How daylight is holistically integrated as an element of the built environment:

A case study of the Scottsdale Arabian Library

by

Nickolas A. Marotta

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Graduate Supervisory Committee:

Jose Bernardi, Chair
Kelly Bauer
Marthe Rowen

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ABSTRACT

For most of our history humans have been closely tied to energy provided by the sun. Phases of light and dark initiate major biological functions within each day and regulate patterns of sleep and heightened alertness. Daylight was historically synonymous with sophisticated architecture, providing a mysterious play of light and illuminating productive tasks. It is only within the last 150 years that humans have sought to improve upon daylight, largely replacing it with artificially fueled systems. A new scientific approach to providing interior light has focused on the visible spectrum, negating the remainder of energy from our lives. This thesis considers the full spectrum of natural daylight, and its potential for improving human health, and well being. The literature review explores a brief history of solar architecture leading into the 21st century. A case study of the award winning Arabian Library in Scottsdale Arizona reveals four methods of passive daylight integration. A phenomenological ethnographic methodology assessed the impact of these four strategies on interior lighting quality, documented from the designer's perspective. As the science of photobiology continues to advance, it has become clearly evident that natural daylight provides more than mere illumination, and should be considered an essential element of the interior built environment.

This is dedicated to the one I love.

Colleen, thank you for being my best friend and confidant.

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CHAPTER 1

INTRODUCTION

Introduction

Background

Natural light provides more than illumination of darkness; chemical reactions within our sun emanate a vast spectrum of powerful energy. Categorized by different wavelengths, this energy includes ultraviolet, infrared, microwaves, and the more recognizable visible spectrum of light. Scientists are just beginning to document and understand the power of the sun, and its positive impact on human beings.

Human beings have evolved under close proximity and connection to the sun. We are physiologically dependent on the sun, and physiologically driven by its regular movement. According to Dr. Leiberman (1991) the major control centers of the brain including the endocrine and central nervous systems are regulated by light. These impacts are commonly recognized in patterns of sleep; when international travel disrupts our expectation of daylight, humans experience jet lag. Human photo-biological systems have evolved over thousands of years.

Alongside this biological connection, our artificially constructed environments are also historically tied to daylight. From the earliest recorded civilizations in Greece, advanced understanding of solar movement has shaped architecture. Sophisticated site orientation and structural designs delivered sunlight deep within interior space. This simple lighting technology was integrated into buildings with remarkable accuracy and saved precious fuels for heating and cooking. Natural light also delivered nonvisual benefits to the building envelope controlling heat and ventilation and adding a mysterious dynamic quality to enclosed space. Natural lighting linked the spaces built by human beings to the surrounding vernacular settings.

According to Ken Butti and J. Perlin (1980), daylighting strategies developed and advanced in pace with architecture. The expansion of the Roman Empire embraced and incorporated local building traditions. Hot arid climates to the south used architectural designs to regulate ample sunlight, while cold and rainy climates to the north sought to collect light; early techniques harnessing natural lighting within architecture eventually became the first building codes and laws. Modern building setback requirements are traced back to medieval laws governing citizens' access to daylight.

Highly relevant designers including Antonio Gaudi, Le Corbusier, and Alvar Aalto brought the integration sunlight to a new level. Gaudi utilized daylight to bring life to his building designs, interweaving poetry within otherwise static materials. As Ester Pons describes the careful attention to surface detail created "living skins" within each structure (Pons, 2002, p.199). Le Corbusier and Alto recognized the potential for natural daylight to elevate the human spirit while promoting a healthy lifestyle. Daily exposure to daylight was commonly accepted as good practice in supporting a healthy lifestyle, and subsequently incorporated within constructed spaces.

Through the turn of the 20th century the promise of affordable electricity and advances in mass production led to reliable artificial lighting systems. By the 1950s interior spaces could be operated 24 hours a day, using regulated, efficient, visible lighting systems. A new scientific approach to providing predetermined static task lighting replaced the holistic considerations of daylighting for health. Within time, artificial lighting had become the preferred source of illumination, even when ample daylight was available.

This approach to interior lighting deign continued well into the 1990's. The rising costs of energy during this period, and a renewed interest in human occupancy well-being began to shape a new paradigm in contemporary architectural design. Sustainable building practices centered on renewable energy sources to offset reliance on limited fossil fuels, and reverse damaging effects of development on the environment. Workplace productivity is also closely related to interior lighting quality, impacting employer's costs through absenteeism.

A review of architectural, scientific, and lighting design literature has identified a gap in research supporting holistic daylight integration. Much of the interior lighting systems research conducted within the last century has been devoted to the quantity of light; understanding specific attributes of the measurable visible spectrum. In order to provide interior light as a holistic element of the built environment, the quality must be first addressed.

According to M. S. Rea quality lighting is determined by four fundamental characteristics: quantity, spectrum, spatial distribution, and duration (Rea, 2002). These qualities specifically address the transitional aspect of daylight. Static levels of artificial lighting systems, often designed to provide a regulated minimum amount of light for prescribed tasks, do not account for the subtle changes associated with daylight.

Designers provide a unique perspective to interior lighting research and data collection. According to Vishal Sing designers utilize divergent thinking as a problem solving strategy. This generative approach considers multiple solutions to any given problem, selecting the best outcome. Because daylight is in constant motion, and interacts with a variety of complex surface reflections, it is difficult to study isolated conditions. The divergent solution model accounts for many possible outcomes, and allows greater flexibility in research methods.

This thesis argues that daylight is a primary element of the built environment, impacting more than just visual task performance. Designers should be empowered to fully integrate this element within constructed space.

Opportunities

A review of literature has uncovered the following opportunities:

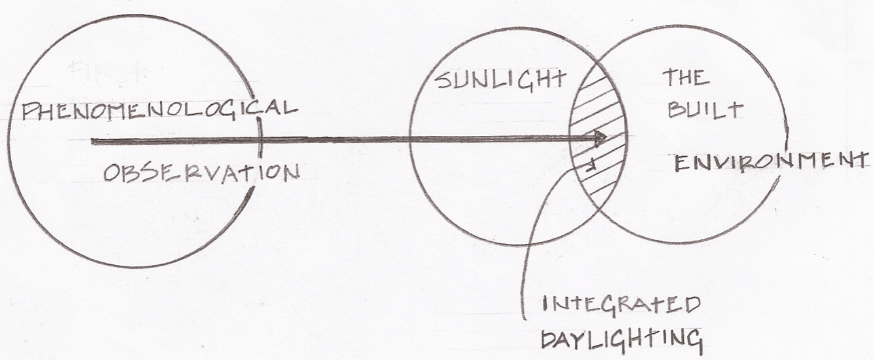
1. Light has a beneficial impact on human health and well being beyond the visible spectrum, which cannot be ignored. There is a gap in the research of daylight as a holistic element of the interior environment.

2. Many experts agree that defining quality light for the interior built environment is a complex and elusive problem; the solution requires interdisciplinary research. There is a gap in research of integrated daylighting solutions for the built environment from the designer's perspective.

Conceptual Framework

This thesis attempts to address three primary areas of concentration: the significance of natural light to human beings, the process of integrating natural light within the built environment, and phenomenological observation from the designer's perspective.

Figure 1: Conceptual Framework



Research Questions

The following research questions were constructed to solve the research problem within the limitations outlined in this chapter:

1. What are the contemporary strategies integrating daylight within the built environment?

2. Is it possible to observe the phenomena of daylight as a holistic element impacting interior space?

3. How can the subject of daylight integrated within the built environment be researched and recorded from the designer's perspective?

Research Problem

The research problem addressed in this thesis asks how to record data about interior lighting quality specifically addressing the holistic impact of full spectrum light on the built environment. Phenomenological ethnographic research was the method selected to address this problem. Phenomenology challenges researchers to question their surroundings, understanding the physical world by removing individual preconceived notions. The ethnographic approach places the researcher within the testing environment, as an active participant. This research approach is further explained in the methodology section of this chapter.

Research Strategy

The strategy for this research was designed in three stages: a preliminary review of suitable project locations, a detailed case study exploration of the selected site, and a rigorous on-site data collection.

The first stage determined a suitable location for this study. The earth is impacted by natural sunlight in various degrees. Certain geographic locations, such as Arizona, receive intense sunlight based on this global positioning, and enjoy clear skies from arid weather conditions. The goal of this research was to document integrated daylight; therefore a project location with the highest likelihood for sunshine was selected.

The second stage in answering the research question was to establish limitations and parameters for data collection. A review of recent public projects in Arizona revealed the Scottsdale Arabian Library. This site was selected for its award winning daylighting integration, and reliable access to interior spaces.

The final stage was to design an observation schedule, and establish guiding principles to filter data collection. The researcher was placed in a fully operational public library, post occupancy. Guiding principles provided from the literature review filtered the subject of daylight into recognizable qualities. These qualities were observed at different times of day, recording the phenomenon of daylight entering space.

Significance/ Justification

Integrating natural sunlight within the built environment is significantly important. Natural lighting can drastically reduce the need for artificial lighting, offering economic savings to building owners, private businesses, and private residents. Emerging scientific research has uncovered data linking sunlight to improved health and wellbeing, including deeper sleep, stronger immune systems, and reduced stress and depression.

Economic Benefits

In a study conducted for the National Renewable Energy Laboratory (NREL) Rob Guglielmetti et al. (2010) established clear economic benefits for commercial buildings, from integrated daylighting systems. Artificial lighting systems typically account for 30% – 40% of commercial buildings total energy use, and have drawn much attention for potential economic systems. When considering commercial buildings as complete entities, however, whole building energy systems models offer even greater opportunity for savings.

Daylighting systems provide readily available renewable energy directly from the sun. Utilities companies, limited by traditional production equipment, struggle to meet higher demands for electricity, especially in summer months when cooling loads are higher. These companies charge commercial customers a higher electricity rate during hours of demand, known as peak load. In some instances large commercial buildings are even forced to shut down nonessential operations, known as load shedding. Successfully integrated daylighting systems offer anticipated saving from reduced electricity usage during daylight hours, Daylighting systems can also lower the overall rate structure applied to commercial buildings, by offsetting the expected peak energy demand equation, and lowering the actual rate charged to building owners.

The economic benefit of daylighting systems extends beyond reduced electricity demand from artificial lighting, when considering individual building mechanical systems as one complete entity. According to Guglielmetti et al. (2010) the relationship between lighting system analysis, and whole building energy use analysis is often ignored in the early stages of design. Artificial lighting impacts the whole building entity by pushing heat into interior volumes. This requires greater cooling loads, and impacts other interrelated systems, sharing limited service and duct space. By optimizing interior lighting systems, the entire building energy use model can be tuned, in some instances reaching the highest levels of efficiency, know as Net Zero Energy Use.

Benefits to Human Health

Emerging scientific research has uncovered exciting data linking sunlight to improved health and wellbeing. The presence of non-visual photoreceptors in the eye confirms the importance of the full spectrum of light. Humans react to natural light in daily activity as well as long-term yearly exposure.

According to M.S. Rea (2002) scientists continue to research the circadian sleep rhythm and its biological effects on human beings. This rhythm is defined as a biological clock that is reset by environmental indicators such as the suns 24-hour cycle. Preliminary research has found that the amount of light as well as its intensity throughout the day has an effect on the quality of sleep, not just the amount, in subjects through the night. The most common experience with interruptions of this cycle is known as jet lag. As the science of photobiology continues to advance, greater importance has been placed on the nonvisual spectrum of sunlight.

Methodology

The research strategies of case study and phenomenological ethnography were used for this thesis. Selecting a building recognized for sustainable building design, in a region with ample sun exposure, allowed the researcher to observe daylighting strategies integrated within space. Through a detailed review of literature and public government websites, the Arabian Library in Scottsdale Arizona was selected. Arizona is positioned low on the globe allowing more intense solar energy, and more sunny days per year. Local government agencies have developed policies encouraging the use of daylight. A public building, with long daily hours of operation is a prime location for on-site observation.

A detailed case study was performed on the Arabian Library, outlining passive daylighting strategies through published images and literature. Three passive daylighting strategies were uncovered in this case study: placing long angled windows low to the ground, selectively using full height large scale windows, top lighting through inverted light wells, and introducing bounced light from adjacent outdoor areas. These strategies were isolated to four primary interior spaces, and a schedule was devised to rigorously observe daylighting integration.

For each specific area the building was first viewed from a distance, detailing the direction each area faces and isolating windows and other noticeable means of natural light. Using a notebook and sketching technique plans sections and elevations as well as quick perspectives were used to document natural light. Each of four areas was observed for approximately one hour, at 9 A M, 12 Noon, and 3 P M.

The purpose of this thesis was to collect data about daylight integration within interior space, from the designer's perspective. In order to narrow the data collection guiding principles were applied as a type of filter. Henry Plummer's research suggested three specific principles that describe the holistic characteristics of daylight in the context of architecture. These characteristics describe the quality of natural light, as it reacts to building materials and structure. Considering these principles as filters for phenomenological observation, the quality of daylight was the subject of data collection.

Visual note taking was the primary method of data collection. This process involved observation, sketching perspective and isometric drawings, along with textural notes. Presenting the designer's perspective entailed data collection with regard to specific language of building design practitioners. The designer's perspective, according to Norman Crowe and Paul Laseau, establishes visual characteristics of interior volumes otherwise hidden to casual observers (1984). Daylight was recorded as visual presence documenting shadow and surface illumination. All drawings were produce by hand, on site without cumbersome drafting equipment. The free hand technique allowed quick yet detailed data collection, crucial to capturing daylight as it constantly moved through space.

Limitations

Public buildings impact a broad cross section of human population and have an expectation of accessibility, free of cost and convenient for research purposes. Contemporary public library design specifically addresses the impact of digital technology on building design. Public libraries offer a variety of post occupancy research opportunities.

The most restrictive limitation in a public library is the expectation of privacy; patrons are not allowed to use photo or video equipment within the library, unless expressly written permission is gained from each and every occupant. The sketch-in-place method used for this study avoided photographing human subjects. Human occupants are included in some of the drawings, but under the close supervision of library staff, this activity does not violate library policy. Limiting the data collection to visual notes and sketches also greatly enhanced the portability of data collection.

Two specific types of drawings limited the amount of data collected in this study. Analytical drawings detailed the integration of daylight within space. These drawings documented the time of day, and solar movement pictorially. Analytic drawings incorporated visual notes, sections, elevations, and perspectives as unified drawings. Descriptive drawings documented the phenomenon of daylight within space. These drawings attempted to detail specific holistic attributes of daylight, as experienced by the researcher. Each descriptive drawing focused on a subject of daylight defined by guiding principles.

Artificial lighting systems were installed through Arabian Library, however daylight was the primary focus of this study. A flexible track system was used through the library interior providing task lighting at reading locations. Permanently fixed linear fluorescent lighting provided a prescribed amount of vertical illumination at the main library stacks. These systems allow future changes in library collections and space planning configurations without major interior renovation. This flexibility greatly enhances the sustained operation of the library.

Conclusion

This chapter has established the significance of daylight as a holistic element of the built environment. It introduced the historical background of daylight and its impact on contemporary architecture. The research problem identified three specific questions, addressed in the following chapters. The research presented in this thesis was justified, limitations defined, and the methodology briefly explained. The following chapters provided a detailed account of the data collection, analysis, and conclusion.

CHAPTER 2

REVIEW OF LITERATURE

The literature review of this thesis is organized into the following sections:

Section 1: The Science of Light

Light

Sight

Differences between Electric Light and Natural Sunlight

Natural Sunlight and Human Health

Affect of Light on Human Health

Circadian Rhythm and Effective Sleep

Medical Cures From Light

Section 2: The Historical Significance of Daylighting

A Brief History of Solar Architecture

Daylighting in the 20th Century

Antonio Gaudi and the Poetics of Light

Le Corbusier and the healing power of light

Alvar Aalto and the Quest For Light

The Decline of Natural light in the Built Environment

Section 3: Contemporary Daylighting

Renewed Interest in Daylighting

Case Studies: Daylighting Strategies

Introduction

The review of literature is broken into three sections, each highlighting the complex interconnection between humans, the built environment, and light. Section one describes the science of light and its relationship to human beings. Categories of this section detail facts that are known, as well as mysteries that remain to be unraveled. Section two discusses the historical significance of daylight within the built environment. Categories document ancient evidence of solar design strategies leading up to highly relevant architecture of the modern age. The third section of this review explains the current state of daylighting with regard to contemporary design goals. Categories detail the reason daylight was systematically removed from interior space, and the forces driving its return as an essential element in contemporary architectural projects.

Section 1 The Science of Light

Light

The sun is the center of our solar system, closely drawing all the planets into alignment, and saturating each with powerful energy. This energy impacts the Earth in the form of heat, radiation, and light. Human beings, like many other living species, are dependent on the energy of the sun, evolving complex biological systems to maximize its benefits.

During the last three centuries physicists including Isaac Newton, John Herschel, and William Huggins have established light as distinct bands of energy produced in waves. These bands of energy are commonly understood as spectrums, including band waves, ultraviolet waves, microwaves, and the visible spectrum of light (Masters, 2009). If the full spectrum of the sun's energy were represented as a line from New York to Los Angeles, the visible array would measure only one dime. Despite this disparity, most of the research conducted on natural sunlight has been dedicated to the visible spectrum.

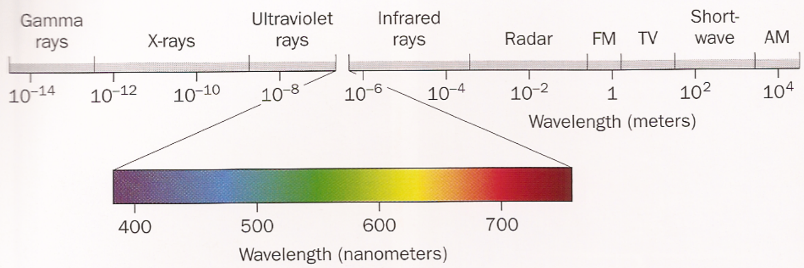


Figure 2: Light as a form of energy. (Winchip, 2008, p.12)

Visible light is composed of band waves, with specific heights measured in nanometers. The human eye recognizes individual colors depending on the height of each wave, from the color violet (400 nanometers) to the color red (750 nanometers). Visible light is easily quantified using radiometry, the measurement of electromagnetic waves. The science of photometry measures the human response to sources of illumination. Together these increments provide contemporary units of measure commonly used by engineers and designer alike.

Historically, candles were used as the basis of scientific measure in photometry. Candle Power or Candela (CD) describes the luminous intensity of a light source aimed in a specific direction. The total amount of illumination emitted by a light source is described as Lumens (lm). Light source intensity, combined with directional data (distance) provides illuminance, described as either foot-candles (fc) or lux (lx). For example an illumination of 1fc is produced by 1lumen of light shining on 1 square foot.

Sight

Visible light is easily reproduced using artificial sources. Artificial light produced in quantity with widely available electric power and advanced lamp technology offers a high degree of occupancy control with simple on/off switching (WInchip, 2008). Because interior spaces have readily available visible light in large quantity, designers have shifted their focus to improving the quality of light. While measuring the quantity of visible light is well defined with light sensing equipment, quantifying the quality of interior light remains very elusive.

In order to define the quality of interior lighting, the subjective impression of building occupants must be collected. As Kevin Houser and Dale Tiller explain the field of psychophysics establishes a functional relationship between physical stimuli and sensory responses. Methods typically used by lighting researchers include questionnaires, rating scales, and paired comparisons. Qualitative analysis, deeply rooted in complex human psychology, is informal because more rigorous scientific testing procedures cannot be applied. Houser and Tiller strongly suggest the need for an understanding of shared lighting preferences, to advance the application of interior lighting systems (Houser & Tiller, 2002).

One such study by Jeong Kim et al. placed 48 participants in a test chamber under similar interior lighting conditions with a simulated window on one wall. When different simulated outdoor views and luminance conditions were shown to participants, varying individual responses of glare sensation were reported. The study shows evidence that individual perception of glare varies even under similar lighting conditions (Kim et al., 2002). Measuring the subjective response in human participants is highly challenging, even under tightly controlled artificial lighting conditions, within a laboratory.

When considering the additional complexities of natural lighting strategies, measuring the subjective response of participants becomes even more problematic. According to Hua, Oswald and Yang "to design and operate a building to make full use of daylight, which is a dynamic source, to meet diverse occupant needs remains a challenge" (Hua, Oswald, & Chang, 2011, p.17). The use of daylight however "has been widely recognized as an important strategy to reduce building energy demand and enhance indoor environment quality" (p.2). Results from a post occupancy study of a university laboratory illuminated with natural light indicated a general high degree of satisfaction. These studies indicate that while complex in its application, natural light is a useful component of the contemporary built environment.

Differences between Electric Light and Natural Sunlight

The human eye has evolved throughout human history to function best under natural light. Natural light, divided into bands of color, stimulates different centers in the brain, affecting mood. The human eye functions as a light-sensing system collecting light through the pupil, and delivering it to a receptive device called the retina. Once collected the retina divides visible light into categories, using rods to see dim light, and cones to see bright light. Most of this light is registered to the brain through the optic nerve creating vision (Edwards & Torcellini, 2002).

Artificial lighting, developed within the last 150 years, has been specifically engineered to operate efficiently. According to Dr. Ott "Many fluorescent lights are concentrated in the yellow-green portion of the spectrum to obtain the most lumens per watt; this unbalanced, narrow spectrum limits blue in the source, which leads to improper functioning of the eye" (Edwards & Torcellini, 2002, p.4).

Lighting manufacturers have worked to develop products that produce the most visible light, using the least amount of electrical energy. Building practitioners specify lighting systems to produce reliable, consistent, minimum lighting levels at any given point during the day, evening, or night. According to Dr. Mardaljevic, contemporary metrics, used for calculating minimum lighting levels, do not account for occupant comfort or temporal aspects of natural light. Utilizing these metrics may provide required minimum levels of task lighting but does not replace natural daylight (Mardaljevic, 2009).

The current model or framework utilized for interior lighting system design focuses on achieving a static minimum level of light in space. This model is based on the assumption that interior light should provide illumination for expected tasks, and that there should be a reliable, uniform, level of interior light at any given time of day. The current framework for professional lighting designers measures visible light at the work plane, or task level rather than measuring light interacting with the human eye. In a paper investigating the contemporary lighting design framework, M. Anderson et al. propose non-visual effects of daylight, as well as the temporal aspects of natural solar movement, should also be considered. By using climate based simulations newly developed outcomes of photobiology research can be translated into environmental design goals. Their proposed approach includes threshold values for illumination in terms of lighting spectrum, intensity, and timing measured at the human eye (Anderson et al., 2001).

M.S. Rea describes the spectrum of natural light, primarily different from artificial sources. Lamp manufacturers as well as lighting engineers have a specific definition of visible light, photopic and scotopic wavelengths, which satisfies minimum levels for task performance. In order to produce the most efficient lighting systems only these specific visible spectrums are produced (Rea, 2002). Many of the human biological functions related to processing light remain unknown, but studies have indicated the human eye can detect nonvisible light.

The affect of light on human health

According to Nick Baker "the forces which have selected the genes of contemporary man are found outdoors in the plains, forests and mountains, not in centrally heated bedrooms" (Baker, 2001, p.2). Throughout thousands of years of evolution humans have successfully adapted biological functions, and behavior patterns to guarantee survival among natural surroundings. It is only within the last 150 years of our existence that humans have replaced these innate skills with a reliance on the built environment.

Despite the comforts of artificially produced climatic conditions, including artificial light, human beings remain "outdoor animals", closely tied to nature. Our ability to reproduce the narrow band of visible light has not satisfied all human biological functions, which are still very closely tied to the composition and movement of natural sunlight (Baker, 2001).

The human body has evolved to utilize sunlight as a nutrient. According to Dr. Ott natural light stimulates essential biological functions in the brain and is essential to the human body (Edwards & Torcellini, 2002). Dr. Liberman similarly argues that the major control centers of the body, the central nervous system and the endocrine system, are directly stimulated and regulated by light. According to Liberman light affects the human body far beyond the general accepted opinion of modern science (Edwards & Torcellini, 2002). This readily available nutrient is collected and identified by humans in many ways.

Invisible bands of energy produced by the sun, but selectively removed from many forms of artificial lighting, directly impact the human body. Ultraviolet radiation (UV) is identified for both damaging and beneficial effects in human beings. Depending on the height of each wavelength, UVR/UVB/UVC strike the earth at different atmospheric locations. Some UV bands affect the outer skin beneficially producing vitamin D and negatively causing skin cancer. Other UV bands, traveling very slowly, are able to penetrate deep within human cell structures. According to Gary M. Halliday et al., UVR can be absorbed by the human DNA strand, and can be used to treat immune based skin conditions (Halliday, 2008).

Circadian Rhythm and Effective Sleep

Prior to the development of artificial lighting systems natural light was only available during the day and, equally important, consistent, total darkness occurred at night. These dominant zeitgebers, or time cues, have led to a major human biological clock, synchronizing bodily rhythms, hormone production, and regulating sleep. Emerging scientific research in photobiology has uncovered a direct link between non-visual photoreceptors in the eye, and neurological processors in the brain, establishing a circadian rhythm in human beings. A biological clock located in the suprachiasmatic nucleus of the brain has a periodicity of 24.5 hours, aligning with the yearly pattern of sunlight. Under normal conditions of dark and light, this time clock resets itself each day (Rea, Figueiro, and Bullough, 2002).

According to Rea, Figueiro, and Bullough "Natural light can be modulated into several fundamental characteristics: quantity, spectrum, spatial distribution, and duration; it is very clear that they interact to influence circadian functions" (Rea, Figueiro, and Bullough, 2002, p.178). The Quantity of light produced by electric sources in typical offices, homes, schools and factories rarely exceeds 1000 lux. Comparatively, outdoors illuminance fluctuates between 2000 lux and 10,000 lux at sunrise, even on cloudy days. Remarkably a 500-lux light source provides more than adequate illumination for visual task performance, but one full hour of exposure is barely enough to stimulate the circadian photo-biological system (Rea, Figueiro, & Bullough, 2002).

The Department of Energy, Pacific Northwest National Laboratory reports that cloud scattered sunlight can be just as intense as direct sunlight, citing the effect of light bouncing from one cloud to another. In a similar fashion to getting a tan at the beach on a cloudy day, ambient solar conditions are very effective at producing high levels of light, occurring in multiple, visual and non-visual spectrums (U.S. DOE, 2001, p.3).

M. S. Rea continues to explain "It is clear that light plays a major role in human behavior and well-being, both at night and during the day" (Rea, 2002, p.178). Studies conducted over the past 20 years have firmly established circadian photobiology as an emerging field of science. It is currently assumed that melatonin is the primary hormone for signaling all circadian photo biological functions, such as sleep and alertness. The melatonin production cycle is very sensitive to short-wavelength light, which is the dominant component of natural sunlight during the day. Nocturnal production of melatonin ceases under exposure to bright light, and resumes once the source is removed. It is presumed that the circadian system can distinguish between bright flashes of light, such as lighting, and longer durations of light, such as daytime hours. For this reason the production of melatonin, signaling sleep or alertness is regulated by darkness at night, and bright, full spectrum light during the day.

According to Thomas Kantermann the average human sleep duration is decreasing worldwide, while the uncontrolled application of artificial light sources has steadily increased. Kantermann argues a twofold effect has developed, impacting human beings otherwise regular sleep patterns (Kantermann, 2013, p.689). Reduced total darkness at night (from artificial light) is just as problematic as spending more time indoors, which can limit exposure to intense bright sunlight.

When daily biological time clocks are combined with our individual heterogeneous genes, and personal behaviorally shaped activity, Kantermann argues a specific "sleep style" emerges (Kantermann, 2013, p.690). Examples of sleep styles include early risers and night owls. Based on our individual sleep styles, Kantermann suggests, a precise window of effective sleep, tightly connected to our circadian clock. The net result is the inability to reset the daily biological clock, combined with interruption of effective nightly sleep.

Medical Cures from light

In addition to the regulatory patterns of sleep, light has been linked to long-term well being and attributed to curing certain medical ailments. L. Edwards and P. Torcellini review of the beneficial effects of natural lighting on building occupants. Natural light has been shown to cure rickets, curtail tooth decay, reduce eyestrain, and support life by strengthening the human immune system.

Exposure to ultraviolet radiation in the region of 290-315 nanometers triggers the development of Vitamin D in the skin. A study by Macbeth and Zuker showed children were more prone to dental decay in winter and spring months while spending more time indoors and under artificial lighting. The production of Vitamin D stimulates calcium metabolism, ultimately increasing bone and tooth development and repair. Sunlight was recognized as a cure for rickets in 1919, through a similar process of Vitamin D production. A later study by Neer and Hollick in 1985 demonstrated the scientific link between ultraviolet exposure and the production of Vitamin-D (Edwards & Torcellini, 2002).

Eyestrain has been attributed to poor quality lighting. A 1997 study at the University of California-Berkley Laboratories suggests that sources richer in spectral content, such as natural sunlight, provide more useable light to the eye. The study compared postgraduate students to the general population, and found that 88% of students were near sighted versus 45% of the general population. Reading is the most visually stressful task for students; these results suggest a link between poor quality lighting and eyestrain. The human eye must first collect visible light, in order to process electrical impulses into cognitive information. The physiological effect of eyestrain can also cause higher stress levels, leading to a decrease in information processing, and ultimately affecting students ability to learn (Edwards & Torcellini, 2002).

Section 2 The Historical Significance of Daylighting in the Built Environment

A Brief History of Solar Architecture

Human beings have the innate survival skill of manipulating and improving their environments. Early in our nomadic past humans were content with mere shelters from the extreme hot, cold, and wet elements. Agriculture eventually tied large societies to permanent geographic locations, generation after generation. Localized building solutions continuously improved our quality of life allowing architecture to take full advantage of every natural resource. Sunlight was central to this endeavor bringing light, heat, and spiritual life to man made structure steadily increasing in sophistication.

Beginning with the earliest excavations from ancient Greece residential building communities show evidence of specific solar principles and alignment. The Mediterranean region offers inhabitants ample year round sunlight and consistently clear weather, with the challenges of limited natural resources from rugged mountain terrain. Citizens oriented a large south-facing patio with a deep roof to collect daylight from the early morning through sunset. According to Ken Butti and John Perlin “Aeschylus suggested that a south-facing orientation was a sign of a modern or civilized dwelling” (Butti & Perlin, 1980, p.10). Scarce wood fuel was the main source of heating, cooking and interior illumination. Integrating daylight within interior space replaced the need for daytime illumination, offsetting fuel shortages.

Early Greek and later Roman societies recognized the benefit of daylight to each and every citizen. Some of the first urban planning and building regulation codes were created to address this problem. Greek laws prohibited the construction of any building that would block existing access to sunlight. These early laws were the foundation for today’s building setback requirements. Then and now, placing a calculated distance between tall structures allows sunlight to penetrate windows on the first floors.

The Roman Empire grew to dominate the Mediterranean and expand beyond familiar local climatic conditions. Butti and Perlin conclude, “because the Roman Empire covered a far greater area than the Greek City states, its architecture had to be tailored to many different environments” (Butti & Perlin, 1980, p.16). Rather than forcing one type of building tradition from the Mediterranean onto distant regions, Roman leaders incorporated local building knowledge. Successful invasion campaigns lead to increasingly colder, rainy, climates with predictably low exposure to sunlight. The architecture of the Mediterranean, with open courtyards and verandas, was unsuitable for this cold weather. Roman designers responded by introducing clear glass panels to seal off airflow without blocking daylight (Butti & Perlin, 1980). Advanced glassmaking technology typically used for utilitarian objects in warmer climates was reconfigured in large sheets.

The strategy to bring daylight within space while keeping cold air out particularly flourished in England. Large public spaces illuminated with daylight remained in use throughout the Gothic and Renaissance periods. By the middle of the 19th century a burgeoning wealthy elite commissioned large day-lit libraries and indoor gardens for their private residences. Designers recognized predictable patterns of available daylight. By utilizing top and side light windows building interiors of northern climates could collect scarce winter sun throughout the day. The formation of saw tooth shaped top lights also regulated the consistency of daylight, especially across large spaces. Placing a series of angled skylights in series directs even amounts of light to spaces below.

Large naturally lit interior spaces were the hallmark of the European industrial revolution of the 1800's. Manufacturers started producing mass quantities of specialized goods, requiring ample light for repetitive tasks. Factories were open long hours, often seven days a week; daylighting was the most economical solution for illumination. One of the products developed and improved through this period of industrialization was clear glass. Increasingly larger glass sheets became increasing less expensive. By the 1850's large fully enclosed glass spaces, typically used as private greenhouses for the elite, were available to the general public.

The Crystal Palace designed in 1850 by Joseph Paxton is one remarkable example of integrated daylighting within public architecture. The Great Exhibition in Hyde Park England, 1851 showcased industrial manufacturing processes and affordable goods to all levels of European society. The exhibition drew an unprecedented gathering; approximately six million people attended the event showcasing over 15,000 objects. Paxton's elegant solution incorporated cast glass panels into a system of modular building sections enclosing over 700,000 square feet of interior space (Jordan, 1969, p.295). Daylighting was the key factor in the success of the event, providing the primary source of interior illumination. Without successfully integrated daylighting solutions the exhibition itself, as well as the production of goods showcased, would not have been possible.

Daylighting in the 20st Century

By the 1900s natural light was synonymous with advanced architectural design and commonly used as an element in commercial buildings, public spaces, and private residences. Relevant architects of this era realized the importance of natural light –beyond its mere technical applications for illumination. Poetic discourse between humans and structures, human movement through space, and human interaction with the surrounding natural environment are key theoretical approaches employed by the most influential designers of this age. The following examples presented from Antonio Gaudi, Le Corbusier, and Alvar Aalto demonstrates these design sensibilities.

These solutions demonstrate passive daylighting techniques, using the built environment to collect and control sunlight without mechanically powered equipment. Passive daylighting strategies offer an advantage over active daylighting strategies, because they are more sustainable long-term solutions. Passive daylighting strategies still require studious pre-planning, design considerations, and must remain important to the building program through its completion. Each of the following projects demonstrates an unwavering commitment to design, persevering each intended daylighting strategy through construction and setting a mark of distinction among great works.

Antonio Gaudi: The Poetics of Daylight

According to Ester Pons, Antonio Gaudi sought to create architectural environments that excited the senses. “His buildings, three dimensional texts, interweave a constructive narrative where textural, chromatic, and decorative influences produce poetic discourse rich in metaphor“ (Raventos-Pons, 2002, p.199). Every surface was actively instrumental in this ongoing dialogue, rather than being static or finished by painting one color as the ending stroke. Gaudi envisioned “living skins” (p.200) of ornament, color, and texture interwoven to produce dynamic excitement for human beings within constructed space.

The southern Mediterranean climate of Barcelona, Spain provides access to ample year round sunlight. The challenges of this environment require designers to temper the intensity of daylight, controlling against unwanted glare. Gaudi used a series of overlapping textures to fully harness this constantly moving energy. At any given time during the day surfaces shine or mute natural light differently. The yearly position of the sun also allows seasonal changes to affect the architecture (Molima, 2009, p.263). Gaudi applied this strategy to the exterior surfaces, as well as the interior and was especially effective in central courtyard style architecture.

Casa Batllo, a tenant improvement designed in Barcelona during 1904, uses an interior courtyard specific to the architecture of this region. This building typology brings light deep within space, especially in tall vertically stacked designs. A central lighting source for multi-level housing shown in Figure 3 directs full spectrum daylight into a shared enclosed space. Adjacent spaces, separated by interior sidelights glazed with diffuse glass, draw controlled light within residential apartments. The interior finishes of tile and glass function in harmony with the size and placement of windows, further controlling the light. As the material descends from upper to lower floors the color of each tile is progressively lightened. Dark tiles at the top absorb much of the intense daylight, while light tiles below reflect more light, within interior spaces (Molima, 2009).

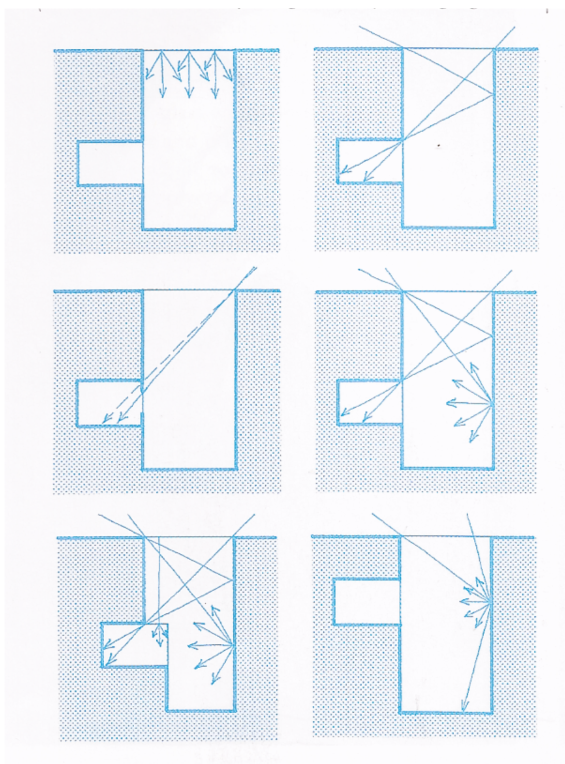


Figure 3: Casa Batllo Courtyard Diagram. *(Molima, 2009, p.267).*

Gaudi's passive daylighting strategies in courtyard buildings provide necessary interior illumination. His special attention to surface detail gives life to interior space. In Casa Batllo there is a constant interplay of natural light across contrasting surfaces. Only the diffusion and transmission of sunlight is needed to bring these seemingly static materials to life. These spaces maintain a level of interaction with occupants through the luminescent quality of these carefully selected finishes.

Le Corbusier: The healing power of light

Le Corbusier produced public and private architectural designs in and around France during the first half of the 20th century. Architectural designers of this era combined poetic and aesthetic design aspirations with a concern for building occupancy well being.

According to Margaret Campbell "light and air" and "always sleep with the window open" were popular European dictums of this period, promoting health and hygiene (Campbell, 2005, p.470). Le Corbusier also devoted great effort to researching American approaches to healing tuberculosis in an effort to provide design solutions. His findings established the use of daylighting as a successful cure for disease. He believed a daily regime of exercise and exposure to the outside world created a stronger long-term resilience, and general good health.

Le Corbusier's' design principles included: placing structures on stilts (pilotis), installing rooftop gardens to compensate for lost natural space, an open floor plan, free façade, and long horizontal expanses of glass. These "Five Points of Architecture" outline essential characteristics needed to introduce nature within space and promote occupant well being. Several of the points are based on the ideal mathematical proportions of monumental Greek structures. A flat roof covering an outdoor terrace however was tied to the vernacular housing of Greek residential communities (Campbell, 2005). A roof top terrace and garden ensured access to the outdoors to a variety of single and multi family housing, without traveling to the country.

His designs considered the movement of human beings through space, carefully integrating natural light to support activity. The multi-family housing project Unite d'habitation built in Marseille, France 1951, provided each residence with daily exposure to natural light through a series of interlocking vertically stacked units. Each unit's small private balcony also provided exterior views. The design allowed a procession of daylight to occur over time.

This entirely new building typology took full advantage of the northern Mediterranean region with ample access to moderately intense sunlight. Less intense sunlight could be more readily introduced within space. Le Corbusier paid special attention to the procession of natural light through space. His designs support a variety of human activity with appropriate illumination, and provide exposure to life-giving sunlight.

Alvar Aalto: Collecting daylight

Alvar Aalto also strongly believed that natural sunlight and interaction with the outdoor environment were essential to long-term human health. According to Menin and Samuel he demanded that natural light be included in his designs stating, “the biological conditions for human life are air, light, and sun” and “the sun is a source of energy that should not remain unused” (Menin & Samuel, 2003, p.73). Aalto was accustomed to the cold climate of northern latitude. Northern light is dramatically different from the Mediterranean region with less intense daylight occurring over shorter duration. These conditions are reflected in his design sensibilities, which look to gather limited light as a precious resource.

One of Alto’s most influential designs, the Viipuri Library, was built in Finland, in 1927 and later annexed to Vyborg, Russia in 1944. The project utilized unusually thick walls, intended to house electrical and mechanical systems. This constraint limited the number and location of sidelight windows. Rather than relying solely on artificial lighting, Aalto developed a series of 58 uniquely positioned skylights (Spens, 1994). In series, the skylights provided consistent illumination throughout the space. The design strategy also demonstrated an unwavering commitment to introducing natural light, as an essential element of interior space.

Northern geographic locations experience limited amounts of sunlight, because the sun sets much lower in the sky. For some projects, the introduction of large vertical windows and overhead skylights could not provide enough daylight. Aalto designed secondary light sources for his Seinajoke Public Library project in Finland 1959. As illustrated in Figure 4, a secondary source called the sky vault is located externally and angled toward the sun (Voiner, 1983. P.197).

Rather than scooping light back into the space, the light vault device is illuminated by the sun. In this manner the outside sky vault is the source of daylight, collecting solar energy that would normally pass over the building. Manipulating the convex shape, overall size, and reflective surface finish regulate the amount of light each sky vault can produce. The sky vault can also be repeated in several locations, to capture daylight for specific interior spaces (More, 1983).

In general, geographic locations with limited exposure to sunlight require the use of multiple daylighting strategies to collect rather than control energy. Aalto demonstrated a keen understanding of complex sun angles, channeling daylight through the building exterior. Establishing this effective pathway is essential for passive daylight integration. Once canalization is developed however the system operates sustainably, requiring little ongoing maintenance.

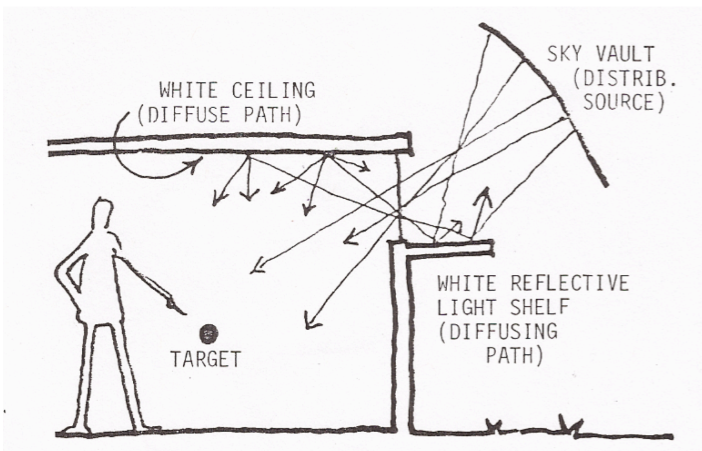


Figure 4: *Sky vault Illustration* (More and Hayden, 1983 p.198).

As stated previously, daylight has been considered an essential element of the built environment throughout most of our history. Vernacular building traditions reinforce the importance of daylight as a resource. This free renewable energy, provided building occupants with interior illumination, a closer connection to nature, and created a deeper interaction with built environments. Historically relevant examples of architectural design embrace holistic aspects of daylight: luminescent surfaces, procession of light through space, and canalization of light within the interior. Localized efforts maximized the benefit of available sunlight in truly ingenious ways.

The Decline of Natural light in the Built Environment

Leading up to the middle of the 20th century natural lighting systems were regarded as the primary source of daytime illumination, and generally associated with advanced sustainable building practices. The human spirit of innovation continued to push the limits of technology in an effort to improve our lives. American inventors and manufacturing companies set their sights on affordable electricity, readily available to all citizens through a networked grid. Within a short time interior environmental conditions could be regulated on demand using artificial lighting, advanced heating and ground breaking air-conditioning technologies. In the United States and abroad the use of natural lighting systems declined, ultimately falling out of favor by the early 1970s.

As early as 1907, open-air schools were mandated by European and American government agencies. Daylight was considered crucial for reading, learning and the physiological development of children. In order to achieve the highest level of natural light, schools were constructed according to optimum solar alignment, and utilized tall ceilings with vast expanses of glass. The trade off for these features was increased construction and development costs, and in particularly colder climates, reduced heating efficiency (Edwards, 2006).

As the production and delivery of electricity improved new mechanical devices were considered for a wider range of artificial environmental control. In the United States this technological innovation was considered a social reform in the promise of Electrifying America. Rather than offering electrification to enhance existing business, electricity offered citizens the ability to create entirely new economies (Jones, 2003). Privately held electrical companies believed by constructing power plants to provide electricity new business would automatically develop around otherwise isolated communities. Electrification created a shift in the American economic paradigm.

At the forefront of this movement were Thomas Edison with the Edison Electric Company and Nikola Tesla with the Westinghouse Electric and Manufacturing Company. The greater vision of nation wide electric power plants was fueled by interim inventions such as the electric light bulb, insulated wiring, and alternating current. All the while these electrical manufacturing companies saw a huge economic potential. The key was to legitimately demonstrate to economic viability of electricity to the growing nation (Luckin, 1992).

By the late 1950's the understanding of interior environmental conditions had shifted from occupant health and well being to focus on perceptions of comfort. Daylight is affected by unpredictable weather conditions and limited by anticipated solar movement. Artificial lighting output of this time period had advanced to a consistent reliable source of illumination. Product engineers had also developed systems that could produce illumination day or night. Fluorescent lighting fixtures offered additional benefits of reduced energy use and longer lamp life when compared to first generation incandescent lighting. Building owners and regulatory agencies began seeking a consistent, measurable level of illumination with quantitative cost structure. These agents and agencies required less and less natural light.

Air-conditioning systems were also highly instrumental in the decline of naturally lit building interiors. Mechanical engineers argued against high ceilings and wide expanses of glass, because they severely affected the efficiency and costs of isolated cooling loads. These building techniques were necessary to integrate natural light, but were not a requirement for many fluorescent systems. Artificial lighting was calculated to provide a minimum level of illumination for predetermined task performance. Once properly engineered these systems could be easily furnished to all interior areas, regardless of building orientation or access to sunlight.

When energy prices soared in the crises' of the 1970's, immense electrical loads needed to cool interior spaces came under even greater scrutiny. According to Lisa Heschong et al. the National Bureau of Standards and Technology concluded in 1974 that windows were no longer a necessary component of classroom in the United States (Heschong, 2002). Rather than looking to improve the technology of single pained untreated glass, mechanical systems engineers demanded designers remove windows. Within time a new paradigm was established, and the windowless classroom became a socially acceptable design strategy.

Amory Lovins has suggested that American's have developed an addiction to comfort during this era. He argues that just because we are technically able to create highly engineered environments, it does not mean these spaces are necessary, or even healthy (Lovins, 1976).

Renewed Interest in Daylighting

By the early 1990s designers began questioning the quantitative design approach of mechanical systems engineers. Despite best efforts to provide adequate light for prescribed task, it seemed something was missing from interior spaces, affecting the health and well being of occupants. The green architecture movement of the 1990s brought attention to the holistic aspects of constructed space, previously ignored by engineers.

In an article written for the Journal of the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) in 2002, Lisa Heshong suggests two major contemporary forces ushering a renewed interest in daylighting for interior environments. The first considers interior lighting systems as a part of the whole-building energy model. Leading up to the green architecture movement artificial lighting efficiency was calculated independently. The second force was a renewed interest in occupant well being, attributed to scientific breakthroughs in human physiological research.

The first major force, whole-building energy models, arose from advanced computer modeling software, technology and calculations. Contemporary buildings utilize intricately complex environmental control systems including heating and cooling, ventilation, and interior lighting systems, working together to create the building envelope. The current trend in architectural design considers these interrelated building systems a one congruent building energy equation. Leading up to the green architecture movement of the 1990s, systems engineers preferred divergent specialization. Under this approach each individual mechanical system is calibrated for isolated efficiency, often at the expense of other systems beyond scope. According to Heschong (2002) “daylight is intrinsically more efficient than any electric source because it provides more lumens per unit of heat content” (p.65). When artificial lighting energy consumption is considered alongside heating and cooling, integrating daylighting systems typically provides a net gain. Artificial lighting systems produce heat alongside visible light; daylight produces far more light per unit of heat gain.

Net-zero energy buildings are at the forefront of whole-building energy model technology. These buildings operate off-grid, reducing systems energy use intensity to the point that 100% of power demand is renewably produced on-site. On-site renewable energy production eliminates loss factors associated with transferring power over great distances, as well as reducing dependency on fossil fuels, finite in their supply. Using interconnected computer modeling systems, building design teams are able to closely calibrate the positive and negative impacts of each environmental control system, at the earliest stages of design development. The specialized software and expertise of each practitioner is loaded into a cohesive building model, allowing the impact of each system to be modified, well in advance of actual building construction (Guglielmetti, et all, 2011).

Rob Guglielmetti et all present a case study of the National Renewable Energy Laboratory Research Facility (NREL), a 220,000 square foot facility in Golden Colorado. The building was contracted to meet zero net energy usage, through the use of solar panels. The high cost of installing a photovoltaic panel (PV) system quickly pushed the program out of budget. Daylighting was found to be the key to reducing total building energy demand, and allow a smaller more affordable PV system to be installed (Gugliemetti, 2010). The design teams approach painstakingly simulated the interrelated environmental control system factors, building program components and space planning, and overall site orientation with regard to solar movement.

The second major force fueling the resurrection of daylighting is a renewed interest in occupancy health and workplace productivity. A growing body of research has suggested the benefits of natural lighting include reduced worker absenteeism, improved psychological mood, higher retail sales, and increased student performance under daylighting conditions (Heschong, 2002). Human interaction with natural full spectrum lighting is not yet fully understood. For this reason it is impossible to artificially reproduce the true quality of daylight indoors. Gleaning the entire benefit of full spectrum lighting requires a holistic approach to environmental design. This new holistic approach is savvy to cutting edge technology, while being specifically grounded in evolutionary human physiological response.

At the heart of each technical calculation lies the individual environmental design expert. One of the most important advances in contemporary building design is an innovative interdisciplinary approach to problem solving. Specialized practitioners and field experts are no longer segregated into “silos” of independent knowledge. Jennifer Veitch suggests that integrating the science of light with occupancy health considerations is the next evolution of the professional lighting design industry. This massive scope encompasses the known quantitative aspects of light familiar to engineers, with the elusive qualitative aspects of human psychology familiar to designer. According to Veitch, an interdisciplinary approach is the most suitable research effort.

Interdisciplinary studies solve problems whose solutions are beyond the scope of a single discipline, area of specialty, or research practice. This research integrates, data, tools, techniques, perspectives, and concepts from two or more disciplines of specialized knowledge. In comparison, traditional multidisciplinary approaches solve a common problem by working separately and maintaining individualized perspectives (Veitch, 2005, p.6). A collaborative perspective is instrumental in defining interior lighting quality, and ultimately enhancing the built environment.

Case Studies: Daylighting Strategies

The Illuminating Engineering Society of North America (IESNA) defines Daylighting as “maximizing the benefits of sunlight into the interior environment, while controlling for the ill effects” (IESNA, 2000). Daylighting has at its core, the fundamental challenge harnessing the sun’s total potential energy, a constantly moving target. Controlling the ill effects of daylight includes the management of unwanted heat and glare. When skillfully employed, daylighting offers practitioners of the built environment one of the most effective modes of building occupancy satisfaction, architectural aesthetic expression, and building energy conservation.

Daylight Harvesting is the activity of capturing the sun’s visible light, for the specific purpose of interior illumination. According to R. P. Leslie, there are two major collection strategies identified within the field of daylighting. Active daylight harvesting employs mechanized collection equipment that track and focus the suns energy. Active Strategies include motorized solar shades, light-focusing dishes, and computer-controlled building skins. Passive collection strategies employ static collection equipment, including clearstory windows, skylights, fixed exterior and interior shading devices, and window glazing technologies (Leslie, 2001).

Many of the advanced active daylighting strategies call for complicated, costly, and cumbersome equipment, while simple passive daylighting strategies are more practical. Installing active systems also requires large up-front investments, long-term maintenance costs, and precise end user data collection. Conversely, passive lighting systems are often integral to the building architecture, and operate with little or no ongoing maintenance. The following case study examples demonstrate successful applications of both active and passive daylighting systems, across a wide variety of environmental conditions.

Building Typology

In a study reviewing traditional daylighting strategies of hot arid regions Belakehal et al. conclude building typology plays a major role in optimizing solar energy. Ancient building techniques of the Islamic world placed various interior spaces around a central courtyard. Facing into this courtyard, each room is equipped with open vaults or opaque screen walls allowing natural light to passively enter throughout the day (Belakehal et al., 2003). The central courtyard is secure, allowing larger open expanses and greater variety of opaque construction materials. This higher concentration of internal daylight allows smaller, secure, external windows without impacting the total interior illumination.

Oriented along the east/west access, interior courtyards were often fitted with high walls. This relationship allowed the permanent building architecture to shade some of the courtyard throughout the day. Passive solar architecture also took advantage of yearly solar movements, as the summer and winter equinox sets the sun at differing locations on the horizon. High courtyard walls were oriented to block intense summer sun, while structural gaps allow winter sun penetration.

The authors conclude that ancient building typologies offer valuable building techniques, especially relevant to the current push for environmentally conscious architecture. Today's technologically advanced materials can take better advantage of historically successful building typologies, such as the central courtyard (Belakehal, 2003).

Energy Efficient Lighting in High End Architecture

In a case study examining an exclusive spa in the United Kingdom, Rusdy Hartungi (2008) presents an argument supporting the application of active solar collection and management systems. The author suggests that much of the literature published on daylighting technology in office spaces focuses on efficient building costs. Architectural aesthetics and occupant visual comfort are often sacrificed in offices for budget considerations. High-end day spas are conversely designed with end-use occupancy considerations as the primary design goal. Because end users expect comfortable, aesthetically pleasing interior spaces, and are willing to pay for them, these attributes cannot be substituted.

The case study examined an energy-efficient lighting design for a spa located in southwest England. The design goals included lighting strategies for an indoor swimming pool, treatment rooms, and general occupancy areas associated with a connected hotel. Because the project was located in the south of England the building experienced reduced access to year-round sun, and expected long periods of overcast weather. The primary method for daylight collection was a heliostat collector, an automated reflective mirror tracking the sun hourly and yearly movement. Once collected solar energy was reflected through a series of internal light pipes, and delivered to interior spaces. The active solar collection system was further augmented with automated shading systems. The resulting combination allowed sunlight to be collected and refocused at independent interior locations, regardless of their position on the site.

The author concludes that active daylight harvesting techniques can be employed to foster energy efficiency in highly aesthetic building programs. These systems require a large upfront cost but have proven successful at providing reliable consistent natural light to interior volumes with remarkably unique tasks. A high level of interior aesthetic beauty, and consistent occupant comfort were the critical features of this design, and justified the use of more costly mechanized harvesting equipment.

Retrofitting Daylighting Systems In Historic Buildings

Carla Balocco and Rachele Calzolari (2008) present a detailed case study proposing contemporary daylighting solutions for use in ancient buildings. A daylighting design including the use of light shelves, a light pipe, and improvements to an existing skylight were proposed for the old library of Palagio di Parte Guelfa, built in Florence, Italy 1232. Because the proposed location was an historical landmark, the building architecture and structure could not be modified.

The primary design goals were to improve uniformity of luminance distribution, produce a comfortable lighting environment under variable sun and sky conditions, and increase lighting energy savings through the reduced use of artificial lighting systems. These goals were accomplished by installing light shelves at exterior window locations. The light shelf guides additional sunlight, otherwise lost, within the building interior. A light pipe system collects exterior sunlight and redirects it through a mirrored pipe to desired interior locations. Renovation to an existing skylight included replacing glass pains with more advanced thermal layers and adding film to block unwanted ultraviolet radiation harmful to sensitive library materials (Balocco & Calzolari, 2008).

The authors conclude that relatively low cost, passive daylighting systems work well to retrofit historic buildings. Passive daylighting systems offer greater energy savings over time. The newly installed features greatly reduced daily electrical energy use, and offered further savings by reduced impact of artificial lighting on cooling load. Most importantly the retrofit components did not interfere with the building architecture and structure.

Findings and Opportunities

The literature review has established:

Human beings spent the majority of their evolutionary history closely tied to natural sunlight. Global architecture had developed and advanced around the sun, taking full advantage of this renewable energy source.

It is only within the last 150 years that humans have come to rely on artificial environmental control systems aimed at regulating comfort. The use of full spectrum natural light has been selectively removed from the built environment within this timeframe.

Artificial lighting systems, designed to selectively reproduce visible light for assigned task performance have replaced the need for daylighting in today's interior spaces. Contemporary opinions in architecture and interior design generally allow artificial interior lighting systems to operate, even when there is ample daylight present.

A renewed interest in the holistic quality of the built environment, as it relates to human occupancy satisfaction, has initiated a paradigm shift in environmental design. Today's professional environmental designer should consider occupancy psychological and physiological well-being, with equal merit when meeting building efficiency and minimum levels of accepted task performance.

Emerging scientific research has confirmed a link between non-visual aspects of light and improved human health and psychological well-being. There is a growing need for these crucial aspects, as human beings spend more of their waking hours within artificially constructed space.

Opportunities

Based on these conclusions the following opportunities have been identified:

1. Light has a beneficial impact on human health and well being, reaching beyond the visible spectrum, which cannot be ignored. There is a gap in the research of daylight as a holistic element of the interior environment.

2. Many experts agree that defining quality light for the interior built environment is a complex and elusive problem; the solution requires interdisciplinary research. There is also a gap in research of integrated daylighting solutions for the built environment from the interior designer's perspective.

Research Questions

The following research questions were constructed to guide this thesis: 1. What are the contemporary strategies integrating daylight within the built environment? 2. Is it possible to observe the phenomena of daylight as a holistic element impacting interior space? 3. How can the subject of daylight integrated within the built environment be researched and recorded from the designer's perspective?

CHAPTER 3

METHODOLOGY

Introduction

This Chapter discuses strategy and steps used to gather, record, and organize the data required to answer the research questions posed in Chapter 2. This Chapter is broken into the following topic sections: conceptual framework, research design, phenomenology, guiding principles for data collection, ethnography, persistent observation, persistent data collection, unobtrusive measures, visual note taking, sketching in situ, tools and techniques, and conclusion.

Conceptual Framework

Western society has traditionally defined intelligence as those logical and rational characteristics, which are easy to test and define. Howard Gardner suggests within the human mind there are multiple intelligences reaching far beyond this basic definition. In addition to the Logical-mathematical intelligence, the human mind should also be measured by its aptitude for Musical, Body-kinesthetic, Linguistic, Interpersonal, Intrapersonal, and most relevant to this thesis Spatial Intelligences. No one person can be defined by one intelligence-set, humans typically have a dominant intelligence supported by several other sets (Gardner, 1993). Each individual is composed of a unique mixture of problem solving, empathetic skills.

When we consider the perspectives of designers and engineers, it is also easy to apply culturally accepted notions of intelligence. The National Council for Interior Design Education defines Interior design as " a multi-faceted profession in which creative and technical solutions are applied within a structure to achieve a built interior environment" (NCIDQ, 2013). The International Association of Lighting Designers describes lighting engineers as possessing "Knowledge of physics, optics, electricity, ergonomics, business, codes, environmental issues, [and] construction" (ILAD, 2013). Human beings, according to Gardner, are apt at numerous and simultaneous methods of understanding.

At its core design creativity utilizes divergent thinking. According to Vishal Sing designers simultaneously consider multiple solutions to problem solving. This type of thinking allows subtle nuances as well as major forces to impact the final outcome to any given problem. Human perception and complex individual psychology plays a major role in defining the quality of interior space (Sing, 2011). Divergent thinking rarely arrives at one final solution; instead this process defines a series of possible solutions with one ideal outcome. Providing an approach to research that intuitively follows the divergent thinking model is the first step in establishing a methodology for research from the designer's perspective.

According to Jennifer Veitch a shift has occurred in modern building practices establishing human occupancy health and well-being as a primary concern for design teams. It is only within the last 20 years that the quality of interior lighting systems has been called into question (Veitch, 2005). The quality of interior lighting involves complicated psychological analysis, and an astute understanding of occupancy behavior patterns.

The goal of this research is to consider the scientific nature of daylighting from the specific framework of designers. The novelty in the approach of this thesis is collecting qualitative data explaining the phenomena of natural lighting integration through ethnographic study. This thesis seeks data supporting the integration of natural light, for the complex goal of enhancing the interior built environment.

Research Design

Phenomenological Ethnography

The literature review establishes that there are both known and unknown attributes of natural light influencing human beings. According to Lisa Heschong, these beneficial attributes of natural light are both visual and nonvisual; simply being in the presence of natural light may improve occupant satisfaction, for example, without directly enhancing levels of light supporting tasks (Heschong, 2002). According to M. Anderson, the phenomenon of natural light is in constant transition, affected by changing weather conditions (Anderson, 2001). In order to collect specific data the researcher must be present in the environment, working with the pace of the sun, without interfering or disrupting the normal activity of that specific built environment.

Phenomenology

Phenomenology, a method of social enquiry developed at the turn of the 20th century by Edmund Husserl, challenges individuals to question their surroundings. This philosophical approach aims to understand the physical world, by removing preconceived notions, suspending socio-cultural beliefs, and actually observing the activities of life. Inspired by the writing of Dilthey "the most fundamental form of human experience is lived experience, first hand primordial unreflective experience." Husserl believed in grasping "true meaning" (Blaikie, 1993, p.30). Phenomenology offers an understanding of the whole system, by considering its essential parts without the restrictions of personal knowledge. This line of inquiry is extremely relevant when questioning the designer's perspective as applied to quality lighting research; many attributes of natural light are still widely unknown. Through the gaze of phenomenological inquiry the researcher may hope to gain new insight into natural lighting benefiting mankind.

Phenomenology enables the researcher to enter a seemingly empty void in the search for true understanding. As Shashi Caan explains, by applying guiding principles phenomenology can be tailored to produce focused and objective inquiry. The pedagogy of Ecole de Beaux Arts and the Bauhaus established visual research and personal investigation as replacement for lecture and memorization. Here students were asked to consider the functionality of materials and process, and how they relate to fundamental design principles. By first considering the end user and larger significance, methods of construction were presented to students as a working system (Caan, 2011). Following the principles of Husserl each student could investigate the larger system, its inherent parts, as well their natural relationship. This process of self-exploration instilled a much deeper understanding of materials than previous teaching methods of fact-memorization.

Within these schools, phenomenological learning focused exclusively on visual literacy, and artistic discovery, but was taken to a new level in post war Italy, by the Reggio Amelia elementary education program. The Reggio pedagogy undertakes physical discovery and sensory experience, for a new type of adolescent learning environment. One example, places students in thought provoking classrooms with unusual shadows, light bending prisms, and colored lenses. Teachers guided and monitored independent discovery. The intended lesson plan, in this example spectrum of light, was presented to students as individual experiences, rather than memorizing one table or chart as a prescribed set of facts for all (Caan, 2011).

Caan suggests phenomenological learning is one of the keys to advancing design to meet today's radically changing social paradigms. Highly evolved systems of building design and construction have endless overlap, ultimately forming our modern interior built environment. The Reggio Amelia pedagogy is used as a model for this study: placing the researcher within an environment, given guidelines for investigation, but possessing flexibility to recognize unexpected results.

Guiding Principles

In order to narrow the focus of study three perspectives of natural lighting interaction were considered: geographic site location and building orientation, building structure openings, and finally the interior landscape as it reacts to introduction of light. In order to more accurately answer the specific research questions posed in Chapter 1, the work of Henry Plumber is presented as a guiding principle.

Plummer has a deep and high regard to natural light "For those architects now leading the way towards a phenomenal architecture, daylight is understood as something more than a commodity" (Plummer, 2009, p.13). Plummer's research goals reach beyond quantifying amounts of daylight for task, or to merely provide energy saving solutions enhancing sustainability. His research focuses on natural light as a binding force within architecture, the "hidden magnitude in the immaterial aspects of buildings" (Plummer, 2009, p.15). In this way Plumber discusses natural light as an essential element of the built environment, and not simply a form of illumination.

He describes seven aspects of natural light, that allow architects of light "to shape marvelous phenomena out of radiation from the sky" (Plummer, 2009, p.9). Historical architectural designs illustrated in Chapter 2 specifically incorporated three of these aspects: canalization, procession, and luminescence. Luminescence: "the capacity of light to penetrate matter and temporarily produce an inward glow and intensity"(Plumber, 2009, p. 216). Luminescence is described as the materialization of light within physical matter, otherwise mute objects imparted with a sense of life through contact with the sun (Plummer, 2009). Canalization: "the channeling of light through a hollow mass" (Plummer, 2009, p.148). Canalization explains the process of conveying the healthful benefits of nature, to as many interior rooms possible. Daylighting solutions go beyond increasing the size and amount of windows, in an effort to “give formless light a memorable character” (Plummer, 2009, p.149). Procession: “the choreography of light for the moving eye” (Plummer, 2009, p.52). Plummer explains “it is not single isolated moments or views that are important for the moving eye, but a continuous flow of human perceptions” (Plummer, 2009, p.53).

The method of this study was to observe the built environment from the exterior, making first hand observation of how natural light entered the interior. The building structure was then considered, and closely observed from the interior and exterior. Natural light was traced to the building interior by examining the structural methods used in passive sunlight collection. Finally the interior volume was observed, with key interior spaces identified, by their relationship to structure and site.

Ethnography

Zena O’Leary describes ethnography as “exploring a way of life, through the point of view of its participants” (O’Leary, 2009, p.116). This method of inquiry bridges the gap between recorded accounts, and actual first hand observations.

Ethnographic studies attempt to understand the reality of the researched; they require immersion through prolonged engagement and persistent observation (O’Leary, 2009). One of the difficulties with prolonged engagement is calling attention to the researcher. Unobtrusive measures, discussed later in this chapter, ensure the researcher is camouflaged, without inhibiting collection of rich data collection.

Persistent Observation

The selected building was broken down into the following areas of interest, based on a preliminary case study of published literature including plans sections and elevations and Internet sources including Scottsdale Public Library’s Website. As defined in Chapter 1, a public library was selected for building access during operational hours of daylight, open both weekday and weekend, and open throughout the year. Arabian Library was specifically selected because for award wining innovative natural lighting design, integrated passive daylighting goals, and the City of Scottsdale’ s culture of sustainable building practices.

The preliminary case study, which follows, identified three specific interior areas and one closely related outdoor space integrating daylight:

Table 1

Specific Areas of Interest for Further Research

Area 1: Central Staff Location: New Materials/Check Out/ Self Check Out/ Help Desk
Area 2: Mixed Use: Quiet Reading Tables/ Main Library Stacks/ Transitional Corridor
Area 3: Main Reading Area: Quiet Reading Tables/ Quiet Lounge Seating/ Main Library Stacks
Area 4: Central Courtyard/ Secondary Light Source

Each of these areas was studied independently during the hours of daylight, in the summer months of May, June, July, and August, encompassing glimpse of the entire library, and its natural lighting integration features.

Persistent Data Collection

The Arabian Library hours of operation, are 9 A M to 8 P M Monday through Thursday, 10 A M to 8 P M Friday and Saturday and 1 P M to 5 P M Sundays (scottsdaleaz.gov, 2013). Three separate data collections were performed: a morning collection at 9 A M or 10 A M, a midday collection at 12 Noon, and an afternoon collection at 3 P M. Data collection was not performed in sequential order, instead twelve collections were performed within a set period of time, May through August. To establish a repeatable methodology the time frame was determined based on the library's anticipated hours of observation. Flexibility in scheduling data collections over a period of time allowed for unexpected closures, such as reduced or limited public building hours of operation.

The following steps were repeated for each area:

Step 1: Prior to arrival to the site a detailed floor plan, site plan, and list of expected passive solar collection strategies was collected from the preliminary case study. An outdoor location at fair distance was selected; ground landmarks such as a sidewalk divot were noted so that each of three visits use the same outdoor location. From this vantage point visual notes were taken to describe 1. Where the specific interior area is located in relation to the site 2. What direction the interior area faces 3. What external daylighting devices are installed and 4. Where the suns position is in regard to the area of intended study. Brief visual notes were transcribed.

Step 2: Walking from the distant outdoor location to the building shell, building scale daylighting strategies were identified by the researcher. Visual notes were collected regarding passive daylight harvesting any obvious shading and regulation devices. Exterior walls were analyzed close up to uncover hidden wall angles, finishes supporting secondary light sources, or other anomalies not evident from a distant vantage point.

Step 3: Using case study notes, and the exterior observation an interior vantage point was selected. This point is selected by the sketching technique parameters, outlined later in this chapter. Once a suitable location was selected, the following two collections were conducted in the same spot. This allowed a comparative analysis of three separate timed intervals throughout the day.

Step 4: While settled within the selected interior location the researcher reviewed the exterior, building scale, and preliminary notes and began to establish how and where natural light was integrated within the space. Visual and verbal notes were collected uncovering the phenomena of natural light. While the researcher is within the space, reading and performing tasks associated with library occupants, the three parameters selected from Henry Plummer were considered.

Step 5: A brief 30 to 45 minute phenomenological perspective drawing was completed using sketch technique. The goal of this drawing method was to select an interior perspective, and set up a drawing to capture integrated daylight.

Step 6: At the end of each drawing session, the sketches were considered complete; additional corrections or embellishments were not added. This ensured the phenomenon of light was captured from within the built environment and not skewed by the researcher's memory.

Unobtrusive Measures

In order to capture the phenomena of natural light entering an occupied, fully operational facility unobtrusive data collection measures must be employed. As evidenced in Chapter 2 much of the scientific research performed on interior lighting systems during the last century has been devoted to artificial lighting sources under strict laboratory conditions. These conditions severely limit the effects of natural light on the built environment, focusing exclusively on the visible lighting spectrum. This thesis argues in favor of the integration of daylighting, because the beneficial effects of full spectrum light on human occupants are shown to be both visual and nonvisual. For this reason first person observation conducted on-site is preferred.

The focus of this study is not human occupants, but it is important to acknowledge their interaction with the researcher. According to Eugene Webb et al. “the patiently visible observer can produces changes in behavior that diminish the validity of comparisons” (Webb et al., 1966, p.113). As evidenced in Chapter 2 many methods of studying interior daylighting require extensive changes to the testing environment, and are unsuited for post occupancy, or phenomenological study.

The strategy for data collection was to approach the building as a typical occupant, dressed as a library patron, equipped with college student accessories: back pack, water bottle, and earphones. According to Webb et al., the mere presence of a researcher may entirely deter occupants from entering a space (Webb, et all, 1966). The researcher must also act as a typical library patron, sitting at typical furniture and utilizing the library in a conventional manner. For this study each visit was limited to less than 3 hours. Webb concludes the effect of the observer on the observed environment may erode over time. This suggests prolonged engagement and persistent observation combined with unobtrusive measures, benefit phenomenological ethnographic research.

Drawing Techniques

Two distinct types of drawings were developed for data collection within this study: analytical visual notes and phenomenological descriptive perspectives. Each drawing type was used to describe the four areas listed in Table 1 in greater detail.

Visual Note Taking

Developing a sense of place is particularly important to designers. According to Norman Crowe and Paul Laseau, designers must first establish a “comprehensive concept, having to do with all the qualities of a place which in combination, make it unique and special” before considering any construction of the built environment (Crowe & Laseau, 1984, p. 38). This sense of place enables designers to recognize valuable characteristics otherwise hidden by the casual observer or passive tourist. Words, pictures, and visual notes contribute to this overall character and ultimately equate to conveyance.

As Crowe and Laseau explain, “Compiling visual notes requires thorough and especially thoughtful effort by individuals”; and state “the act of creating a drawing is much more compressive than merely taking a photo” (Crowe & Laseau, 1984, p.39). It is the considerable effort of analyzing and recreating specific environmental attributes that separates hand drawings from photographs. Drawing forces observers to look more carefully at their surroundings. The details in a photograph, so clearly understood on-site, may be lost when the photo is later viewed.

Visual note taking is the primary method of data collection for this study. A variety of electronic device can be used for collecting visible light data, such as a light meter, as mentioned in Chapter 2. Each man-made electronic device, however, must be selected and calibrated on the basis of known, definable characteristics. Using a visual note taking method, with defined limitations allows greater flexibility in data collection. Unexpected results can be recorded in the form of visual notes, and detailed drawings.

In Situ

The sketch-in-place method allows research to be conducted recording the phenomena of natural light, within the built environment. Sketching is particularly important to designers. These methods are specifically sought to communicate the experience of natural light, beyond mere numerical data.

In situ is beneficial to this study as a technique of drawing what is seen, without modifying the environment. Drawings are not enhanced from memory after the session has ended. The drawings record a set place at a set time, as experienced by the artist. This is in contrast to rendering drawings from photographs, as the artist is specifically in tune to the environment and experience.

By establishing a foreground, middle ground, and background in each drawing, evidence of natural light integrating three-dimensional space is collected. Looking for obvious points of entry such as window openings, establishes natural light as the subject of each drawing. A drawing timed to approximately thirty minutes ensures the phenomenon of moving light is isolated as a still moment in time.

Technical Tools/Study Instruments

In order to create a repeatable methodology the following tools and instruments were compiled. The goal of this method of data collection is portability and to remain unobtrusive within the predetermined interior space.

Pen/Sketchbooks: A standard, repeatable, method of data collection is selected to isolate artist technique. This will establish a similar series of data collections in the form of drawings. Each individual collection is a unique hand drawn image, not requiring free drafting equipment or convention.

Pad: a 9” x 12” acid free white paper sketch pad bound with lay-flat binding was used for each data collection interval. The book was large enough for detailed sketches of large interior spaces, drawings in series, and text notations. The lay flat binding was important for digitally scanning the results into an electronic document.

Pen: The Pilot Precise V-5 extra fine black ink with rolling ball tip was selected for each drawing. While used by professional designers, this reliable portable pen is also commonly sold at office supply stores adding to its reliability.

GPS Locator/ Electronic Compass: In addition to a pen and pad the researcher was outfitted with a smart phone including, global positioning satellite (GPS) locator and services, Google aerial maps, and an internal electronic compass. The benefit to the GPS and locator and aerial maps are to quickly establish the sun’s orientation to the building. Google maps are particularly useful on-site in establishing hidden rooftop daylighting strategies and equipment otherwise inaccessible to typical library patrons.

Sketching in situ requires selecting a vantage point to best capture the intention, and essentially the information, conveyed by a natural setting. For this reason the researcher may need to continuously shift and relocate to find a suitable outdoor vantage point. Once the view, ground position and distance are established, a quick check of navigation documents the location. This ensures the same spot will be visited in future collections.

An electronic compass was useful in deciphering the buildings position in relation to the major geography. Standing physically perpendicular to exterior walls allowed the use of an electronic compass to confirm the major orientation.

Electronic Plum-bob: Many smart phones offer integrated electronic plum-bob applications. This research used the IPhone 5 with internal gyroscope. This technology also accurately reads angled walls, and quickly quantifies slightly angled walls and windows.

Conclusion

This chapter introduced the research methodology and steps utilized for the following case study. This chapter also discussed the study instruments and drawing technique used for data collection. The following chapter will provide the results of the case study and phenomenological ethnography of Arabian Library in Scottsdale, Arizona.

CHAPTER 4

RESULTS OF DATA ANALYSIS

Introduction

This chapter addresses the strategy used to collect analyze and organize the data required for this study. In order to solve the research problem specific research was performed in two specific areas of data collection: Section 1: a detailed preliminary case study to identify a suitable facility for research. Section 2: an on-site phenomenological ethnography of key interior spaces demonstrating holistic daylighting integration.

Section 1: Preliminary Observation/ Case Study: Scottsdale Arabian Library

Introduction to Project Selection

In order to answer the research questions addressed in Chapter 2, the author suggests selecting an existing building for further study, one highly likely to receive sunlight and culturally positioned to advance sustainable building practices. Based on global positioning and yearly weather conditions, some areas in the world offer more favorable environments for passively harvesting sunlight. In reaction to naturally abundant sunlight, state and local government agencies have the ability to respond with incentives encouraging sustainable design. Within these broad criteria, public architecture projects have unique programs intended to satisfy the needs of diverse user groups. Of the many public project categories, City Libraries are open to the public free of charge with little restriction, during daylight hours, 7 days a week, all month long, and throughout the calendar year. It is along this line of reasoning that The Scottsdale Arabian Library has been selected for this study.

Every artificially constructed environment is inherently tied to its natural geographic location on the earth. Global positioning describes the longitude and latitude position, which in turn predicts the intensity of natural sunlight; sunlight strikes the earth at an angle decreasing in intensity from equator to pole. According to the National Renewable Energy Laboratory, the Southwestern United States Lies at 32 degrees, in an excellent location for harnessing natural light (NREL.gov, 2013). Arizona is also located within the Sonoran Desert and typically experiences arid, sunny weather conditions through the year. Based on data collected during daylight hours, the Western Regional Climate Center (WRCC) denotes clear days as having 0/10 to 3/10 average ratio sky cover, where cloudy days have 8/10 to 10/10 ratio sky cover. Scottsdale Arizona receives an average of 211 clear sky days (www.wrcc.dri.edu, 2013). Arizona lies in a region receiving intense, year-round sunshine, reliably dry weather conditions, and typically clear skies.

Arizona has positioned itself as an international leader in the production, use, and awareness of solar energy. The Arizona Renewable Energy Standard requires 15 percent of the State's energy needs come from renewable energy sources by 2025 (scottsdaleaz.gov, 2013). "We have every intention to be the nation's leader in solar production with an eye toward being an export leader as well," states Leisa Brug, Arizona Energy Policy Advisor (aztechcouncil.org, 2013). In 2007 the State unveiled plans for constructing new a 200 mega-watt alternative energy plant entirely powered by the sun. Approximately twice the height of the Empire State Building the Enviromission Solar Updraft Chimney will be the world's largest solar power plant of its kind. Though massive in scale, the Solar Chimney follows a longstanding tradition of state municipalities encouraging the integration of natural sunlight to promote sustainable construction.

In 1998 The City of Scottsdale became the first municipality in Arizona to establish a Green Building Program. The program initiated a policy of "healthy resource and energy-efficient materials and methods in the design and construction of homes" (Scottsdale.gov, 2013). The city council continued to develop a culture of sustainability by unanimously approving Resolution No. 6644, The Green Building Policy, in 2005. This resolution made Scottsdale the first city in the US to require all new, occupied city buildings of any size to be Gold Certified under the Leadership in Energy and Environmental Design Program (ICC, 2010). Among other interior environmental considerations, daylighting is specifically addressed and encouraged by the LEED Program.

The city remains progressively in sync with the rapidly evolving framework of sustainable environmental design. In 2012 the City Council adopted the current suite of building codes including the 2012 International Energy Conservation Code (IECC) and International Green Construction Code (IGCC). According to the City of Scottsdale Website, "The new code provides flexibility to adapt to Scottsdale's geographic conditions and environmental quality of life while promoting uniformity of performance criteria from city to city" (Scottsdaleaz.gov, 2013). With such a rich history encouraging sustainable design and building practices, and specific ordinances supporting the use of daylighting, the City of Scottsdale is ideal for selecting an existing building satisfying the criteria of this thesis research.

The broad array of occupancy and extensive access to facilities for research, limited the scope of this thesis to public buildings. In 1990 the United States Department of Justice initiated the Americans with Disabilities Act (ADA). This act prohibits discrimination against persons with disabilities and offers specific guidance for designing and building public accommodations and commercial facilities. (ADA.gov, 2013) This regulation ensures the built environment is constructed to accommodate occupants with disabilities, however the regulations also improve the interior environment for all occupants. This thesis is focused on publicly accessible buildings, allowing the data collected to be relevant to a greater array of building types, regardless of size, enhancing the public good.

Of the many relevant public architecture projects, libraries cater to an especially wide range of occupancy types, including the iGenration also known as Digital Natives. According to Jill Nishi "Public libraries throughout the country serve as vital community hubs that provide access to information and opportunities to all people--regardless of their age, ethnicity, income, or level of education" (Nishi, 2011, p.36).

Contemporary public library design also offers a glimpse into the effects of rapidly changing digital culture and its impact on environmental design. Digital Natives are a section of society born in the digital age (after 1980) and predisposed to electronic technology, digital search engines, and technology driven architectural design (Zimmerman, 2011). As new technology continues to saturate the fabric of society, public library design will serve as a benchmark, demonstrating methods for preserving traditional methods of text media circulation, while catering to the needs of now and future technology driven media.

A detailed search of recently constructed, award winning, public library projects within the city of Scottsdale, Arizona is the basis for this case study. Built in 2007, Arabian Library has won the AIA Arizona Honor Award in 2008, Metropolis Magazine Smart Environment Award in 2008, ALA Library Building Awards National Honor Award in 2009, and IIDA SW Chapter Design Excellence for Public Facility in 2008.

Figure 5: *Timmerman, B. (2011) Arabian Library. [Photograph of library entrance]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/49arabian-library-richardbauer/ecdt5487/.*

Project Overview and Case Study

Arabian Library is a 20,800 square foot public facility completed in 2007, with a cost of $8.4 million dollars. The library is one of 4 satellite branches, all named after celebrated horse breeds, serving the main Civic Center Library. Pictured in Figure 5, the facility holds over 100,000 library materials and replaces a preexisting 8,400 square library housed in the adjacent middle school. The newly constructed library sits among Desert Canyon Elementary School, a municipal Fire Station, Public Swimming Faculty, and outdoor skating park at the base of the McDowell Mountain Preserve 10215 East McDowell Mountain Ranch Road, Scottsdale, Az.

Deeply rooted in poetic metaphor, Arabian Library is conceptually inspired by Antelope Slot Canyon of Arizona's "high country" shown in Figure 6. Here millennia of water and wind have carved elegant caverns and recesses within richly translucent red rock. Because the library is located among several unrelated phases of residential housing and nondescript light commercial shopping centers, project designers turned to the natural landscape for inspiration. The site sits at the base of dramatic 4000-foot mountain vistas, among native desert vegetation, and rugged

Miocene rock. Though located within the Sonoran Desert, the site experiences distinct seasonal weather, with periods of lush and arid vegetation. The landscape, surrounding environment, and library facility are closely intertwined enhancing the buildings exterior appearance, as well as the functionality of interior space.

Figure 6: *(2007) Antelope Canyon, Page Arizona. [Photograph of Arizona desert slot canyon]. Retrieved March 12, 2013 from http://www.globeimages.net/img-antelope-canyon-,page,-arizona,-united-states-12853.htm*

City Librarian, Rita Hamilton, challenged the design team to create a functional, aesthetically pleasing facility that is also sustainable. Flexibility leads to building structures with greater longevity, this is especially important to the radically changing culture of American libraries. According to the American Library Association, branches are no longer warehouses for books and quiet isolation, transitioning into social centers of collaboration. With the increased availability of electronic resources, occupancy satisfaction plays a greater role in the usefulness of free libraries. Today's public library offers free Wi-Fi access, wide-open spaces for collaboration, and encouraged conversation and activity. Personal listening devices have shifted the expectation of privacy, but the library still offers quiet rooms geared toward traditional library users. The net result is a more lively active environment, adaptive to continuing change, but also familiar in its offering of community based resources (ALA.org, 2013).

An innovative building program requires an innovative, interdisciplinary, approach to design and construction. The architectural and interior design team, Richard and Bauer, dealt with highly advanced building systems, including natural and artificial lighting, heating ventilation and air-conditioning, and plumbing systems. According to Nancy Levinson, each system is individually complex but in order to achieve a holistic built environment significant attention was given to balancing system interactions (Levinson, 2009). Building mechanical systems, typically require vast floor space for locating mechanical units and wall space for ducting, and often adversely impact one another. A large open plan, as shown in Figure 7, encourages natural lighting integration, with fewer walls as obstacles interfering with light.

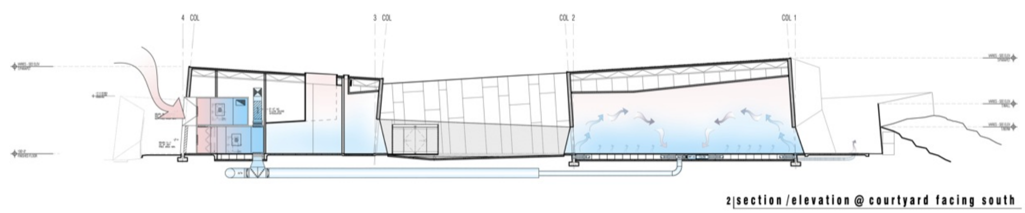


Figure 7: *Bauer, K and Richard, J. (2011) Section Elevation at Courtyard Facing South. [Digital illustration]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/mechanical_section-077-m3-2//.*

Placing ventilation equipment below a raised floor structure recirculates cold air directly around occupants, leaving the uppermost volume to sink heat. The system is also easily reconfigured thanks to moveable carpet squares, and inherent flooring flexibility. Natural light, otherwise obstructed by interior walls, passes freely and deeply into the interior spaces. Collectively a third result, one positively supporting sustainable facilities sustainable emerges. Future changes in space planning or fluctuations in the size of permanent collections have reduced impact on existing air handling performance and natural lighting integration. With fewer walls to tear down the amount of landfill waste is reduced, fewer new walls to build simultaneously reduced financial cost. Throughout the library complex seemingly unrelated mechanical systems are specified to the state of the art, but also fine-tuned to work in concert with one another (Levinson, 2009).

Site

Arabian Library occupies the previous lot of the smaller obsolete Desert Canyon Elementary Library. This allowed the design team to reuse the exiting parking lot, reducing landfill waste and preserving additional natural landscape, key elements in LEED Certification. Arabian Library is oriented slightly northeast directly facing the McDowell Mountain Preserve. Views to the outside, weather McDowell Mountain Park to the east, patios with desert gardens to the north and west, or the vegetated interior courtyard, satisfy LEED requirements benefitting occupant satisfaction. These window openings with scenic view give respite and reflection to patrons and staff, while introducing natural light deep within the interior space (Chang, 2009).

Road noise from Thompson Peak Parkway along the north, as shown in Figure 9, and intense afternoon heat from the setting sun along the west challenged the design team. Richard and Bauer utilized full height site walls, shown in Figure 8, to block heat and noise, off-setting each wall from the main structure. The voids allow heat to dissipate, and noise to travel away from the main building, and also create two distinct patios. The patios increase effective facility square footage by providing seasonal outdoor space. The overall building orientation is carefully considered to maximize the efficiency of several mechanical systems, forming a synergy in operation.

Natural desert landscaping offered three distinct advantages in tying the building to its site, as demonstrated in Figure 10. One of the overriding goals of the design team was to merge the large, newly constructed structure into its natural surroundings, rather than creating a landmark to stick out. Natural landscape, including palo verde and mesquite trees, various cactus varieties, and low lying sages uniformly create the facility's planters, gardens and site vegetation. Because desert landscaping distinctly changes with desert season's plant varieties produce beneficial shade during the late summer monsoon, while levels of natural sunlight increase in winter when trees are bare.

Figure 8: *Timmerman, B. (2011) [Photograph of library exterior site wall]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/ecdt5427/*

Figure 9: Bauer, K. Richard, J. (2011) *Arabian Public Library*. [Digital illustration of site plan]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/0504x-site-layout1-1/

Figure 10: *Timmerman, B. (2011) [Photograph of Arabian Library from distance]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/ecdt5437/*

The City of Scottsdale also requires certain native plant be relocated within the site, rather than being destroyed, as a part of its sustainability initiative. Once professionally relocated these plants live and germinate the site naturally resulting in substantially less water and yearly maintenance costs (Chang, 2009).

Building Structure/ Shell

Because Arabian Library is in an environment of consistently intense sun, a major design consideration was the exterior finish material. Painted surfaces require continual maintenance, adding to annual operation costs. The design team chose recycled Core-ten Steel, a proprietary manufacturing method first developed for the railroad industry at the turn of the 20^{th} century. The steel reacts to local weather conditions and intentionally rusts to form an impenetrable patina. Core-ten Steel makes up the majority of the exterior skin and some interior features. The resulting patterns and coloration are unique and continuously change with time, adding character to each wall plane (Chang, 2009).

In addition natural materials stone and living materials were relocated from site during construction. Eliminating materials transportation dramatically reduces the impacts from fossil fuels, which in turn supported the design teams LEED Certification goals. Granite and Miocene stone recovered during construction were sourced as roofing material, planter boxes, and decorative rock gardens.

Daylighting Strategies

Low Level Side Light Windows

Throughout Antelope Canyon, glowing tracery rays of light pierce slots and voids within the porous and eroding stonewalls. According to Levinson, this metaphor is applied to the majority of windows in the library providing daylight on the ground, without allowing glare at typical task levels (Levinson, 2009). A series of angled sidelights are installed at heights varying from 6’ to 7’ high, running into the floor. The sidelights are used in conjunction with full height site walls so that the windows facing traffic and adjacent residential views are concealed. Low-level windows facing west are also protected by exterior site walls, which block unwanted radiant heat and allow ambient light to enter.

A similar passive lighting strategy is employed along the major circulation paths, shown in Figure 11, with angled glass windows running the length of each wall. Walkways are bathed in dynamic light, while desk height surfaces located above 30” are uninterrupted by glare. At other locations, where the glass walls extend beyond 30” in height shading strategies including window tinting, mitigate unwanted glare. In an effort to connect the interior volume to the landscape two courtyards flank the teen and children’s reading rooms, each with full height glass walls.

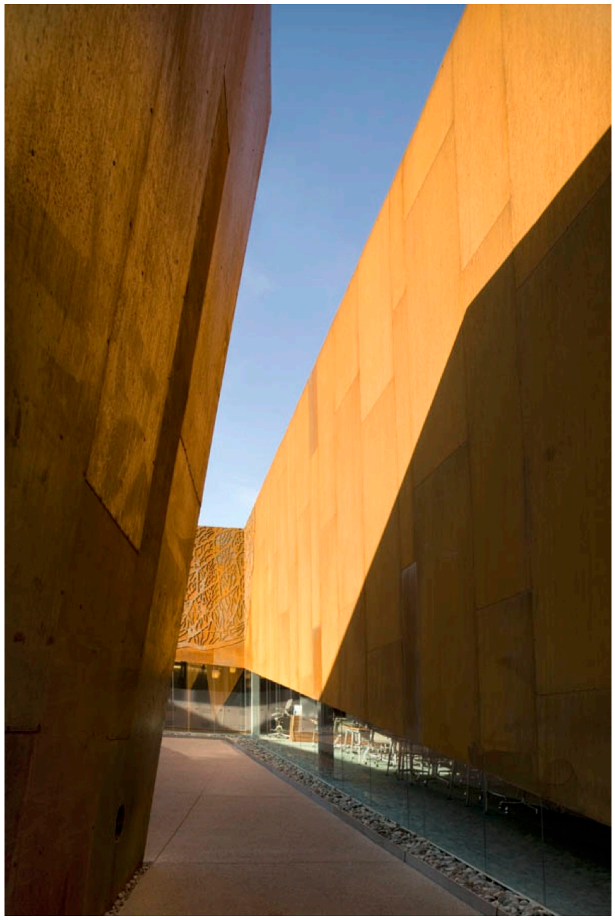


Figure 11: *Timmerman, B. (2011) [Photograph of library low level sidelight windows]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/ecdt5437/*

Full Height Window at Main Reading Room

The main reading room adjacent to central library stacks is the one and only location of a full height, or picture window. The window provides controlled natural light into the space, natural views outside the space, and reinforces the building's slot canyon metaphor. This window, shown in Figure 11, is directly in front of the main parking lot providing patrons with a glimpse into the main reading room to patrons upon their arrival, From the parking lot patrons meander through sloping walls into the central courtyard flanked by sloping tinted windows.

This window is composed of clear glass, completely un-shaded, and runs vertically from floor to ceiling, stretching halfway across the room. An open reading room sits to the southeast corner and a laptop computer bar with moveable occasional furnishings and desk lamps sits to the northeast. The result is dramatic views of native plants and nearby mountains, clearly visible from almost every corner of the room. Darker corners are utilized for computer users preferring an environment suited for backlit devices.

Figure 12: *Timmerman, B. (2011) [Photograph of library full height picture window]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/ecdt5437/*

Bounced Light Through Patios

By locating angled ground level windows, varying between 7’ to 10’ in height, unwanted exterior views, direct sunlight, and noise are prevented from entering the interior. A busy 4-lane road lies to the north of the building and due to Arizona’s low sun angle. The western elevation is extremely hot in the later afternoon. According to Lisa Heschong (2009), large clear-glass windows are susceptible to radiant heat gain, effectively a type of greenhouse effect. Glass walls are also ineffective at blocking noise transmission, a distraction to library patrons and staff alike. The site walls, constructed of the same Core-ten steel plate; act as a barrier for both heat and noise. The ingenious location of these site walls adds additional value to the building program. Offsetting these two site walls forms two elongated triangular outdoor patios, evident in Figure 12.

Figure 13: *Bosclair, M. (2011) [Photograph library outdoor patio and reflective wall surfaces adjacent to interior space]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/07-166-01a/*

The large solid wall, approximately 15' away from the main building structure, creates a secondary light source for the interior volume. Direct midday and afternoon sunlight, otherwise intense, is tempered by being "bounced" into the building. Light colored hardscape and patio furnishings reflect light, but absorb heat. The inside surface of the darker Core-ten structural wall also reflects light toward and inside the building. This allows larger and more effective window openings. Because the site wall absorbs and deflects much of the heat, long windows can be considered natural light inlets.

Central Courtyard

As discussed in Chapter 2 central courtyards are typical features found in the architecture of hot arid desert climates. Historically these features allow airflow, water collection, private outdoor spaces, and outstanding integration of natural light.

Arabian Library takes advantage of these principles, feeding rainwater into a native stone landscape feature running along the perimeter. Patio chairs and tables sit amid rock features, landscape planters, and a large palo verde tree. The activity, plants, and hardscape garden form an outdoor setting, sufficient in supporting interior occupancy with a view into nature.

Figure 14: Timmerman, B. (2011) [Photograph of library courtyard feature]. Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/ecdt5353/

In order to open the interior volume to the surrounding landscape, all four walls capture pleasant garden views. According to Jade Chang (2009) a metaphoric “slot” was constructed of angled structural walls and curtain glass enclosure. The windows are treated with film allowing direct sun deep into the interior, while tempering glare and ultra violet. While gathering views beyond, the glass curtain also allows advanced passive daylight collection, year round.

Inverted Light Wells at Future Rooftop Gardens

Some of the more complex passive natural lighting strategies in the building include an inverted light well atop the restroom and computer lab. Each location cleverly separates two interior volumes, a computer lab/reading room to the north, pictured in Figure 13, and restrooms to the east. By providing a sealed interior ceiling, and four sides of glass bridging the gap, natural light is allowed to freely enter the space. The controlled separation allows a lower light level amid the computer room; desktop and hand held computers are typically backlit. The restrooms, requiring special ventilation and washable ceiling and wall surfaces, would otherwise require separation, doubling the benefit from the added light well.

Each of two inverted light wells is constructed as a future roof top garden, with all the necessary plumbing, drainage, and structural support intact. The gardens have the potential to function as educational labs, food production gardens, and by the library itself or the adjacent school. The light well has four sidewalls of clear glass. The effect of the light well surpasses a simple skylight, by allowing both direct and indirect light into the room, increasing exposure. The net result is also beneficial to space planning efforts, creating two private spaces on the reverse side (Levinson, 2008).

Interior Furnishings and Finishes

Arabian library utilizes a contemporary bookstore-café model for its interior space plan, resulting in a more open feel, and greater opportunity for natural lighting integration. Furniture size and placement, furnishing fabric selections, and overall interior finishes offer great potential for distributing additional daylight within the interior volume.

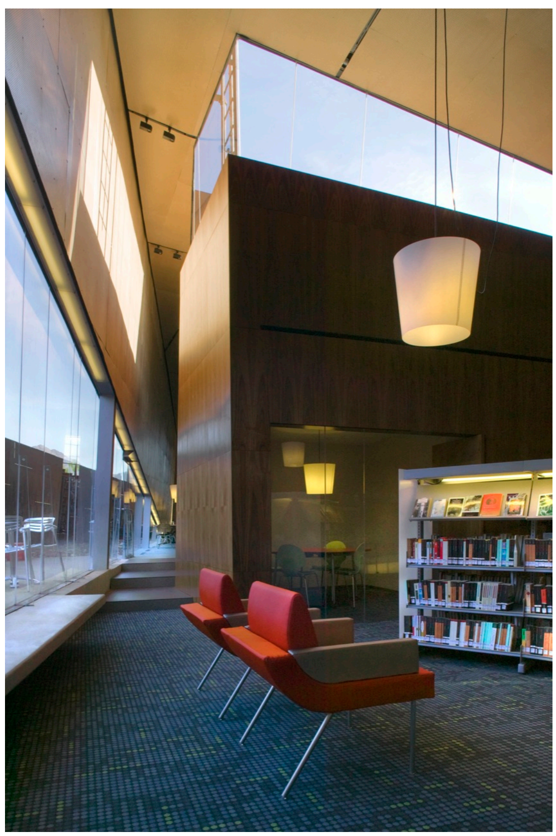


Figure 15: *Timmerman, B. (2011) [Photograph of library inverted light well at private study location] Retrieved March 12, 2013 from http://www.archdaily.com/130435/arabian-library-richardbauer/ecdt5353/*

Interior furniture selection makes a statement about the entire facility, and its intimacy with patrons and staff. Furniture is approached at the user scale, defining how each room is to be utilized, weather it can be reconfigured, even leading occupants to extend their library visit. Furniture is notably light, modular, and ergonomic encouraging relocation and breakout groupings throughout the library. Informal seating groups are created by library staff to change the interior throughout the year or by visiting patrons simply setting up a space to read. In conjunction with permanent furniture groupings, such as staff desks, large worktables, and main stacks, the library interiors are functional and flexible (Levinson, 2008).

In keeping with the goals of a sustainable built environment, the design team carefully selected locally sourced and recycled content materials wherever possible. Interior walls are clad in Straddling's light wood peg-board using recycled cotton insulation as a sound and heat barrier. The matte finish and inherently light color aid in reflecting natural light, while the offset-hole pattern allows airflow. An Armstrong suspended ceiling carries the pegboard panels, unifying the entire space. Locally sourced glazing from Cooks Arcadia Glass, and reclaimed stone from the site reduce environmental impacts from transportation (Levinson, 2009).

Artificial Lighting

The scope of this thesis does not include natural artificial lighting strategies, but it is notable to mention, in relation to fully integrated natural light. This thesis argues that natural lighting should be considered first, and artificial lighting utilized as enhancement, or employed when natural light is not available to extend facility operation hours. The design teams combined goals were to offer library patrons a comfortable and well-appointed space, while providing the city with a sustainable building.

Specific artificial lighting is located at designated task areas; this lighting supplies a minimum foot-candle during all hours. Affixed to each of the permanent stacks, linear fluorescent lighting provides vertical foot-candles, at each shelf. Moveable track lighting and pendant fixtures allow low cost space-planning reconfigurations. The tracks, mounted in between peg-board ceiling panels, supply versatile moveable pendant location, along swag style cord sets.

Permanent desk lamps are a final layer of task lighting allowing individual occupants and staff to turn on or relocate specific table light.

The resulting flexibility in complementary, artificial lighting allows individual area square footage, library material stacks, or simply furniture quantity to be reduced, enlarged, or relocated without major renovation.

Conclusion

The preceding case study identified 3 primary areas for further research within this thesis. As outlined in Chapter 3 these areas were visited at multiple times during the day and identified holistic daylight integration. Key architectural and structural elements emerged the preceding literature review of Arabian Library. These elements, and the surrounding interior environment are analyzed through the filter of three parameters described by Plummer. Data is organized and collected in the following section. Phenomenological data is collected in visual notes and organized in the following section.

Section 2: Phenomenological Ethnographic Observation

Introduction

This section organizes the data collected during three months of phenomenological ethnographic observation. Based on the preliminary case study four specific areas of research were identified. Observations of the four areas were collected on site in series of visual notes, recorded in sketchbooks and later digitally organized into graphic matrices. The digital matrix figures contain two types of drawings: analytical drawings showing how daylight is integrated within interior space, and observational perspective drawings recording the phenomenon of daylight as it enters the interior environment.

Guiding principles were used to limit the scope of research and the amount of data collected for each specific area. Each drawing was produced on site, reinforcing the phenomena of daylight as it occurs in the actual space, and unaltered by later corrections or additions. Because sunlight is in constant transition the amount and location of daylight changes as each drawing is completed. The drawings were completed in one hour or less, to prevent distortion of drawing content.

Methodology

The preliminary case study in the previous section of this chapter identified four specific passive daylighting strategies at the Arabian Library: low level side lighting, a traditional full height window, an inverted light well, and secondary daylight from an external source. These strategies have been historically used to harness and control. Each of these strategies is associated with a specific interior area defined in Table 2.

Table 2

Interior Areas Associated with Daylighting Strategies

Area 1: Self Check Out/ Help Desk: demonstrating low-level side lighting.
Mixed Use Area/ North Patio: demonstrating inverted light wells and low level side lighting
Main Reading Room/ Main Picture Window: demonstrating traditional fenestration technology
Central Courtyard: demonstrating secondary daylight sources

A solar impact study was conducted using a three dimensional model provided by the project designer, through an informed discussion. This study places a three dimensional digital model of the building exterior on top of a satellite map of the site, using free software provided by Google. The satellite map was set to July 14^{th} as an approximate date in the middle of the data collection time frame.

The satellite mapping software was set to different times of day in order to determine three ideal site visits representing the phenomena of daylight in each of the aforementioned areas. It was determined that the collection times of 9 A M, 12 Noon, and 3 P M adequately provided a glimpse of the transitional impact of natural light on the interior of the building. The results, presented in Table 2, provide a formula for persistent data collection.

Table 3

Preliminary Solar Impact Study

Time	Virtual solar impact study image using Google Sketchup
9 A M 7/14/2013	
12 Noon 7/14/2013	
3 P M 7/14/2013	

Following this method, each of four areas was observed at three separate times of day during a three-month period. The goal of this thesis is to provide a repeatable methodology for future related studies. This case study approach offers researchers a defined timeframe, to accurately document a finite amount of data. Most of the spaces were observed on different days, within the three-month time frame. This allows subtle variations in solar position to be included in the analysis of daylight integration. The limitation of three months prevents dramatic variations in solar equinox to impact the data collection. The data collection schedule is presented in Table 3.

Table 4

Data Collection Schedule and Calendar

	Area	Collection 1	Collection 2	Collection 3
1	Self Check Out/ Help Desk	5/16/2013	5/14/2013	5/17/2013
2	Main Reading Room	7/22/2013	7/23/2013	7/24/2013
3	Mixed Use	7/8/2013	7/8/2013	7/9/2013
4	Central Courtyard	7/24/2013	7/25/2013	7/26/2013

Limitations

Observational vs. Analytical Drawings

All of the data in section 2 of this study was collected on-site in the form of visual notes. Visual note-taking limits the amount of data collected in each image. The researcher made a conscious focused effort to depict the phenomenon of daylight entering space. Unrelated data was omitted from each drawing, strengthening the focus of each image. A complete set of drawings was created on site using sketches, sections, elevations, and detailed interior perspectives.

Each drawing was limited to a set timeframe and completed on site. Drawings were not altered after the researcher left the library, nor were additional drawings created from memory. All drawings were limited to one hour or less, to prevent distortion from moving sunlight. Two distinct types of drawings were created: observational perspectives and analytical details, recording the phenomena of daylight entering interior space.

Observational perspective drawings depict the subject, building strategies integrating daylight, exactly as it appears. The environment was not altered. The researcher found a suitable location to draw, usually in a seated position that captured the phenomena of daylight within the library setting. The frames of foreground, middle ground, and background were used to show the depth daylight entered the interior. Physical objects such as people, bookshelves, and ceiling planes were used to frame the content and subject of each observational drawing.

Analytical drawings use outside informational data to enhance the subject, and uncover deeper meaning. Each analytical drawing summarized the phenomena of daylight at specific times of day. The tools outlined in Chapter 3 enhanced each analytical drawing. Important information about the building structure was gleaned from satellite images, electronic measurement devices, and a GPS locator. This data was represented in the frame of visual notes, but was not observed as phenomena of the environment.

This method of collection is in contrast to the use of photography, which captures every aspect of the built environment. Drawings provide a precise emphasis on particular details, by enhancing specific subject matter without depicting every aspect of the environment. Photographs were however necessary to provide background for later on-site research.

The photographs provided in Section 1 of this chapter outline Arabian Library's strategic building designs utilized to integrate daylight. The use of photography is prohibited in the Arabian Library without permission. Sketching is not prohibited, and was actually encouraged by library patrons and staff during this study. This supports the goal of a repeatable methodology because this type of study to be conducted in a variety of building interior.

Holistic Lighting Principles: Filters for Data Collection

Three guiding principles were applied to filter the subject matter and limit the amount of information collected: *Canalization* "the channeling of light through a hollow mass". *Procession* "the choreography of light for the moving eye". *Luminescence* "the materialization of light within physical matter…objects imparted with a sense of life through contact with the sun (Plummer, 2009). These principles were selected from the research of Henry Plummer studying the many effects of lighting in contemporary buildings. His book, *The Architecture of Natural Light, 2009*, specifically considers the quality of daylight.

These holistic principles identify historically relevant aspects of solar architecture outlined in Chapter 2 of this thesis. The work of Alvar Aalto demonstrated a concentrated effort to maximize the canalization of daylight within space. Le Corbusier was particularly astute at incorporating the procession of daylight in his designs. Antonio Gaudi harnessed luminescence as a design feature by carefully selecting surface finish materials.

Following a specific pattern the three guiding principles were considered for each of the four interior areas within Arabian Library. Beginning with the site orientation each area was observed at 9 AM, 12 Noon, and 3 P M. Drawings were labeled according these classifications: A site orientation, B building structure, C interior landscape. Each drawing was configured with a time and date stamp in the upper corner as a graphic sundial. The arms of each dial related to the time of day, respectively 9, 12, or 3 arms affixed to each dial.

Area 1 Self Help/ Check Out Desk

Overview

The self-help and circulation desk area of the library is the central hub for library staff, patrons, and materials. Self-service kiosks augment a traditional librarians desk, surrounded by new materials and merchandise for sale. The area is located directly across from the main entrance and is designed for constant movement and transition of building occupants. There is no seating provided in this area, permanent desks and low shelving define pathways.

Canalization

Daylight enters the space through a long glass wall partition encompassing most of the east elevation. This wall is a part of the three-sided glass partition discussed at length in area 4. The interior space is closely related to the central courtyard. The courtyard acts as a daylight collection center; bouncing light off adjacent walls and bright colored hardscape, back into the interior volume.

Considering the location of this area in Figure 16, the integration of daylight within the interior volume is completely dependent on the central courtyard. The central checkout would not have access to daylight using a solid roof building typology, because it is in the middle of the floor plan. The courtyard distributes light back into the interior through two features, described in Figure 18 direct daylight and bounced secondary source. The direct component is limited to the early morning hours, because the windows stop at approximately 8 feet above finished floor. After 10 am direct sunlight strikes the upper solid portion of the wall and is partially shaded.

The shape of the eastern wall, shown in Figure 18, further enhances and controls integrated daylight. The wall is slightly angled at 3 degrees, allowing more early morning daylight to enter the space, but also allowing more daylight to bounce back into the upper volume of the interior.

Bounced, secondary daylight is a completely unexpected result from the shape and location of the eastern wall. The preliminary case study suggests a greater morning component of daylight, with severely limited afternoon contribution. The exterior ground and wall surfaces reflect daylight, as a secondary source. The outdoor concrete is a light finish, glowing as the sun moves across the courtyard. Bounced light is most pronounced during the midday hours, as the direct overhead component of sunlight is most intense.

As the sun moves away from the courtyard, the preliminary case study also suggests the component of daylight is removed from the interior. Another unexpected result is the continued integration of daylight, collected from adjacent courtyard walls. The inside wall of the far eastern portion of the courtyard collects sunlight in the early afternoon, shown in Figure 17, Drawing 1B-6. The reflected light impacts the interior directly, by bouncing back into the space, and indirectly by providing a visible glowing object at distance.

Procession

This area is a central hub for library materials, checked in and out by patrons and relocated within the building by staff. Views out into the central courtyard are very important to this space. The view provides a constant transition from darker interior space, to brighter exterior space. This phenomenon of daylight offers patrons standing in line an interesting active environment, and also provides visual clues for way finding. Because daylight enters the space behind library staff, a constant backlight draws attention to the circulation desk.

Area I is accessed through the main entrance, directly across the central courtyard. Patrons meander through a series of outdoor spaces the look directly onto the large glass wall facing east. In this manner patrons can see into the building, and the space they are about to enter while still outside. This creates a strong connection between indoor and outdoor space, and gives clues to the source of illumination inside.

Procession of daylight benefits the activity of checking out books, asking for help, and generally waiting in line. All of these activities, performed by patrons, face directly into the outside courtyard. The outdoor area provides daylight as well as pleasant views to the interior. Moveable furniture, landscaping and shade draw patrons to the courtyard, even in the hot summer months. Outdoor occupant activity has a benefit providing patrons with something interesting to look at, while waiting in line.

Daylight also positively impacts the new materials and merchandising section of the library. Part of the building program, discussed in the preliminary case study, is the to give the library a modern bookstore feeling, characterized by open shelves and a café. Arabian Library not only offers items for sale but showcases new materials and monthly items of interest. The procession of daylight plays a key role in the interaction of this area, with passing patrons. Because the shelves are aligned perpendicular to the east window wall, daylight streams across the new material on display. At any given time of day the sun hits different spots, highlighting many different shelves.

There is evidence of unwanted glare at the permanent staff help desk location. The windows surrounding this desk are heavily tinted, suggesting that the glass was altered after occupancy. In the early morning hours the sunlight directly enters the space, but by 10 or 11 am, the sun is partially and then fully blocked by the building structure. The preliminary case study suggested a comprehensive strategy, the library opens at 10 A M on most days and is not open to the public in the early hours. Since the area would not be in use, early morning glare is not a problem to visiting patrons. The staff desk location, however, suggests this space is occupied during the morning hours; librarians often sort books and prepare for the day. This explains the need for dark tinting on the glass behind the staff desks.

This area is a transitional space, other than the staff location there is no seating provided. A main corridor connecting the entrance to central stacks running along the display and shelving set ups. Daylight offers especially useful illumination at the ground floor. Early morning daylight streams across the main walkway, well past noon. In the later afternoon hours secondary light is also visible along the ground plane. The impact of this available light makes the floor brighter than the adjacent library interior. This allows time for adjustment to lower interior lighting levels, giving patrons entering the space a chance to acclimate.

Luminescence

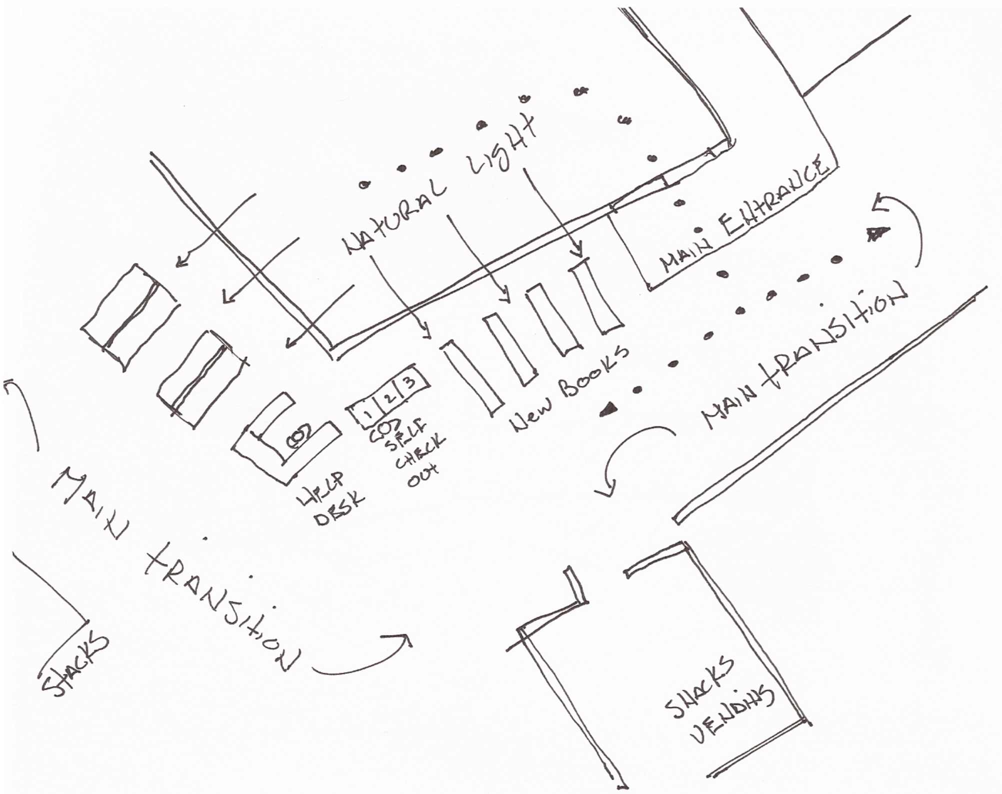
The furniture fixtures, and finishes of Area 1 reflect natural light deep into the interior space. Lighter colored materials with carefully selected matte and diffuse surfaces greatly increase the ambient light within the space. This is most pronounced in Figure 20, the observation drawing shows heavy contrast between walls and floors.

Daylight also bounces high onto the walls, and deep within the space due to the pressed wood panels enclosing the walls and ceiling. These panels are further explained in Figure 24, drawing 2B-3. A series of 1/8" holes are punched into the wood panels. The holes absorb some of the light, while reflecting the majority back into the room. This offers gentle control for direct glare, but has an opposite effect on angled light striking the walls and ceiling at angles. In combination with the matte surface finish, the wood panels actually reflect light deep within the space.

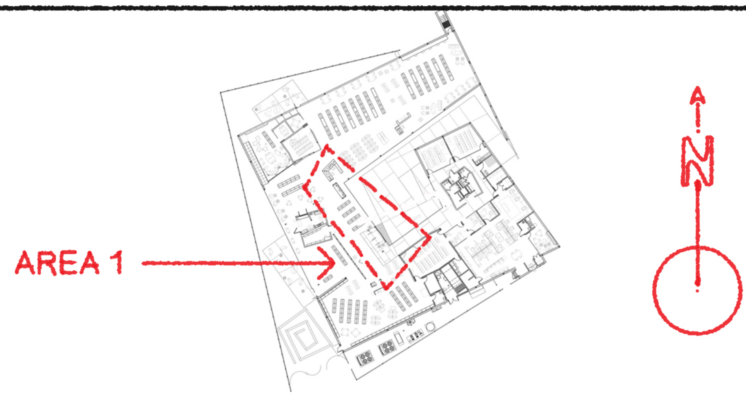
Over time these wood panels have settled, giving the surface a shimmer and shine evidenced in Figure 20. Daylight entering the space causes this static material to glow and actively shine throughout the day. Because the daylight is in constant fluctuation, and because it is affected by moving clouds, and affected by the regular position of the sun at different times of day, seemingly plain wood panels are latent with life.

Based on the analytical drawings in Figure 17 the researcher anticipated dark ceilings after the midday sun had passed over the top of the courtyard. The analysis in Figure 18, however, shows that daylight enters the space high across the ceiling well past Noon, reflected up off the floor. The subtle impact of reflected secondary light from within the courtyard is unmistakable when a more detailed observation drawing is completed (Figure 19). Because the floor surface is light in color daylight is reflected up onto the ceiling. This in turn flows deeper into the interior space because of the high ceiling, and open floor plan. Together these three elements support luminescent daylight integration.

Another luminescent material is the frosted glass panel affixed to the back of each self-serve station. Detailed in Figure 18 these panels appear to be a retrofit design, controlling glare evidenced by the window tinting on adjacent glass. The panels are highly effective at keeping direct glare off of the task surface at each kiosk; computer screens face forward and are not affected by glare. An unexpected result at these stations occurs after midday, when the panels retain an ambient glow from secondary patio light. During these times the glass panels draw the eye, by effect of surface frosting. This subtle cue supports way finding in this area, acting as a signal to patrons passing through.



Drawing 1C-1: Interior Furniture Floor Plan Not To Scale



Drawing 1C-2: Overview Floor Plan with Area Location Image: Richard and Bauer Architecture (2007). Floor Plan of Arabian Library. (ArchDaily, 2013)

Area Summary:
Located adjacent to the library enterance, the Central Materials Checkout Desk includes self-serve kiosks, traditional circulation desk, help desk, new library materials and retail. The area is adjacent to a small café with vending.

Figure 16: *Area 1 Main Help and Circulation Desk. Analytic overview and visual note matrix.*

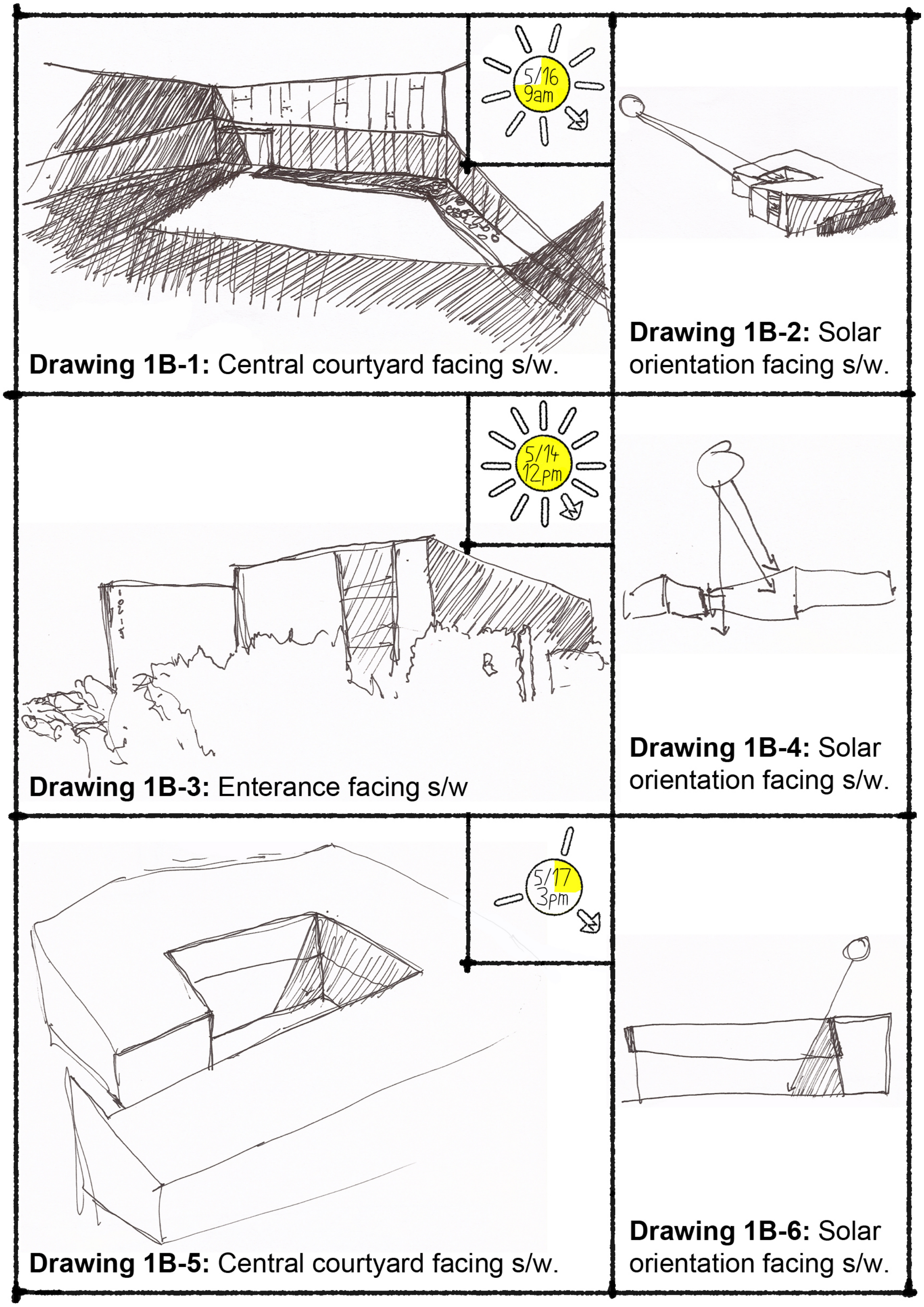
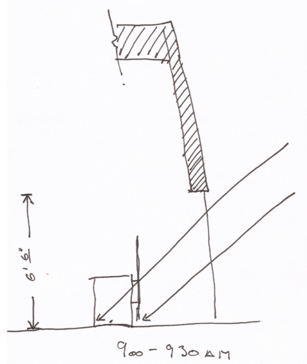
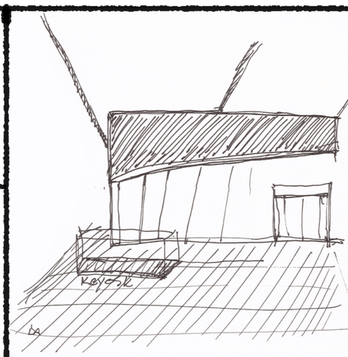


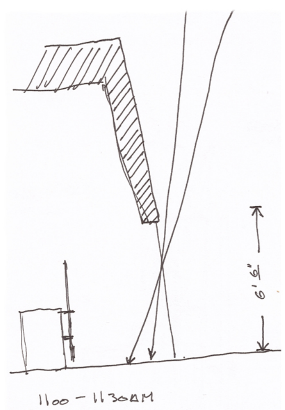
Figure 17: *Area 1 Site and solar orientation. Analytic visual note matrix.*



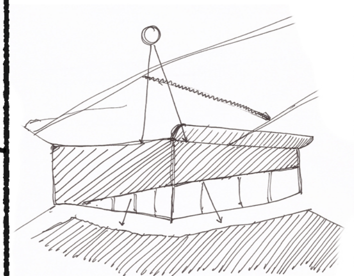
Drawing 1B-7: Interior section facing North./ Direct daylight./ Window wall at Self Checkout.



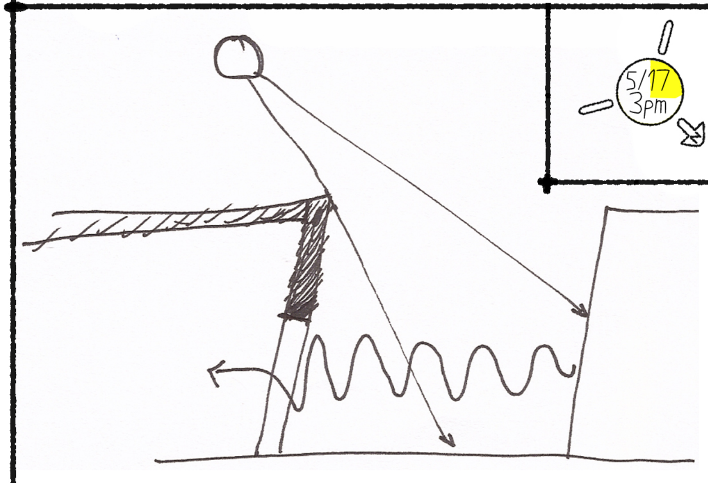
Drawing 1B-8: Interior perspective shadow study facing east



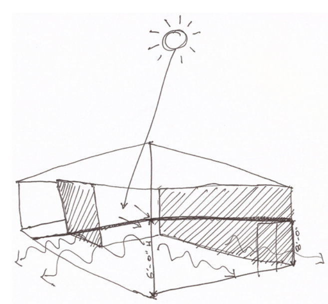
Drawing 1B-9: Interior section facing north./ Obstructed daylight./ Window wall at Self Checkout.



Drawing 1B-10: Interior perspective shadow study facing southeast.

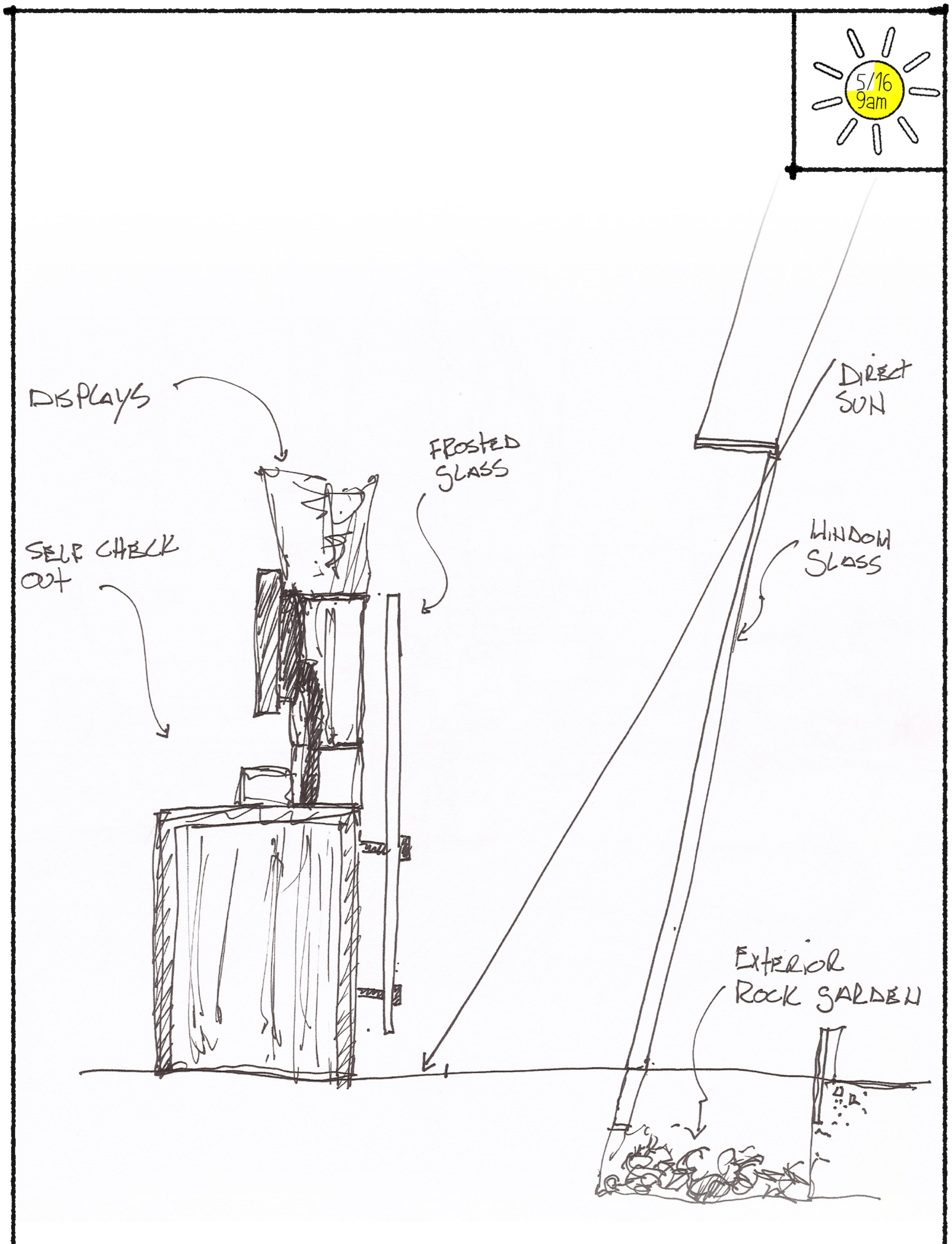


Drawing 1B-11: Interior section facing north./ Bounced daylight./ Window wall at Self Checkout.



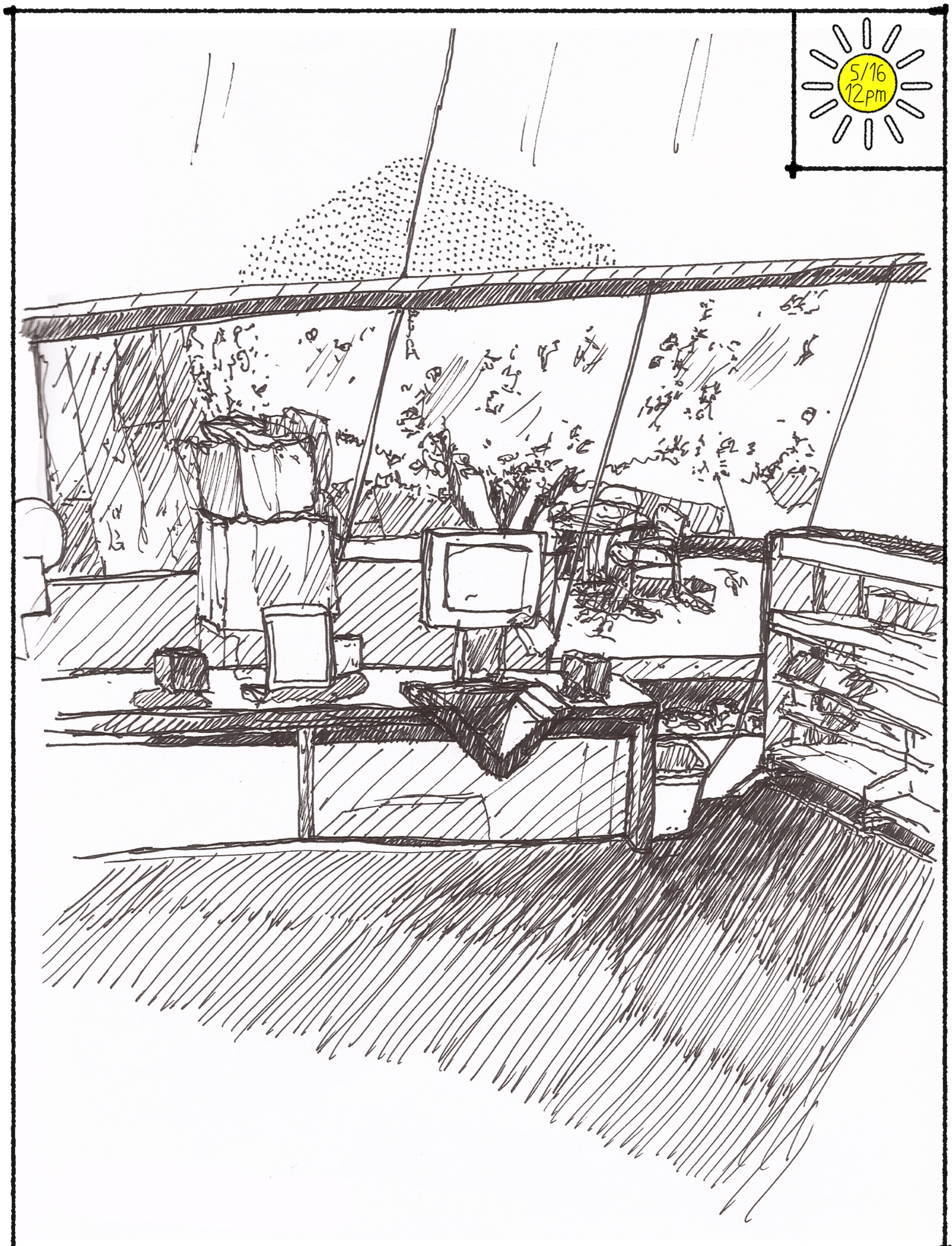
Drawing 1B-6: Solar orientation facing s/w.

Figure 18: *Area 1 Architectural features integrating daylight. Analytic visual note matrix.*



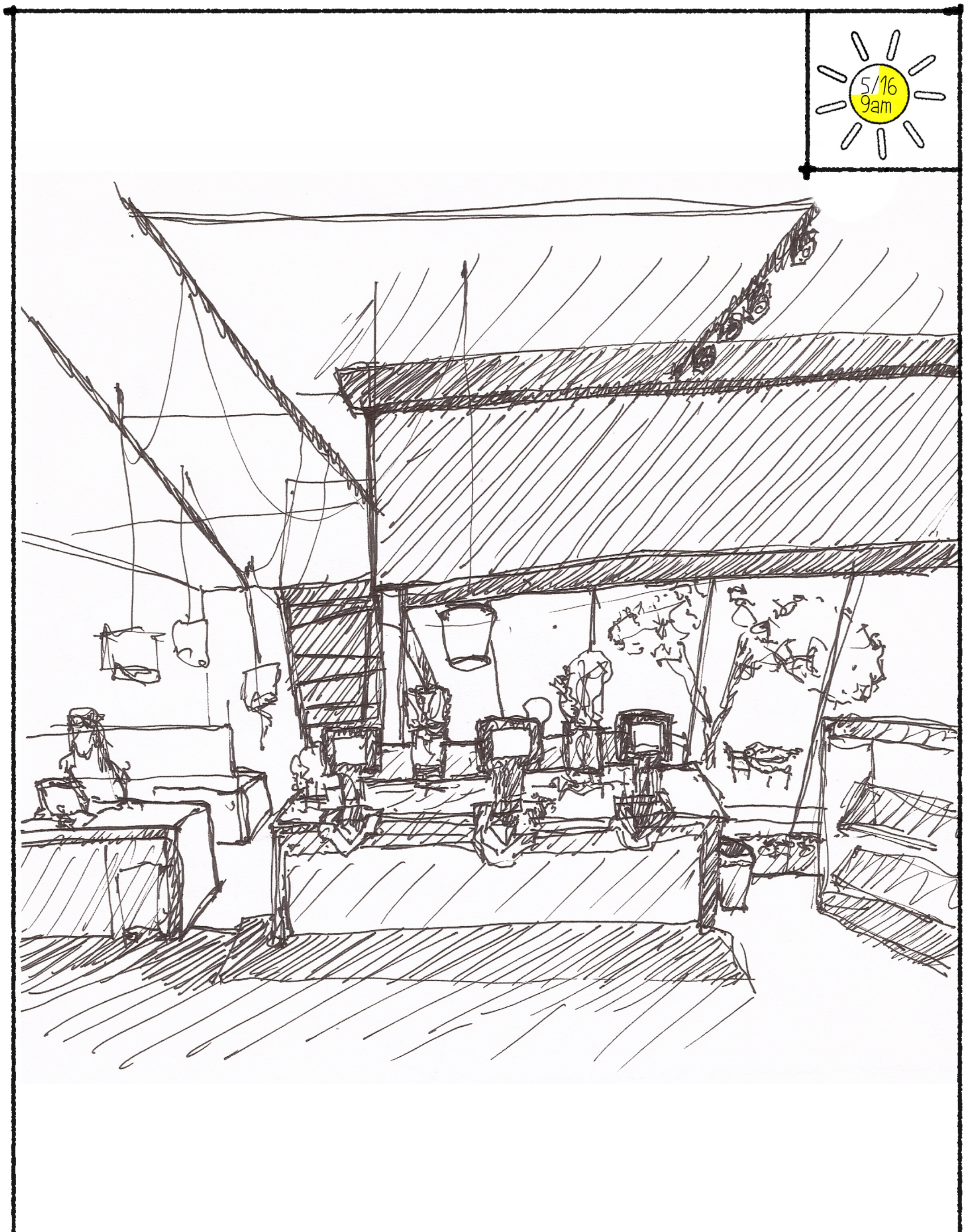
Drawing 1B-13: Enlarged interior section detail.
Facing north at 9am 5/16/2013

Figure 19: *Area 1 Architectural feature at Self Help kiosk. Analytic visual note.*



Drawing 1C-3: Interior Perspective facing east on 5/16/2013 at 12 P M.

Figure 20: *Area 1 Interior observation perspective. Architectural features integrating daylight.*



Drawing 1C-4: Interior Perspective facing east on 5/16/2013 at 9 A M.

Figure 21: *Area 1 Interior observation perspective. Architectural features integrating daylight.*

Area 2 Main Reading Room

Overview

The main reading room is located in the upper northeast corner of the building. Here a full-height picture window runs from floor to ceiling and halfway across the room. The reading room houses light, moveable lounge chairs, sofas, low tables to form informal reading areas and a long row of large fixed study tables. Along the north wall a fixed concrete bar houses electrical outlets and desk lamps for laptop users. The room is split into two distinct halves. The southeast portion is fully exposed to daylight, and specifically oriented to focus occupant's attention to adjacent views and natural landscape. The northeast portion has much less daylight entering the space.

Canalization

Daylight enters the main reading room through a large window, facing northeast, offset to one side. The window is constructed of clear glass and simple aluminum framing with no window tinting. Early morning daylight enters the space directly until just after noon, at this point the building blocks the direct component. Through the afternoon a diminished amount of bounced light enters the space, there are no adjacent structures to bounce light back into the space.

The room has a steep level change approximately 4'-0" between interior seating areas and outdoor landscaping, shown in Figure 24. This level change dramatically impacts the amount of daylight entering the space. By sinking the interior further below the outdoor grade, daylight enters at a higher angle, and effectively strikes the ceiling plane.

The outdoor landscaping immediately adjacent to the window plays a key role in controlling the amount of light entering the space. A large palo verde tree sits directly in the visible spectrum of sitting and standing occupants, shown in Figure 24. This level change allows daylight entering the space to be slightly tempered by seasonal changes. Arabian Library is located in the Sonoran Desert, but there are distinct rainy seasons, and dry seasons impacting the size and fullness of each plant. During a rainy July and august, plants and trees can become lush, green, and full.

Daylight is also channeled back into the space through the unique phenomena of views at a distance. All day long the tall mountains to the east are in direct sunlight. Long after the sun has moved over the top of the building, and past the vertical plain of the full height window, as shown on Figure 24, daylight can still be detected within the interior. When sitting, standing, or walking through the space the human eye is drawn to the glowing surfaces of the mountains and surrounding landscape, as shown in Figure 26. The window only allows a short period of direct daylight, but delivers contribution throughout the entire day.

Procession

The main reading room is a final destination for library patrons. The interior landscape is designed as a path leading through areas with progressively reduced social activity. Beginning with the entrance and check out, patrons move through small group discussion and public computer terminals toward a designated quiet area. The central stacks are adjacent to these quiet study tables and comfortable seating, utilized by a mixed group of adults. Physically navigating from the parking lot into the main reading room reinforces the procession of daylight across this space.

There is only one full height window of this type in the library, which is visible upon arrival at the main parking lot, Figure 27 Drawing 2C-6. Visiting library patrons typically park and walk directly past the picture window, offering a glimpse into the main reading room. This window comes into closer view as patrons meander through the locking entrance gate Figure 37.

The first phenomenon of procession in this area is the physical connection between indoor and outdoor spaces, and the memory of external lighting conditions. Because patrons follow a path from their car to the interior seating area, there is a connection between the two spaces. The human eye can move from local task surfaces, to adjacent parking spaces and landscape, out to serene mountain views at a distance, and then back to the local work surface. This provides a continuous array of daylight from within the interior space.

The second phenomenon of procession involves the distinct levels of light in the space, split in half by the offset window location. It is important to note the children and teen reading areas, but a discussion of occupancy is not included in the scope of this study. These areas branch off from the main entrance funneling age groups into interior spaces specifically outfitted for age specific social activity. The main reading room is open to all ages, but through the selection of materials and furnishings, the space bears evidence it is intended for a mixed adult user group.

Digital natives and traditional text material users make up this age group, according to the preliminary case study. This population is reflected in the split configuration of the main reading room. Half of the room is windowless, with a long fixed bar hosting electrical outlets and desk lamps. This area is obviously provided for portable computer users. Conversely the large quiet study tables, hosting 4 seats each are located directly in the path of direct morning sun and ambient reflected sun, into the early hours of 1:00 P M. Glare is a concern to computer users, where it may be unnoticed to traditional text readers. Rather than configuring the window in this space to control glare, the solution is to offset the location to one side, providing a specific area for either reading task.

An unencumbered window is important to mention, it fully supports the integration of daylight procession from exterior view. Artificial light sources are installed throughout the library to provide interior task lighting. The contribution of daylight specific to tasks, such as providing light directly on the tabletops, varies dramatically. Once the early morning sun repositions atop the structure, the contribution wanes. But the bright, visible impact of the exterior landscape is fully accessible to the entire room all day long.

Anyone sitting in this reading room, during the hours of daylight, has immediate access to natural light. Patrons sitting at the computer bar can simply turn around and enjoy a relaxing shift in light quality by peering out of the window. Occupants sitting at the tables can simply look up, when facing to the east. The general ambient quality of light, best demonstrated in Figure 24 drawing 2B-8, also completely fills this space. Because of the intentional level change, daylight entering the space strikes the ceiling plane high and penetrates deep.

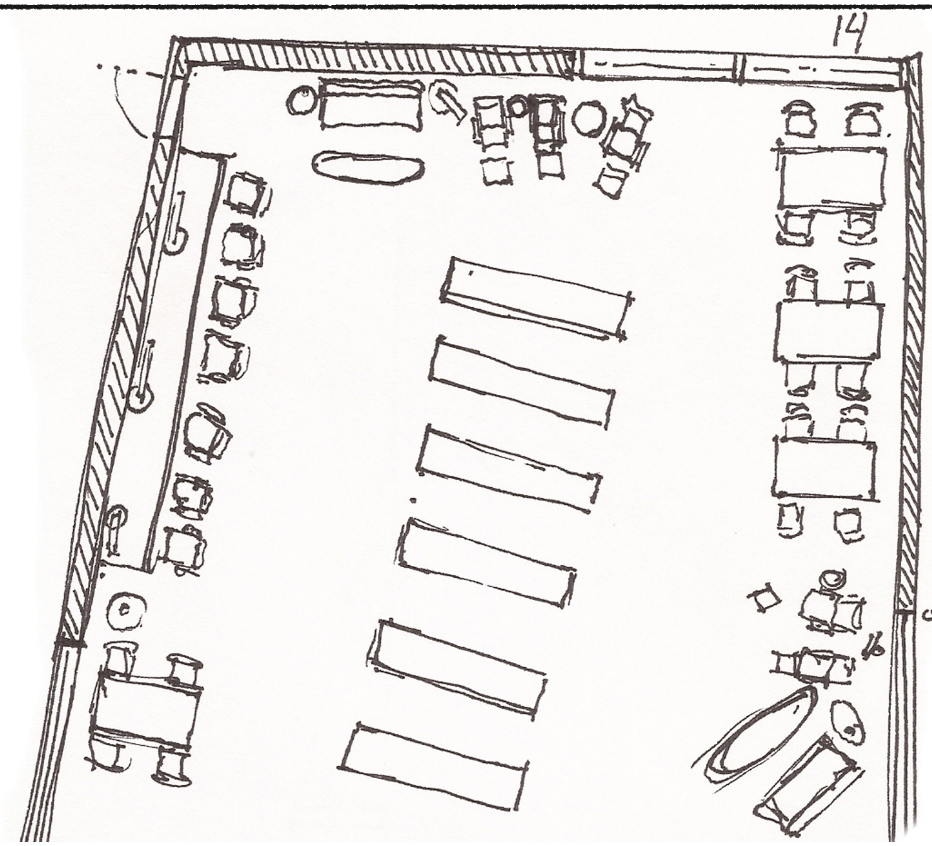
Luminescence

The materials used throughout this space are similar to those described in Area 1. Lightly colored carpet and furniture impacts the contribution of daylight, reflecting ambient light within the interior space. The matte finish wood pegboard used as a continuous wall and ceiling finish have the highest impact on daylight integration in the main reading room. The surface absorbs and reflects daylight across a large unified surface.

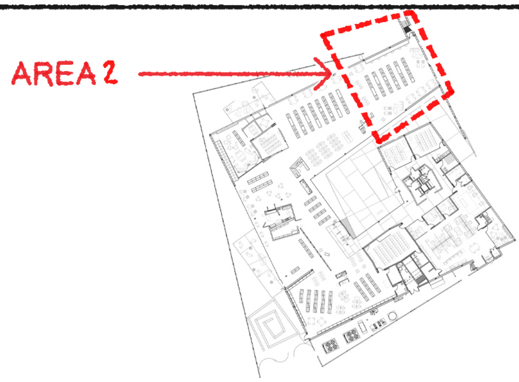
The wood surface has settled into place slightly altering the surface quality of each panel. Described in Figure 25, the panels are 4' by 8' sheets of wood affixed to the walls and ceiling in an angled pattern. The result is a constant play of daylight, reflected artificial light, and reflected light from furniture, furnishings and occupancy.

The geometry of the room is much different from the full glass partition wall found in Area 1. The main reading room has approximately 20' high ceilings, an open floor plan, and one offset window. The result is a dramatic luminescent ceiling surface, and changing subtle light high on the interior walls. As show in the interior observation perspective Figure 26 the eye is constantly drawn an up the wall.

The exterior view is very much a part of this interior space; it is clearly visible from all parts of the main seating area. Lowering the interior room places the outdoor view directly in the visual plane. This draws immediate attention from seated and standing position. The luminescent quality of the outdoor landscape, and directly adjacent hardscape should be considered an aspect of the interior, because of proximity. As explained in the series of analytical drawings in Figure 24 and 25, changing seasonal weather affects the growth and visibility of exterior landscaping. This in turn changes the interior view of nature, specifically considering brightly colored tree blossoms. The quality of daylight entering the space may also be impacted by the existence of dense foliage. The overall luminescent quality of the distant mountains is also present within the interior space.



Drawing 2C-1: Interior furniture floor plan. Not to scale.



Drawing 2C-2: Overview floor plan with area location. Image: Richard and Bauer Architecture (2007). *Floor Plan of Arabian Library.* (ArchDaily, 2013).

Area Summary: Located at the far north end of the library the Central Reading room offers large study tables, group seating, and moveable lounge chairs with ottomans and tables all around one large window. Area 2 is used for quiet study, with a long laptop bar in the darker north corner.

Figure 22: *Area 2 Main Reading Room. Analytic overview and visual note matrix.*

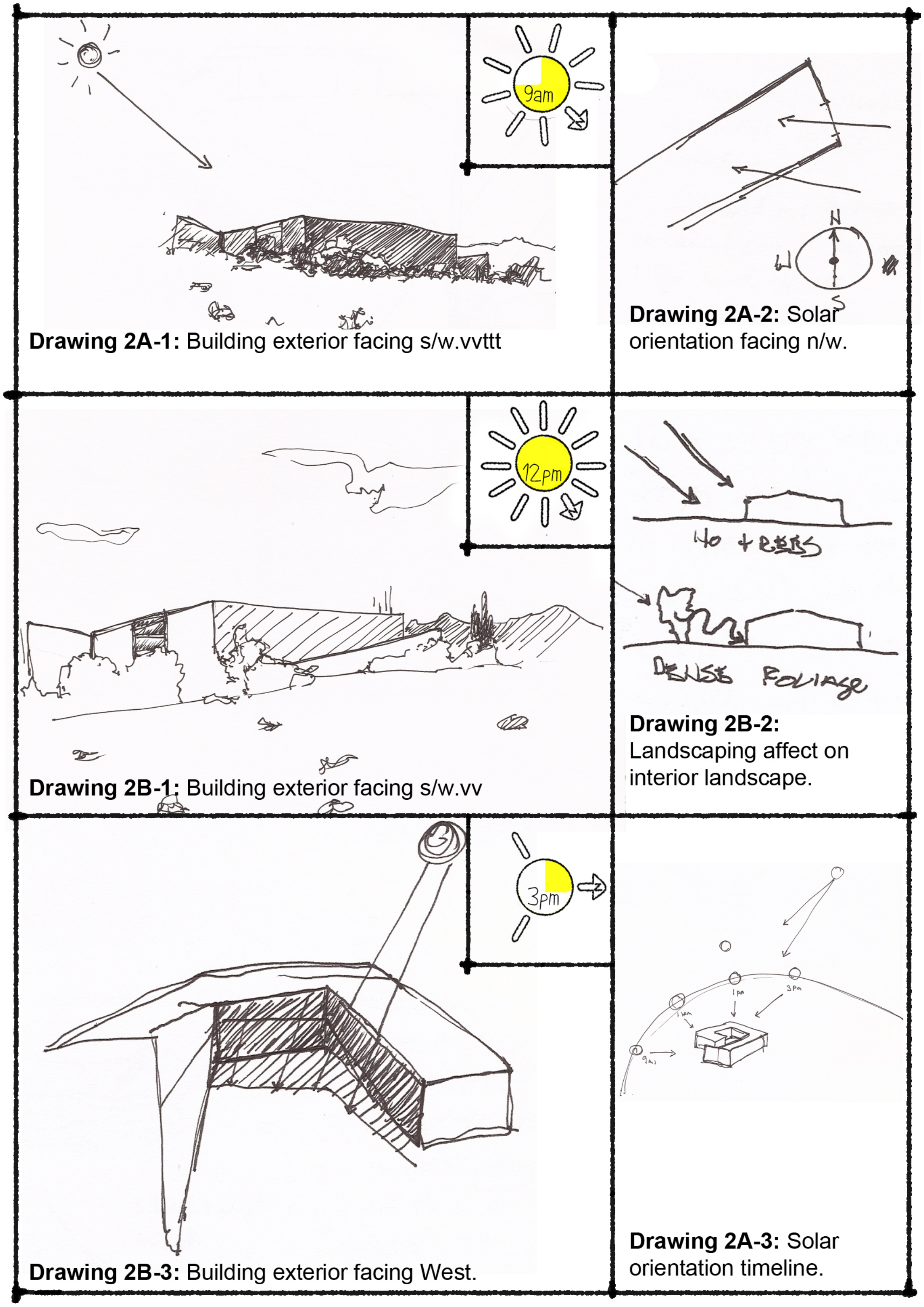
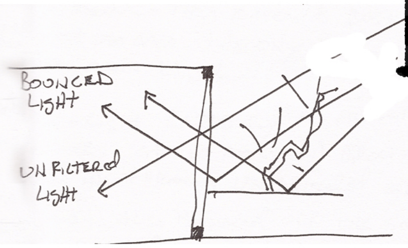
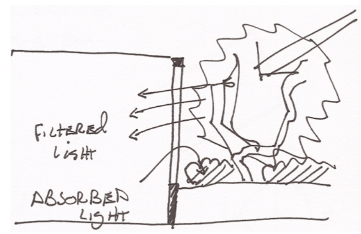


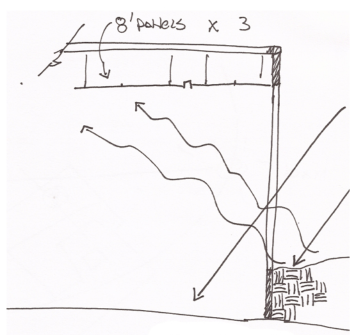
Figure 23: *Area 2 site and solar orientation. Analytic visual note matrix.*



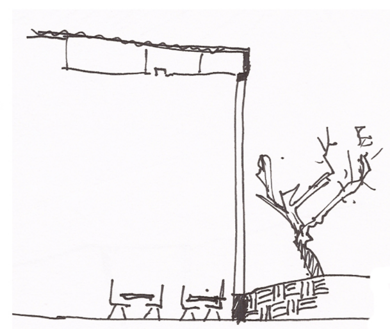
Drawing 2B-4: Building section facing north/ Effect of landscape selection on interior daylight.



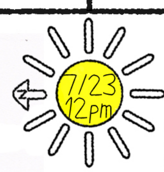
Drawing 2B-5: Building section facing north./ Effect of landscape selection on interior daylight.

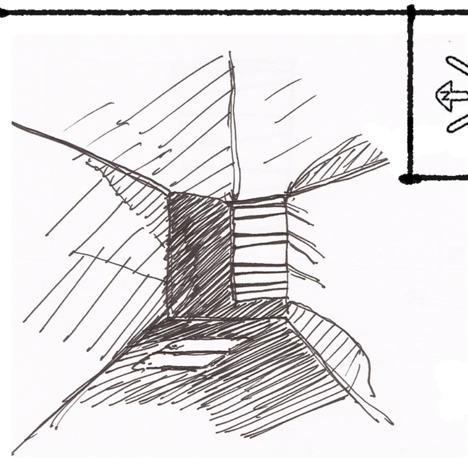


Drawing 2B-6: Building Section facing North/ Interior volume sunken below outdoor landscape.

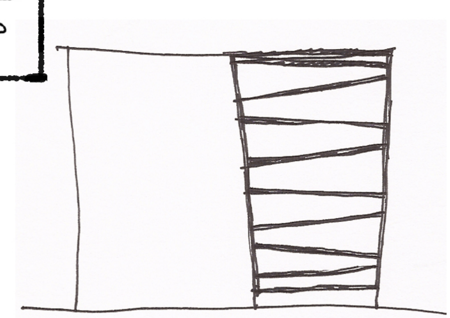


Drawing 2B-7: Building section facing north/ exterior trees in relation to interior furniture/ Direct view to nature.





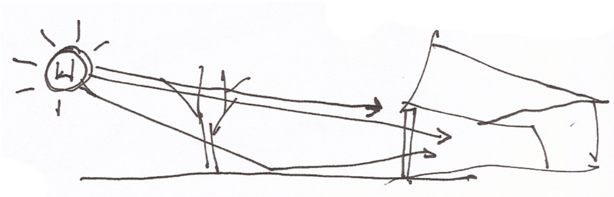
Drawing 2B-8: Interior Perspective facing east/ shadow locations in relation to offset height window.



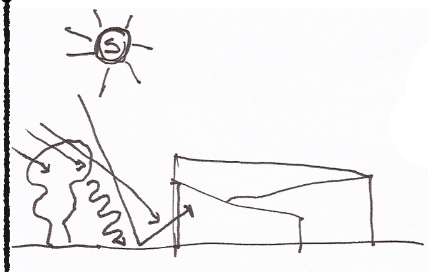
Drawing 2B-9: Interior elevation facing east/ offset full height window integrates daylight into half the space, regulates daylight in half the space.

Figure 24: *Area 2 architectural features integrating daylight. Analytic visual note matrix.*

Yearly Sun Angle Anaylisis

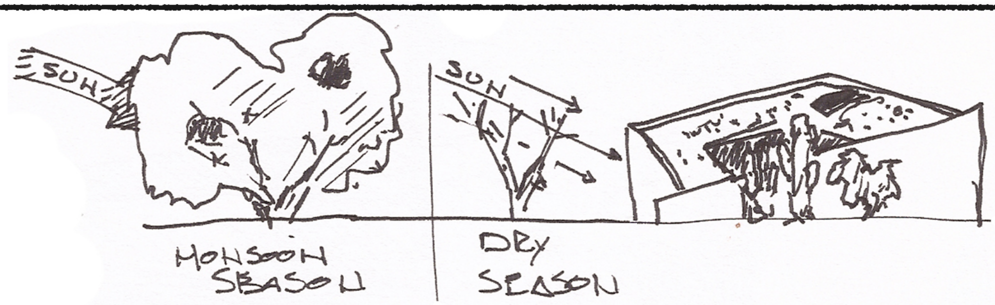


Drawing 2B-10: Building section analysis, proposed example of lower winter sun, with dormant tree.



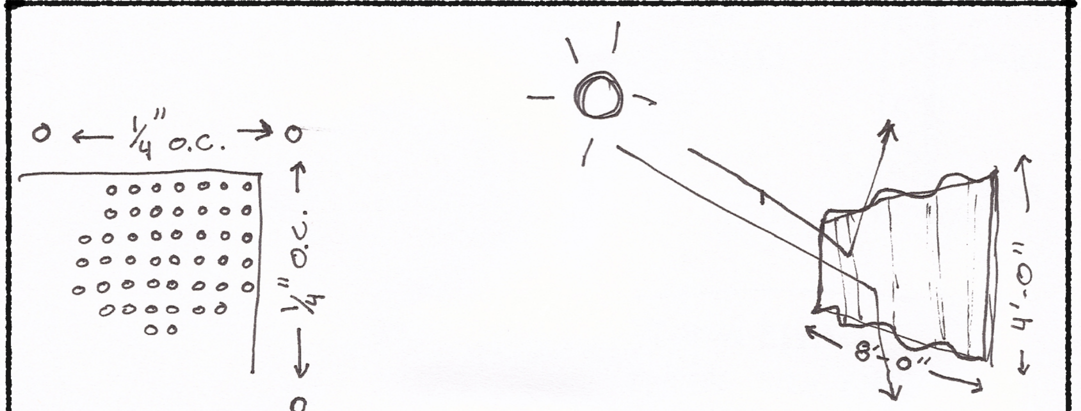
Drawing 2B-11: Building section analysis, proposed higher summer sun with active foliage tree.

Outdoor Landscaping Foliage Analysis



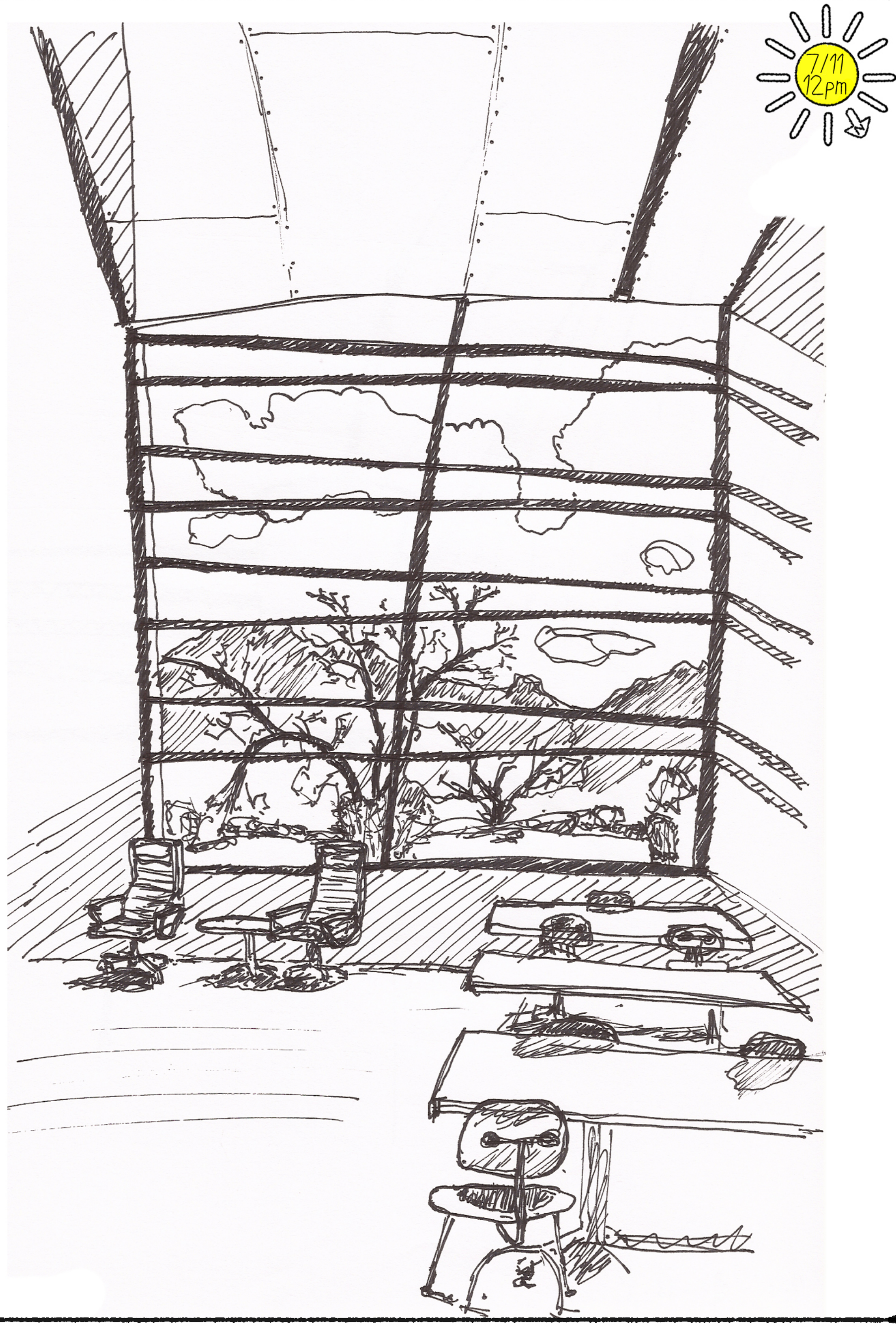
Drawing 2B-12: Building exterior perspective analysis, as mentioned in the case study Arabian Library is located in the Sonoran Desrt. Despite the name, this southwest region experiences a predicted rainy season and the native landscaping actually appears dense during part of the year.

Interior Materials Analysis



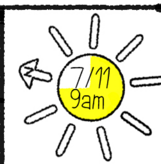
Drawing 2C-3: Interior wall surface details. Interior walls and ceilings are fitted with prefabricated light colored compressed wood pegoard panels. These panels have settled, giving an undualting surface. Typical hole pattern.

Figure 25: *Area 2 architectural features integrating daylight. Analytic visual note matrix.*

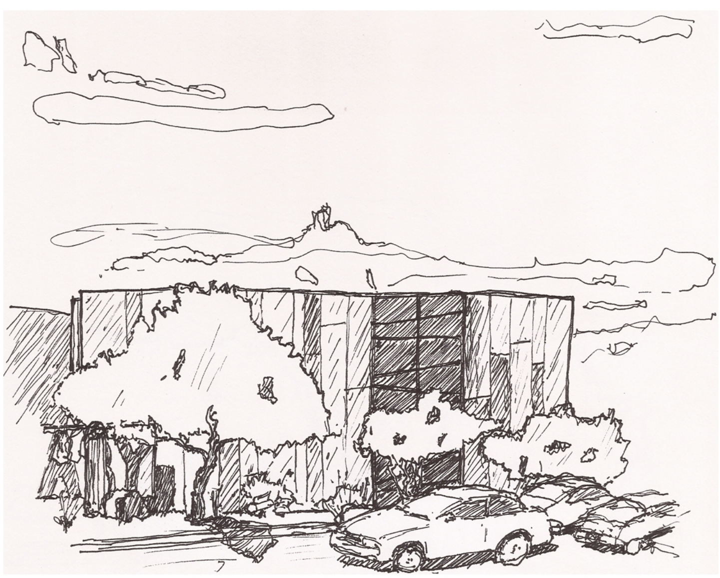


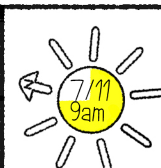
Drawing 2C-4: Interior Perspective facing east on 7/11/2013 at 12 P M.

Figure 26: *Area 2 interior observation perspective. Architectural features integrating daylight.*



Drawing 2C-5: Interior Perspective facing east on 7/11/2013 at 9 A M.





Drawing 2C-6: Exterior Perspective facing west on 7/11/2013 at 9 A M.

Figure 27: *Area 2 interior and exterior observation perspectives. Daylight contribution from landscape.*

Area 3: Mixed Use Reading Area/Enclosed Study Rooms/ Central Stacks

Overview

Area 3 is comprised of the central library stacks, large reading and small group meeting tables, and two separate enclosed spaces: a computer room and private meeting room. The area faces north/west, directly into McDowell Mountain Peak Parkway, a busy 4-lane street outlying neighborhoods as shown in Drawing 3A-1. A multi use patio acts as a shield from unwanted noise and views and offers occupants serene views into desert gardens and café style seating areas. The central stacks, private meeting room, and computer room are all independently illuminated using specific artificial lighting systems.

Canalization

Canalization occurs through three primary daylighting strategies working together in this space: low-level side lighting and a four-sided inverted light well top light above an enclosed computer room, and secondary daylight bounced from light colored site materials and a reflective Core-ten site wall surface of the adjacent patio. These three sources of daylight intermingle in different intensities throughout the day. There is no clear directional force form any one source, as the sun moves along its regular pattern each system of integration accept daylight differently.

The inverted light well appears to be a top lighting strategy at first glance, after closer observation, a deeper sophistication can be seen. The photographic images in section one of this chapter show a four-sided glass enclosure constructed from the roof of the interior computer and study rooms. The analytical drawings in Figure 30 show daylight high up on the interior walls. Due to the angle of entry, from above, direct daylight could not cause this reflection. Satellite images from Google Maps reveal the inside bottom of this light well (not visible from the interior) was painted white. Daylight enters the interior space directly through the glass sides, as well as indirectly from the bottom.

The low level side lighting strategy used in area 1 is repeated in area 3. A long angled glass window runs the entire length of the wall in this area. Detailed in Figure 33, large reading and activity tables are lined up along the window, with a walkway transitioning the private reading room and central library stacks in Figure 30. Because area 2 is in the northwest corner of the building, direct daylight does not enter through the sidelight until after 1 PM. This suggested another purpose for the location of this angled window feature.

Ambient secondary daylight is a key component of this area. An outside patio was created in between the site wall and building structure. The site wall not only blocks noise from the nearby roadway, it limits unwanted views into adjacent residential communities and the constant traffic. A lightly colored concrete slab and locally sourced ground cover materials provide an intense glow at midday. The patio area reflects muted daylight through the landscaping into the interior volume.

The patio and low level window configuration creates a glowing outdoor space that feeds into the interior volume. The height of the outdoor site wall is carefully aligned with the height of the angled window in the building. This alignment blocks late afternoon sun, as shown in Figure 29 Drawing 3B-4 and 3B-5. A shadow begins to form at the base of the wall as the sun moves from midday to late afternoon. This shadow continues to extend toward the building at 3 P M. The solid upper portion of the wall (above the angled window) blocks harsh direct sun from entering the space. The reflected ambient light is allowed to bounce in at the lower height of the wall. This creates a controlled integration of daylight and acts as a secondary light source impacting the interior volume.

Procession

There are two primary sources of daylight in area 2: top light entering the space from above and sidelight entering from the north. These two sources intermingle through the day as the sun moves across the building structure. The inverted light well not only allows direct daylight to enter, but bounces reflected sunlight from a hidden source. The patio to the north also introduces unexpected daylight, bounced back into the interior from the site walls. Together these transitional sources of illumination feed the human eye with activity and visual interest.

The reading tables along the north-facing wall are specifically impacted by the top lighting strategy. Patrons can look up or over at the high ceiling and walls to enjoy bright daylight without getting up from the tables. Daylight, shown in Figure 33, impacts the very end of the wall and cross illuminates most of the ceiling. Because the inside bottom of the light well is highly reflective, additional daylight enters the room at al times of day. The majority of light entering the space is due to the reflective paint. The direct component of this window is far less impactful, direct light only enters through the window at midday, and is partially blocked by the roof structure in the early afternoon.

The low level sidelights primarily let reflected light enter the interior space. The building structure is slightly angled at three degrees, away from the site wall. This slight angle allows the direct component of daylight to freely enter the space in the early afternoon. This angled wall feature greatly increases the amount of reflected light that enters the space. The site wall is perpendicular to the ground suggesting that the daylight striking the wall from Noon to 3 P M is actually collected by the low level side light, depicted in Figure 29.

The structural configuration of these sidelight windows provides important views onto the patio. From the seated positions along the wall, transitional walkway, and most of the library stack areas, patrons can clearly see out into the patio deck. This area is intensely bright between 11 AM and 3 P M. The solid wall structure, shown in Figure 29 Drawing 3B-5, mitigated unwanted glare. The site wall also enhances the side light strategy by blocking possible glare in the late afternoon, as the sun sets to the west.

Low Level sidelight windows bring daylight into the interior space. From any of the seated and standing positions library patrons can simply look out onto the bright surfaces of the patio, to experience daylight. Without changing seated position, the level of interior illumination experienced by the researcher, fluctuates from outdoor surfaces, to task lighting.

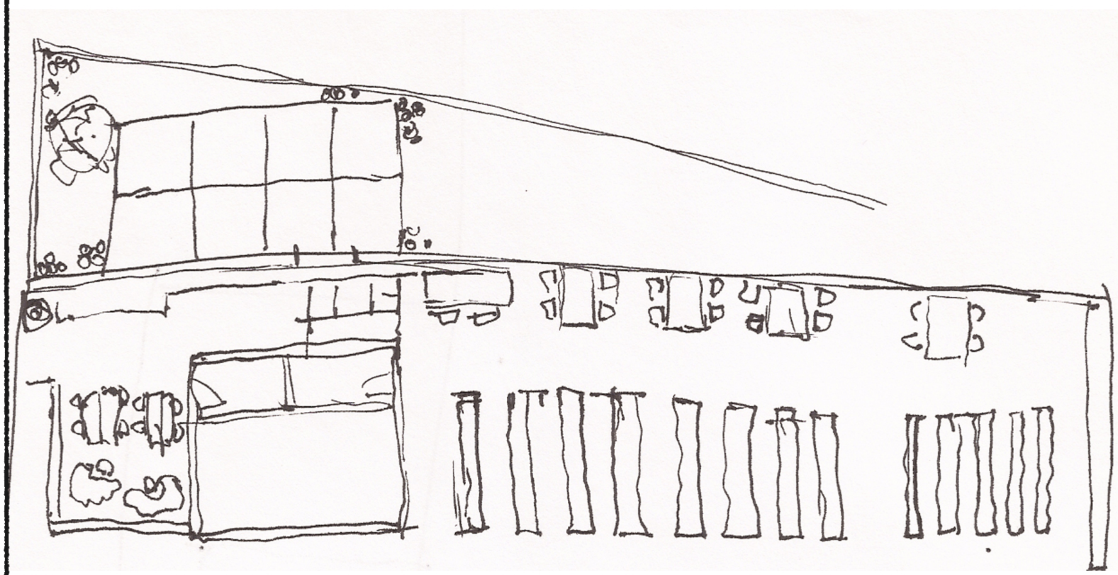
Luminescence

The floor wall and ceiling surfaces in area 3 are fitted with the same finishes found in Area 1 and 2: lightly colored wooden pegboard and carpet tiles. These finishes display the same luminescent quality described in area 2, because area 3 has a similar high ceiling. Daylight entering the space shimmers and shines across slightly warped wood panels that have settled over time. The surface quality is shown in figure 32 Drawing 3C-6.

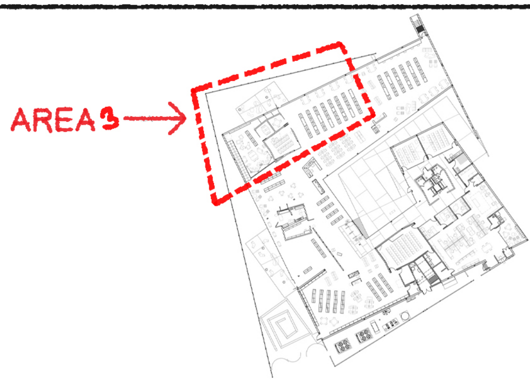
Daylight bouncing off the upper wall surfaces fills the room with energy, and makes the space come alive at different times of day. This daylight does not impact the task surfaces of the tables along the walls, because it is so high on the ceiling. While seated along the wall the presence of daylight is clearly visible. The result of this feature is the ability to look onto highly contrasting surfaces at will. Without leaving the seated position, several different daylight conditions are observed; direct light at the top and side light locations, reflected light along shimmering surfaces, and secondary daylight bounced low onto the ground.

Light colored carpet tiles are especially important in area 3 because the main transition between the patio and main reading room runs along the angled glass wall. Daylight streams into the room and across the ground plane, providing a well lit path throughout the day. As shown in Figure 32 daylight can positively impact the floor surface, without negatively impacting workstations. The tables are partially blocked by the solid portion of the upper wall.
The trees and walls enclosing the patio control direct light; unwanted direct daylight strikes these solid objects and is absorbed or deflected.

The materials selected for the outdoor wall surface, furnishings and hardscape provide a combination of reflective and glowing surfaces. These outdoor finishes are an important attribute of interior space. These materials are in close proximity to the row of seating along the window, and act as interior finishes. Natural rock and Core-ten steel mute and absorb daylight, while concrete slabs reflect daylight back into the interior. At any given time there are focal points within the patio area. Overall this area provides a combined effect of transitional light, visible to the interior space.



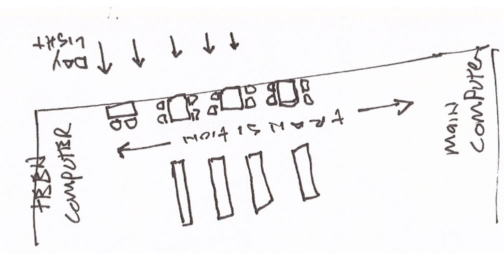
Drawing 3A-1: Interior furniture floor plan/ Adjacent outdoor patio. Not to scale.



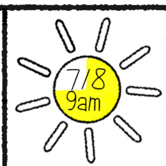
Drawing 3A-2: Floor plan with area location.
Image: Richard and Bauer Architecture (2007). *Floor Plan of Arabian Library.* (ArchDaily, 2013).

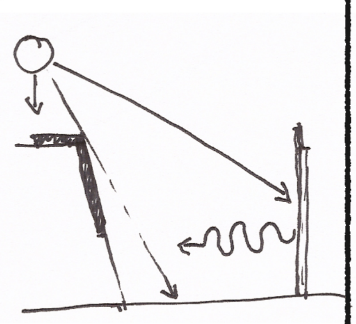
Area Summary:
Located at the far north end of the building this mixed use reading room and group study area joins the central stacks with private study rooms. This unique solution allows top lighting to feed the main room, while study rooms remain shielded.

Figure 28: *Area 3 overview and site orientation. Analytic visual note matrix.*

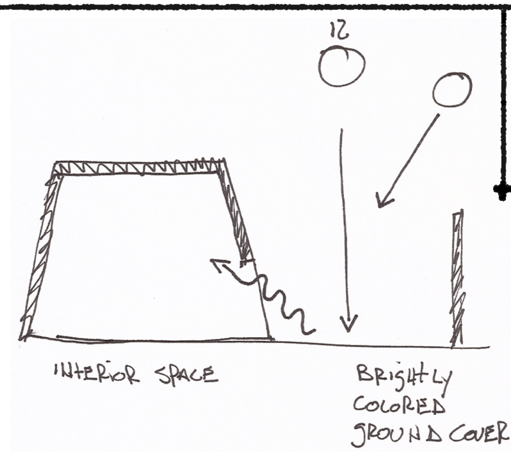


Drawing 3A-3: Interior space plan demonstrating daylighting./ Natural light feeds a walkway transition between functions.

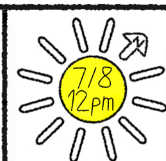


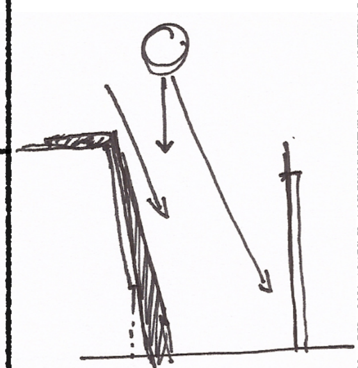


Drawing 3B-1: Section elevation facing n/w.

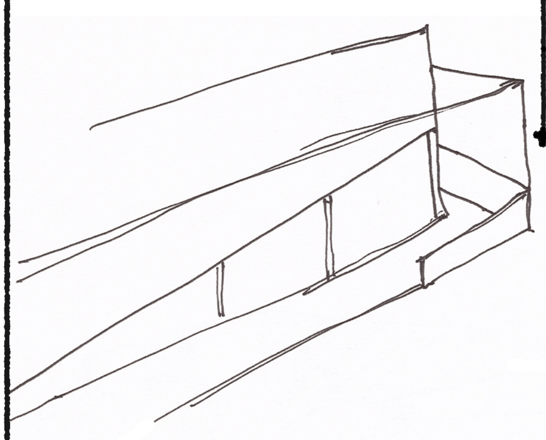


Drawing 3B-2: Indoor, outdoor section elevation facing n/w.

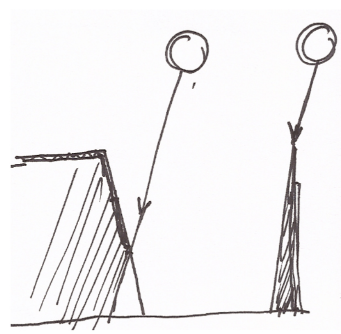




Drawing 3B-3: Section elevation facing n/w.

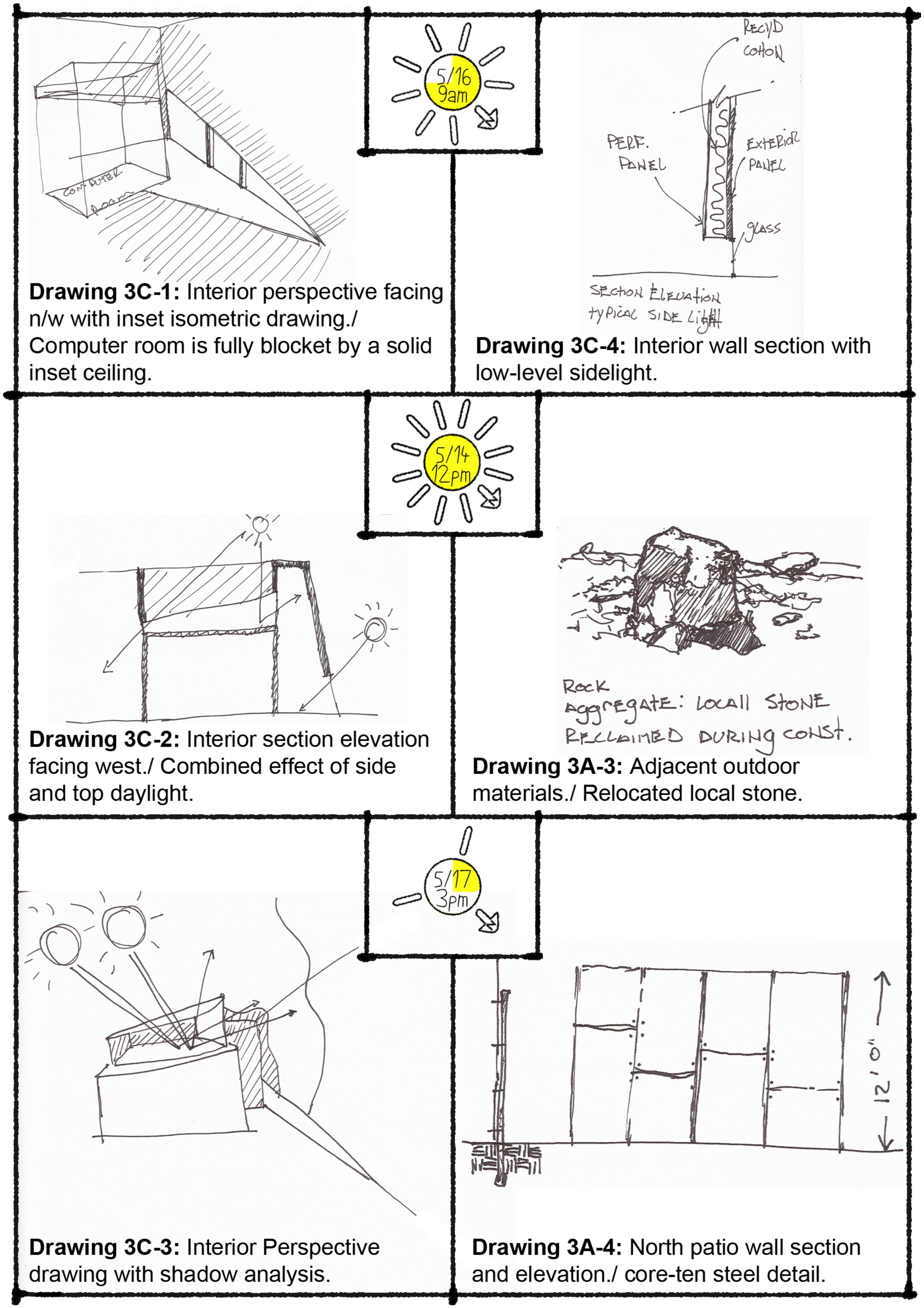


Drawing 3B-4: Isometric cut-away demonstrating air gap at north patio./ Outer site wall is a solid material up to top.



Drawing 3B-5: Section elevation facing n/w.

Figure 29: *Area 3 solar orientation. Analytic visual note matrix.*



Drawing 3C-1: Interior perspective facing n/w with inset isometric drawing./ Computer room is fully blocket by a solid inset ceiling.

Drawing 3C-4: Interior wall section with low-level sidelight.

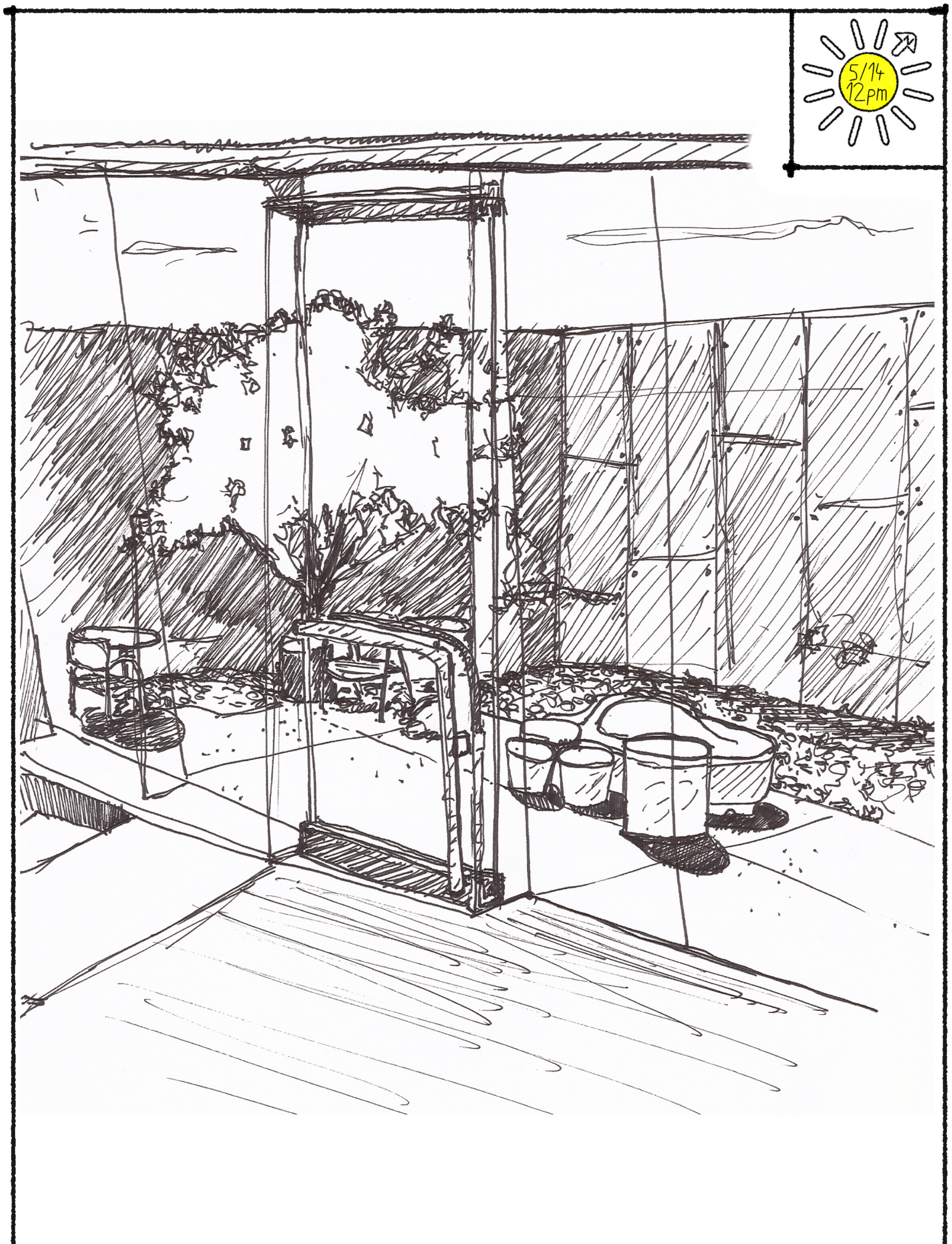
Drawing 3C-2: Interior section elevation facing west./ Combined effect of side and top daylight.

Drawing 3A-3: Adjacent outdoor materials./ Relocated local stone.

Drawing 3C-3: Interior Perspective drawing with shadow analysis.

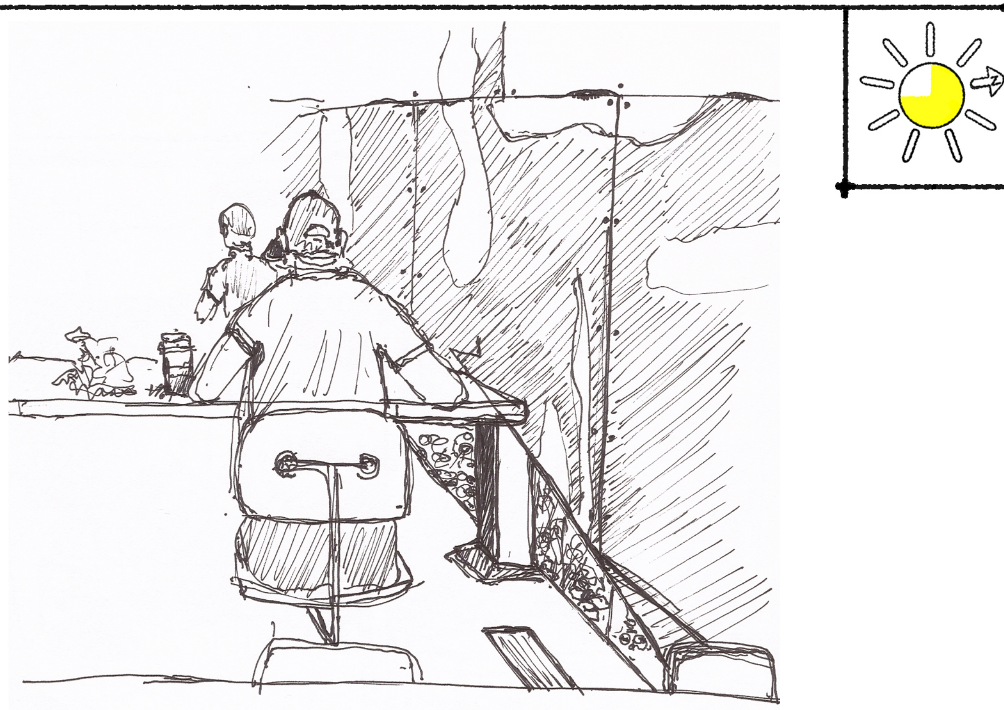
Drawing 3A-4: North patio wall section and elevation./ core-ten steel detail.

Figure 30: *Area 3 site and solar orientation. Analytic visual note matrix.*

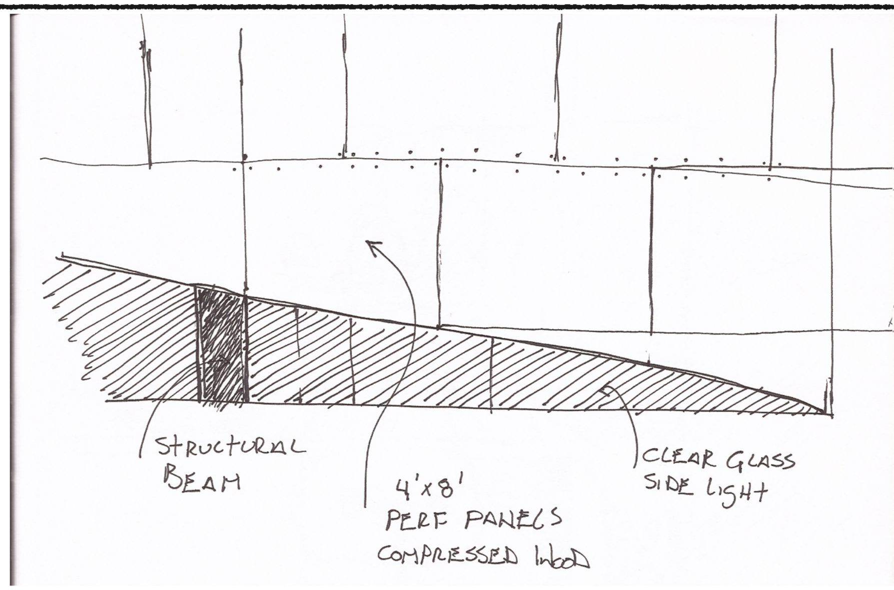


Drawing 3C-5: Interior Perspective drawing looking into adjacent north patio/ facing n/w at 12 P M 5/14/2013.

Figure 31: *Area 3 interior observation perspective. Daylight contribution from adjacent patio.*

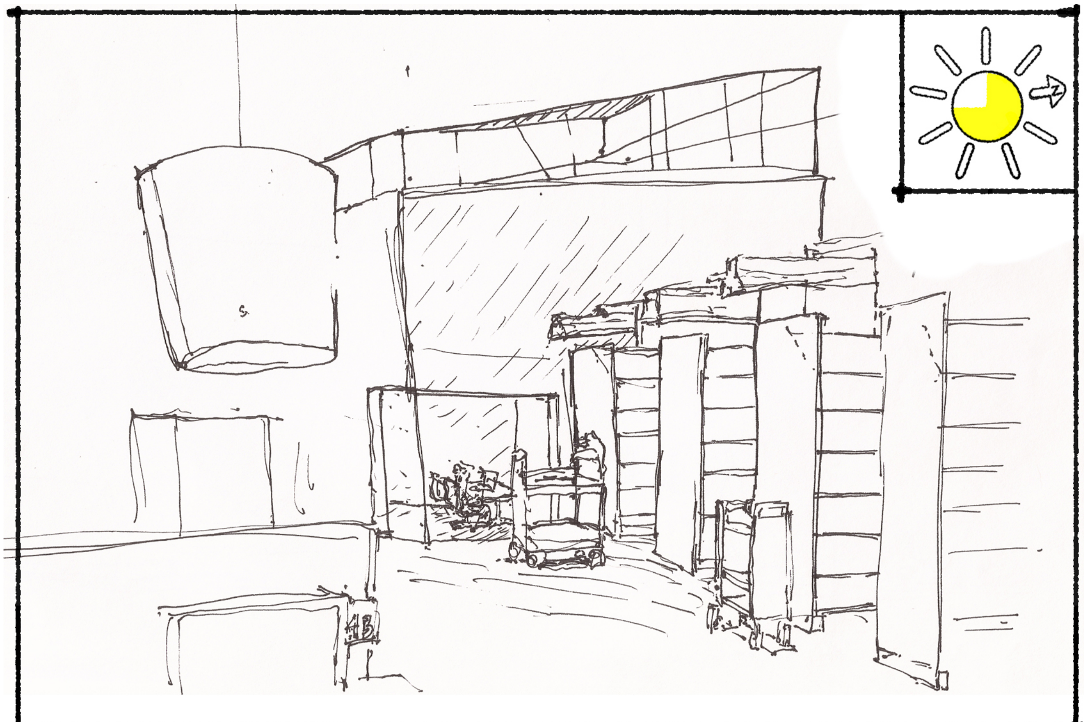


Drawing 3C-6: Interior Perspective facing west at fourth table location.

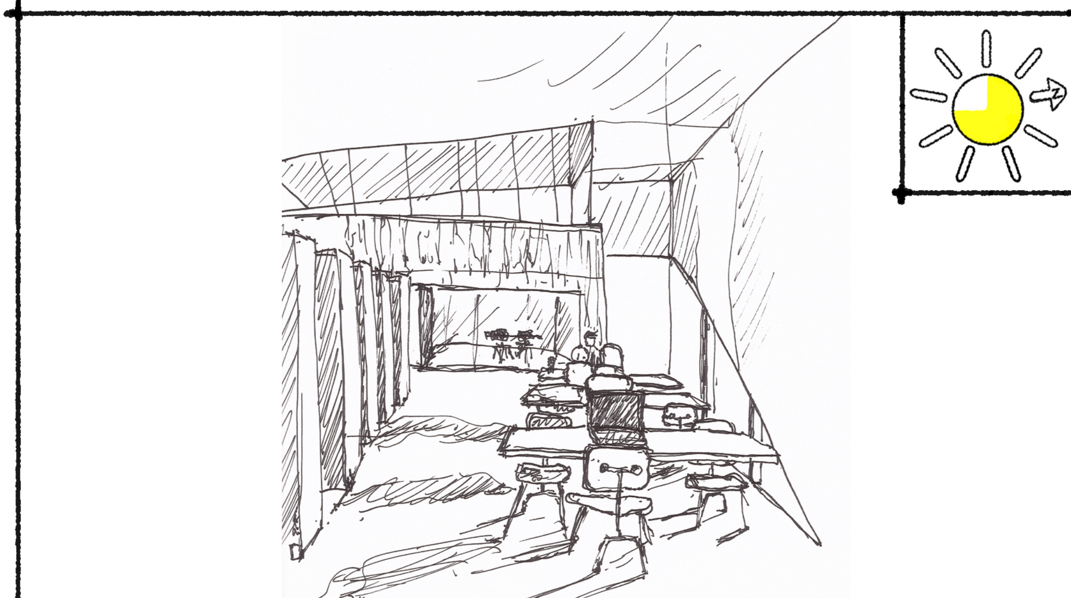


Drawing 3C-7: Interior elevation of slanted low-level sidelight at table 4.

Figure 32: *Area 3 interior observation perspective with analytic visual note. Architectural features integrating daylight and natural views within interior.*



Drawing 3C-8: Interior Perspective Drawing of lower computer room facing west.



Drawing 3C-9: Interior perspective drawing of upper computer room facing west.

Figure 33: *Area 3 interior observation perspectives. Interior daylight integration.*

Area 4: Central Courtyard and Desert Garden

Overview

One of the most important passive daylighting strategies of the library is the building typology, a central courtyard structure. All of the interior spaces are organized around a central outdoor patio and garden space, effectively opening up the inner volumes to daylight. The preliminary case study identified a series of windows along this outdoor space leading the researcher to expect large quantities of direct daylight, impacting interior space. Surprisingly, the greatest impact from the outdoor courtyard is caused by reflected light entering the interior. Because there are so many angled exterior walls, and light colored hardscape materials, the courtyard acts like a large secondary light source.

Canalization

The courtyard is located along the east/west access following the daily movement of the sun. Acting as a part of the building metaphor, a slot-canyon, the courtyard is set back from an angled, meandering, and path from the main entrance. An angled window begins along this path, and continues along all four sides of the interior courtyard. As the window moves along the wall it increases in height. The north wall of the courtyard has an angled sidelight, as the wall turns, facing west, the window is 10’-0” in height, turning again to the south, the wall begins to slightly dip, finally lowering to a height of 7’-0” along the interior east facing wall.

The unique shape and size of the interior courtyard relates closely to the surrounding building scale and orientation. The central courtyard allows canalization of daylight during the middle of the day. This is especially important to offset peak load hours of energy production; as described in the literature review many utility companies charge higher rates during the day because energy demand increases. By placing a large open space in the middle of the building floor plan daylight is easily provided to otherwise dark enclosed space. The angle and height of the walls composing the courtyard also impact the amount of light reflected into the interior. During the midday ours of 11 – 2 pm direct sunlight is tempered by building structure, but also allowed to enter deeply within the space.

The continuous glass wall establishes a connection between interior and exterior space. As each patron enters the library exterior, they meander around a long path. This path continues until the window stretches into a door where patrons enter the space. Once inside the building, the memory of the exterior courtyard is transformed to expectation. The eyes adjust to the interior light level, but are constantly drawn to the brighter exterior. Each patron enters the interior space from the outside, giving a personal sense of outdoor weather conditions, relating the two spaces to one another.

Procession

The procession of daylight is reinforced by the location of the angled window, and the presence of an aperture along four sides of the courtyard. As the sun moves along its normal path, approaching midday, daylight impacts the outdoor space at continuously changing angles. At any given time part of the courtyard is in shadow and part in brilliant sun. This creates comfortable outdoor seating spots, as evidenced in Images 4B12 and 4B13, even in the heat of July allowing people inside to watch people sitting outside, a visual break.

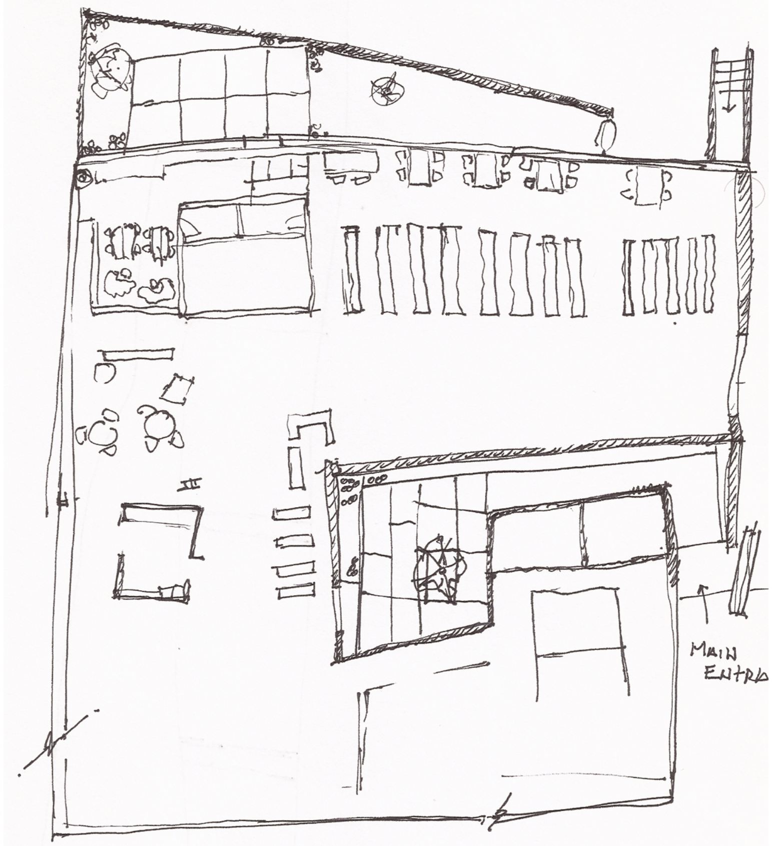
The shadows also bathe large expanses of glass in cool shade, without limiting the reflected light to enter deep within space. As evidenced in the series of interior perspectives 1C3 and 1C4 daylight enters high up the wall and deep into the ceiling plane of the adjacent self-checkout space. Otherwise unconnected interior spaces are conjoined by daylight, as the light moves from room to room.

The amount of daylight reflected high onto walls and ceilings, from the outdoor spaces, was unexpected, considering case study images. Daylight striking the ground plane is reflected from light colored hardscape, adjacent Core-ten steel walls, and natural plant materials. The case study images of this area depict direct sunlight, but do not show reflected light entering the interior. Drawing series 4B7 – 4B9 detail a long curtain wall window across all 3 walls forming the library interior, and facing into the courtyard. It is only through first hand observation that the secondary, bounced light is identified as a contributing factor to space.

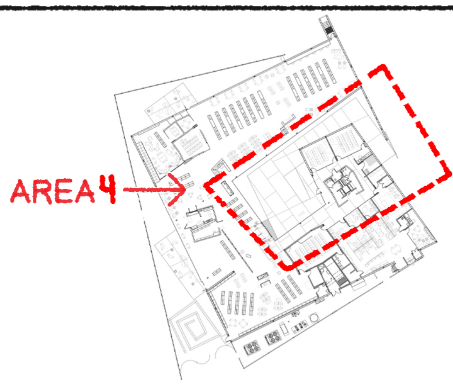
Luminescence

Although the central courtyard is an outdoor space, an interior landscape emerges, because the area is enclosed and able to be locked at night. The library has installed permanent café style seating groups and upgraded finishes. A permanent art installation adorns the south wall, beautiful desert landscaping fills a central garden and rock gardens with water feature enclose the space along the outer perimeter. These elements work together to encourage outdoor activity, even during the hottest summer weather.

The literature review has established the physical and psychological benefit views into nature offer building occupants. By creating an inviting outdoor space, the library encourages patrons to congregate. The library signage, shown in drawing 4B-10 and 4B-11 acts as a locking gate after closing hours. The end result is a pleasant scene of activity, native plants, and patrons. Interior occupants enjoy visually interesting exterior views.



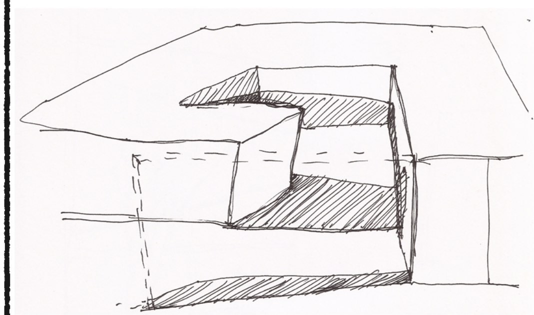
Drawing 4A-1: Interior furniture floor plan. Not to scale.



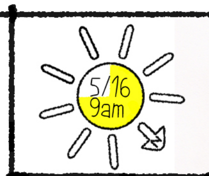
Drawing 4A-2: Overview floor plan with area location. Image: Richard and Bauer Architecture (2007). *Floor Plan of Arabian Library.* (ArchDaily, 2013).

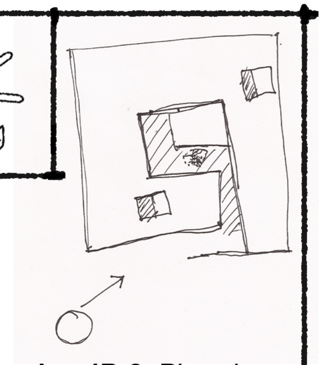
Area Summary:
The Central Courtyard is formed by a long mearndering enterance path, and interior patio with gardens. Interior walls are finished in Core-ten steel, feeding indirect daylight into a long angled glass curtain wall on all four sides.

Figure 34: *Area 4 overview and site orientation. Analytic visual note matrix.*

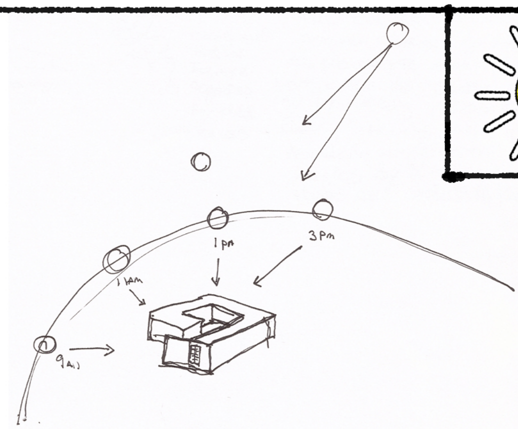


Drawing 4B-1: Building exterior perspective facing s/w.

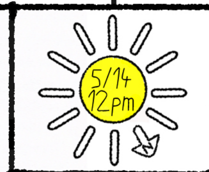


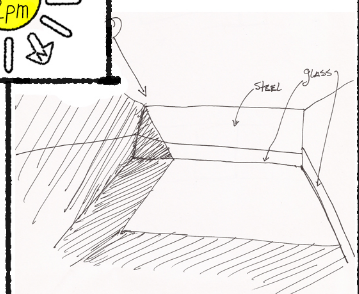


Drawing 4B-2: Plan view of solar orientation facing West.

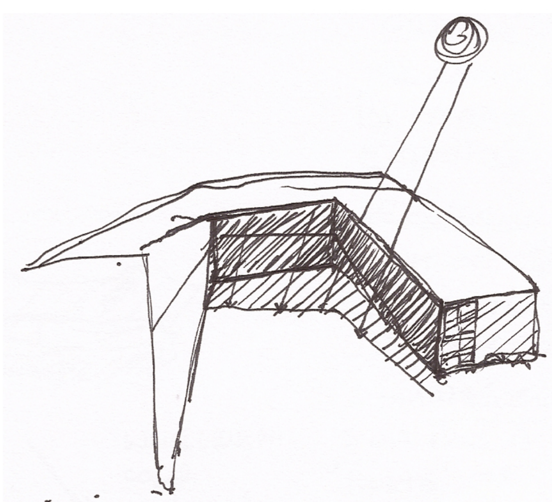


Drawing 4B-3: Exterior solar analysis time-lapse perspective facing s/w.

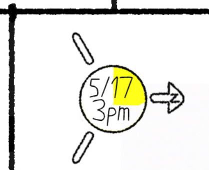


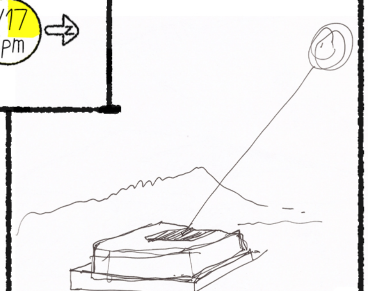


Drawing 4B-4: Interior courtyard perspective facing west.



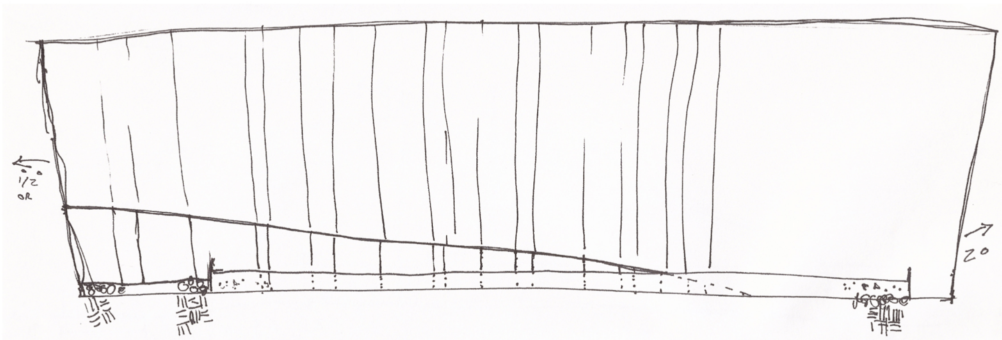
Drawing 4B-5: Interior courtyard perspective facing west.



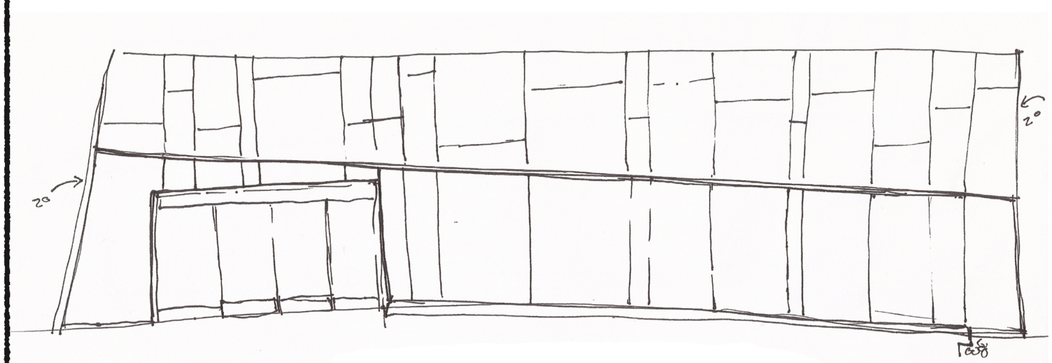


Drawing 4B-6: Building exterior solar analysis facing east.

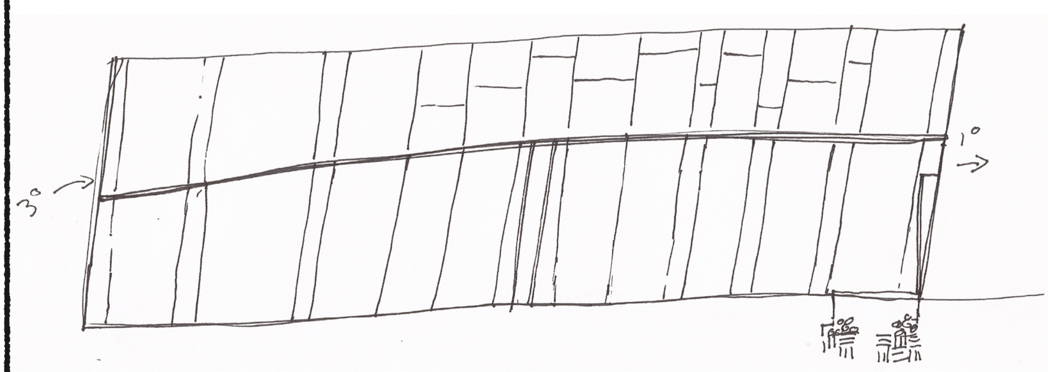
Figure 35: Area 4 solar orientation. Analytic visual note matrix.



Drawing 4B-7: Courtyard elevation facing north.

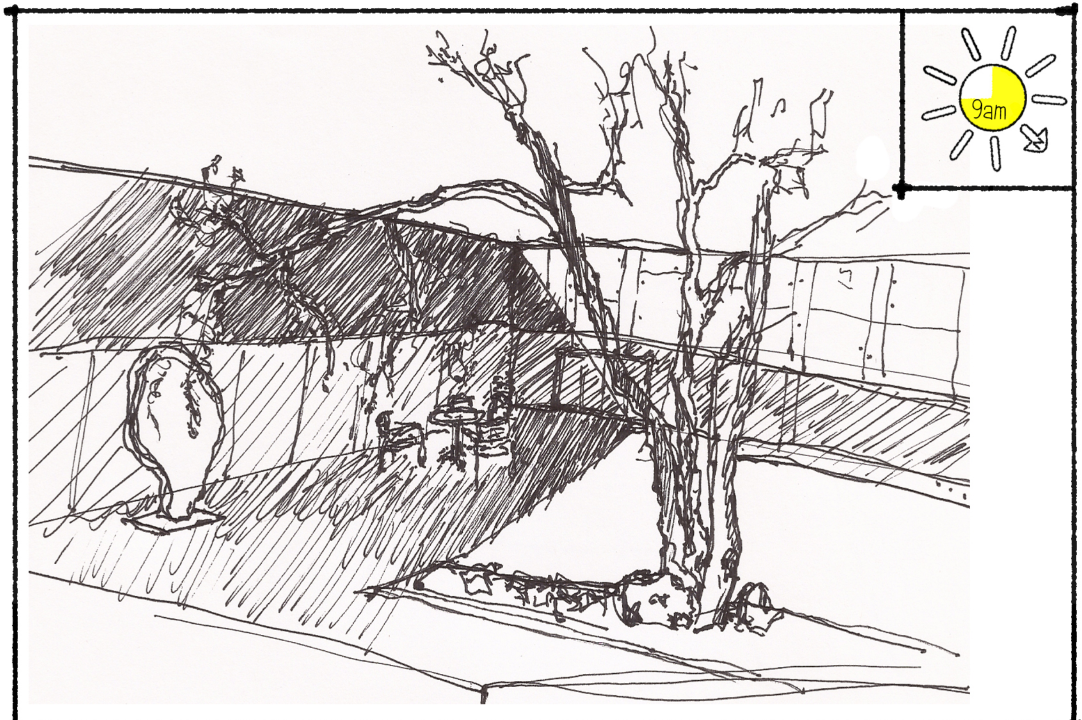


Drawing 4B-8: Courtyard elevation facing west.



Drawing 4B-9: Courtyard elevation facing south.

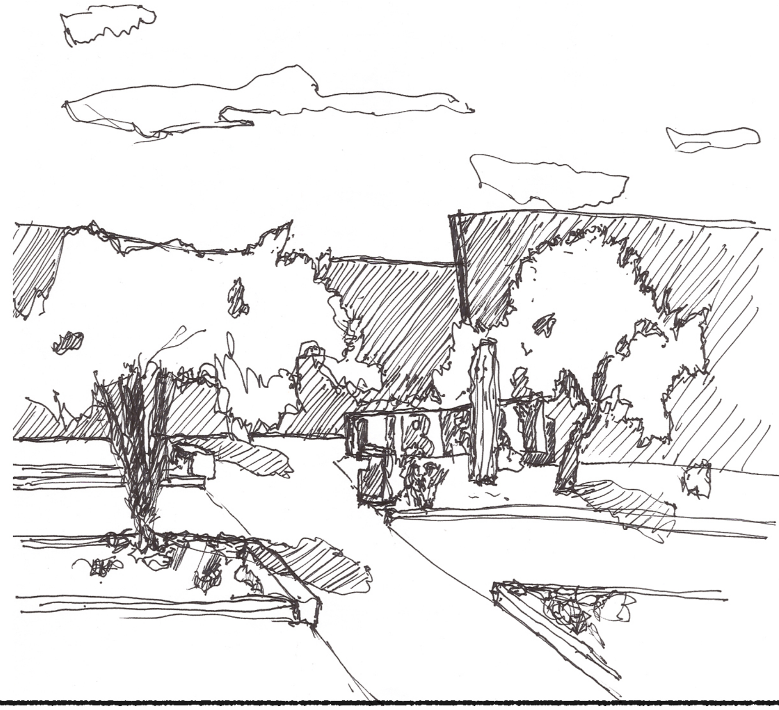
Figure 36: *Area 4 courtyard elevations. Analytic visual note matrix.*



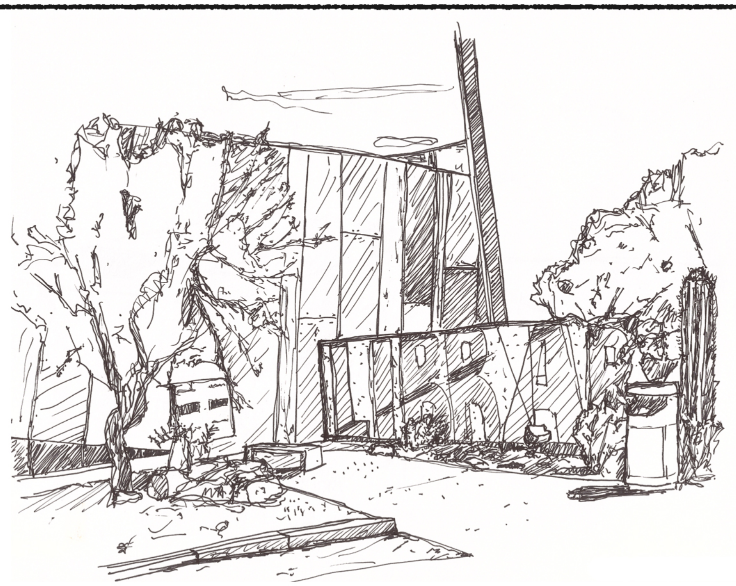
Drawing 4B-12: Courtyard perspective facing sw at 9 A M.

Drawing 4B-13: Courtyard perspective facing sw at 12 P M.

Figure 37: *Area 4 courtyard interior observation perspective. At 9 Am and 12 P M.*

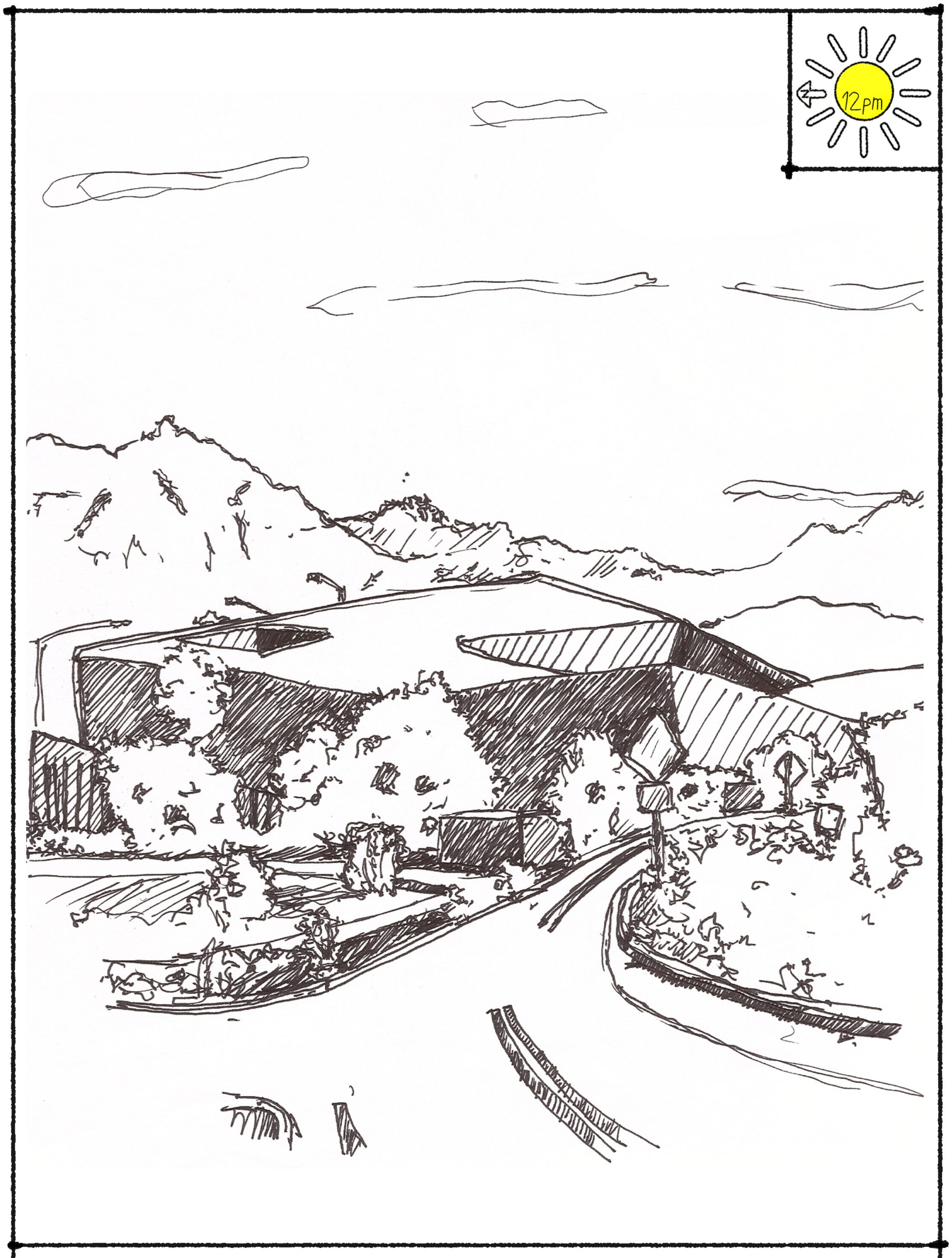


Drawing 4B-10: Exterior perspective at library enterance with gate open facing west.



Drawing 4B-11: Exterior perspective at library entrance with gate closed facing northwest.

Figure 38: *Area 4 exterior observation perspectives. Locking gate at main library entrance.*



Drawing 4A-3: Exterior perspective facing east at 12 Noon.

Figure 39: *Area 4 exterior observation perspective. Library facing east at 12 Noon.*

CHAPTER 5

CONCLUSION

This chapter discusses the results of the case study and data collection in Chapter 4 within the context of literature review in Chapter 2. The topics included in this section are the conclusions to the research questions and implications for further research within the limitations of this thesis and beyond.

Based on a review of literature, exposure to full spectrum daylight has a physiological and psychological benefit to human beings. Many experts agree that the quality of interior lighting must be addressed in order to advance the built environment, and better account for human comfort. In order to address the complex problem of human comfort and the quality of interior lighting, experts call for an interdisciplinary approach to research.

A gap in the research of holistic daylighting from the designer's perspective has been identified through a review of literature. Good designers consider interior lighting as an integrated element of interior space, closely related to all the other facets of building structure that impact human occupancy. A graphic language recording visual notes as sketches, sections, and detailed three-dimensional perspectives forms one of the languages, described by Howard Gardner as "natural" to visually creative individuals. Utilizing this natural language to document the phenomenon of daylight eliminated a learning curve for designers researching the integration of daylight in space. The data in this thesis was collected in the form of visual notes, perspectives, and analyzed graphically rather than numerically.

Lighting engineers seek a qualitative prescribed level of light assigned for set tasks often reproduced efficiently through artificial sources. A specialized language, identified through the literature review, was used in a large body of lighting engineering and scientific research. The data found in most of the lighting science and engineering literature was recorded with sophisticated light metering equipment, and calculated as digital models. These devises were expensive, complex and suggest a communication barrier for design researchers.

The methodology proposed in this thesis offers designers an opportunity to contribute an alternative perspective daylight research. An approach considering the holistic benefits of natural light, and the beneficial impact to human beings can supplement the growing body of quality lighting research.

Many of the attributes of full spectrum daylight are still misunderstood. Emerging research in photobiology has confirmed a link between human health and the nonvisual spectrums of light produced by the sun. It will take many years for scientific research to confirm all of the benefits daylight provides to human beings. It is very clear however that limiting the amount of full spectrum lighting provided within interior space in an effort to exclusively reproduce visible light has negatively impacted human occupancy.

Conclusions to Research Questions

Contemporary Strategies Integrating Daylight within the Built Environment

The first research question asked what are the contemporary strategies integrating daylight within the built environment?

The built environment is inarguably linked to its natural surroundings. Different geographic locations experience local landscape and weather conditions impacting the availability of resources. Ultimately the human response to each unique setting drives architectural design solutions. Some environments enjoy access to ample daylight and must design limiting control strategies, while others experience limited daylight, developing advanced methods of collection and distribution.

Arabian Library was selected for this study based on passive construction methods integrating daylight, uncovered in the literature review. Geographic locations with a high degree of intense sunlight and clear skies offer inhabitants with an abundant natural resource, free of cost. Chapter 4, Section 1 identified Arizona as a culture of renewable energy and sustainable architectural design. The researcher expected buildings constructed in Scottsdale Arizona as a suitable subject for this thesis. The context of the literature review greatly narrowed the scope of the methodology used in this thesis.

Two general daylighting categories emerged from the literature review: active and passive. Active daylighting techniques employ complicated mechanical equipment to harness limited amounts of daylight. These strategies push the limits of technology, requiring a large initial investment, and ongoing maintenance costs. Passive daylighting techniques rely on anticipated solar movement and utilized structural designs to draw daylight deep within interior spaces.

Passive daylighting strategies were the primary focus of the research collected in Chapter 4. The preliminary case study identified four passive daylighting strategies prior to site visits. In the context of data collected through the literature review, a comprehensive overview of the library was constructed. Passive daylighting strategies were clearly identified in photographs and associated with four specific library interior spaces. This limited the amount of data collected forming a reasonably repeatable methodology.

Projects discussed in the literature review with a high degree of sunlight typically used design strategies that control the amount and quality of daylight entering space. Beginning with the earliest examples from Ancient Greece and the Middle East the courtyard typology was central to integrating daylight within the interior, while preventing unwanted heat. Antonio Gaudi adapted the courtyard typology in the 20^{th} Century. His designs utilized the luminescent quality of interior materials to provide a constant interplay of reflected light.

The Arabian Library successfully incorporates a courtyard strategy in a manner adapted to the arid, intensely bright climate of the southwest United States. The building interior is finished with matte finished wood panels, which shimmer in contact with daylight. The central courtyard opens up the building interiors, and provides direct and reflected light onto these surfaces. Artificial light remains static throughout the day; daylight however constantly shifts location and fluctuates in intensity. This combined effect offers a dual purpose, meeting required task lighting levels while providing interesting and comfortable interior spaces.

The library also uses the courtyard strategy in an unexpected way, creating a type of micro-courtyard above the floor plane. An inverted light well, a four-sided clearstory window in Area 3, covers the top of the large computer room and two small private study rooms. The dimensions of the rooms below are large enough to consider the four-sided assembly as a small courtyard floating above the main reading room. This light well provides an illuminated secondary light source, as well as direct daylight contribution to the main reading and mixed-use areas.

The inverted light well strategy provides a constant procession of daylight through the main reading room, without impacting the private rooms below. A solid ceiling forms the bottom of the light well blocking daylight from entering the computer room and private study rooms. This example maximizes the benefit of available daylight, by limiting exposure to some interior spaces. Even though the library has access to ample sunshine, some of the strategies observed in this study actually collected daylight from adjacent secondary sources.

Projects discussed in the literature review with limited access to sunlight typically implemented strategies that harnessed and collected daylight. The work of Alvar Aalto demonstrated his desire to provide building occupants with daylight that he considered essential to long-term health and well-being. His designs integrated limited daylight of Scandinavia utilizing externally mounted secondary sources. This strategy reflected daylight back into space, depending on the shape and surface finish of each source.

This strategy is adapted to Arabian Library within two patio features. The central courtyard and north patio in Area 3 and 4 provide ample access to daylight. The proximity of interior space creates a secondary light source condition similar to Aalto's light vaults. Site walls along the north patio and adjacent building structures creating the central courtyard reflect ambient light off a subdued Core-ten steel finish.

The Arabian Library successfully adapts traditional building technology to the southwest region through unexpected design solutions. Passive collection strategies seem unnecessary in this geographic location, because of the consistent availability of intense daylight. Secondary light sources however, provide the component of transitional light to interior space.

Daylight as a Holistic Element of Interior Space

The second research question asks: is it possible to observe the phenomena of daylight as a holistic element impacting interior space?

According to the literature review, designers expectations and chief goals for interior lighting systems are shifting away from visual task performance. Recent discoveries linking human well being to light are forcing building design practitioners to place human needs ahead of building efficiency and economics (Bellia, 2011). Lighting efficiency for task performance is typically measured with photo sensing equipment. Lighting quality however remains elusive, closely related to complex human psychology and individual subjective response.

The observations in Chapter 4 clearly show natural light impacting interior space outside of task performance areas. The most noticeable light distributions in the main reading Area 2 and mixed use reading Area 3 were across the ceiling plane and low to the ground plane. In some instances desk height was not impacted by daylight. But the daylight greatly impacted the overall space, making it seem larger, more inviting and alive with transitional light.

In Figure 35 the combined effect of top lighting from the inverted light well, and side lighting from the low level windows is demonstrated in two perspective drawings. Activities in this space require a prescribed minimum level of task light, provided artificially by static light fixtures. This level of light is completely overpowered by the surrounding daylight, top light streams across the ceiling and walls. Daylight from above also changes with moving weather patterns giving the room a constant sense of activity. The moving procession of daylight draws greater attention than the static levels of artificial light, providing occupancy with visual interest.

Many of the drawings from chapter 4 capture exterior views of nature and the impact of daylight reflected from adjacent outdoor structures. Outdoor landscaping has a major impact on the quality of light reaching interior space, as evidenced in Figure 30. From a comfortable seated position indoors, the researcher identifies bright, transitional daylight shown in the outdoor landscape. Each time the researcher looked up from the task plane the level of light at the human eye increased. Prolonged views to the exterior offer longer durations of this intense light. Properly integrated views to nature allow the interior occupant to be outdoors, without physically leaving the room.

The holistic nonvisual attributes of daylight also benefit human occupancy. According to the literature review simply being in the presence of full spectrum natural light offers physiological nutrients to the human body. Emerging scientific research is continuing to uncover more data supporting the benefit of sunlight to humans; this strengthens the argument in favor of integrating daylight to interior space.

Figure 31 demonstrates the non-visual impact of daylight on library occupants. Daylight enters the space from low-level sidelights by directly contacting adjacent occupants and indirectly reflecting off walls and surfaces. Incidental contact with daylight is impossible in windowless rooms, rooms that may otherwise be considered well lit from an engineer's perspective observing artificial task lighting output. Even though the daylight in Drawing 3C-6 is not providing task illumination, it is still contributing to the holistic quality of the space. Placing a researcher in a fully operational, occupied space offered the advantage of encountering this type of data collection.

The Designers Perspective

The final research question asks: how can the subject of daylight integrated within the built environment be researched and recorded from the designer's perspective?

This thesis methodology empowers designers to collect relevant data regarding daylight as an element integrated within space. The observations collected in Chapter 4 describe the qualitative attributes of daylight. Henry Plummer's research on the holistic principles of natural light was used to filter the data collection, and limit the results to a manageable scope. The major difference in this collection strategy is the ability to acknowledge unexpected aspects of daylight within actual space. Section 3 of this thesis explained the visual note taking method. Using a series of drawings and site visits the researcher quickly established a sense of place, tying the building to its natural landscape.

The designer's perspective contrasts with the lighting engineer's perspective. The key difference established in the literature review is that of quantity versus quality. Lighting engineers have sought to provide minimum levels of static light, available on demand at any time of day. This goal has channeled engineering research toward the limited known visible spectrum of daylight and established a scientific, quantitative approach toward designing artificial lighting systems. Many of the research methods utilized in lighting engineer studies required highly regulated laboratory testing conditions.

The case studies in detailed Section 3 of Chapter 2 documented daylighting techniques that enhanced the aesthetic beauty of interior space, utilized specific geographic building typologies, and integrated natural light without disrupting design continuity. Designers are concerned with the quality of light as it relates to the interior volume. In the example presented from Rusdy Hartungi the aesthetic appearance of high-end salon interiors was crucial to the performance of the space. This framework presented an alternative approach to daylight beyond simple task lighting.

At its core, design creativity utilizes divergent thinking. As discussed in Chapter 3 designers typically consider multiple solutions to any given problem, and select the best outcome. This generative approach, according to Vishal Sing, plays a major role in defining the quality of interior space; designers consider subtle nuances alongside major forces impacting solution outcomes. Human perception and individual psychology plays a major role in defining the quality of interior lighting. The divergent thinking model was particularly useful recording transitional daylight. It allows known and unknown attributes of daylight entering space to be considered as one total force.

The methodology in Chapter 3 provided the researcher with guiding principles to identify daylight integrated within space. Without measuring a specific quantity of light, the holistic principle of luminescence draws attention to light interacting with surfaces. In Area 3 for example, low-level sidelights did not provide daylight at some of the tables, the desk height was beyond the window opening. These windows still provided beneficial daylight to occupancy, by physically contacting legs and feet, and visually entering the adjacent space. Three brief site visits to this space identified the impact of full spectrum lighting, not just the visual task. These additional unexpected benefits were only realized by actively participating in the space post occupancy.

Implications for Future Research

This research asked how is daylight fully integrated within the built environment. In order to limit the data collection, passive daylighting strategies and the structural systems responsible for integration were the focus of data collection. The ethnographic phenomenological method used in this study was particularly successful in public libraries, offering the potential for similar future studies with different focus. Post occupancy ethnographic research was also successful at documenting unexpected results.

Placing the researcher within an actively occupied interior environment required unobtrusive data collection. According to Webb et al., the physical presence of researchers can alter the behavior of subjects. The strategy for this study used a simple disguise, a graduate student reading and sketching in the library, to conceal the data collection. Rather than locate a visibly obtrusive data collection area, the researcher simply blended in with the flow of occupancy.

The library prohibited photography, therefore this study enlisted visual note taking sketch techniques. This data collection method worked very well under post occupancy conditions. Library patrons were particularly interested in the drawings and comfortable with the method. This allowed the researcher to create drawings without interruption. The persistent data collection actually added to the level of rapport. Some patrons looked forward to observing the drawing process.

This result suggests an opportunity for future research on occupancy patterns, directly related to daylight integration. Hand drawn diagrams can be created, using the methodology of this study, to log library patrons entering and exiting interior spaces. Because there are little restrictions on sketching (compared to photography) post occupancy observations can be collected throughout the day. These analytical drawings can be augmented with descriptive perspective drawings documenting the conditions in each space. Over the course of three months an accurate study of daily occupancy patterns, organized by age group, gender, and even library material preference can quickly be assembled.

Research conducted from the designer's perspective can also be combined with research conducted from the engineer's perspective in an interdisciplinary study. This thesis provided detailed drawings cataloged by date, time, and geographic position. The visual data collection can later be used to create a three dimensional digital model.

Conclusion

The science of photobiology is still in its infancy. Researchers in this field continue to uncover data explaining the link between full spectrum daylight and long-term human well-being. It is clear that artificial lighting systems, designed produce the limited spectrum of visible light, do not deliver key transitional elements, found in daylight, essential to human physiology. Artificial lighting systems offer building occupants an advantage, delivering interior illumination through considerable engineering effort. Integrated daylighting systems bridge the remaining gap.

This thesis has demonstrated the holistic contribution daylight provides to interior space. Full spectrum light provides fluctuating transitional properties that do not necessarily contribute to visual task performance. The data collection has shown these additional benefits work in unison with artificial lighting systems. Passive daylighting strategies can be integrated in new building design, as well as retrofit into existing, even historical building programs.

The intersection of lighting science engineers and designers perspectives reveals gaps in knowledge pertaining to the quality of interior light. Future interdisciplinary research offers the opportunity to uncover additional benefits of daylight in humans, as well as advancing the understanding and application of quality lighting in interior space.

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APPENDIX A

IRB EXEPMTION FORM

Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Jose Bernardi AED
From:	Debra Murphy, Director Research Compliance Office
Date:	02/07/2013
Committee Action:	**IRB Review Not Required**
IRB Action Date:	02/07/2013
IRB Protocol #:	1301008747
Study Title:	How is Natural Lighting Integrated within the Built Environment: A Case Study of Arabian Library, S

The above-referenced protocol has been reviewed and it has been determined that IRB oversight is not required because the study does not meet the criteria under Federal Regualtions, 45 CFR Part 46 for research involving human subject participation..

You should retain a copy of this letter for your records.