deeper into rooms from higher elevations.

New buildings also afford for greater opportunities to provide for nuanced electric lighting systems and controls. Though design should be flexible in all spaces, special considerations should be made for classrooms in which specialized visual tasks may be conducted, such as art and science and engineering spaces that may benefit from reduced solar glare and higher illumination for high contrast tasks even more so than other classroom spaces. Where specialized tasks are conducted that require handling or focusing on minute details such as construction or experiments, or the use of digital mediums such as computers, lighting design should provide for additional lighting systems such as task lights other lighting systems which can be adjusted specifically for the area in which these specialized activities occur. More nuanced lighting controls are likewise needed in order to provide for variable lighting in classrooms. Though one could argue greater occupant control of lighting may lead to inconsistence in illuminance and color temperature between classroom to classroom, and may allow occupants to light rooms below recommended lighting levels for classroom activities, greater control of electric systems would also allow for lighting that is better suited to occupant needs. In particular, nuanced controls could allow occupants to only turn lights on over regions where natural lighting is not sufficient. Current solutions and multi-switches often only allow every other light to be turned on or off, however, new controls could allow for regions of the classroom which are classroom which are too far away from windows and natural light to be supplemented by electric lighting and vise-versa. Likewise, wen digital mediums of instruction are used in combination with classroom activities, greater flexibility in lighting control may allow for a better balance between contrast needed for screens and the contrast needed for reading and writing, than current solutions which only allow lights to be completely off, half or one-third on/off, or completely on at best. In particular, dimmers, which provide for the greatest flexibility in classroom illumination, and which some teachers have expressed a desire for, would be a low-cost solution to current lighting controls that only allow for fractions of lights to be turned on or off.

Lastly, while the impact of occupants' views to the outdoors on human psychology and stimulation is difficult to quantify, special consideration for the aesthetic design of views to the outdoors – for example through landscaping and the addition of natural features such as trees and plants – that is perceived positively also promotes window use. As the findings show, teachers' perception of what is "distracting" may not necessarily be tied to views afforded by windows but may in fact be tied to personal preference. However, views to the outdoors that involve social experience or a connection to nature are viewed more positively. As such, access to positive views may incentivize occupants to leave shading devices open, allowing for greater access to natural daylight illumination and color temperatures.

TARGETING CHANGE

Following the findings of this study, who should lead for change in promoting healthy lighting in classrooms by not only promoting the use of natural daylight but the integration of effective electric lighting solutions?

Though architects ultimately apply these considerations through design, administrators and public officials may have greater impact on the actual implementation of healthy lighting as clients of designers which push for these changes in classroom spaces. As a result, targeting change for healthy lighting in classroom spaces through a diverse set of groups in our society may be optimal. Teachers and students alike should be informed of the effects of indoor lighting, administrators and public officials should push for lighting design consideration in new building construction and retrofits, and policy measures should promote the integration of natural lighting should be drafted in addition to future architectural emphasis on the problem.

At the most basic level, informed teacher and student occupants may choose to behave differently in order to promote their own health within classroom spaces. Not only can occupants choose to use their shading and electrical controls differently in order to promote higher illumination and color temperatures within the classroom, but where classrooms are lit inadequately, occupants may also choose to expose themselves to natural light through different mediums. For example, especially in mild climates such as those in Southern California, occupants can promote greater times spent outdoors in order to offset the effects of indoor lighting; even an hour spent outside in full daylight can offset the development of myopia or promote natural circadian cycles. Informed occupants may also vocalize the need for healthy spaces to designers and public officials alike.

As clients of architectural designers, pubic officials and school and district administrators also wield incredible power in directing and demanding classroom design considerations. Likewise, through greater demand these actors may prompt for solutions which diverge from standardized classrooms and portable solutions.

On a greater order, legislation and policy guidelines provide the framework for healthy lighting consideration in building construction. Just as policies and guidelines currently exist for electric illumination (such as ASHRAE, CHPS, and IESNA) and impact standard building design, classrooms may benefit from policies which promote other aspects of healthy lighting such as natural daylight availability, outdoor views, and cooler color temperatures. Currently, policies involving these measures are typically voluntary, such as with the implementation of LEED.

The collaborative effort of informed occupants, school officials, policy makers, and designers is needed in order to push for the application of in healthy light design and solutions in classrooms.

RESEARCH LIMITATIONS AND FUTURE RESEARCH

Various suggestions are made in order to improve upon the thesis presented. At the core, the studies presented would benefit from a larger sample-size. In the research presented, less than 30 classrooms were studied across 5 schools due to time constraints in the research process, the private and regulated nature of public schools for the purpose of protecting minors, and schools' limited availability due to limited time and resources. In addition to the limited number of samples, schools that were studied resided primarily in a singular location of Southern California region, and may not accurately depict lighting conditions in the region or even within the county. Future research in which more time is spent collecting data from diverse schools and in which outreach is conducted more effectively may increase the sample-size and depict a broader picture of lighting within a region's school system.

This study would also benefit from survey questions which more accurately describe visual tasks and available controls and fixtures.

Though the collection of point-in-time measurements was designed to be undisruptive to the classroom schedules of teachers and students through, future research may benefit from the collection of data which simplifies measured lighting availability in classrooms. In particular, the collection of luminance measurements to create HDR photographs would provide useful information and may be used to map where classrooms are well-lit and where they are not, as well as how deep natural lighting penetrates, and the percentage of area that is adequately illuminated. Mapping lighting conditions across whole classrooms may provide for more nuanced findings to inform classroom lighting design that addresses the interaction of daylight near windows, and the need for additional lighting in classroom regions that do not receive the same daylight benefits.

Future research in understanding the blend of social and building design behind security concerns in U.S. schools may improve architectural daylighting designs that address both the needs of the school and the benefits natural lighting affords to developing bodies. Likewise, future research on how to best implement national, state, and district policies or administrative design guidelines regarding natural daylight may also prove useful.

CONCLUSION

Overall, classrooms studied in this research exhibit inadequate lighting conditions in terms of both illuminance and color temperature; while classrooms on average meet minimum recommended illuminance levels of 300 lux, about one third of classrooms exhibit illuminance levels below 300 lux, classrooms which do meet recommended illuminance levels only meet the lowest baseline standard, and indoor lighting systems currently only provide for 3500 K color temperatures, even when shades are open. Overall these lighting conditions are unhealthy when compared to light's biological influence over developing human bodies and adult human bodies alike. The work likewise reveals the implementation of rigid controls which are often ill-suited to promote the use of natural daylight, do not respond to program and use patterns within both high schools and elementary schools, and fail to provide for nuanced control over classroom spaces as a whole. This lack of control not only fails to promote natural daylighting but in fact promotes the use of electrical lighting such that teachers must have lights on "most of the time" if not "all of the time".

In both existing classrooms and future construction, architectural design must address these problems through an emphasis on the use of the window, natural daylight, and more effective electric lighting systems. Some of these solutions include the implementation of effective exterior fixed shading, separate windows placed above the height of seven feet or two meters, up-lighting electric fixtures, and more nuanced controls which better address use patterns in elementary and high school classrooms as well as special subjects. However, while these solutions must be implemented by architectural designers, change is limited without the collaborative effort of occupants, school officials, and policy makers who can make informed decisions on lighting solutions, generate demand from the architects for quality lighting as clients, and create effective policy measures that require future construction to consider the impacts of natural and electric lighting on human biology and experience.

APPENDIX

A. ILLUMINANCE DATA (LUX)

	MORNING			AFTERNOON		
SCHOOL/ CLASSROOM	**DAYLIGHTING**	**ELECTRIC LIGHTING**	**DIFFERENCE (DL – EL)**	**DAYLIGHTING**	**ELECTRIC LIGHTING**	**DIFFERENCE (DL – EL)**
1.1	14	361	347			
1.2	3	265	262	99	416	316
1.3	3	230	227	40	237	198
1.4	10	288	277	57	434	377
2.1	2	323	321	3	517	513
2.2	13	369	357	8	426	418
2.3	15	436	421	17	440	424
2.4	2	216	214	4	227	223
3.1	3	638	635	25	574	549
3.2	2	399	397	2	401	399
3.3	2	578	575	3	468	465
3.4	9	404	395	4	166	162
4.1	2	274	272	5	214	209
4.2		135			198	
4.3	19	162	143	16	359	342
4.4	2	334	331	2	334	331
5.1		746				
5.3					242	
5.4					521	
5.5	173	605	433	161	578	417
5.6		647		8	639	631
AVERAGE	17	390	351	28	389	373
RANGE	2 – 173	135 – 647	143 – 635	2 – 161	166 – 639	162 – 631

	DAYLIGHTING	**ELECTRIC LIGHTING**
MEETS RECOMMENDED 300 LUX (%)	0%	77%
DOES NOT MEET RECOMMENDED 300 LUX (%)	100%	33%

B. INDOOR:OUTDOOR AVAILABLE ILLUMINANCE DATA

	MORNING			**AFTERNOON**		
SCHOOL/ CLASSROOM	DAYLIGHT	NATURAL LIGHT	**DAYLIGHT RATIO**	DAYLIGHTING	NATURAL LIGHTING	**DAYLIGHT RATIO**
1.1	14	3290	0.42%			
1.2	3	1745	0.17%	99	42800	0.23%
1.3	3	2870	0.09%	40	27000	0.15%
1.4	10	6970	0.15%	57	27500	0.21%
2.1	2	8190	0.03%	3	41600	0.01%
2.2	13	15310	0.08%	8	19000	0.04%
2.3	15	65300	0.02%	17	66500	0.02%
2.4	2	2530	0.09%	4	33900	0.01%
3.1	3	1571	0.17%	25	27200	0.09%
3.2	2	5060	0.04%	2	29100	0.01%
3.3	2	9300	0.02%	3	24800	0.01%
3.4	9	7420	0.13%	4	27200	0.02%
4.1	2	3327	0.07%	5	68200	0.01%
4.3	19	5740	0.32%	16	64500	0.02%
4.4	2	5450	0.04%	2	71000	0.00%
5.5	173	5110	3.38%	161	4240	3.81%
5.6				8	53100	0.01%
AVERAGE	17	9324	0.33%	28	39228	0.29%
RANGE	2 – 173	1571 – 65300	0.02% – 3.38%	2 – 161	4240 – 71000	0.00% – 3.81%

C. COLOR TEMPERATURE DATA (K)

	MORNING			**AFTERNOON**		
SCHOOL/ CLASSROOM	**DAYLIGHTING**	**ELECTRIC LIGHTING**	**DIFFERENCE**	**DAYLIGHTING**	**ELECTRIC LIGHTING**	**DIFFERENCE**
1.1	5343	3325	-2018			
1.2	4043	3357	-687	4309	3315	-994
1.3	4277	3350	-927	4280	3360	-920
1.4	4203	3383	-820	4444	3474	-970
2.1	3517	3323	-193	4217	3383	-833
2.2	4567	3380	-1187	5065	3340	-1725
2.3	5243	3380	-1863	5693	3387	-2307
2.4	4845	3345	-1500	6273	3347	-2927
3.1	4833	3277	-1557	4590	3327	-1263
3.2	3668	3386	-282	4527	3360	-1167
3.3	3900	3253	-647	3583	3367	-217
3.4	6910	3370	-3540	3627	3170	-457
4.1	12267	3343	-8923	4653	3357	-1297
4.2		3443			3442	
4.3	4067	3417	-650	4795	3430	-1365
4.4	5030	3230	-1800		3230	
5.1		3415				
5.3					3480	
5.4					3497	
5.5	6698	3933	-2765	7335	4403	-2933
5.6		3507		3730	3510	-220
AVERAGE	5213	3390	-1823	4741	3430	-1311
RANGE	3517 – 12267	3230 – 3933	-193 – -8923	3583 – 7335	3170 – 4403	-217 – -2933

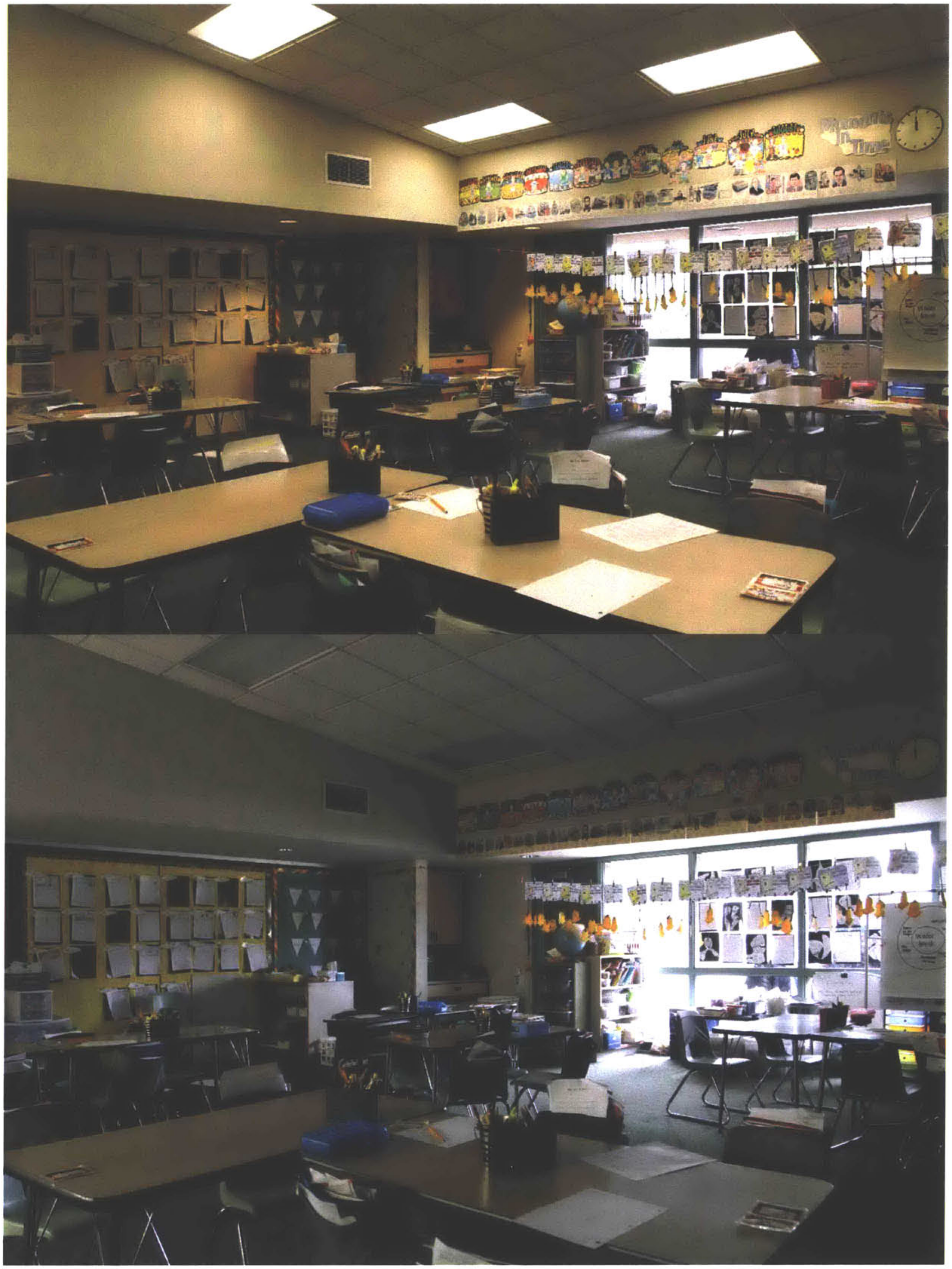
D. PHOTOGRAPHS

The following photographs are organized by classroom. Each page provides a set of classroom images when the lights are turned off and when the lights are turned on, except where photographs are unavailable. In these circumstances photographs could not be taken due to either time constraints, the presence of minors, or the requests of the teachers. Each set is labeled in the format 'X.x' where big 'X' is inidicative of a school, and little 'x' is used to denote one classroom in that particular school. All photographs presented were taken at the same white balance, and at exposure values of zero (EV 0).

1.1

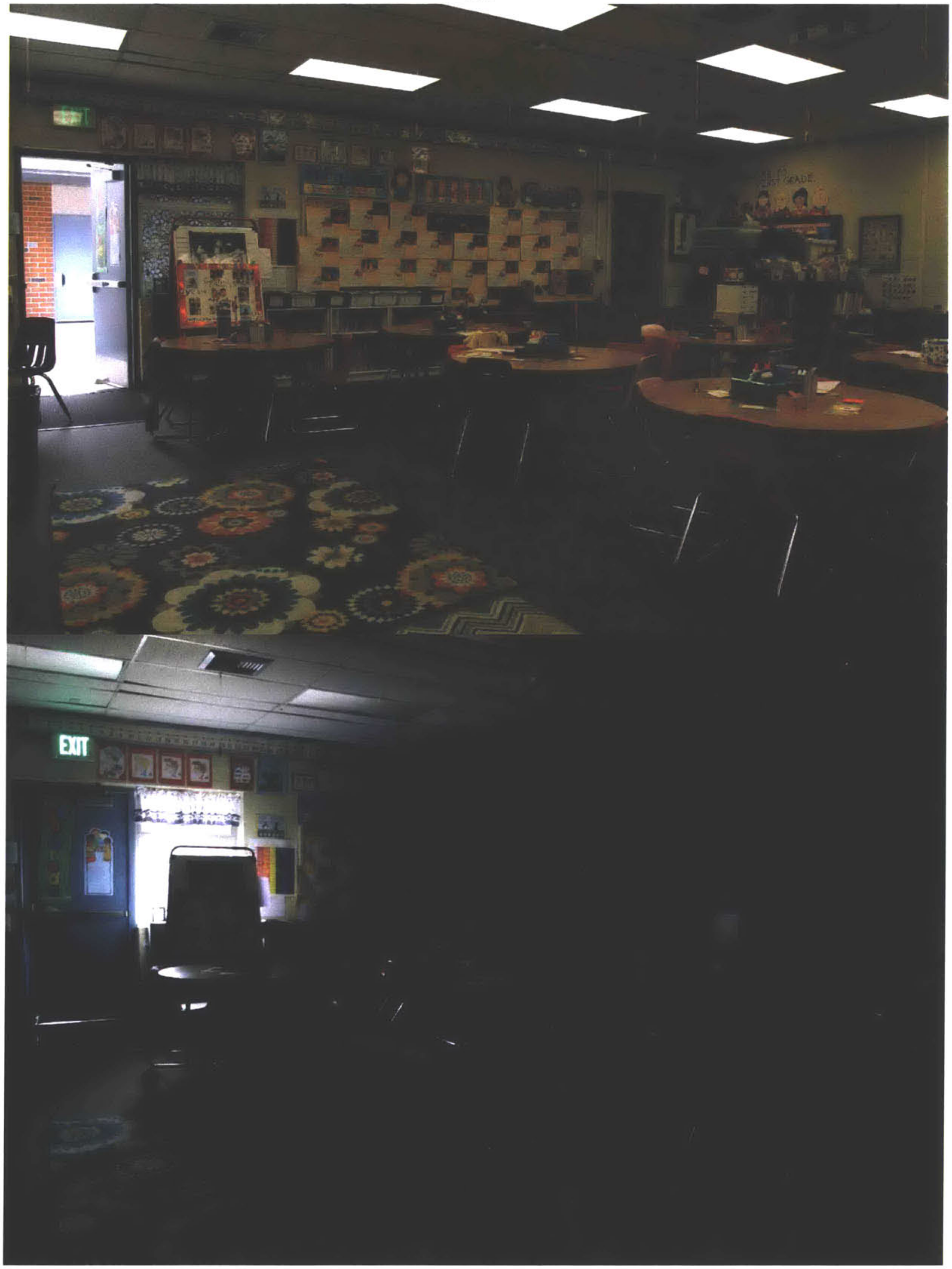
1.2

1.3



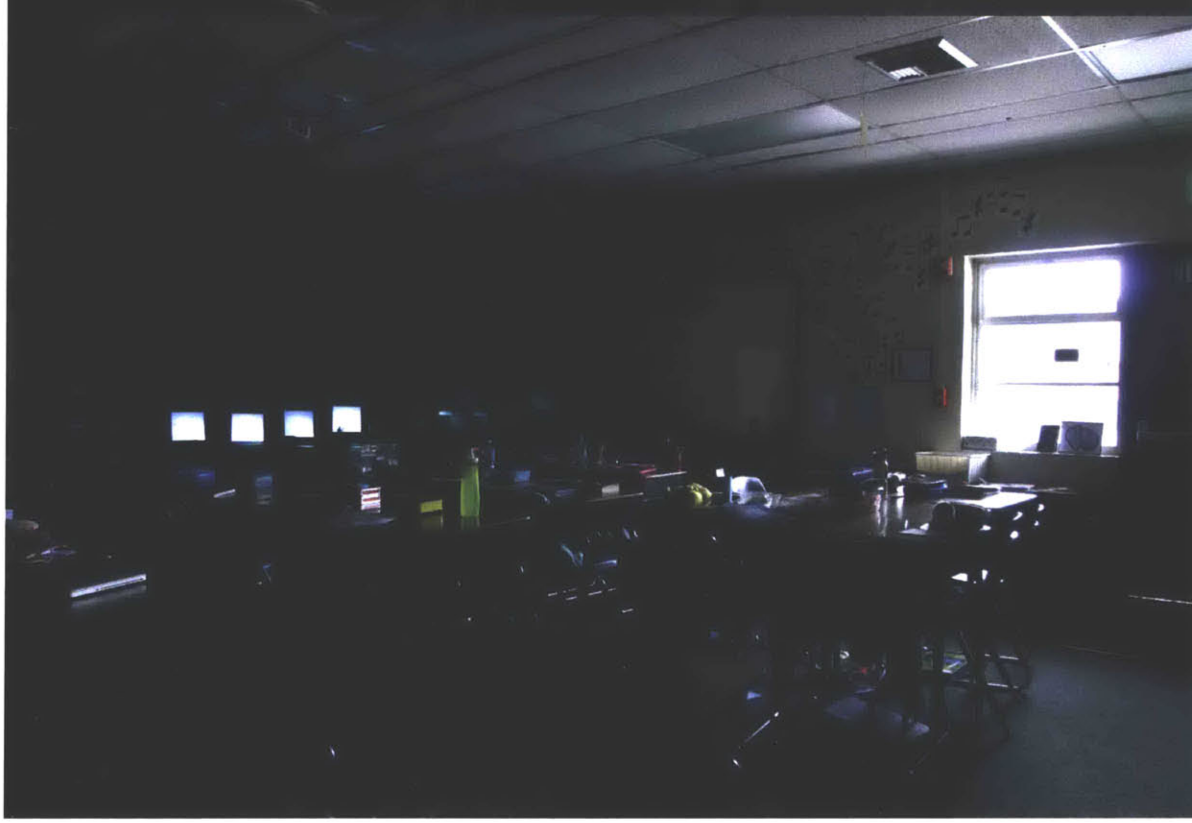
1.4

2.1



2.2

2.3

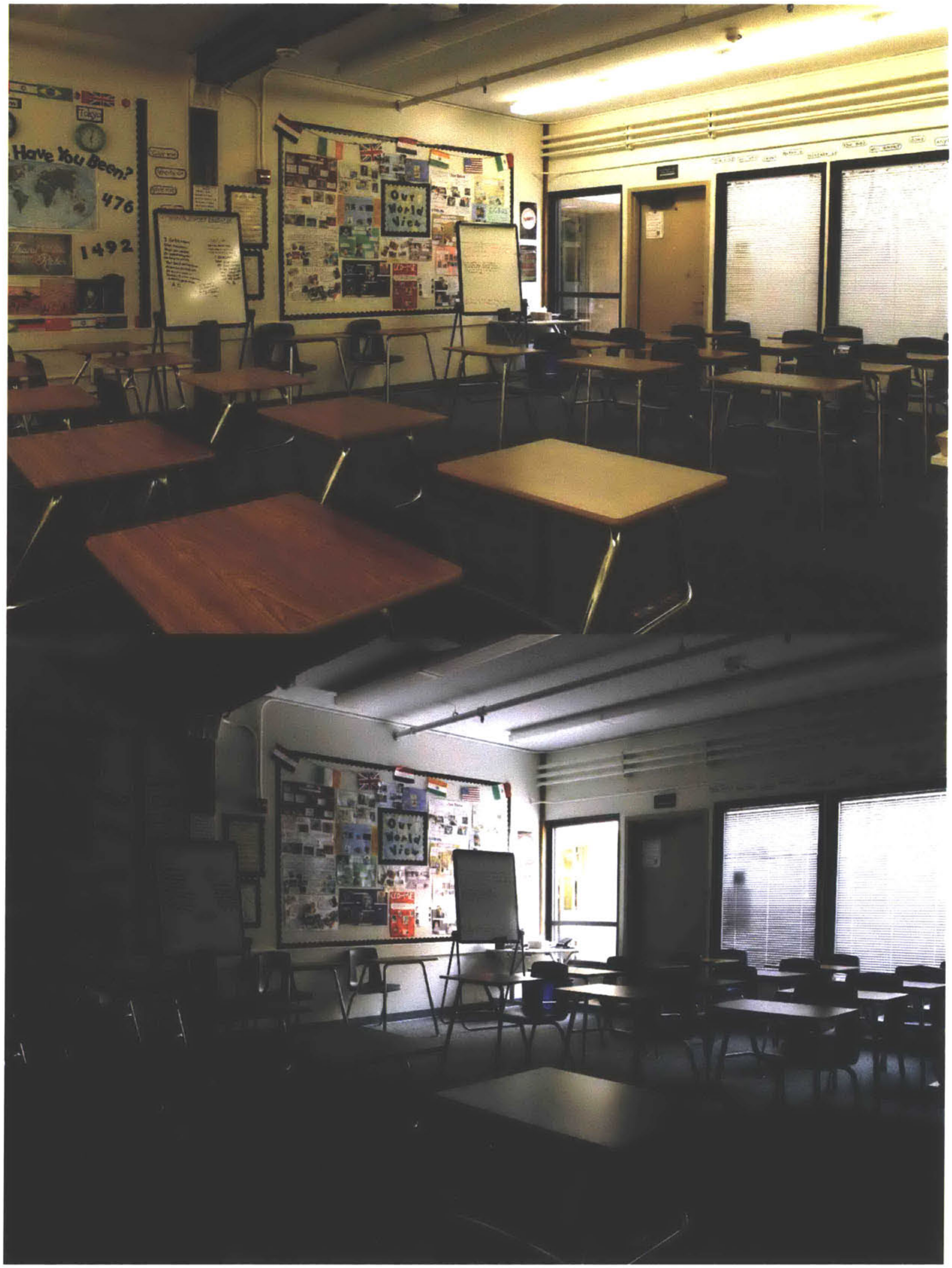


2.4

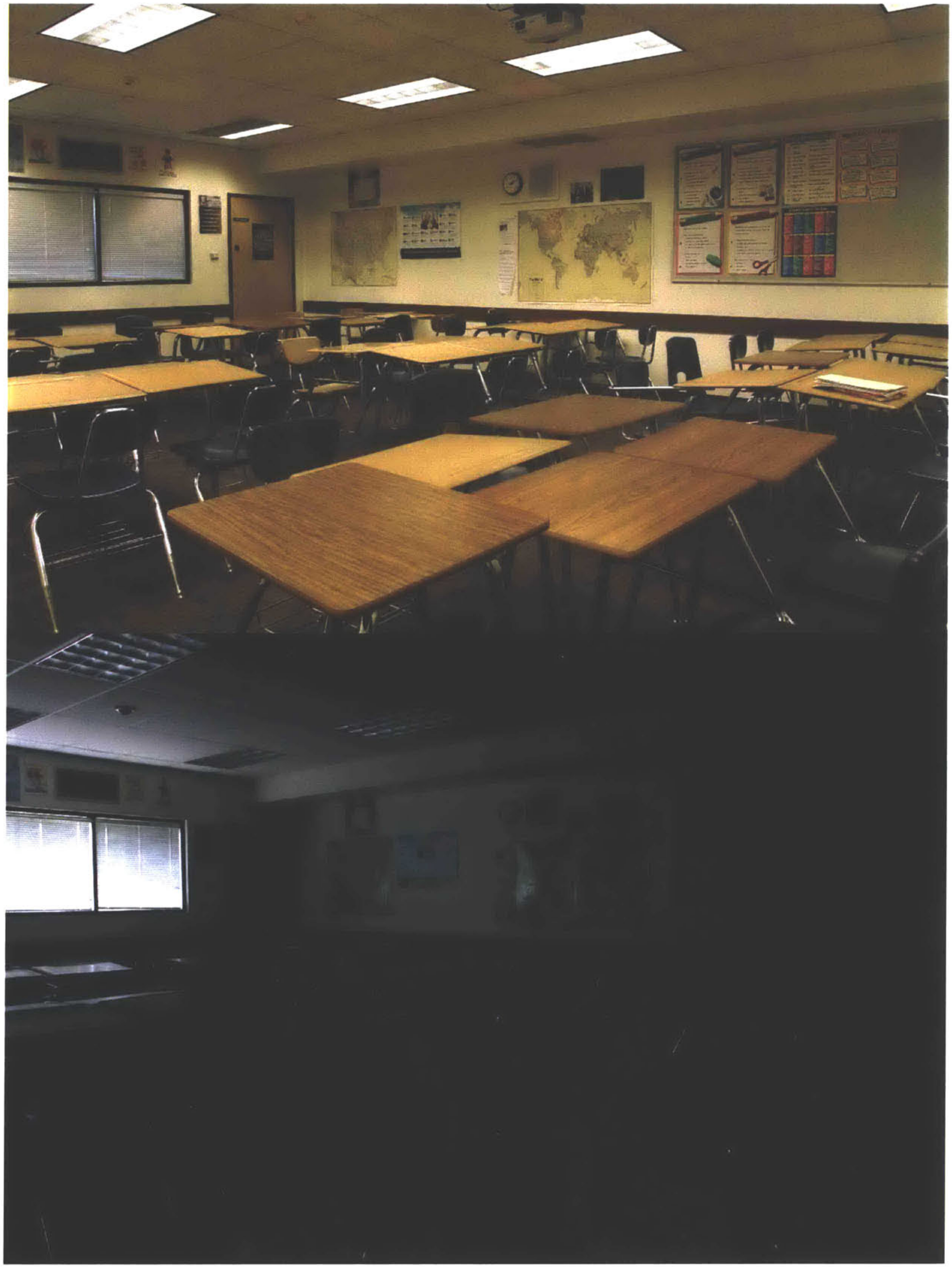
3.1

3.2

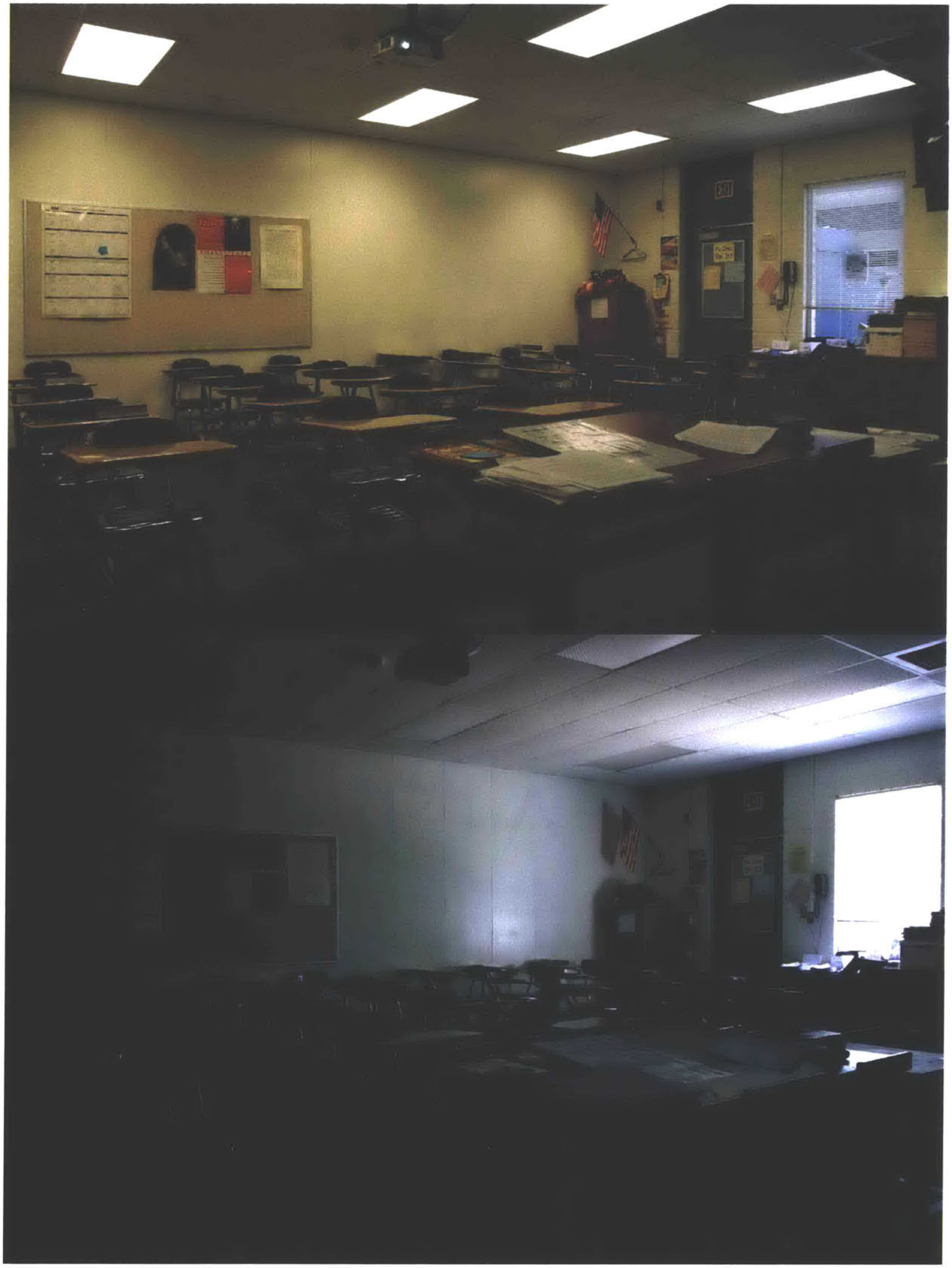
3.3



3.4



4.1

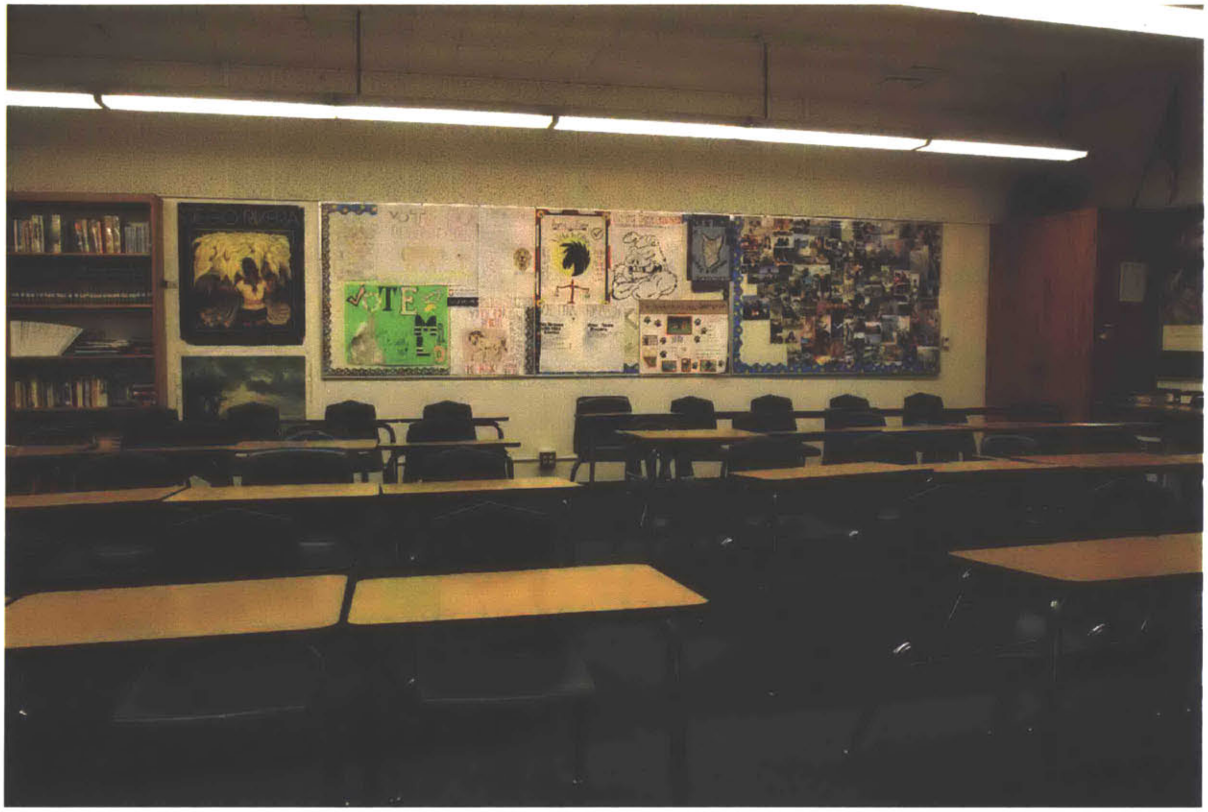


4.2

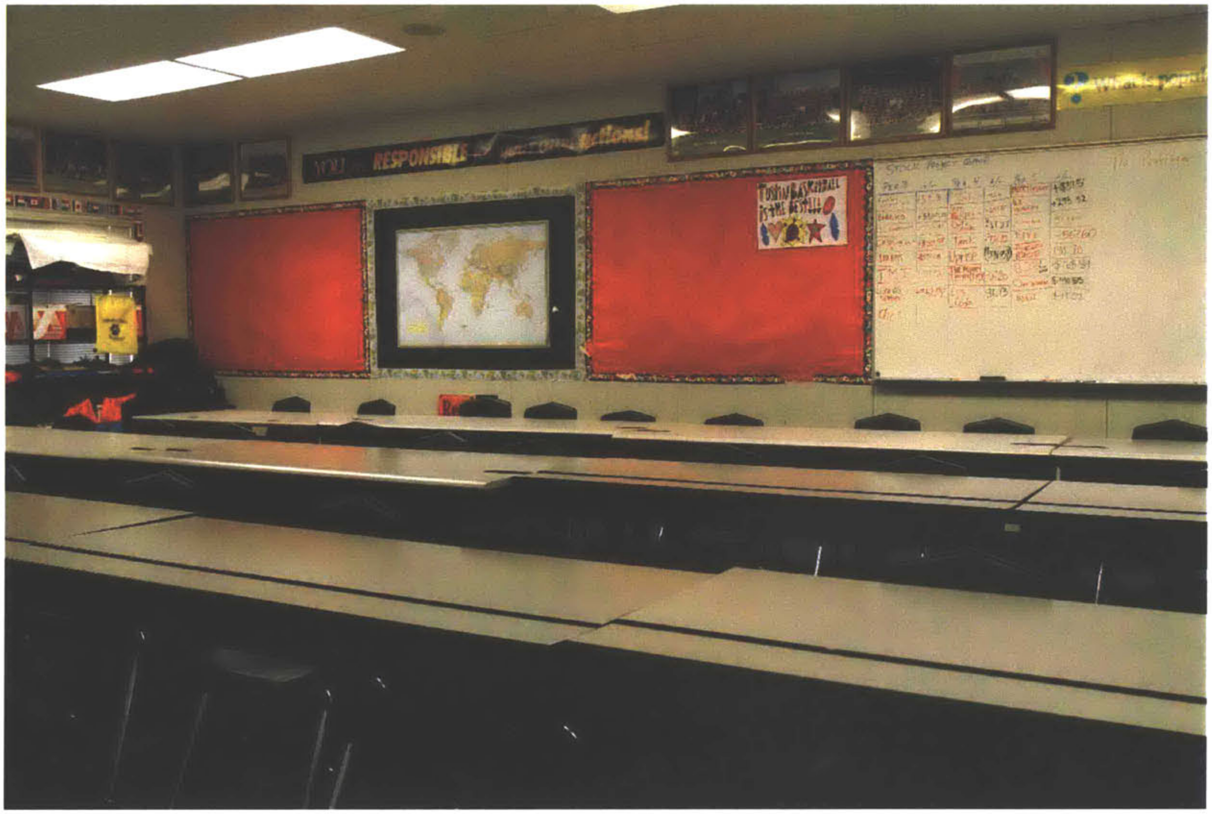
4.3

4.4

5.1



5.3



5.4

5.5

5.6

E. ADDITIONAL SURVEY DATA

Figure 21. Reported switching behavior over school day

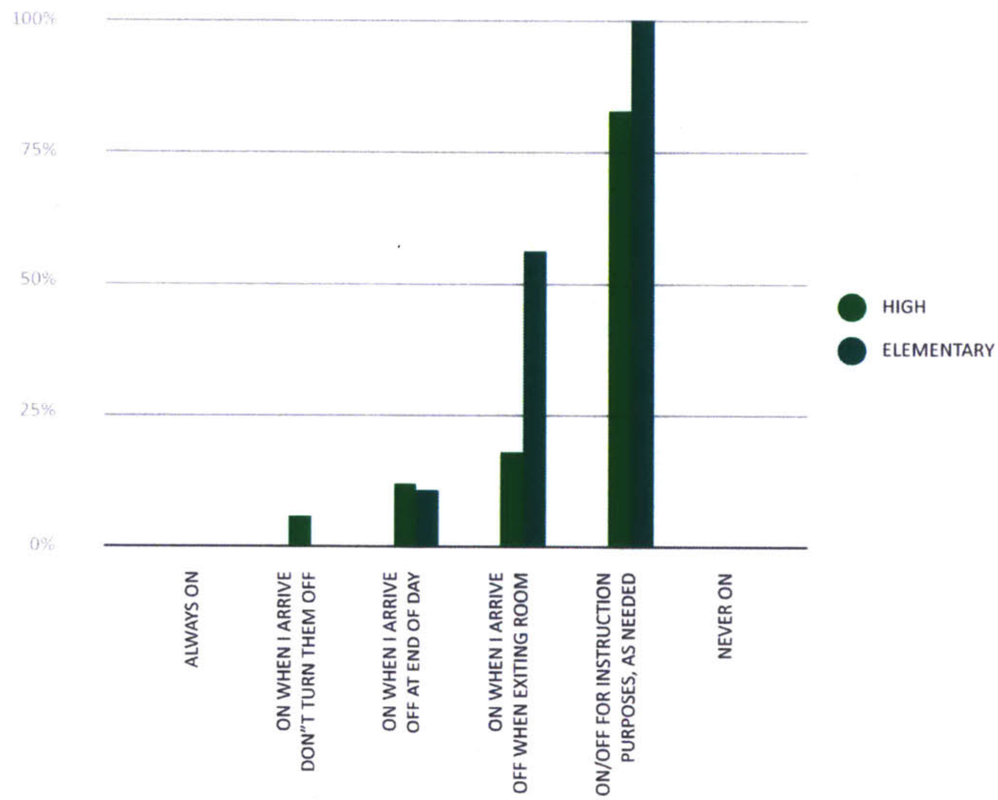


Figure 22. Shading devices in elementary and high schools

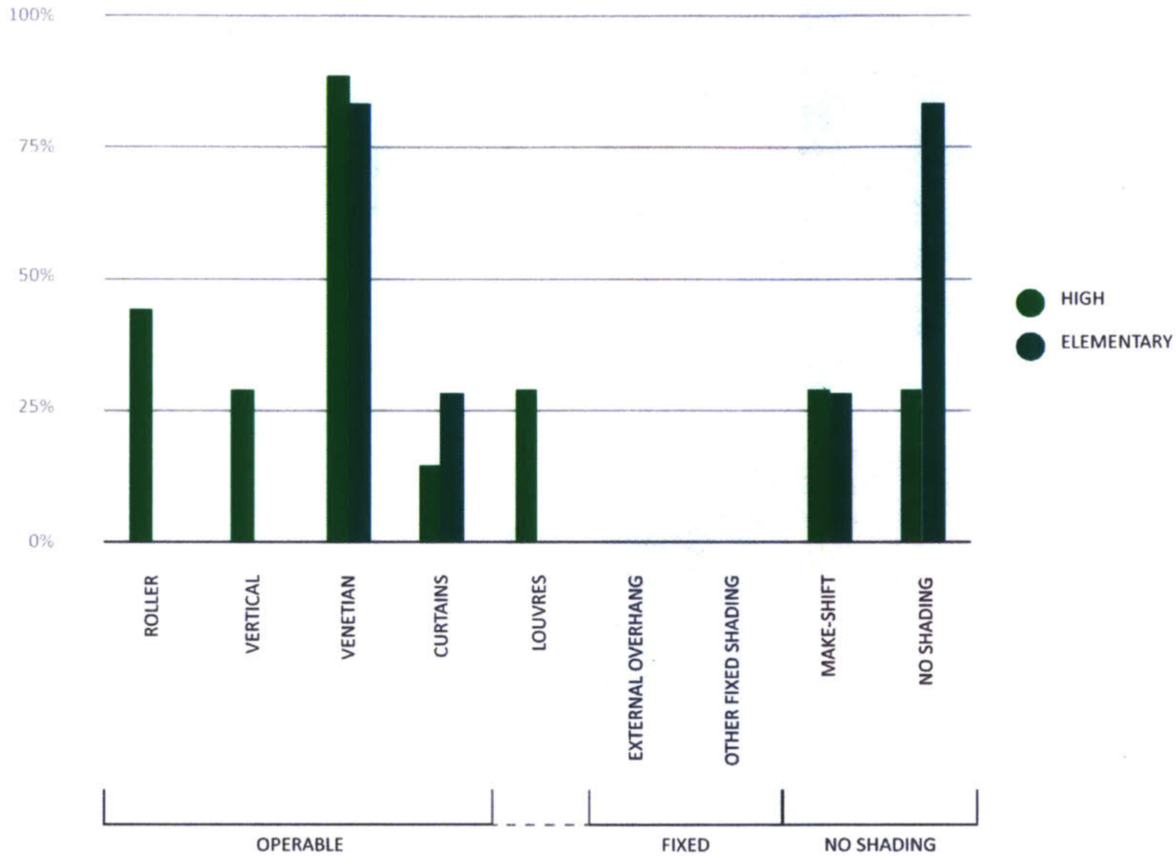
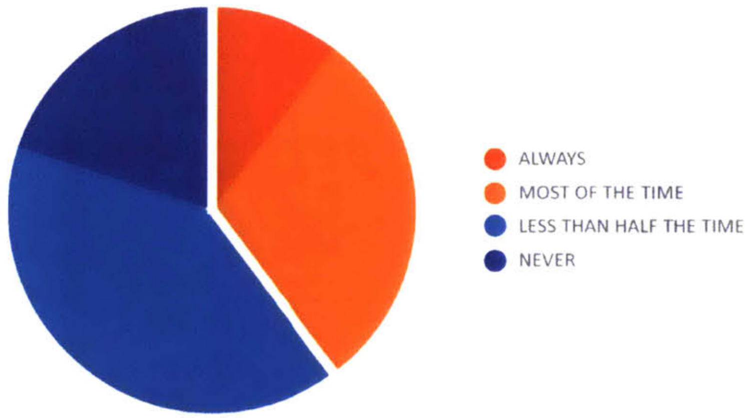


Figure 23. Shades open/closed



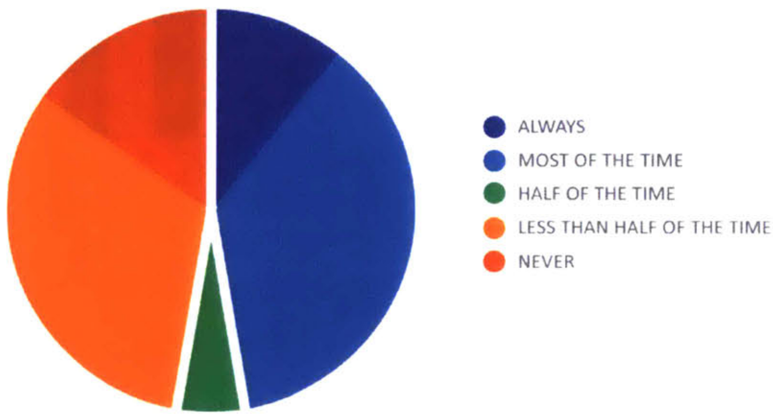


Figure 24. Reported glare as a problem

Figure 25. Reported summer daylight availability

Figure 26. Reported winter daylight availability

Figure 27. Reported light availability (including electric light)

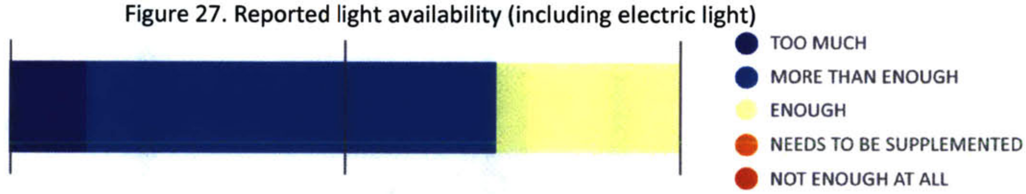


Figure 28. Reported satisfaction with shading systems

Figure 29. Reported satisfaction with overall lighting quality

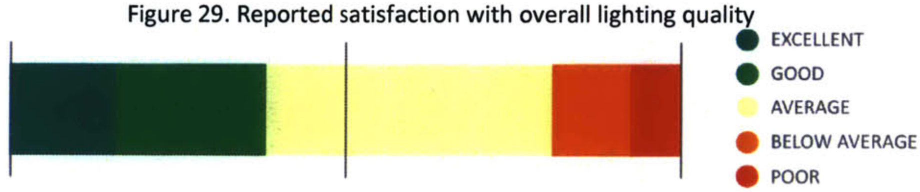


Figure 30. Reported views to the outdoors

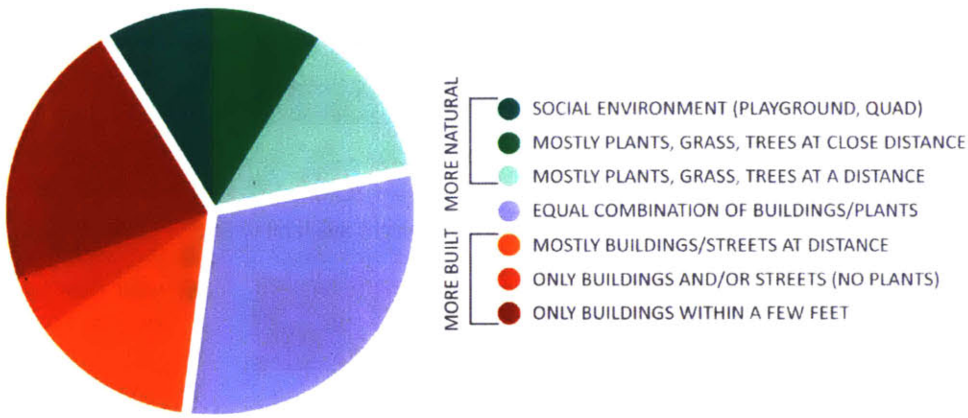


Figure 31. Comparing elementary and high school views to the outdoors

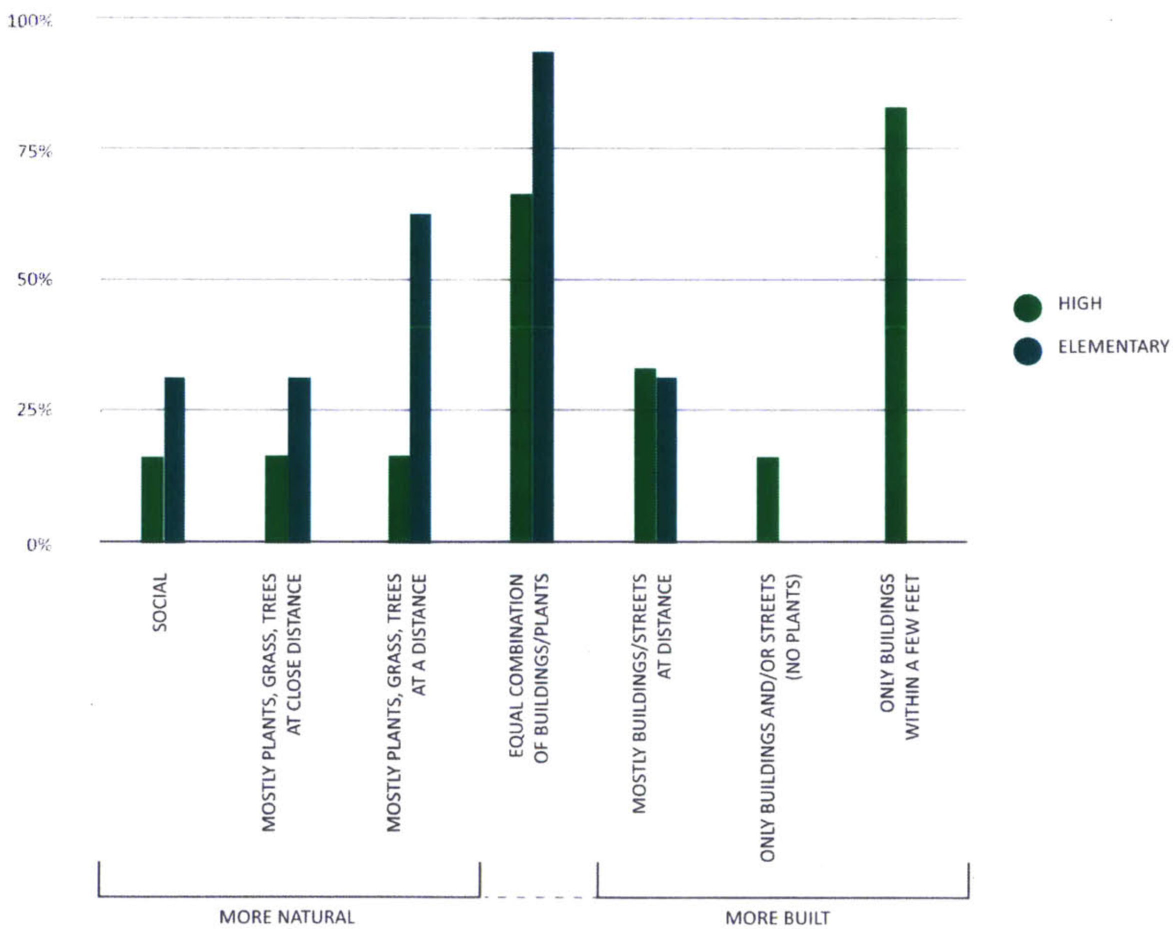


Figure 32. Teaching Methods: Teachers reported implementing...

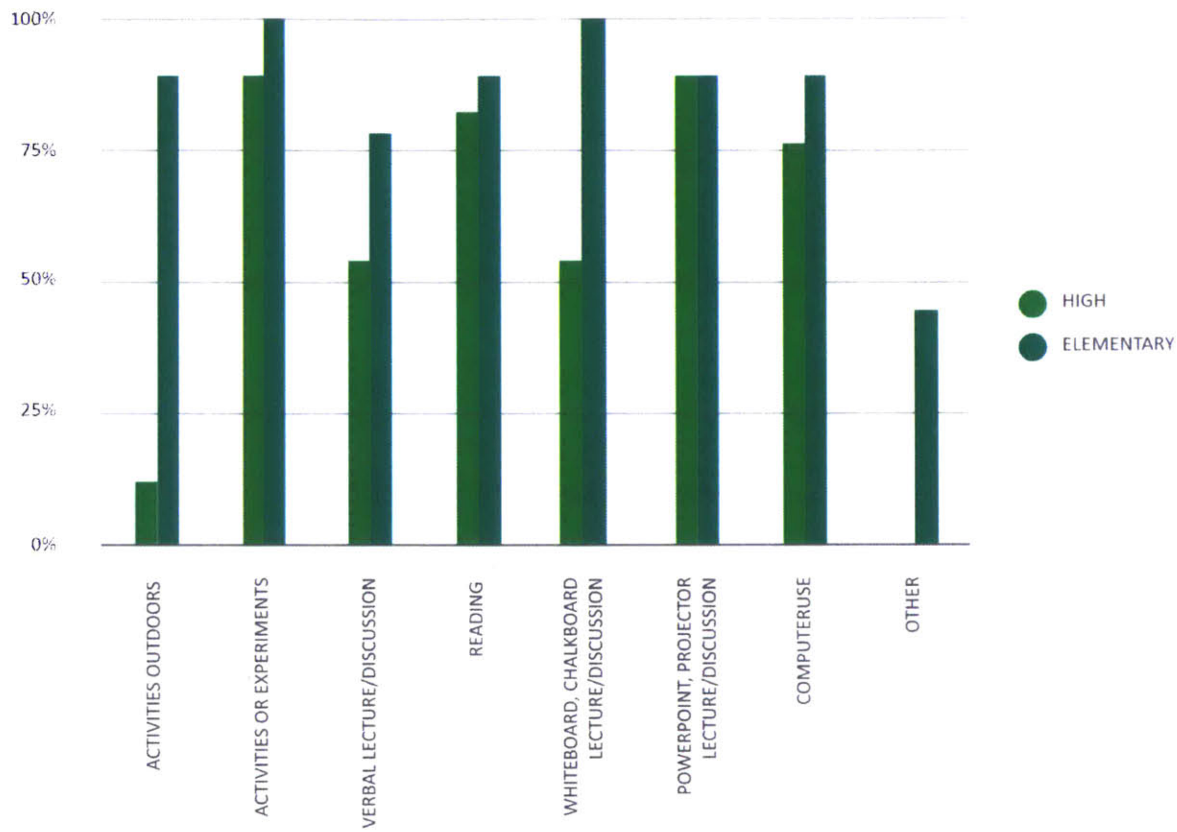
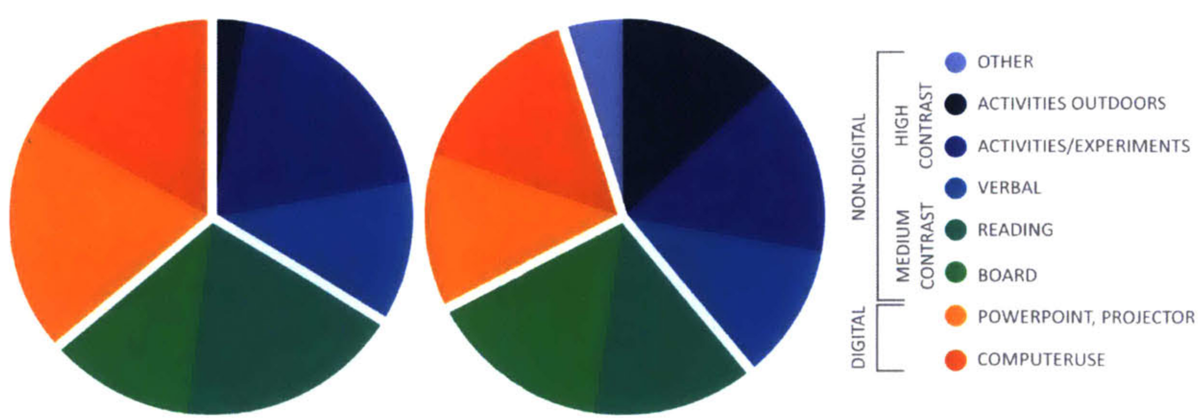


Figure 33. Methods implemented in elementary and high schools



F. APPROVAL FOR STUDY – MIT COUHES

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Leslie Norford 5-418D
From:	Leigh Firn, Chair COUHES
Date:	12/23/2015
Committee Action:	**Expedited Approval**
COUHES Protocol #:	1512328601
Study Title:	Illuminating Education: Quantifying Composition and Use of Lighting in K-12 Classrooms
Expiration Date:	12/22/2016

The above-referenced protocol was approved following expedited review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

If the research involves collaboration with another institution then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. You may not continue any research activity beyond the expiration date without approval by COUHES. Failure to renew your study before the expiration date will result in termination of the study and suspension of related research grants.

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated.

Prospecitve new study personnel must, where applicable, complete training in human subjects research and in the HIPAA Privacy Rule before participating in the study.

COUHES should be notified when your study is completed. You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.

G. APPROVAL FOR AMENDMENT TO STUDY – MIT COUHES

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Leslie Norford 5-418D
From:	Leigh Firn, Chair COUHES
Date:	02/09/2016
Committee Action:	Amendment to Approved Protocol
COUHES Protocol #:	1512328601A001
Study Title:	Illuminating Education: Quantifying Composition and Use of Lighting in K-12 Classrooms
Expiration Date:	12/22/2016

The amendment to the above-referenced protocol has been APPROVED following expedited review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

This approval covers the following change(s)/modification(s):

-The survey has been revised to include one question regarding which discipline participants teach in school.

If the research involves collaboration with another institution then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. Please allow sufficient time for continued approval. You may not continue any research activity beyond the expiration date without COUHES approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated.

Prospecitve new study personnel must, where applicable, complete training in human subjects research and in the HIPAA Privacy Rule before participating in the study.

COUHES should be notified when your study is completed. You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.

H. QUESTIONNAIRE/SURVEY

ILLUMINATING EDUCATION:
QUANTIFYING COMPOSITION AND USE OF LIGHTING IN PUBLIC K-12 CLASSROOMS

Instructions

You are invited to participate in a survey on the use of electric and natural lighting systems in Orange County/Los Angeles public school classrooms.

The purpose of this survey is to study the actual use and consumption of artificial and natural lighting in K-12 public classrooms in order to understand how occupants actually interact with lighting systems (as opposed to the expected use by designers) and how much light occupants are receiving (in comparison to research which describes the benefits/detriments of consuming light at various levels and spectrums).

In particular, the study aims to answer: How do students and teachers use and operate light on a day-to-day basis? How much and what composition of light intake are students receiving? Are there differences in use and light quality between schools of different age groups, socio-economic standing or other social variances? What are the gaps between design or expected occupant behavior and actual use of lighting systems in schools?The survey is carried out by a researcher who is an Undergraduate Bachelor of Science in Architecture (BSA) candidate at MIT (Massachusetts Institute of Technology), and has been approved by MIT's Committee on the Use of Humans as Experimental Subjects (COUHES).

Participation in this survey is completely voluntary, and you may decline to answer any or all questions. You may also end your participation at any time without any consequences. The data collected in this study will be confidential; the survey is anonymous and no data will be tied to your identity.

We would like you to fill out this questionnaire in relation to your particular working conditions in the classroom. Please respond to all items as openly and honestly as possible.

All responses to the questionnaire will be treated as confidential and will be accessed by the researcher and faculty advisor only. All questions or comments can be addressed to Mariana Ballina at mballina@mit.edu or (949) 547-2028.

Written Consent

☐ I have read the above information and freely agree to participate in this survey.
☐ I do not wish to participate in this survey.

GENERAL INFORMATION

What is your gender?

☐Male ☐Female

What is your age group?

☐ <20 years ☐21-30 years ☐31- 40 years ☐41-50 years ☐51-60 years ☐61 +

At what school do you currently teach?

School: ____

What grade(s) do you currently teach in the classroom?

☐K ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10 ☐11 ☐12

If you teach multiple grades, which grade do you primarily teach or which grade composes most of your student body?

☐K ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10 ☐11 ☐12

If applicable, what subject do you primarily teach?

☐English ☐History/Social Science ☐Visual Art ☐Performing Art ☐Math ☐Science
☐Special Education ☐ Other (Please Specify): ____

For how long have you been teaching?

☐1-3 years ☐4-6 years ☐7-9 years ☐10-15 years ☐15+ years

How many students are in your class during any given period?

Number: ___________

How many hours do you spend in the classroom on a typical school day?

☐ <1 ☐1-3 ☐3-5 ☐5-7 ☐7+

What type of classroom do you teach in?

☐Conventional classroom with a door ☐Portable classroom ☐Other (Please Specify): ______________________

What methods of teaching do you employ in a given week?

☐Lecture/discussion (with whiteboard or chalkboard)
☐Lecture/discussion (with overhead projector, PowerPoint or similar)
☐Lecture/discussion (only verbal or with demonstrations)
☐Reading
☐Activities or experiments
☐Computer use
☐Activities outdoors
☐Other (please specify) ______________________

What teaching method do you employ most often?

☐Lecture/discussion (with whiteboard or chalkboard)
☐Lecture/discussion (with overhead projector, PowerPoint or similar)
☐Lecture/discussion (only verbal or with demonstrations)
☐Reading
☐Activities or experiments
☐Computer use
☐Activities outdoors
☐Other (please specify) ______________________

If you wish, describe how you spend your time teaching on an average day:

____
____
____

USE OF LIGHTING SYSTEMS

What kind of lighting controls are available in your classroom?

☐One manual on/off switch
☐Multiple manual on/off switches for different levels of lighting
☐Manual dimmer(s)
☐Automatic dimmer(s)
☐Occupancy sensor which I turn on/off
☐Occupancy sensor which I cannot turn on/off
☐Separate lighting for designated task areas
☐Other (please specify) ______________________________

Where are manually operated controls (switches, dimmers, etc) located?

☐At the entrance, inside the classroom
☐Near the teacher's desk
☐In an arbitrary location
☐Other (please specify) ______________________________

What kind of windows do you have?

☐Windows placed below the height of 6 feet
☐Windows placed above the height of 6 feet
☐Skylights
☐Other (please specify) ______________________________

How often do you turn the lights on/off in the classroom?

☐I don't turn the lights on or off; they are always turned on
☐I turn the lights on when I arrive and don't turn them off
☐I turn the lights on when I arrive and turn them off only when I leave at the end of the day
☐I turn the lights on when I arrive for class and turn them off when I leave the class for a period of time
☐I turn on and off the lights for instructional purposes as needed
☐I never turn the lights on
☐Other (please specify) ______________________________

How often are the lights <u>on</u> in the classroom?

☐Always ☐Most of the time ☐Half of the time ☐Less than half of the time ☐Never

How often are the lights off in the classroom?

☐Always ☐Most of the time ☐Half of the time ☐Less than half of the time ☐Never

If you turn the lights off during class time, what is the primary reason?

☐There is enough daylight, I don't need the lights on
☐To use the projector
☐For activity-related purposes
☐For a demonstration
☐Other (please specify) ____________________

USE OF SHADING DEVICES

Are the windows in your classroom equipped with any shading devices?

☐Roller blinds
☐Venetian blinds
☐Curtains
☐Louvers
☐External overhang
☐Other fixed form of shading
☐Make-shift solutions
☐Other (please specify): ____________________
☐There are no shading devices

How often do you adjust the shades?

☐Never
☐Once every few months
☐Once or twice a month
☐Once or twice a week
☐Once a day
☐Multiple times a day
☐Other (please specify): ____________________
☐Not applicable

How often is the shading system <u>completely closed</u> to daylight?

☐Always ☐Most of the time ☐Half of the time ☐Less than half of the time ☐Never
☐Not applicable

How often is the shading system <u>mostly closed</u> to daylight?

☐Always ☐Most of the time ☐Half of the time ☐Less than half of the time ☐Never
☐Not applicable

How often is the shading system <u>mostly open</u> to daylight?

☐Always ☐Most of the time ☐Half of the time ☐Less than half of the time ☐Never
☐Not applicable

For what reasons would you typically adjust the shading device(s)?

☐I close it when it is too bright
☐I close it when it is too hot
☐I close it for instructional purposes (i.e. for computer projections)
☐I close it when views to the outdoors are distracting
☐I open it when it is too dark
☐Other (please specify): ____________________________________

VIEWS

What do you mostly see viewing out your classroom windows?

☐Mostly plants, grass and trees that are within a few feet from the window
☐Mostly plants, grass and trees at a distance
☐A somewhat equal combination of buildings/streets and plants/trees
☐Mostly buildings and/or streets at a distance
☐Only buildings and/or streets (no plant life)
☐Only buildings within a few feet from the window
☐Interior hallway
☐Other (please specify): ____________________________________

How would you characterize your view out the window?

☐Unattractive ☐Attractive ☐Neutral
☐Obstructed ☐Panoramic
☐Calming ☐Distracting ☐Stressful

Other comments on views to the outdoors:

____
____
____

PERCEPTION

How would you rate the overall lighting quality in the classroom?

☐Excellent ☐Good ☐Average ☐Below Average ☐Poor

Overall, how much light do you think is available in the classroom?

☐Too much ☐More than enough ☐Enough to complete tasks ☐Not enough

If the lights are turned off during the summer (or early fall, late spring) is there enough daylight?

☐More than enough ☐Enough ☐Some light but needs to be supplemented ☐Not enough light at all

If the lights are turned off during the winter (or late fall, early spring) is there enough daylight?

☐More than enough ☐Enough ☐Some light but needs to be supplemented ☐Not enough

In general, if the lights are turned off is there enough daylight?

☐More than enough ☐Enough ☐Some light but needs to be supplemented ☐Not enough

How satisfied are you with the controls you have over electric lighting (1 being the least satisfied and 5 being the most)?

☐1 ☐2 ☐3 ☐4 ☐5

Do you feel that the controls allow you to achieve multiple levels of lighting?

☐Yes ☐No ☐Not sure

How satisfied are you with your current shading devices (1 being the least satisfied and 5 being the most)?

☐1 ☐2 ☐3 ☐4 ☐5

How often is glare from electric lights a problem?

☐Always ☐Most of the time ☐Sometimes ☐Rarely ☐Never

How often is glare from sunlight a problem?

☐Always ☐Most of the time ☐Sometimes ☐Rarely ☐Never

For you, personally, when is glare from sunlight the most problematic? (season, time of day, etc.)

____

For your students when is glare from sunlight the most problematic?

____

In your own words, please describe how you use your shading devices:

____
____
____

In your own words, please describe how you use the electric lighting system in your classroom:

____
____
____

Additional comments on the lighting conditions in your classroom?

____
____
____

REFERENCES

Allen, Edward, and Joseph Iano. 2006. *The Architect's Studio Companion: Rules of Thumb for Preliminary Design*. John Wiley & Sons.

"Best Practices Manual." 2002. Collaborative for High Performance Schools, CA. http://eric.ed.gov.libproxy.mit.edu/?id=ED478351.

"Daylight Factor | Daylighting Pattern Guide." 2016. Accessed April 23. http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/daylight-factor.

"Daylighting." 2011. In *Advanced Energy Design Guide for K-12 School Buildings*, 110–33. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Dolgin, Elie. 2015. "The Myopia Boom: Short-Sightedness Ia Reaching Epidemic Proportions. Some Scientists Think They Have Found a Reason Why." *Nature* 519 (7543). http://www.nature.com/news/the-myopia-boom-1.17120.

"Entry & Foyer Lighting Planner: Color Temperature." 2016. *Lumens Light + Living*. Accessed April 14. http://www.lumens.com/lighting-planners/entry-lighting-planner.html.

Figueiro, Mariana G, and Mark S Rea. 2010. "Lack of Short-Wavelength Light during the School Day Delays Dim Light Melatonin Onset (DMLO) in Middle School Students." *NeuroEndocrinology Letters* 31 (1): 92–96.

Gilchrist, Kathryn, Caroline Brown, and Alicia Montarzino. 2015. "Workplace Settings and Wellbeing: Greenspace Use and Views Contribute to Employee Wellbeing at Peri-Urban Business Sites." *Landscape and Urban Planning* 138 (March): 32–40.

Harter, James K, Frank L Schmidt, and Corey L.M. Keyes. 2003. "Well-Being in the Workplace and Its Relationship to Business Outcomes: A Review of the Gallup Studies." In *Flourishing: The Positive Person and the Good Life*, 205–24. Washington D.C.: The American Psychological Association.

Hathaway, Warren E. 1995. "Effects of School Lighting on Physical Development and School Performance." *Journal of Educational Research* 88 (4): 228–42.

Heschong, Lisa. 1979. *Thermal Delight in Architecture*. Cambridge, Massachusetts: The MIT Press.

Hunt, DGR. 1979. "The Use of Artificial Lighting in Relation to Daylight Levels and Occupancy" 14: 21–33.

———. 1980. "Predicting Artificial Lighting Use: A Method Based upon Observed Patterns of Behaviour." *Lighting Research & Technology* 12: 7–14.

Inoue, T, T Kawase, T Ibamoto, S Takakusa, and Y Matsuo. 1988. "The Development of an Optimal Control System for Window Shading Devices Based on Investigations in Office Buildings." *ASHRAE Transactions* 104: 1034–49.

Judge, Timothy A, Carl J Thoresen, Joyce E Bono, and Gregory K Patton. 2001. "The Job Satisfaction-Job Performance Relationship: A Qualitative and Quantitative Review." *The American Psychological Association*, Psychological Bulletin, 127 (3): 376–407.

Kensek, Karen, and Jae Yong Suk. 2011. "Daylight Factor (overcast Sky) versus Daylight Availability (clear Sky) in Computer-Based Daylighting Simulations." *Journal of Creative Sustainable Architecture & Built Environment (CSABE)* 1 (November). http://www.sersc.org/journals/CSABE/vol1/2.pdf.

Konica Minolta. 13:22:16 UTC. "Color Seminar." http://www.slideshare.net/dfoley2019/color-seminar.

Lindsay, CRT, and PJ Littlefair. 1993. "Occupant Use of Venetian Blinds in Offices." *Watford Building Research Establishment*.

Love, JA. 1998. "Manual Switching Patterns Observed in Private Offices." *Lighting Research & Technology* 30: 45–50.

Rea, Mark S. 1984. "Window Blind Occlusion: A Pilot Study." *Building and Environment* 19: 133–37.

———. 2000. *The IESNA Lighting Handbook*. 9th ed. New York, NY: Illuminating Engineering Society of North America.

Reinhart, Christoph F. 2012. "Daylight Availability Metrics." PDF presented at the 4.430 Daylighting. http://ocw.mit.edu/courses/architecture/4-430-daylighting-spring-2012/lecture-notes/MIT4_430S12_lec12.pdf.

Reinhart, Christoph F., and K Voss. 2003. "Monitoring Manual Control of Electric Lighting and Blinds." *Lighting Research & Technology* 35 (3): 243–60. doi:10.1191/1365782803li064oa.

Rubin, Arthur I., Belinda L. Collins, and Robert L. Tibott. 1978. *Window Blinds as a Potential Energy Saver: A Case Study*. NBS Building Science Series 112. Washington: U.S. Dept. of Commerce, National Bureau of Standards.

Sze, Jennifer L. 2009. "Indoor Environment Conditions In New York City Public School Classrooms - A Survey." Cambridge: Harvard University Graduate School of Design.

Wilt, Adam J. 2016. "Cine Meter II for iOS: Color Metering." *Adam Wilt*. March 2. http://www.adamwilt.com/cinemeterii/colormetering.html.

Wu, Wei, and Edward Ng. 2003. "A Review of the Development of Daylighting in Schools." *Lighting Research & Technology* 35 (2): 111–25.