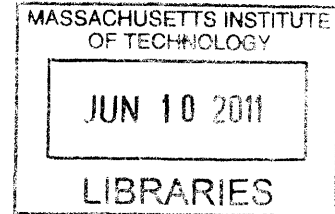


**Daylight Variability and Contrast-Driven
Architectural Effect**

by

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Abstract:

Natural light is a dynamic and ephemeral tool for expressing the quality of architectural space. As a compliment to more traditional avenues of daylighting research that assess performance in terms of quantitative illuminance goals and glare-based discomfort, my thesis defines light variability and contrast as a finely tuned architectural effect. Under the rapidly growing context of energy conscious research, my thesis attempts to re balance our definition of “performance” to include those perceptual and aesthetic aspects of light that are often disregarded by the world of simulation. Contrast is important to the definition of space and it is essential in understanding how architecture is enhanced and transformed over time by the dynamic and variable characteristics of daylight. Through an analysis of contemporary architecture from around the world, this thesis has developed a new typological language that categorizes architectural space in terms of contrast and temporal variation. Using this system of categorization, my thesis proposes three new metrics for the quantification of contrast and light variability to provide a more holistic analysis of daylight performance.

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Chapter 1

Introduction

1.1 Architecture: the Interaction between Geometry & Light

“A building speaks through the silence of perception orchestrated by light. Luminosity is as integral to its spatial experience as porosity is integral to urban experience” [Holl, 2006].

If architectural space can be defined as the interaction between geometry and light, then daylight space can be defined as the choreography between these two elements and their perceptual qualities. Most architects would agree that daylight is an important asset to the design of good architecture, but *what* aspects of light quantify or qualify the design performance of a space? How does an architect determine how much light is acceptable and how best to integrate that light into a set of design intentions? Many of today’s metrics that quantify daylighting “performance” do not address factors of perceptual appeal because they define light as a biological requirement rather than an element of emotional and experiential delight. Although there is an understanding of the minimum amount of illumination that is required for the human eye to perform visual tasks, there is little consensus on how much contrast or brightness makes that space more or less *exciting*. We, as architects, have been designing visually dynamic and perceptually engaging buildings for centuries, but the invention of the computer has transformed the past 20 years of contemporary practice in both positive and negative ways. The computer has facilitated our development of metrics that quantify daylight performance, but we have pushed these metrics in a singular and often non objective direction. Task-plane illuminance requirements and energy-efficiency have dominated the contemporary field of daylight performance, but “This blind worship of specific levels of illumination is all too often directly responsible for the defeat and compromise of good designs [Lam, 1977].”

In the contemporary context of heightened environmental awareness, we feel more pressure to evaluate architecture in terms of sustainable performance criteria [Reinhart, et al, 2006]. Although as designers, we are trained to place value in the concept of spatial experience, we are now required to quantify our design intentions in terms of net energy balance and human health. As these requirements become more pervasive in our architectural education and the justification of design quality, we must position the term 'environmental' to include those perceptual qualities of light that have become secondary in our dialogue about performance. Architecture must 'perform' in both qualitative and quantitative criteria and we must work to re-establish the role of emotional and perceptual indicators in our language about performance [Steane and Steemers 2004]. Architects use light to illuminate surface and draw our attention toward elements of spatial and material significance. It can be staged as a series of dramatic moments or patterns, or it might be read as a diffuse and subtle set of tones that draw our eyes upwards in personal reflection. In the larger context of the discipline, Light is only one aspect of architecture, but it reveals the meaning and intentions of space. "Light reveals architecture, and in return architecture must reveal light" [Millet, 1996].

The very character and purpose of light is dependent on a set of design principles which are revealed to the observer through experience, and not through a planar map of illumination levels. In that case, what types of information do begin to distinguish these varied characteristics of light and how might we develop a typological understanding of their architectural effects? How does daylight vary from location to location and how do hourly and seasonal changes in quantity and orientation alter its effects within space? This thesis aims to establish the role of daylight as a fundamental element of visual interest through a typological approach to the design intentions of architectural lighting, the role of contrast in describing spatial definition, and the impacts of light as a dynamic natural source.

1.2 A Typological Approach to Architectural Daylighting

Visual interest in architectural daylighting refers to the aesthetic and perceptual aspects of illumination that render a space interesting. The subjective nature of design makes indicators such as visual interest difficult to define, but a closer look at contemporary architecture from around the world suggests that there are certain similarities in how architects choose to choreograph daylight for varied programmatic needs and experiential effects. These "types" of daylight could be organized to represent a categorization of strategies that can foster a language about the qualitative effects of illumination in architectural space. For example, the direct and dramatic penetration of sunlight through the courtyard roof of the Smithsonian Institute highlights the intended ephemerality of

its use (Figure 1.1). The courtyard is intended for occasional occupation by its visitors who are moving through the space en route from one location to another. They have no need for controlled illumination levels or protection from direct sunlight. Some may argue that this fleeting connection to the harsh perceptual effects of light and shadow evokes a certain delight in the human subject, who spends the rest of his day trapped within the monotony of his office cubicle [Steane and Steemers 2004].

On the opposite side of the spectrum, the north-facing monitors that illuminate the Dia Beacon Museum (Figure 1.2) in upstate New York cast an even and unflinching light onto the tightly climatized environment of the galleries. These spaces were designed to maintain an even distribution of daylight without drawing attention away from the artwork or the scale and uniformity of the appropriated warehouse. In this case, contrast and light variability are best kept at a minimum to achieve the intended spatial effects of the architectural design.

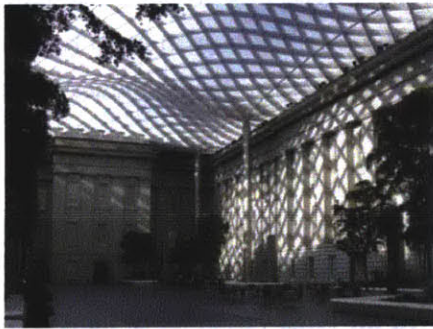


Figure 1.1: Smithsonian Courtyard, Washington D.C. Image courtesy of Dmytro Kosenkov.



Figure 1.2.: Dia Beacon Museum. Image courtesy of urban75

Through an analysis of these spaces and others, it becomes clear that there is a need for more comprehensive classifications of architectural daylight so that we may communicate more effectively about the formal intentions of space and evaluate them alongside existing daylight metrics to provide a more holistic analysis. “This vocabulary of lights can provide a tool that enables the emergence of a typology of daylighting in architecture. The typological approach, already part of the design practice in architecture, favors a relationship between qualitative and quantitative aspects of daylighting [Demers, 2007].” This thesis will strive for a vocabulary of daylight-driven effects to further our understanding of perceptual performance in architecture.

1.3 Contrast and its Role in Spatial Definition

In order to develop a typological understanding of daylight-driven effects in architecture, it is necessary to first define the role of daylight in generating contrast and spatial definition.

Spatial definition depends on the balance between light and dark, the eye's ability to perceive those differences, and the brain's ability to extract that information to formulate an understanding of depth and complexity [Liljefors, 1997]. In a sense, this notion of space is entirely dependent on the photo sensors in the human eye and the brain's interpretation of that information into a kind of spatial map. In daylighting, illumination levels determine whether we can see our surroundings, while contrast and luminance determine the complexity and richness of its perceived composition. The luminous effect can be described as a combination of four factors: "the source (its intensity, its directional characteristics, its color); the geometry (its relationship between source and the receiver or receiving surfaces); the surfaces that receive or modify light, becoming secondary light sources in themselves by reflecting, redirecting, and coloring light; and the person who views the source and illuminated surfaces as he or she moves around [Millet, 1996]."

The evaluation of these four elements into universal aesthetic preference or design criteria is not, however, a simple task. We can experience pleasure in a diverse mix of spaces that represent both high and low contrast, dynamic and static lighting conditions. The human brain is subjective in its response to formal composition and the use of light and contrast in the disciplines of art and architectural design is varied.

In the 17th century, the Dutch painter Johann Vermeer became known for his ability to render light and color with a richness that had not yet been achieved. In his painting entitled *Young Woman with a Water Pitcher* (Figure 1.2), Vermeer captured the tonal variations in light as it was filtered by the stained glass window and absorbed by the fabric and skin of the female subject. What was most impressive about Vermeer's work was the way in which he could capture diffuse light as it was transmitted through or bounced off of objects in the surrounding scene. His paintings came alive through the thin and arduous layering of pigments which describe the tonal complexity of each surface [Alpers, 1983]. In the 18th century, the Italian painter Antonio Canaletto pushed the perception of spatial depth through the blurring of objects located farthest away from the foreground of the visual field and the projection of shadows out into the perspectival view. Using a camera obscura to simulate the depth of a given scene, he was able to more accurately render the effects of illumination and detail as it would be experienced from the perspective of an observer [Canaletto, 1983]. Figure 1.3 shows this effect through *The Rotunda of Ranelagh House*.

The difficulty these painters faced over 300 years ago with the task of accurately representing light and its perceived visual effects continue to challenge architects and daylighting designers today. We still struggle with the accuracy and time intensive nature of rendering light as well as our methods for describing and calculating the quantitative and qualitative nature of that light. As the



Figure 1.3: Woman with a Water Pitcher, Johann Vermeer (1662)



Figure 1.4 The Rotunda of Ranelagh House, Antonio Canaletto (1754)

techniques of painting continued to evolve towards more realistic methods of light rendering and spatial representation in the 19th century, artists in the 20th century began to unpack the notion of space as a compositional map of color and contrast. The work of Piet Mondrian represents this departure from object and field to an abstracted 2-dimensional space [Ching & Jarzombek, 2011]. Painted in 1908, Red Tree Oil on Canvas (Figure 1.5) shows Mondrian's evolution from an impressionistic style to a more detached and compositionally rigid notion of flat space in Composition II (Figure 1.6) and No. 9 (Figure 1.7).



Figure 1.5: Red Tree Oil on Canvas, Piet Mondrian (1908)

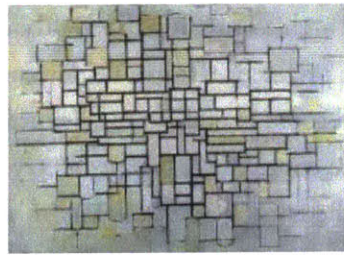


Figure 1.6: Composition II, Piet Mondrian (1922)

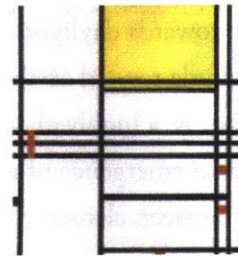


Figure 1.7: No. 9, Piet Mondrian (1939)

The architecture of the modern movement followed this same trend as the aesthetic expectations of architectural expression began to change. The order of architectural language moved away from the voluptuous and ornamental and towards a more orthogonal and reductive organization. If we discuss the architectural intentions of 17th century Baroque architecture with those of 20th century Modernism, we can see a dramatic shift in the expression of volume and the choreography of light. Baroque architecture embraced the volumetric massing of bold elements and curved domes, employing light as a figure that emphasized the geometry of space [Ching & Jarzombek, 2007]. This expression can be seen in Francesco Borromini's San alle Quattro Fontane in Rome in Figure 1.8 (a). Modern architecture, however, reduced the amount of ornamental stimuli in the field and drew attention to the ordered composition of orthogonal elements and a minimalist

expression of space. The Barcelona Pavilion, by Mies van der Rohe exemplifies these qualities in Figure 1.8 (b). An attitude about transparency and modulation began to develop alongside this abstracted reduction of elements, thus freeing architecture from the mass and volume of past generations [Ching & Jarzombek, 2007 ; Curtis, 1996].

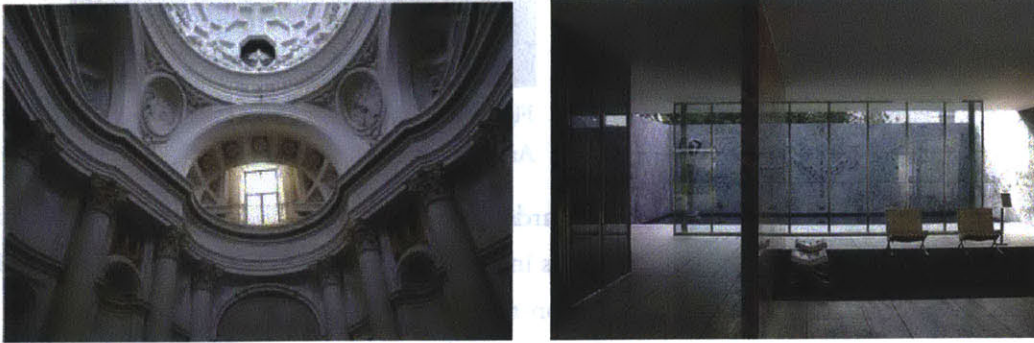


Figure 1.8: a) San Carlo alle Quattro Fontane in Rome, Italy (1638-1646). Image courtesy of flickr.com, Francesco Borromini b) Barcelona Pavilion, Mies Van Der Rohe (1929). Image courtesy of Scandinavian-berry.blogspot

In today's context, we can look back and reflect upon the shifting pressures that have affected our attitude towards daylight and architectural design. Although there is and always will be an evolving attitude toward aesthetic preference, it can be determined that light, contrast and its role in defining space is a highly charged topic in architectural expression. In the last two decades, we've experienced an emergence of more complex surface geometry and a renewed sense of delight in the interaction between elements of the natural and built environments. Contemporary architecture could be described as a hybrid between monolithic, minimal, and complex pattern-driven design. Styles have grown increasingly more diverse as geometric modelling software have liberated the architect from a dependency on flat or regular surfaces and modes of fabrication. The result of this liberation includes some highly dramatic and articulated spaces whose interaction with direct sunlight brings the question of contrast and its role in spatial definition to the foreground of the discussion on daylighting design. Some spaces are designed for task-oriented activities and require an even distribution of light, but those that do not require this level of control should not be subjected to the same performance restrictions that are imposed by an orthographic analysis grid. Contrast and spatial definition must be analyzed through a perspectival view of space and evaluated against its intended programmatic use to determine whether the effects are appropriate and whether they support the architect's original intention. Likewise, architects must become aware of the impacts of contrast and direct light penetration over time and learn how to manipulate these elements to achieve their desired intent.

1.4 Time-based Variability and the Ephemeral Quality of Daylit Space

Unlike artificial light sources, which can be adjusted to meet a desired visual effect regardless of location and time, daylight is sensitive to an array of influences. The latitude of a given location affects the length and intensity of daylight hours across the year while climate affects its strength and variability on an hourly scale. Surrounding site conditions can amplify or diminish the sun's ability to penetrate within an interior space and its often difficult to predict how these conditions will change over time, especially within the plastic and transformative fabric of an urban environment. "As light passes through small holes, it spreads out, frays and bends. The resulting shadows do not necessarily look like the silhouettes of the objects that cast them. Light bends in ways that yield shadows with bright bands, dark bands, or no sharp edges [Holl, 2006]." How then, can we inform our designs with a richer understanding of this dynamic and variable source of illumination so that we can exploit its perceptual effects?

In their book titled *Environmental Diversity in Architecture*, Mary Anne Steane and Koen Steemers discuss the importance of environmental and visual diversity in the built environment, describing the need for both temporal and spatial diversity in architecture. Steane describes a number of ways in which a building can encourage temporal diversity through its orientation, the size and location of its apertures, and the spectral quality of its finishes. In a study conducted on the relationship between luminance diversity and the perceived quality of interior space, "The more diverse the luminance in the field of view, the more 'pleasant', 'cheerful', 'bright', 'radiant', 'clear', 'visually warm', and 'strong' the space was reported to appear." The same study reported that students in a library were turning on individual task lights even though illuminance levels measure 1500 lux at the work plane [Steane and Steemers, 2004]. It was inferred that the student's desire for more light was not related to inadequate illuminance levels, but to a desire for diversity within their visual field. This raises an important issue in the discussion on contrast and temporal diversity in architecture. Although our codes and recommendations are concerned with task-based illuminance levels, occupants seem to be more interested in the visual diversity of their surroundings, establishing a need for new metrics that can quantify and place value in perceptual qualities.

1.5 The Power of the Perspective Image

In order to analyze these qualities of light described by Stean and Steemers, we must establish a medium for representing contrast and luminous diversity. The digital images is a medium that can support both qualitative and quantitative analysis as it is, after all, a physical record of light exposure within space [Demers, 2007]. Furthermore, architects often choose to represent and communicate

design intentions through an image or set of images that express a vision of space. Although these images can and often do unveil some phenomenal qualities of abstract representation, it can be agreed that the selection of light sources and the sharpness of their rendered contrast and distribution is inherent to how we describe an architectural bias. “The image, already used as a design tool and representation support by architects, should be considered as a tool for the analysis of light. Digitally, images have potential of transformation but also support a lot of quantitative information [Demers, 2007].” Demers proposes that photographs and renderings provide a detailed map of information that can be used to analyze both qualitative and quantitative aspects of light. Unlike the orthographic plan or section, the perspective represents a vision of space that we can directly relate to in our own perceptual experience. In order to capture these perceptual qualities over time, however, one must introduce a method for capturing multiple renderings or photographs so that a single view may be analyzed through multiple frames. This temporal view of space would allow us to quantify and compare the visual effects between different architectural environments to develop a vocabulary about contrast-driven daylight design.

1.6 Structure of Thesis

This thesis will introduce the need for visually dynamic metrics through a critical analysis of existing daylight performance tools in the context of contemporary architecture. Through a survey of existing spaces, this thesis will develop a new typology for contrast and temporal diversity in daylight design. Using this typological study, this thesis will then propose three new metrics for describing and quantifying contrast and temporal diversity through the use of digital images. These metrics will then be applied to a series of abstract case studies to test their adequacy in describing and ranking those qualitative visual effects discovered in the typological study. In the final chapter, these metrics will be applied to a series of existing architectural spaces and compared against current daylight performance metrics to discuss the need for a more objective and holistic approach to analysis.

Chapter 2

Research Context

2.1 Introduction

As the previous chapter made clear, contrast is an important element in the expression of architectural space, yet there is a lack of existing metrics that qualify contrast as an indicator of performance in daylighting design. In this chapter, we will introduce a series of architectural examples that explore the use of contrast in opposing ways, thus pointing to the need for a more typological and objective approach to our analysis of their daylight performance. A review of the existing metrics that quantify daylight performance will include an analysis of their limitations in describing the nuanced qualities that arise out of this series of existing architectural examples.

2.2 The Expression of Contrast in Architecture

From the evolution of historical light-rendering techniques in the field of painting, to the expression of volumetric forms in Baroque architecture and the abstraction of functional elements in the modern movement, contrast has played a pivotal role in our evolving aesthetic preferences regarding spatial definition. Spatial definition in architecture depends on the balance between light and dark, the eye's ability to perceive those differences, and the brain's ability to extract that information in order to understand the depth and complexity of our surroundings [Liljefors, 1997]. There is no doubt that architectural language has and will continue to evolve over time, but for the purpose of discussion, we will look at four contemporary examples and examine the differences inherent in their expression of contrast and spatial differentiation.

The first example is Norman Foster's renovation of the Smithsonian Institute Courtyard in Washington, D.C (Figure 2.1). The articulated glass roof structure of the courtyard allows for a dramatic penetration of direct sunlight, imposing strong patterns of contrast onto the walls and floor of the enclosed space. Designed for temporary occupation and public gathering, the space's programmatic use does not require a controlled lighting strategy. On the contrary, it takes advantage of its surroundings and the dynamic nature of sunlight through transparency to create a diverse

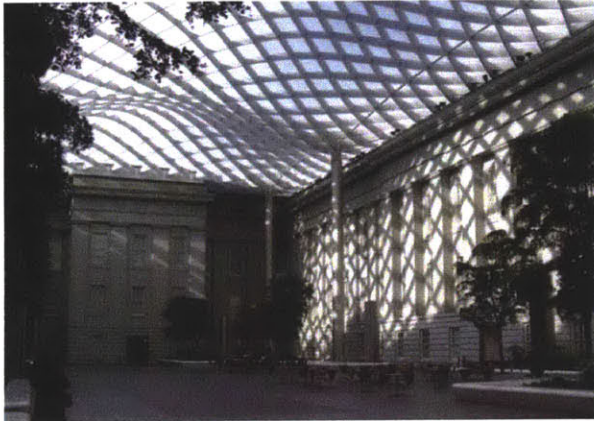


Figure 2.1: Smithsonian Courtyard, Washington D.C.
Image courtesy of Dmytro Kosenkov.



Figure 2.2: Dominus Winery, Yountville, CA
Image courtesy of Hege Homb Dedichen.

and visually engaging environment for its occupants.

The second example, Herzog and De Meuron's Dominus Winery located in Yountville, California (Figure 2.2), differs in its attitude toward the surrounding environment, allowing light to filter in through an exterior gabion wall. The architects sought to create a unified relationship to the landscape, using local stones to provide a naturally cool thermal environment with visually engaging effects [Ursprung, 2002]. The interior spaces maintain a variable relationship to incoming light, but the overall lighting levels are dim in comparison to the Smithsonian Courtyard. Occasional spots of direct sunlight on the floors and walls of the circulation corridor create an abruptly contrasted environment. This daylight strategy filters direct sunlight from the South-facing façade, while drawing attention to the materiality of its exterior

wall, highlighting the seemingly organic non-uniformity of its composition. One could argue that this strategy produces a highly contrasted interior like that of the Smithsonian Courtyard, but with more controlled variations over the course of the day and a darker base composition, overall.

For the third example we will consider Steven Holl's Church of St. Ignatius in Seattle, Washington (Figure 2.3). This space is vastly different in character from the two previous examples, composing sunlight into a series of carved, indirect figures which accentuate its volumetric qualities

[Holl, 1999]. The light within this church could be described as more selectively diffuse, with compositional lines and volumes being defined through distinct spatial geometries. This example represents less extreme contrast than that of the Smithsonian Courtyard or the Dominus Winery, but still maintains a dynamic relationship to the exterior as shifting light levels cause figural volumes of light to change over time [Holl, 1999].

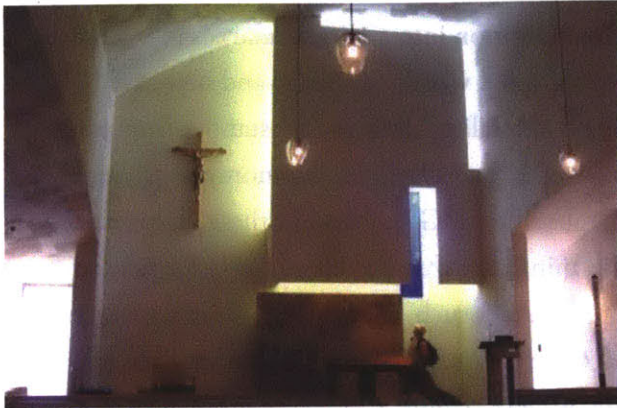


Figure 2.3: Church of St. Ignatius, Seattle, WA. Image courtesy of Architecture Revived.

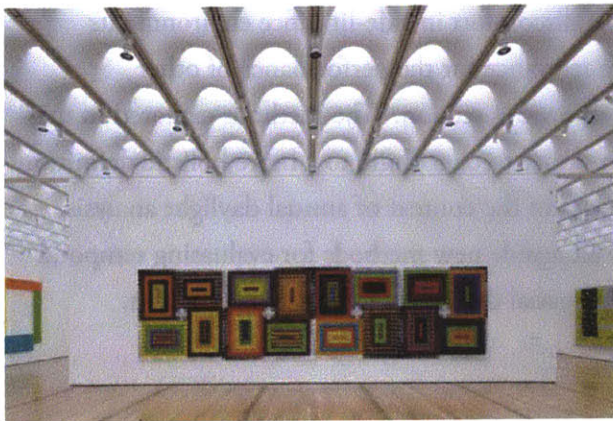


Figure 2.4: High Museum of Art, Atlanta, GA. Image courtesy of Michael Schwartz

The final example, Renzo Piano's High Museum of Art in Atlanta, Georgia (Figure 2.4), employs an indirect daylighting strategy similar to that in the Church of St. Ignatius, although it differs in the stability of its internal illumination as the light tubes that compose the roof collect and distribute diffuse Northern light. The programmatic use of this space as a gallery necessitates an even distribution of internal lighting levels, while preventing any direct sunlight that may damage or distract from the artwork. As a result, the presence of strong contrast and temporal instability is minimized across the space.

These four contemporary examples represent varied site conditions, both urban and rural; varied latitudes, from Georgia to Seattle; and varied programmatic uses from art gallery to public atrium. They represent dramatically different compositions of contrast and temporal light stability, and

yet they all produce visually stimulating environments that enhance the architectural expression of interior space. In considering this diverse range of architectural examples, our goals are to define the daylighting characteristics that distinguish them and determine what that tells us about the nature of contrast and luminous diversity. Although the notion of 'quality' is, admittedly, a difficult element to quantify due to its subjective nature, it seems very possible that there are metrics that could account for the perceptual aspects of daylight illumination. If it's possible to define certain distinguishing characteristics such as spatial contrast and to understand how this contrast varies

within a larger categorization of lighting ‘types,’ then this definition and categorization could help architects communicate their objectives more comprehensively. In turn, this typological approach can serve as a foundation for a new set of metrics that would compare contrast and light variability on a temporal scale.

2.3 Existing Daylight Performance Metrics

Using these examples as context, we will now transition into a critical analysis of existing daylighting performance metrics to expose the need for more visually dynamic and objective methods as they relate to spatial contrast and daylight variability. There are substantive limitations to Illuminance-based metrics such as Daylight Factor (DF) and Daylight Autonomy (DA), and Luminance-based metrics such as Daylight Glare Probability (DGP). Most of these illuminance-based-metrics is that they were developed to analyze minimum threshold levels in task-oriented spaces such as offices, libraries, and schools [Lam, 1977]. As such, they do not address a larger spectrum of programmatic uses in architecture and often encourage uniformity rather than diversity in daylighting design. Spaces such as the Dominus Winery (Figure 2.2) are intentional in their high-contrast, low-light strategy and require an objective metric that accounts for those design intentions in the analysis of their performance. Luminance-based daylight metrics, on the other hand, were primarily designed for the assessment of discomfort in side-lit office environments [Weinhold & Christoffersen, 2006] and hold little relevance for the performance of other programmatic uses such as those introduced in the previous section. The methods explored in this thesis do not seek to discount existing metrics, but rather to contribute to a more holistic definition of performance. We should consider existing metrics in the context of annual daylight analysis, contrast analysis, and temporal data visualizations alongside new methods for evaluating temporal performance in order to reaffirm the importance of spatial definition in daylighting design.

2.3.1 Commonly Used Daylight Metrics

Before we can discuss those multi-layered metrics that define daylighting performance on an annual scale, it’s important first to define the units of measurement used to quantify light. Illumination or ‘Illuminance’ is a physical measurement that describes the total luminous flux that falls on a surface, per unit area [Lam, 1977]. Illuminance is, perhaps, the most widely applied measurement of light and creates the foundation upon which most other metrics such as Daylight Factor and Daylight Autonomy are based. Codes and standards most commonly reference illuminance measurements across a work plane to determine the amount of light recommended for various tasks [IESNA, 2000]. Luminance is a physical measure of the luminous intensity per unit of

surface, travelling in the direction of a specific angle [Lam, 1977]. It describes the amount of light that is emitted from a surface within a solid angle of emergence. Both illuminance and luminance are photometric measurements that quantify light as it relates to the spectral sensitivity of the human eye [CIE, 1926].

Daylight Factor (DF) may be the most ubiquitous and wide-spread illuminance-based metric. Using illuminance measurements, daylight factor measures the ratio between the amount of diffuse light that reaches a surface within a space and an external reading under overcast sky conditions (Figure 2.5). In other words, it is defined as a ratio between the illuminance at an internal point within a building and the external, un-shaded horizontal illuminance under a CIE overcast sky [Moon & Spencer, 1942]. This strategy was originally created to address the amount of light that enters a building, while avoiding the difficulties associated with fluctuating sky conditions and the dynamic nature of sunlight [Waldram, 1950]. From an architectural standpoint, the insufficient information available in Daylight Factor only decreases awareness about the dynamic nature of daylight and its performative capabilities. Because daylight factor calculates a ratio between

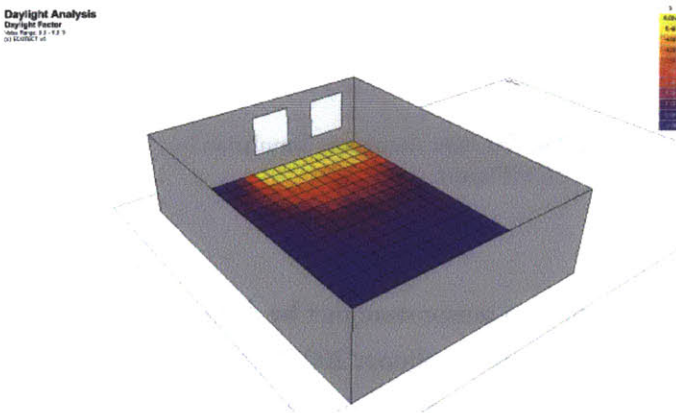


Figure 2.5: Daylight Factor Simulation in ECOTECH

interior illuminance and what is measured under overcast sky conditions, it serves as a worst-case-scenario in daylight quantification [Reinhart, Mardaljevic & Rogers, 2006]. As all other sky conditions emit more light, it can be assumed that a given sensor point will achieve the recorded DF% or higher. Although logical, this assumption assumes a ‘more-is-better’ attitude towards daylight and promotes the implementation of fully glazed building envelopes regardless of climate or programmatic use [Reinhart, Mardaljevic & Rogers, 2006]. DF is useful when a maximum amount of light is desirable, but it cannot be successfully applied to spaces like the Dominus Winery, where high-contrast, low-light conditions are preferred.

If we were solely concerned with bringing light into a building, then we could maximize our design with daylight factor, but many of the problems we approach in architectural design deal with controlling, animating, and understanding the impacts of sunlight under varied conditions [Steane & Steemers, 2004]. In the case of the High Museum by Renzo Piano, the use of DF would provide little value to the optimization of its daylighting strategy, which seeks to control the penetration of direct sunlight. This static metric must be complimented with more dynamic and visually engaging data about the temporal nature of space so that architecture may seek to ‘perform’ in multiple ways.

2.3.2 Annual Illuminance-Based Metrics

Annual illuminance-based metrics such as Daylight Autonomy include a more dynamic range of information about the performance of a surface, but are still limited to a static representation of space that is based on a plane of sensors. Daylight autonomy was first referred to as a percentage of the year when the minimum illuminance threshold was met by daylight alone and did not require supplemental electric lighting. In 2001 it was redefined as the percentage of occupied time throughout the year when the minimum illuminance requirements at a sensor were met by daylight alone [Reinhart & Walkenhorst, 2001; Reinhart, Mardaljevic & Walkenhorst, 2006]. As a metric, daylight autonomy can evaluate annual illuminance thresholds, taking into account building orientation and climate-driven sky types. It is useful in determining whether a surface within a space achieves a minimum threshold of illuminance and what percentage of the year it’s maintained (Figure 2.6). Continuous Daylight Autonomy (DAcon) is a similar method of evaluating annual performance through illuminance thresholds across a sensor plane, but it awards partial credit for illuminance levels that fall below the minimum threshold [Rogers, 2006]. Although the minimum illuminance threshold may be 500 lux, the metric awards partial credit for those sensors reading less than 500 on a weighted scale, supporting the notion that some daylight is still better than no daylight [Reinhart, Mardaljevic & Rogers, 2006]. This approach allows for a smoother gradient of threshold compliance and accommodates the research that concluded that many people work comfortably at illuminance levels below the standard minimum threshold of 500 or even 300 lux [Reinhart & Voss, 2003].

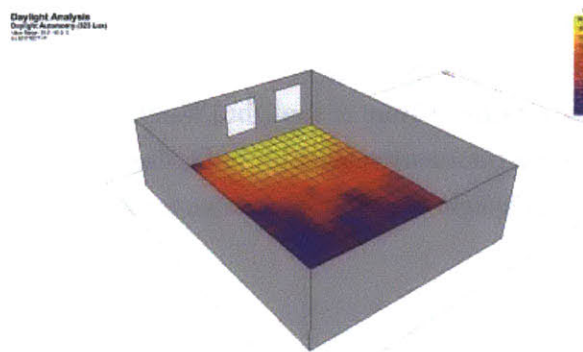


Figure 2.6: Daylight Autonomy Simulation in ECOTECT/Daysim

Neither of these metrics, however, is capable of expressing the temporal variations that occur across the year or visualizing the dynamic nature of daylight as represented by examples such as the Smithsonian Courtyard (Figure 2.1) or the Dominus Winery (Figure 2.2). It is important to consider them, however, because they accommodate a broader and more climate-specific range of annual data than DF, but they do not address the presence of temporal light variability. This thesis seeks to introduce a more visually dynamic method for analyzing contrast in order to accurately represent the characteristics displayed within architectural space.

2.3.3 Glare

Unlike daylight factor and daylight autonomy that measure illuminance across a surface, glare metrics are based on luminance, which measures the amount of light that is emitted from a surface in the direction of our eye. In the context of the architectural examples and illuminance-based metrics such as DF and DA that were introduced earlier in this chapter, luminance-based metrics would initially appear to be more appropriate for quantifying characteristics such as contrast because they describe light as we envision it perspectively. Most luminance-based metrics such as glare, however, were developed to describe human discomfort due to high levels of contrast within the visual field and do not provide a method for visualizing the luminous diversity of space. As luminance, brightness, and contrast are subjectively evaluated, those methods that do describe glare are

fragmented across no less than seven established metrics and lack wide-spread consensus among daylighting designers [Kleindienst, 2010].

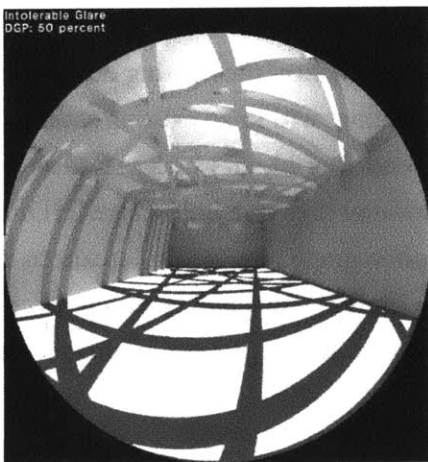


Figure 2.7: Daylight Glare Probability Simulated by DIVA for Rhinoceros

Daylight Glare Probability (DGP) is the most ubiquitous metric within this group and represents a percentage of people that are disturbed by daylight-based glare in a side-lit office environment [Weinold & Christofferson, 2006]. The resulting value, a percentage from 0-100%, has only been validated for 20% DGP or higher and like other glare metrics, it was developed to calculate discomfort in task-oriented settings [Weinhold & Christofferson, 2006; Kleindienst & Andersen, 2009]. These

comfort-based metrics must be used objectively as many architectural spaces do not require low-glare tolerance in their programmatic use. Figure 2.7 shows an example DGP analysis produced in the DIVA for Rhinoceros toolbar, an analysis plug-in developed by the Harvard Graduate School of Design.

For the purpose of this research, it is important to remember that spaces such as the Smithsonian Courtyard use direct light to impose an intentionally dramatic set of temporal effects. Luminance may serve as an appropriate unit of measurement for the quantification of contrast within our field of view, but we need a new set of metrics that can assess those contrast-driven characteristics of architectural space to encourage objective indicators of performance that compliment design intentions.

2.4 Digital Images & the Quantification of Light

It has been established that illuminance-based metrics such as daylight factor and luminance-based metrics such as glare do not provide a dynamic or visual understanding of those contrast-based characteristics seen in the architectural examples presented earlier in this chapter. It was determined, however, that luminance can serve as an appropriate unit of measurement for the study of contrast as it measures the amount of light that is emitted from a surface in the direction of the eye. Other areas of research have established contrast as a qualifier of daylight performance, using the digital image as a medium through which multiple layers of information can be abstracted.

In order to gain photometric measurements such as luminance, the lighting designer traditionally depended on photocell equipment to acquire readings within an existing space or a scaled physical model. Computer programs with ray trace rendering engines such as Radiance now allow us to gain luminance values through the production of high-dynamic-range (HDR) images [Greg Ward, 1994, 2005]. Renderings and digital photographs are used by architects to communicate design intent because they can be adjusted to capture visual effects within space the way they would appear to an occupant. This makes them a suitable medium for luminance-based metrics that involve contrast analysis [Demers 2000, 2007].

In her work on contrast and brightness analysis through the use of digital images, Demers used histograms to identify the dominance of bright, dark and middle-range pixel values [Demers, 2007]. These values were then codified to develop a typological classification of daylight strategies, which break each image into a four-part quadrant that quantify the dominance of white, black, and grey pixels within the frame. There are fifteen total categories that combine values that range from

four white quadrants to black, white, and grey hybrids. Each typology can be determined by the mean value of pixels (brightness) and their standard deviation (contrast) [Demers, 2007]. Creating a typological understanding of contrast in daylit space is valuable to the architectural community because it can help to generate a visual dialogue about daylight design strategies.

This thesis embraces the need for a typological approach while maintaining a critical attitude towards the use of histograms in contrast analysis. Although a histogram can analyze variations in pixel brightness across an image, it removes each value from the context of its composition and places it in a gradient from low 0 to high 255, as seen in Figure 2.8. The image on top shows a highly articulated wall of structure through which direct sunlight casts large patterns on the floor. The image on the bottom shows a much denser pattern of direct sunlight with a greater optical sense of contrast, but the histograms appear quite similar. This allows us to compare the number of grey pixels to that of black or white and identify dominant levels of brightness, but it does not quantify the contrast generated when black and white pixels are located side-by-side. Images represent space through the perspective of the occupant, but translating those images into rgb histograms removes individual pixels from their composition and tells us nothing about the contrast we see. This thesis builds upon Demers work to provide a typological representation of contrast, but proposes the need for a new metric that differentiates between compositional changes in brightness.

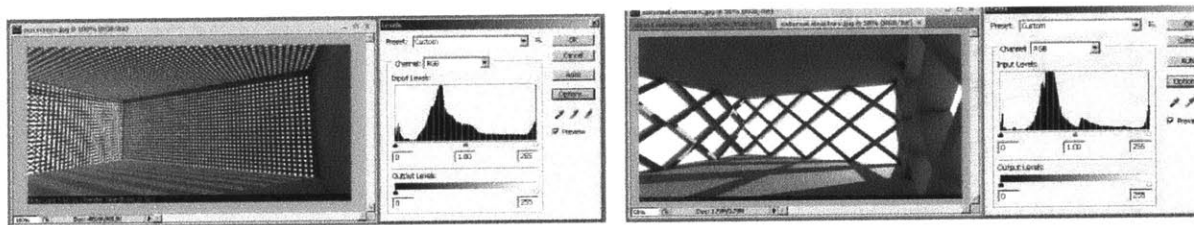


Figure 2.8: Rendered Images with Associated Histograms in Photoshop, Showing the Range of Pixel Brightness between 0 and 255

2.5 Visualizing Temporal Data

It has been determined that an analysis of luminance can be used to explore contrast through digital images, and contrast can be used to describe spatial diversity in architecture. When applied to the temporal complexity of real space under changing sky conditions, however, multiple images over the year would need to be studied in order to understand the dynamic qualities of architecture as it is experienced over time. One of the most challenging aspects of annual daylight analysis, whether it be luminance or illuminance-based, is representing the large quantity of resulting data

into both quantitative and simultaneously visual information. Daylight autonomy compresses annual illuminance data into a single map that represents the percentage of time in which successful threshold levels are achieved.

The next step beyond these visually compressed annual metrics is the inclusion of temporal maps and associated renderings which allow the designer to visualize the daylight variation in space over time [Kleindienst et al, 2008 ; Lee, 2009]. Spatio-Temporal Irradiation Maps (STIMAPS) were proposed as a way of representing annual data across a single graph that shows days of the year on a horizontal scale and hours of the day on the vertical [Glaser, 1999](Figure 2.9). This method provided the designer with annual data and some indication of when that data changed throughout the year, allowing the designer to address performance goals with more accuracy. Although the ‘smoothness’ of the map depends on the number of annual instances and the interpolation method between each data point, the method has been validated for illuminance readings with 56 annual

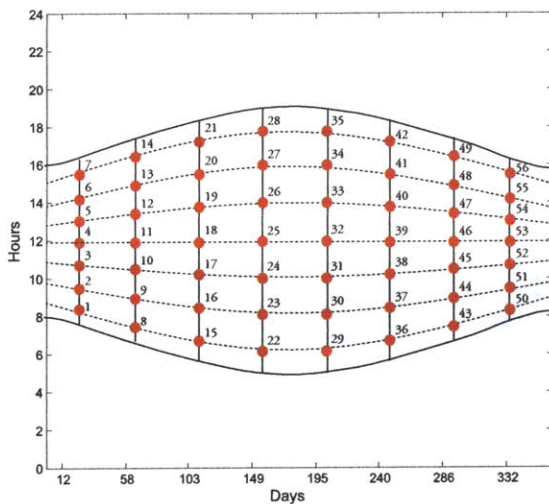


Figure 2.9: The Location of Data Points on a Temporal Map, 56
Based on the Temporal Grid Used in Lightsolve [Kleindienst et al, 2008]

periods representing 7 daily and 8 annual intervals [Kleindienst et al, 2008]. This mapping technique was used in the development of Lightsolve for Google Sketchup, which generates temporal maps for illuminance alongside associated renderings at each of the 56 annual instances [Kleindienst et al, 2008; Lee, 2009](Figure 2.10). Each of the intervals represents symmetrical moments during the year. This simulation method provides the designer with goal-based illuminance thresholds and allows him or her to navigate the resulting temporal maps with associated renderings to provide a clear visualization of both the quality and quantity of light in the space over time [Kleindienst et al, 2008; Lee, 2009]. This method is valuable in its combined approach for representing annual data alongside associated renderings to provide both quantitative and qualitative readings of space.



Figure 2.10: The Lightsolve Interface, Showing a Default Room with Temporal Tlluminance Maps on the Top and Annual Renderings on the Bottom [Kleindienst et al, 2008 ; Lee, 2009; Lu, 2008]

When approaching the analysis of temporal contrast, it becomes necessary to consider what will be measured in each image (luminance) as well as how it will be quantified over a series of images to produce a more dynamic reading of the architectural space. The approach must include images and temporal maps to communicate a visual and simultaneously numeric set of information so that spaces can be compared

2.6 Summary

A great deal of research has been completed in the fields of annual daylight analysis, contrast analysis, and temporal data visualization. There is a well-established need for more dynamic annual metrics as well as a typological and visual approach to understanding the variable nature of light and the importance of contrast as a qualitative indicator. Elements of the Lightsolve project have provided a platform for this research simulation and visualization method, while Demers' work has helped to support the use of brightness and contrast as a typological platform for quantitative and qualitative analysis [Kleindienst et al, 2008; Demers, 2007]. The next chapter in this thesis will introduce a broader range of architectural examples that will develop a new typological language for classifying various aspects of contrast and light variability. This approach will be used to generate a new set of metrics that help to complement our existing tools for quantifying daylight performance.

Chapter 3

Architectural Context

3.1 Introduction

The previous chapter began with a critical look at existing daylighting metrics and strategies for contrast evaluation within architectural space. We then presented the need for more visually dynamic and spatially dependent methods for quantifying contrast and temporal variability in order to develop a broader scope of daylight performance criteria. We will now turn to existing architectural examples to develop a more effective typological vocabulary about the range of daylight strategies that represent various applications of contrast. Given the interdisciplinary nature of this project and its aim of transcending the boundaries between design and environmental analysis, we will begin with architecture and work backwards toward a quantitative method of analysis. A survey of existing architectural spaces from around the world led to the development of a classification strategy for the degree of contrast and hypothesized temporal variability present in each space. These categories were then distilled down into a series of case study spaces and digitally modeled to create a set of annual renderings. The quantitative methods for evaluating contrast and temporal variability, which will be introduced in more depth in the following chapter, emerged out of a range of perspectives about the distinguishing characteristics of each space.

3.2 Developing an Architectural Typology Regarding Contrast

In order to understand the various characteristics of contrast that occur within space, a number of contemporary examples were analyzed to produce a matrix of typological conditions. Each example was studied using the trained intuition of an architect and then positioned within a

gradient to represent various levels of perceived contrast within architectural space and the degree to which those levels were determined to change over time. The left side of this gradient was meant to contain highly variable and contrasted daylight strategies while the right side was reserved for minimally variable, low-contrast strategies. This typological approach was necessary to establish an eventual method for quantifying contrast, because it allowed us to understand the gradient of possible daylight strategies and to develop a numerical scale against which each space could be valued and compared.

3.2.1 The Preliminary Matrices

The first architectural examples illustrate clearly opposed contrast characteristics that establish a high and low for each end of the contrast spectrum. The first example to emerge on the far left or 'high contrast' side of the spectrum is Santiago Calatrava's Milwaukee Art Museum (Figure 3.1). The atrium located beneath the central structural 'wings' allows for the direct penetration of sunlight through a highly articulated glass roof. This space represents a high degree of contrast and temporal variability as light moves constantly across the overhead structure, adjusting the pattern of incoming light on the floor. On the far right or 'low contrast' side of the spectrum, is the Modern Art Gallery in Renzo Piano's addition onto the Chicago Art Institute (Figure 3.2). The double layered roof that covers this gallery consists of a top layer of reflective metal louvers that blocks direct sunlight and a second layer of translucent glass that diffuses incoming light into an evenly distributed luminous glow. This space represents a low level of contrast as well as a low level of temporal variability due to the diffusing characteristics of its top-lighting strategy.



Figure 3.1: Milwaukee Art Institute, Atrium.
Image courtesy of ellauniverse.blogspot



Figure 3.2: Chicago Art Institute, Modern Gallery.
Image courtesy of Renzo Piano Building Workshop

The initial matrix positioned these two examples at each end of the spectrum and was composed of eight total categories that ranged from high contrast on the left to low contrast on the right (Figure 3.3). The titles for these categories were, in this rendition, a work-in-progress, but describe the qualitative differences between each column. At this time, we developed the term 'spatial

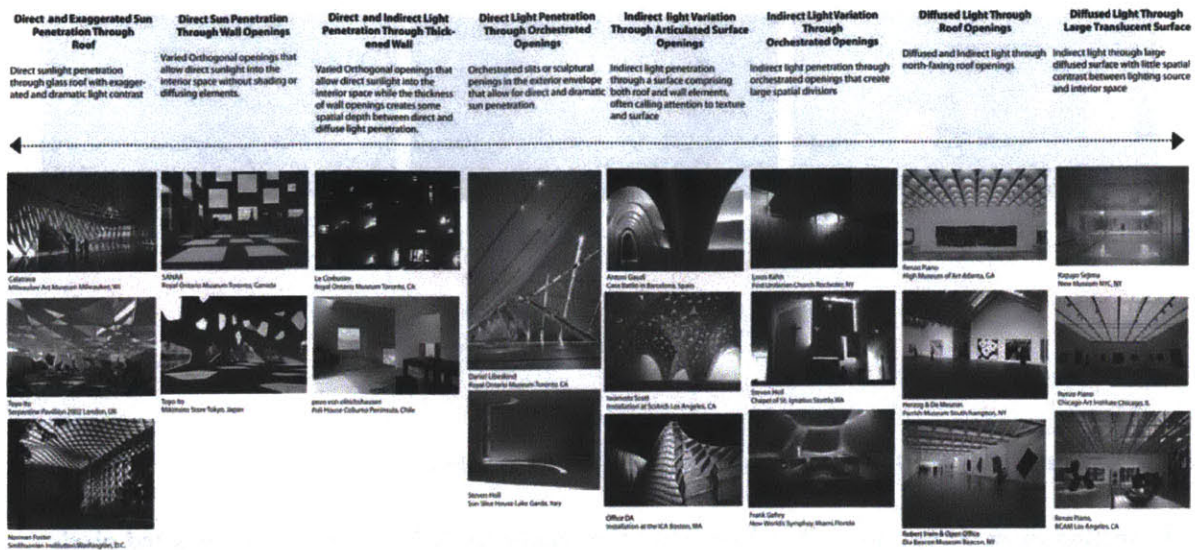


Figure 3.3: Preliminary Contrast Matrix

contrast' to distinguish between various daylight characteristics; it is illustrated through a comparison of the Zollverein School of Management (Figure 3.4), the Sun Slice House (Figure 3.5), and the Dia Beacon Museum (Figure 3.6). All three spaces show some level of contrast between dark and bright areas within the image, although the Zollverein School of Management has sharper and more frequent spatial subdivisions or 'peaks' in the brightness between light and dark areas. The Sun Slice House contains a more 'linear' or figural division between light and dark, whereas the Dia Beacon Museum has much smoother gradation and fewer spatial subdivisions.



Figure 3.4: Zollverein School of Management. Image courtesy of Thomas Mayer

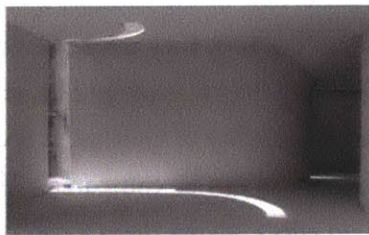


Figure 3.5: Sun Slice House. Image courtesy of Steven Holl



Figure 3.6: Dia Beacon Museum. Image courtesy of urban75

This concept is described in figure 3.7, which abstracts each space into a simplified model and each model into a map of enlarged pixels to represent the distinction between 'peaks,' 'lines,' and 'gradients.' Each cluster of contrast is conveyed by a field of circles that represents the strength in brightness of each pixel from 0 to 255. The thick red circles represent pixels whose brightness is closer to 255, while the thin circles represent values closer to 0. Spatial contrast is determined by the difference in brightness between neighboring pixels and can be seen by how sharply the values drop

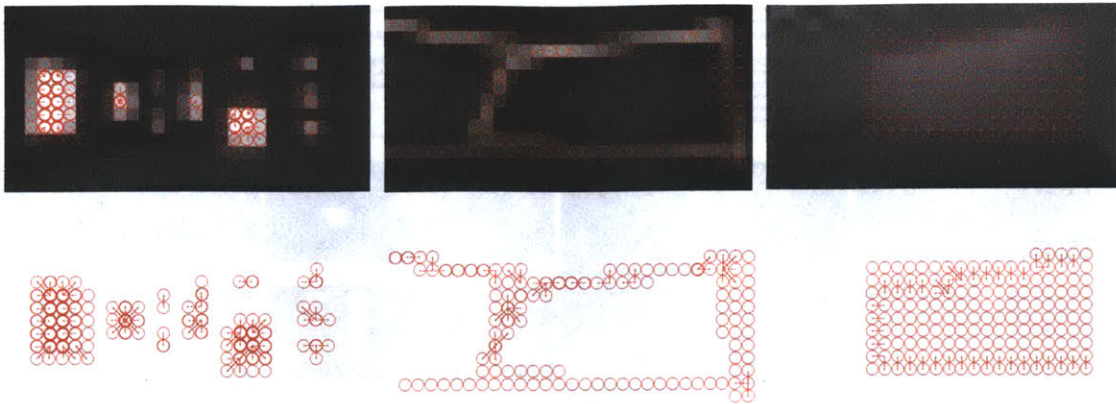


Figure 3.7: Spatial Contrast, (from left to right) 'Peaks', 'Lines,' and 'Gradients'

off, creating more abrupt figural breaks or smoother gradients. When a cluster of thick red pixels is surrounded by a perimeter of thin red circles, then 'peaks' of contrast are present. When a field of circles shows little variation in thickness, then it represents a smooth 'gradient' of contrast. The spaces that populate the left side of this initial matrix display sharper 'peaks' of contrast while those on the right side show smoother 'gradients' between areas of brightness. The spaces that occupy the middle set of categories represent some combination of the two, including more figural 'lines' or distinct and isolated shapes of light.

This preliminary attempt at categorizing architectural space through its daylight characteristics represents a certain amount of intuition from the perspective of a trained architect. The goal was not to place value on either side of the contrast spectrum, but to distinguish between contrast-driven effects to better understand how they might be defined more explicitly. The naked eye can analyze a photograph and identify the presence and location of contrast within space, but in order to understand the magnitude and stability of contrast as it changes over time, it is necessary to establish a framework through which spaces can be compared. This allows the designer a scale on which to locate and describe a desired effect, giving them a comprehensive understanding of contrast and its dynamic impacts. A typological approach to categorizing these effects brings us one step closer to quantifying the conditions they represent.

Due to the limited number of examples represented in the initial matrix, a reiterative strategy unpacked and expanded it to accommodate a broader set of categories. The addition of new examples helped to test and strengthen each category, raising the need for additional columns when new strategies emerged. This second matrix represents a more in-depth survey of architectural spaces, doubling the number of examples to forty two and adjusting the total range of categories from eight to eleven (Figure 3.8). This expanded matrix shifted examples from within its organization

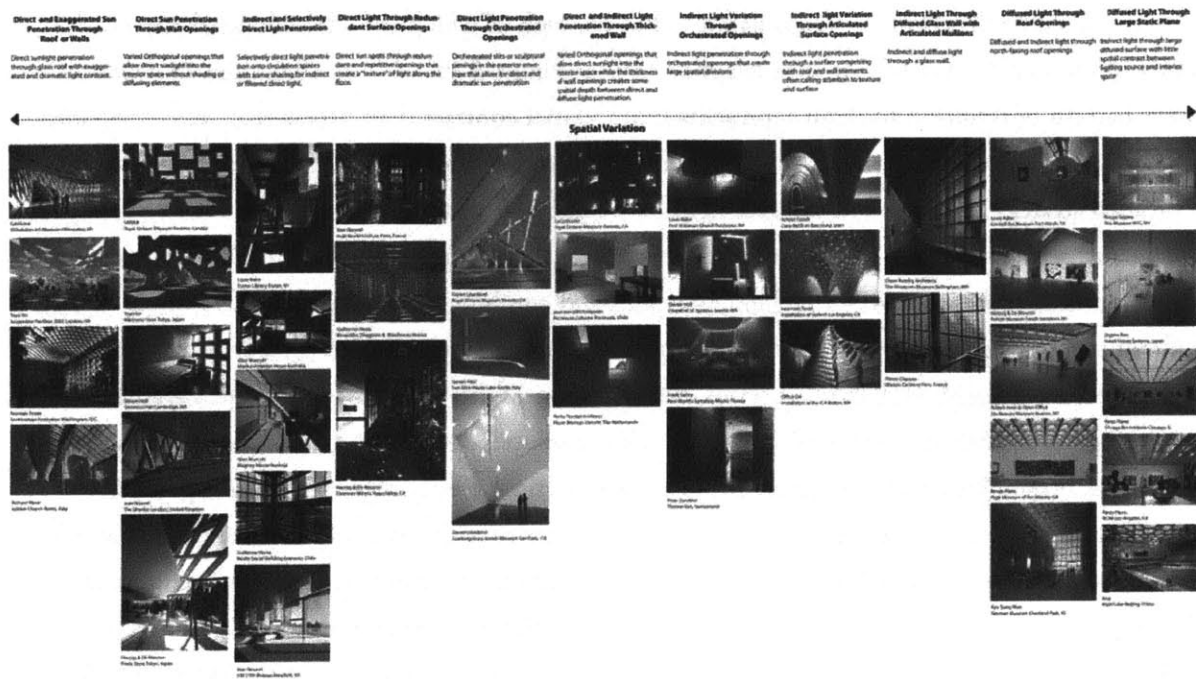


Figure 3.8: Second Preliminary Matrix

to develop a more resolved set of categories. Some spaces that were originally located on the left side of the spectrum, were moved closer to the right as our notion of ‘spatial contrast’ began to distinguish between boundary conditions within the image. For example, the column containing the Poli House by Pezo Von Ellrichhausen, originally located on the right side of the initial matrix, moved toward the center of the second matrix. This adjustment occurred when it was determined that the bright window openings did not create sharp peaks or hard boundaries of contrast against the interior space, as was seen in the Royal Ontario Museum. On the contrary, the thickness of the wall cavity in which the openings are set creates a smoother gradient of light as it enters the space. This can be seen by the tonal variations surrounding each window opening. The effect is a ‘Direct and Indirect’ penetration of light, which is more similar in contrast to the First Unitarian Church, located in column seven, than it is to the Royal Ontario Museum, located in column two. This expanded matrix represents a process of trial and error that occurred throughout the development of this typological study. In order to define a set of qualitative and subjective principles, such as contrast, we must anticipate a certain level of resistance and a healthy degree of debate. This spirit of collaboration enables us to transcend the boundaries between architecture and technology to establish a new set of metrics that are dedicated to the values of both disciplines.

The most difficult spaces to define in this second matrix are located within the third column, which is titled ‘Indirect and Selectively Direct.’ Upon further review, we determined that this

category could be divided into two separate columns, each of which should be located toward the center of the matrix. Glen Murcutt's Magney House (Figure 3.9), with its distinctive louvers and direct pattern of resulting sunlight represents more spatial contrast than others that were originally located within the same category. Jean Nouvel's 11th Avenue building (Figure 3.10) employs a combined strategy of direct and indirect light penetration, similar to the Magney House, but it uses screens rather than louvers, which emit light in a softer set of gradients. These middle categories, many of which represent hybrid daylight strategies and combined contrast effects, are often difficult to distinguish and even harder to define. While it is impossible to categorize all examples of architecture through such explicit terms, the intention of this thesis is to generate a gradient of typological conditions against which similar characteristics can be compared. An overall range of contrast is established, despite some flexibility between adjacent categories. This typological comparison, however subjective through the development of each category, establishes an original attitude towards the use of contrast and temporal diversity in evaluating daylight in architecture. This approach may be used to establish more objective criteria for the analysis of environmental performance in architecture as design intentions must be taken into consideration before metrics can be applied for evaluation.

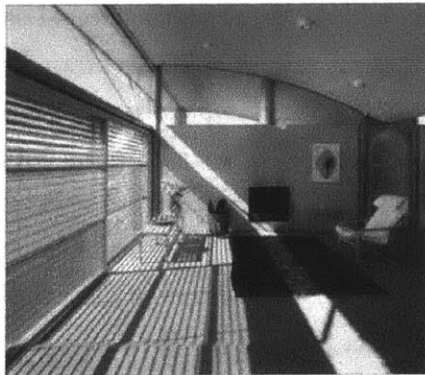


Figure 3.9: Magney House. Image courtesy of Nature In Buildings

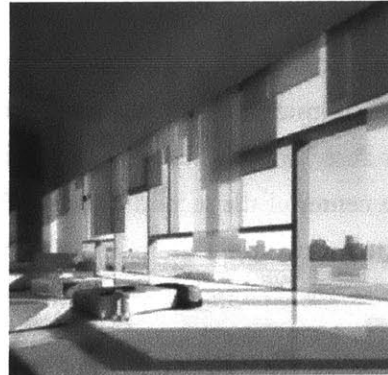


Figure 3.10: 100 11th Avenue. Image courtesy of redchalksketch

3.2.2 The Final Matrix

Using the first two matrices as grounds for discussion and refinement, we created the third and final matrix of existing architectural spaces. The matrix contains seventy five examples and spans fifteen categories, creating a more articulated gradient of contrast-driven effects (Figure 3.11). An increase in the overall number of examples allows for more accurate differentiation between columns, although there are an uneven number of examples in each category as some typologies are more common than others.

- 1
Direct and Exaggerated
Through Roof
- 2
Selectively Direct and Exaggerated
Through Roof or Walls
- 3
Direct & Dramatic
Through Walls
- 4
Direct & Screened
Through Walls & Roof
- 5
Direct & Filled
Through Walls or Roof
- 6
Partially Direct & Partially Screened
Through Walls
- 7
Direct
Through Walls
- 8
Linear Direct or "selectively Direct"
Through Roof or Walls
- 9
Partially Direct & Partially Filled
Through Walls
- 10
Partially Direct & Partially Indirect
Through Roof or Walls
- 11
Spotted Indirect
Through Roof or Walls
- 12
Surface Indirect
Through Roof or Walls
- 13
Indirect
Through Walls
- 14
Indirect & Dispersed
Through Roof
- 15
Indirect & Diffuse
Through Roof or Walls



Figure 3.11: Final Matrix of Contrast-Driven Effects

The first three categories, referred to (from left to right) as 'Direct and Exaggerated,' 'Selectively Direct and Exaggerated,' and 'Direct and Dramatic' represent the far left or high contrast end of the spectrum. The 'Direct and Exaggerated' column contains those spaces with transparent, top-lit daylighting strategies in which the direct penetration of sunlight plays a dominant role in the choreography of visual effects. It includes the Smithsonian Courtyard by Norman Foster and the Serpentine Pavilion by Toyo Ito. The next column, referred to as 'Selectively Direct and Exaggerated' describes similar contrast characteristics, but accommodates those spaces that have some opacity in their structure as can be seen in the Millennium Church by Richard Meier. The third column, known as 'Direct and Dramatic,' includes spaces like the Prada Store by Herzog and De Meuron and the Zollverein School of Management by SANAA. The architecture in this category is defined by direct sunlight through an articulated transparent façade and displays high spatial contrast. The obvious differences between the first and third column are due to the orientation of the transparent light-emitting surface. When unobstructed sunlight is allowed in through the roof, it creates contrast on all four walls as well as on the floor. When it enters through the wall, it can only affect three vertical surfaces and the floor, reducing the overall contrast perceived within the space.

The next three categories, (from left to right) 'Direct and Screened,' 'Direct and Filtered' and 'Partially Direct and Partially Screened,' represent the high-to-middle portion of the contrast spectrum. The fourth column, 'Direct and Screened,' contains the Centrifugal Pavilion by Obi Architects which represents those spaces with smaller gauge surface openings, resulting in some direct and some indirect light. The fifth column, 'Direct and Filtered,' is similar in definition to the previous column, except that it contains spaces such as the Dominus Winery by Herzog and Meuron which is defined by a smaller and less frequent pattern of incoming light. The sixth column, 'Partially Direct and Partially Screened,' is characterized by the presence of a fully glazed façade which filters light through a set of louvers such as the Magney House by Glen Murcutt.

The middle three categories are labeled (from left to right) 'Direct,' 'Partially Direct and Partially Filtered,' and 'Linear Direct.' While the column labels are self-explanatory, they are difficult to populate as the spaces that fall within them represent some form of hybrid contrast. The seventh column, 'Direct,' includes spaces such as the fully glazed Bombala Farmhouse by Collins and Turner. This category is defined by fully-glazed, side-lit conditions that allow for maximum sun exposure with minimal obstruction. Category eight is distinguished by the presence of a fully glazed façade which filters light through a smaller gauge screen such as the Nestle Social Building by Guillermo Hevia Architects. The last category in this group, 'Linear Direct,' is composed of spaces like Daniel Libeskind's Imperial War Museum, which emits light through clearly defined slit(s) in the wall which result in dramatic and figural shapes.

The middle-to-low contrast categories, 'Partially Direct and Partially Indirect,' 'Spatial Indirect,' and 'Surface Indirect,' are composed of spaces that primarily emit indirect light with smoother gradients of contrast. The 'Partially Direct and Partially Indirect' category includes architecture like the Poli House by Pezo Von Ellrichausen, which allows for the direct penetration of sunlight through thick outer wall openings. Instead of creating sharp contrast boundaries, these windows diffuse light through their depth. The next category, 'Spatial Indirect,' operates in a similar way, but only through indirect light such as can be seen in the First Unitarian Church by Louis Kahn. The twelfth column, 'Surface Indirect,' is made up of non-planar surface conditions that create indirect lighting patterns, providing low-level contrast. This column contains more computationally complex spaces such as the Sci-Arch Installation by Iwamoto Scott Architects.

The final set of categories in this matrix, labeled 'Indirect,' 'Indirect and Dispersed,' and 'Indirect and Diffuse,' represents the far right or low-contrast end of the spectrum. All three columns are defined by indirect lighting strategies, from the Whatcom Museum by Olson Kundig to the Chicago Art Institute by Renzo Piano. The differences among these three columns is characterized by whether the space is side-lit or top-lit and by the degree of resulting surface articulation through mullions and other structures. The lowest contrast spaces, located within the 'Indirect and Diffuse' column fifteen, are represented by translucent overhead lighting and minimal surface noise.

Although there was no initial bias in the specific programmatic use of each space and its location within the matrix, there are definite patterns that emerge as a result of this system of classification. Those spaces located to the far left of the matrix, falling under 'Direct and Exaggerated' or 'Direct and Dramatic,' tended to represent circulatory, atrium, or unspecified public uses. Those spaces located to the far right of the matrix, 'Indirect and Dispersed' and 'Indirect and Diffuse,' were almost all gallery spaces with highly specific lighting needs. Spaces that fell in the middle of the matrix under 'Selectively Direct' or 'Partially Direct and Partially Screened' represented a mixture of programmatic uses but were dominated by residential examples. Interestingly enough, many of the religious programmatic spaces and concert or performance venues fell in the second half of the matrix under 'Partially Direct & Partially Indirect' and 'Spatial Indirect.' It may be no surprise that certain trends emerged through this typological approach to categorizing contrast as there are intuitive rules of thumb for the appropriate use of direct and diffuse lighting strategies for various programmatic uses. For example, it would be inappropriate for a museum to employ a 'Direct and Exaggerated' daylighting approach in its galleries as it would create figural conditions of light that would distract from the artwork. Likewise, there is no need to minimize incoming light through an atrium space that is often meant to provide a transitional and variable experience for its occupants,

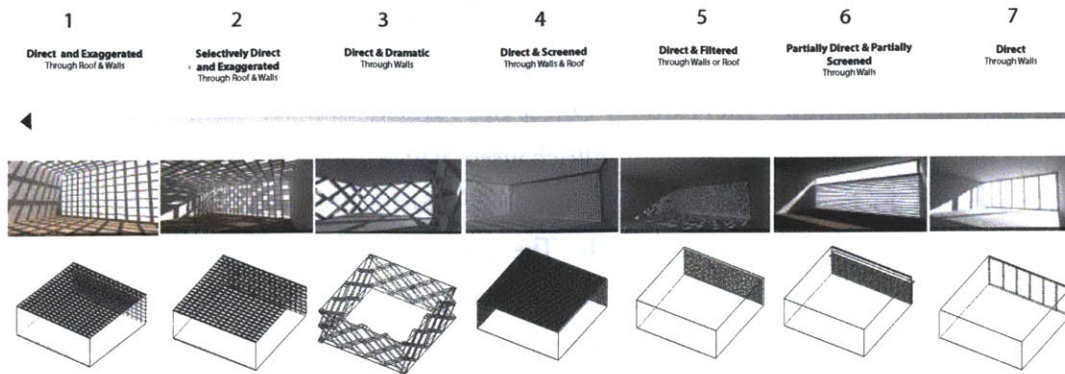


Figure 3.12: Matrix of Typological Spaces

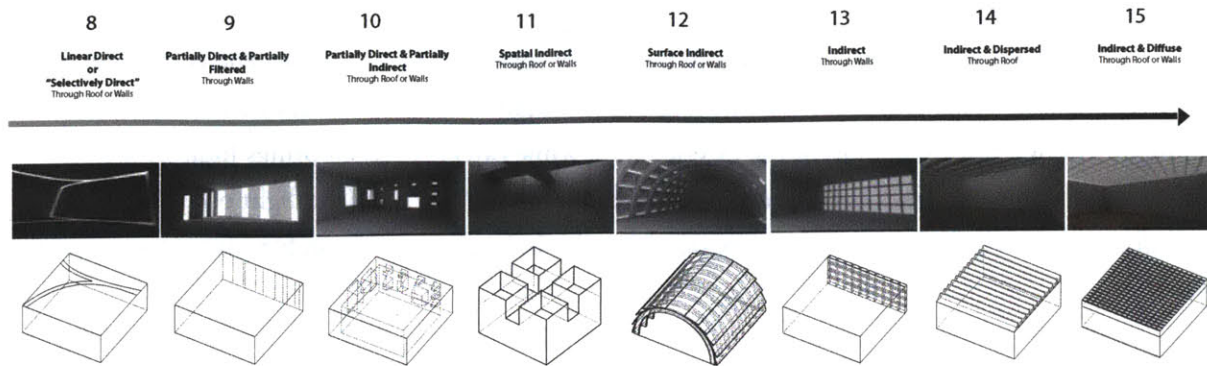
who may spend the rest of their day in an artificially controlled office environment. In either case, there are definite correlations between programmatic use and the use of contrast in this gradient of contrast-driven daylight strategies.

3.2.3 The Typological Matrix

The final matrix of contrast-driven architectural effects made it possible to distill each column down into a single representative space so that we might understand the gradient on a more explicit level. Each category of the matrix was compressed into a single model that represents the characteristics of the existing examples, but with abstracted levels of detail.

The examples represented in figure 3.11 were organized into fifteen categories based on the presence of redundant contrast characteristics. The resulting typological spaces were a simple reduction of those characteristics into abstracted digital models that share similar floor plan and ceiling height dimensions for the ease of comparison. Our intention was to loosely model each typological space after an existing architectural space, as represented by the previous matrix, while maintaining 30 ft. by 30 ft. floor plan dimensions and a 10 ft. ceiling. This was done so using Rhinoceros, a NURBS based geometric modeling program that is used by students and professionals alike to generate a wide array of architectural forms. In this initial set of typological models, little time was spent on recreating the complexity of materials or interior finishes that might contribute to the overall contrast characteristics.

Categories one through three represent the high contrast, high variability end of the spectrum. Category one has a transparent glass roof structure and south-facing façade with a simple grid of mullions that cast harsh shadows onto the walls and floor. Category two uses the same



gridded structure as the previous space, but introduces some translucent glass panels to soften the incoming shadows. Category three uses a hexagonal grid of structure on four walls to allow direct sun penetration in onto the floor. The difference between these categories comes from the location of openings in the roof and walls. Categories one and two are top-lit, which means that contrast and temporal variability will occur within them throughout the year, while category three is dependent on the time of day and year as sunlight must penetrate through vertical openings in the façade.

Category four allows light in through both the walls and ceiling, while categories five and six allow for varying degrees of direct penetration through a single vertical surface. Categories four and five have similarly scaled light-emitting openings, but category four casts an even array of light through holes in the roof and walls, while category five emits smaller, more sporadic pattern of light through a single wall. Category six is modeled to represent a clear-story window above with evenly-spaced louvers below, emitting shadow lines onto the walls and floor. Due to the location of openings in category four, contrast is high throughout the year, while it varies with the seasons in category six, which determines its placement to the left of the group.

Categories seven through nine sit in the middle of the matrix and represent a moderate amount of contrast and temporal variation. Category seven has one fully-glazed wall that allows direct sunlight into the space, but does not experience the same degree of spatial contrast as those to the left due to its lack of shadow texture. Category eight has isolated linear openings in the roof and walls, which allow for direct light penetration through isolated moments. This causes a high degree of spatial contrast, but only across a small percentage of the image. Category nine has a fully glazed wall, similar to category seven, but combines some translucent panels to minimize the strength of incoming shadows.

Categories ten, eleven, and twelve move further toward the low contrast end of the spectrum, each representing some technique for emitting indirect light. Category ten allows for some direct sunlight through thick openings in the exterior wall, while category eleven brings indirect light in through large north-facing roof monitors. Category twelve emits indirect light onto a curved exterior surface, which shows some temporal variability in brightness, but stable contrast across the year.

Categories thirteen through fifteen portray the low contrast end of the spectrum, with stable luminosity across the visual field. The difference between these can be seen in the location of light-diffusing surfaces, where category thirteen has a fully glazed translucent wall, category fourteen uses small, north-facing monitors, and category fifteen emits light through a translucent roof. Due to the nature of materials in each of these models, little temporal variation is expected throughout the year, and the visual field remains relatively stable.

The purpose of these typological models was to render each condition through a quick digital model so that more explicit readings could be determined from its abstract form. The next chapter will use this typological matrix to propose three new metrics that describe the elements of spatial contrast and temporal variability that have been explored through this gradient of contrast-driven effects.

3.3 Summary

In this chapter, we have taken the need for new contrast-based metrics and positioned it within the context of contemporary architecture to develop a more comprehensive understanding of possible daylight-driven effects. A new typological language was developed to further understand this range of conditions; each category was populated with existing examples to create a framework through which specific characteristics may be defined. The reduction of each category into an abstract typological model provides a spring board into the next chapter, which proposes three new and distinct metrics for the quantification and comparison of contrast and temporal variability within architectural space.

Chapter 4

Thesis Method

4.1 Introduction

In the previous chapter, we conducted a survey of contemporary global architecture to develop a typological language about the range of contrast-driven effects in daylight design. Each example was placed within a larger matrix to establish a gradient from high contrast on the left, to low contrast on the right. Using this system of categorization, we distilled each column of the matrix into a single abstract digital model to facilitate a more directed discussion about the specific characteristics that distinguish each space. We created several terms: ‘spatial contrast’ describes the placement of each example within the gradient from left to right, ‘temporal variability’ and ‘annual’ describe intuitive differences in the quality of daylight between each space. This chapter will examine those characteristics presented by the typological matrix and will present three new metrics that will be numerically defined to explain how they contribute to an overall understanding about contrast and temporal variability in architecture.

4.2 Learning from the Typological Matrix

Daylight is a dynamic and highly variable natural source of illumination within architectural space. It reveals a variety of effects over time and cannot be understood through a static representation or a singular approach. A new group of metrics that quantifies contrast and temporal variability will provide a more holistic understanding of their combined impacts. In this section we will discuss the rationale that placed each architectural example within the larger contrast gradient represented by the typological matrix. Our analysis will determine what characteristics of spatial

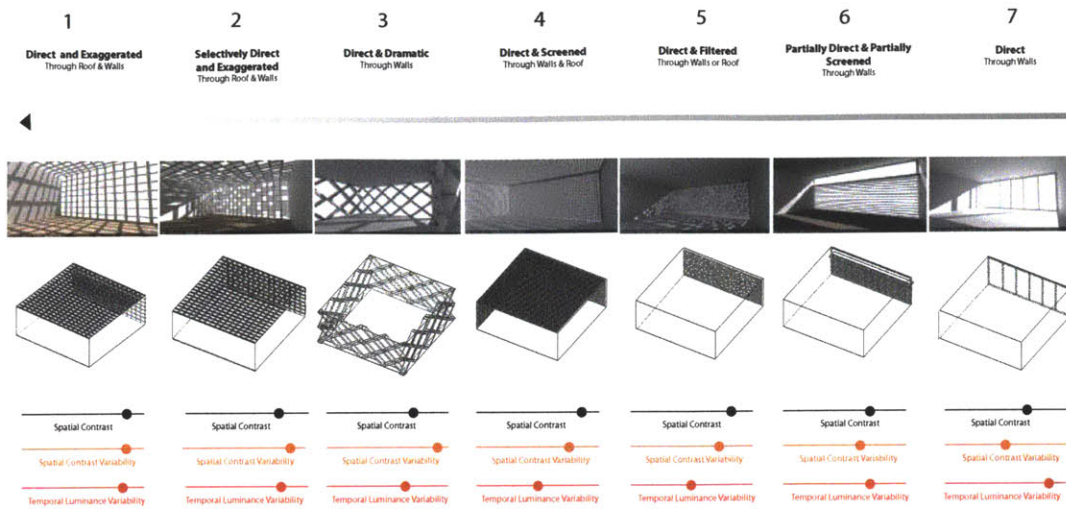
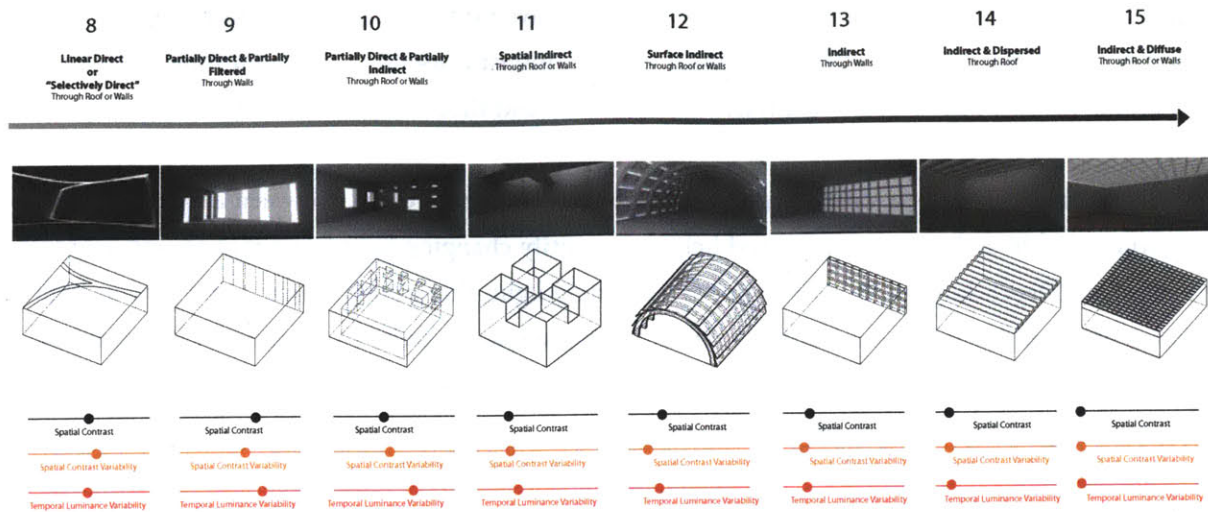


Figure 4.1: Matrix of Typological Spaces with Sliding Bars

contrast and temporal variability contributed to our initial categorization of each example. These characteristics will then be compared to explain their importance and indicate how they might be quantified.

Spatial contrast describes the presence of peaks, lines, and gradients within an image. This compositional balance between values serves as the basis for two of the quantitative metrics proposed in this thesis. The first metric, Spatial Contrast, identifies the difference between local luminance values within a given image while the second metric, Annual Spatial Contrast, shows how those values accumulate over time. Both metrics contribute to a broader understanding of contrast within architectural space, but one quantifies a single moment of time while the other accounts for a dynamic reading of how those moments vary. The third metric that emerges out of this matrix is called annual luminance variability, which tracks an overall change in brightness across the year. Before expanding on each of these metrics, we must first understand them intuitively to determine how they differentiate those qualitative effects present within each image. The typological matrix, reintroduced in Figure 4.1, includes a set of sliding bars beneath each category. These sliders show the amount of ‘spatial contrast’, ‘annual spatial contrast’ and ‘annual luminance variability’ hypothesized within each image. The position of each slider varies across categories and often displays different rankings for each of the three metrics. This approach was meant to separate the contributing characteristics of contrast and variability to understand them as a group of factors that work together in the production of daylight-driven effects.



The distinctions among these three metrics are important to understand as each example within the typological matrix represents unique combinations of spatial contrast, annual spatial contrast, and annual luminance variability. Some categories within the typological matrix, such as category ten, receive a low score for spatial contrast and annual spatial contrast, but a higher score for annual luminance variability. Although a fair amount of indirect light is emitted through each opening in the thick exterior wall, the space receives a minimal amount of direct sunlight across the year and thus a low score for cumulative spatial contrast. On the contrary, category ten experiences a fair degree of luminance variability. This distinction is useful when you consider spaces like Louis Kahn's First Unitarian Church, which allows for the penetration of indirect light through large, translucent roof monitors. There is never a high degree of spatial contrast present within the church, as daylight washes the walls in smooth gradients of illumination, but luminance levels still experience a high degree of variation, with fluctuating light conditions affecting the brightness of those gradients across year.

Those spaces that receive a large quantity of direct sunlight generally result in high values of spatial contrast. It's important, however, to understand how those values vary across seasons. A side-lit space, such as those described by categories six and seven, can achieve high spatial contrast during the winter months, when the solar altitude is lower to the ground, but may achieve a minimal degree of spatial contrast during the summer months. The dynamic nature of sunlight makes it critical to distinguish between static and annual representations of space. Architectural spaces such as the Prada Store (category three) and the Magney house (category six) may experience large jumps

in spatial contrast over time, as more direct sunlight is driven into the space depending on the orientation of light-emitting surfaces. Annual spatial contrast is useful in distinguishing between spaces that achieve high levels of contrast across the year and those that achieve it intermittently.

Annual Luminance Variability describes the cumulative difference between areas of brightness within architectural space and helps to quantify changing light levels that are independent of contrast. Depending on the orientation of incoming light, this annual metric can represent high degrees of variability even when spatial contrast levels are low. In order to account for the nuanced variations that can occur within daylight space, it's important to compare these metrics to gain a better understanding of their combined performance criteria.

4.3 The New Metrics

This section will examine each of the proposed metrics in more detail. The qualitative aspects of daylight that each metric seeks to address will be presented as well as the quantitative approach used to calculate and represent them. Those metrics that rely on an annual set of renderings or photographs will be explained through application in the following chapter.

4.3.1 Spatial Contrast

The spatial contrast metric builds upon the term introduced in chapter three, and differentiates between more traditional methods of contrast definition that rely on RGB histograms, brightness ratios and standard deviation. This metric addresses the need for more compositionally dependent methods of contrast analysis as sources of brightness within architectural space are perceptually dependent on their local surroundings. Figure 4.2 illustrates this notion through the simple representation of black and white pixels. When the composition is split down the middle, with half the pixels representing RGB 0 (black) and the other half representing RGB 255 (white), the histogram shows two columns of brightness values on either side of the spectrum (0 and 255). If we rearrange the composition to create more perimeter area between white and black pixels, the histogram remains unchanged. The red values to the right of the figure, representing Spatial Contrast, show the differences between neighboring white and black pixels. In this case, the change in composition affects the difference between neighboring values, increasing the Spatial Contrast. This method of quantification illustrates the impacts of spatial composition on our perception of contrast as in the ways in which it creates patterns and boundaries within architecture. Figure 4.3 reiterates this method through a simple representation of peaks and gradients that occur as a result of the difference between neighboring values.

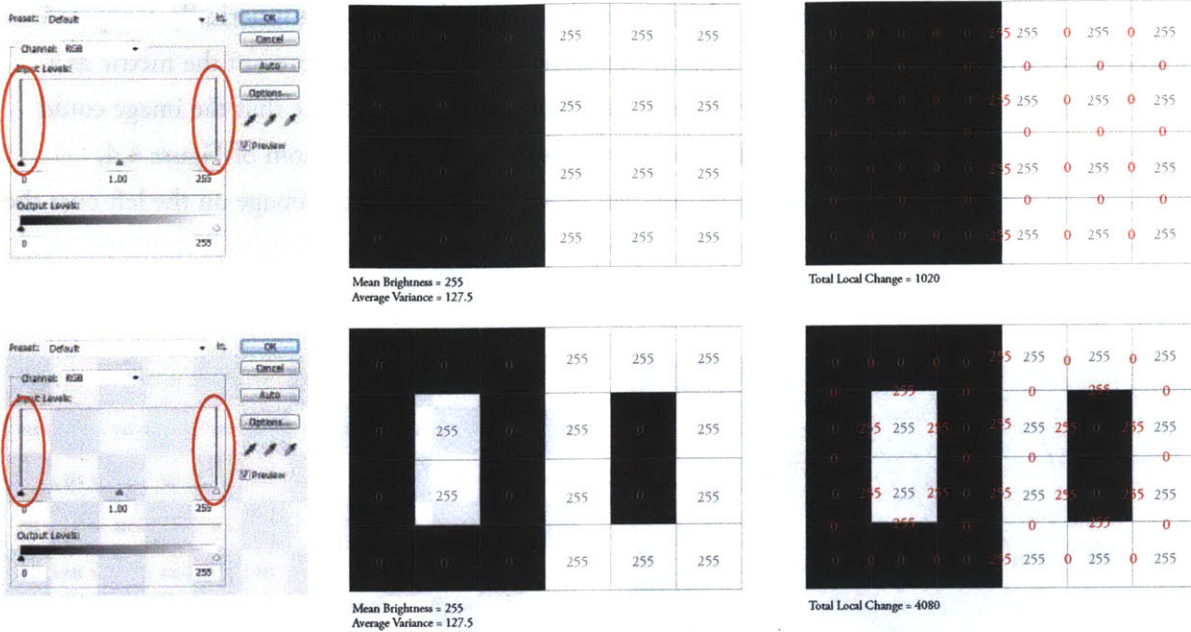


Figure 4.2: Representation of RGB Histograms and the Impact of Pixel Composition on Spatial Contrast (seen in Red Values to the right).

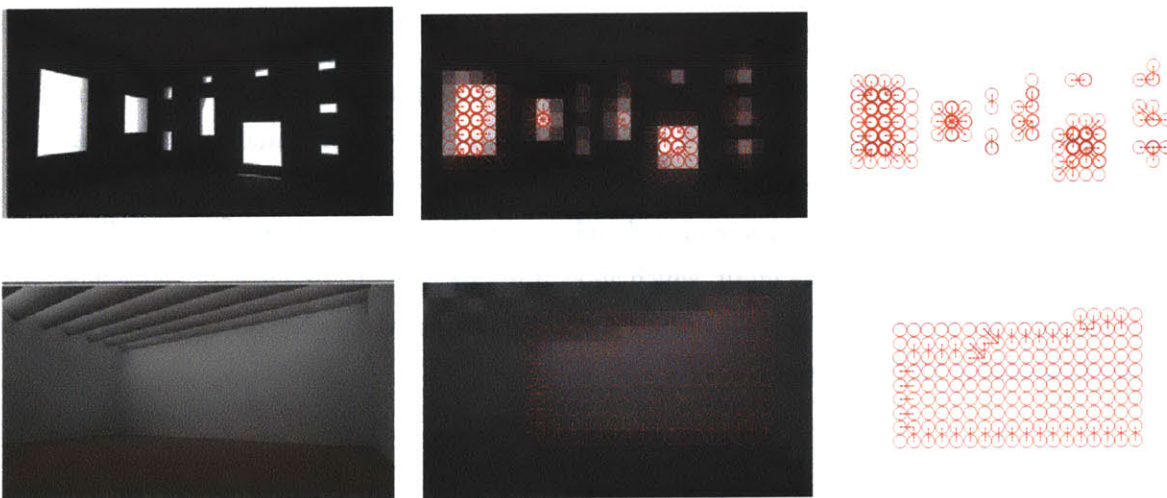
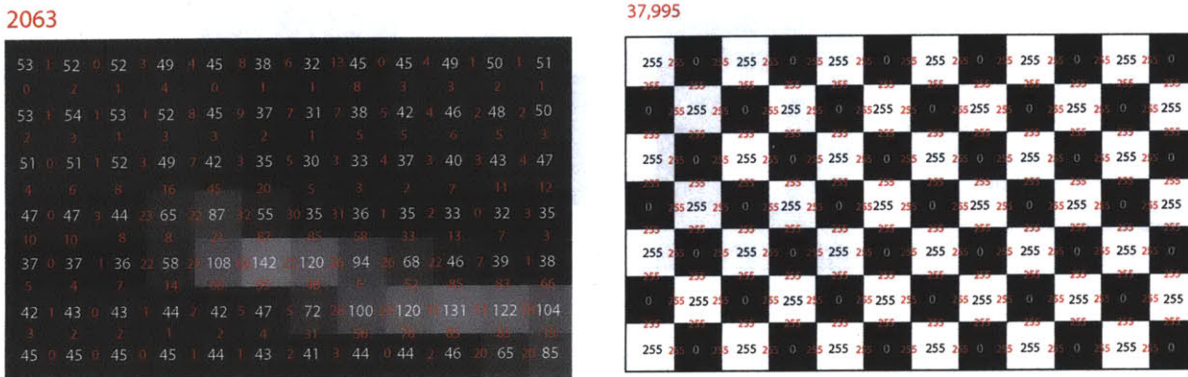


Figure 4.3: Peaks and Gradients of Spatial Contrast, Represented by the Strength of Red Circles

Building upon the simple representations of black and white pixels shown in Figure 4.2 and the peaks and gradients illustrated in Figure 4.3, we will now look at a more detailed example that calculates spatial contrast across a larger image. Figure 4.4 contains a pixelated image of daylight within space and represents the local differences between the brightness of each pixel and that of its neighbor. If we add up all the local differences, represented in red, we can compute a total sum of difference across the image. The problem with this number, as it exists currently, is

that it's dependent on the pixel density of the original image and cannot be numerically compared to images of a different density. To get around this issue, it's necessary to represent the metric as a ratio between the total difference in local values and the maximum difference that the image could achieve as a result of its pixel density. This ratio, expressed in red at the bottom of Figure 4.4, represents spatial contrast as the difference between local pixel values in the image on the left over the 'maximum' checkerboard of black and white values on the right.



2063/37,995 = 5.4 % Spatial Contrast

Figure 4.4: Ratio of Spatial Contrast Over a Hypothetical High Based on Pixel Density

In order to apply these methods of quantification to images that represent a higher resolution of pixel density, we programmed a code that facilitates the computation of spatial contrast. Through the use of Matlab, a high-level language program that uses matrices to compute large sets of data quickly and efficiently, each image was imported and converted into a two-dimensional RGB matrix. Matlab has several options for data input, which allow it to process a diverse range of image files. In its current state, the program for spatial contrast reads jpeg images of any pixel density, but is also capable of processing HDR formats.

To explain the program in a comprehensive manner, we will use Figure 4.5 to describe the computational process. Once an image file is imported into the Matlab environment, the data is converted into a matrix of RGB values (between 0 and 255) that represent the brightness of each pixel. From there, the program extracts two new matrices, representing the difference between each row (shown in red) and column (shown in blue). Although the conceptual diagram for calculating local differences seems straightforward, processing pixel information as a matrix requires us to deal with resulting matrices that differ in size. For example, the original image matrix (shown in black) is 4 x 4 in dimension, whereas the resulting row difference matrix is 4 x 3 (shown in red) and the column difference matrix is 3 x 4 (shown in blue). The difficulty arises when we recombine the row difference and column difference matrices to create a data set that represents the original scale of the

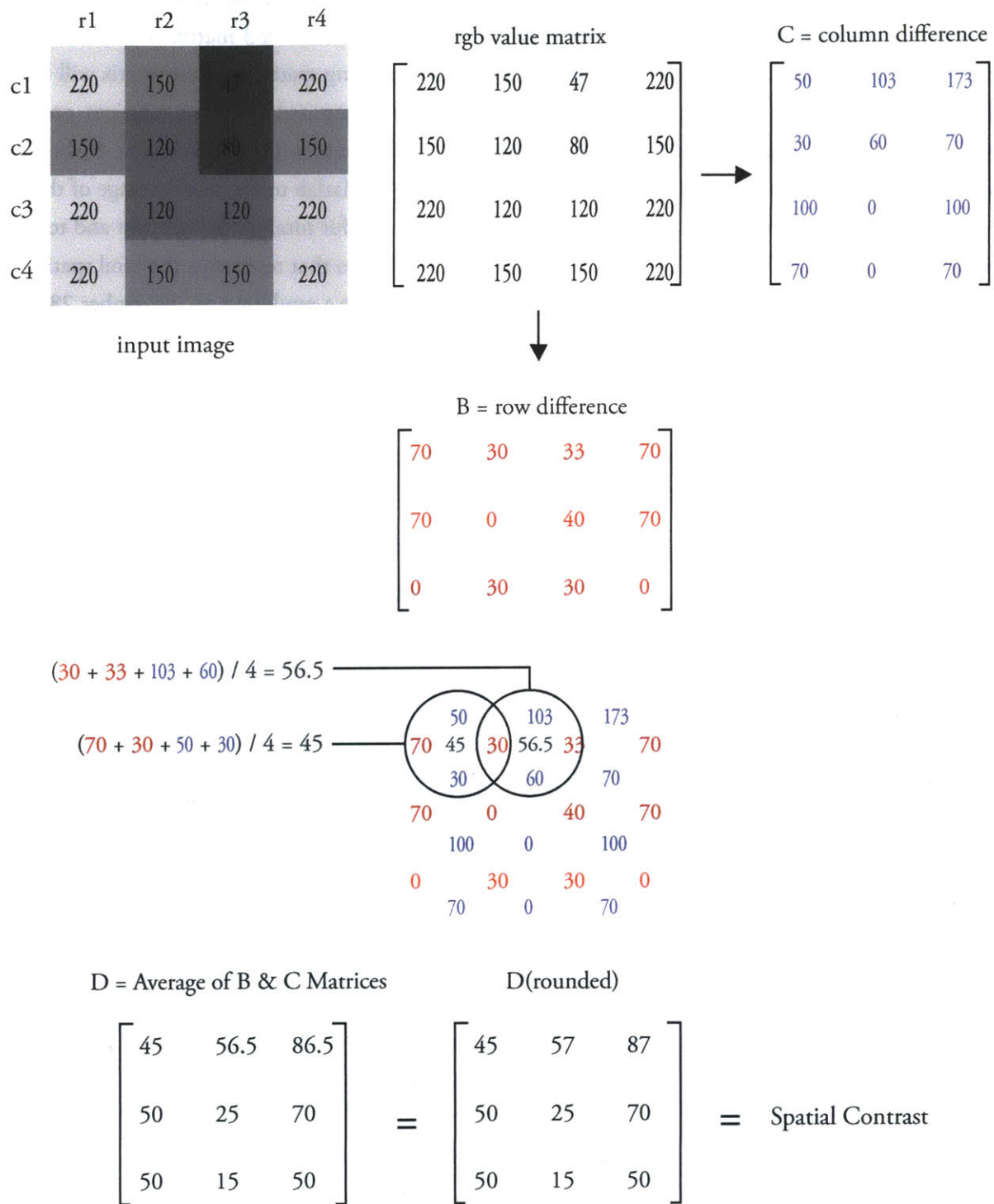


Figure 4.5: Matlab Logic for Spatial Contrast (See figure B.2, Appendix B for Full Source Code)

image. In order to achieve this, the program must take the average of neighboring row and column differences (represented by the blue and red matrix) to create a rounded 3 x 3 matrix. This means that for an image with a pixel aspect ratio of 480 x 640, the resulting spatial contrast matrix will be 439 x 639 in size. The resulting ratio of spatial contrast can be computed using two matrices, one representing the original image and the other representing a black and white checkerboard of the same pixel density (see Figure 4.4). Each matrix is processed in Matlab to create an average of the row and column differences and then summed to produce a value for total spatial contrast and total hypothetical contrast. These two values are then turned into a ratio that represents the total spatial contrast of the image. Figure 4.6 illustrates these results: a) shows a rendering on November 28th at 15:33 with a spatial contrast reading of 0.83% while b) shows a rendering on May 30th at 16:59 with a spatial contrast reading of 0.966%. In summary, the Spatial Contrast of an architectural rendering or photograph can be computed to produce a resulting black and white representation and a ratio, which can be used to compare it to the typological gradient of daylight effect introduced at the beginning of this chapter.

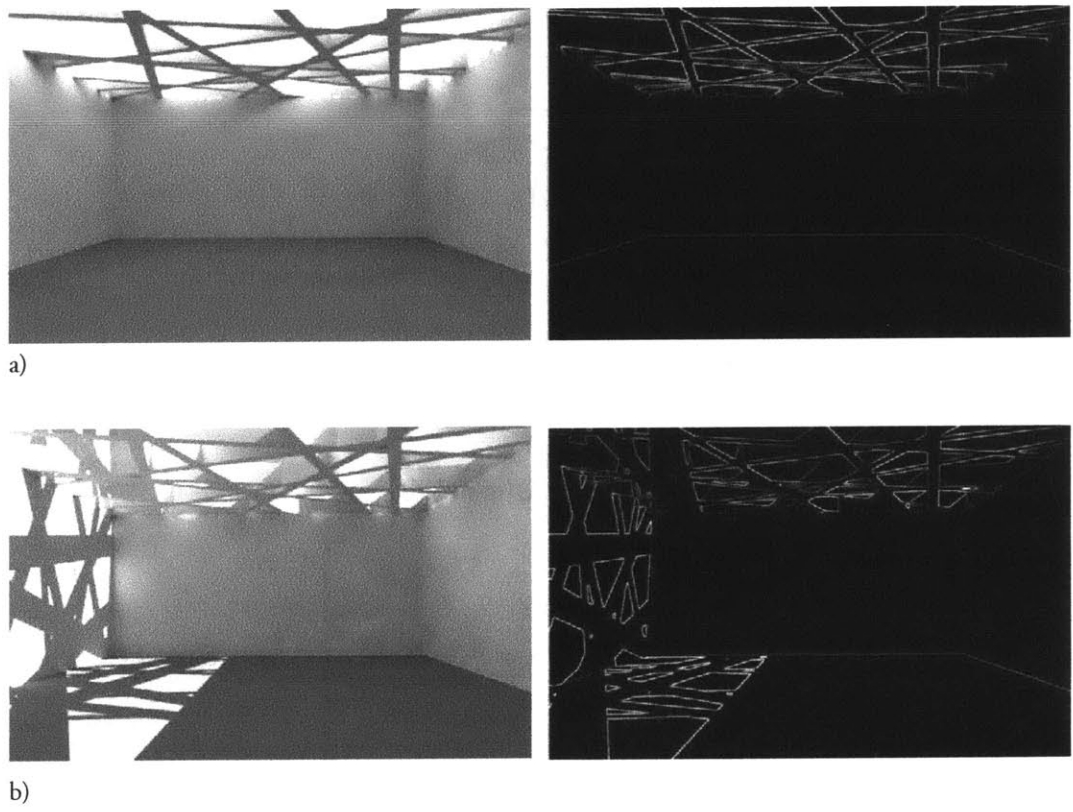


Figure 4.6: Visualization of Spatial Contrast Across Two Images
a) Rendering on November 28 at 15:33 with Spatial Contrast at 0.83% b) Rendering on May 30 at 16:59 with Spatial Contrast at 0.966%

4.3.2 Annual Spatial Contrast

In order to understand the dynamic nature of sunlight and its changing impacts on architectural space, we created a second matrix, Annual Spatial Contrast, to quantify its cumulative effects over time. It becomes critical to quantify the effects of spatial contrast on an annual scale. Since daylight is such a variable source of illumination, it is important to understand it through visually dynamic means of representation. Figure 4.7 illustrates this variable quality through a series of abstract renderings taken in 30-minute intervals from 9 a.m. to 4:30 p.m. As the band of

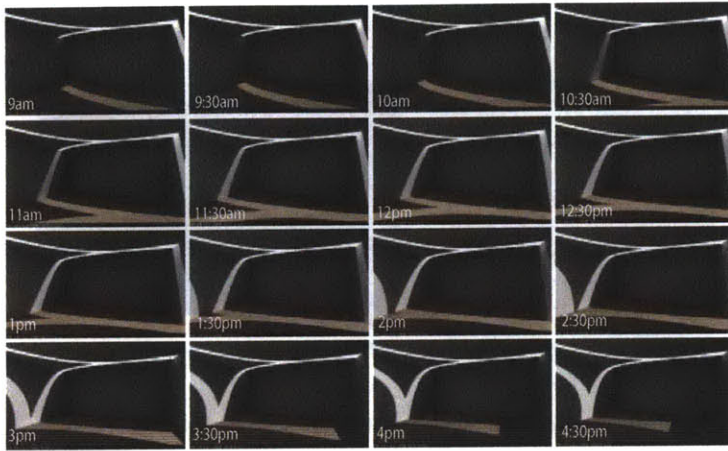


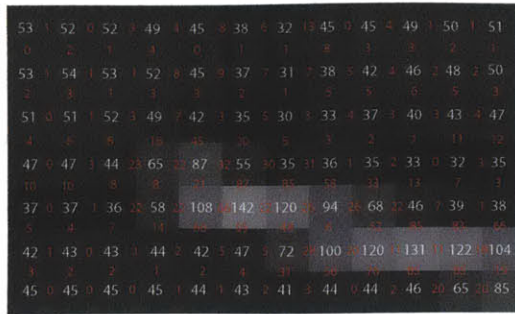
Figure 4.7: Daylight Renderings Shown in 30 Minute Intervals

direct sunlight present within these abstract representation moves across the model, it comes into contact with the walls and floor, resulting in various degrees of spatial contrast. In order to quantify and compare this effect across a series of images, a consistent interval of time must be established through which values may be accumulated and plotted. The frequency of instances represented in Figure

4.7 cannot be maintained across the year without substantial rendering time. In Chapter Two, however, we introduced a validated method for interpolating annual illuminance data across a set of 56 periods of time, corresponding to 8 annual and 7 daily intervals [Kleindienst, et al, 2008]. This metric will analyze spatial contrast across the intervals, but rather than relying on weighted averages within each period according to weather conditions [Kleindienst, et al, 2008], it will rely on clear sky conditions only and be evaluated for the corresponding instances (and associated sun positions). This variation can be considered as an upper boundary for contrast and variability as long as openings, depth, orientation, and positioning allow the limited set of 56 moments to reveal sun patches and adequate brightness. As such, it will provide a ratio for cumulative annual contrast as well as a spatio-temporal map of when that ratio changes over the year. The specific method for producing renderings across those 56 annual moments will be introduced in section 5.2.

The basic process for calculating annual spatial contrast is shown in Figure 4.8, which contains two pixelated RGB maps (one taken from a rendering at 10 a.m. and the other at 10:30 a.m.) with overlaid local contrast values in red. The sum of these values is added between each

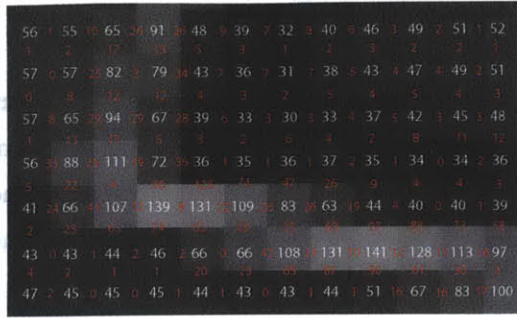
2063



10am

a)

2427



10:30am

b)

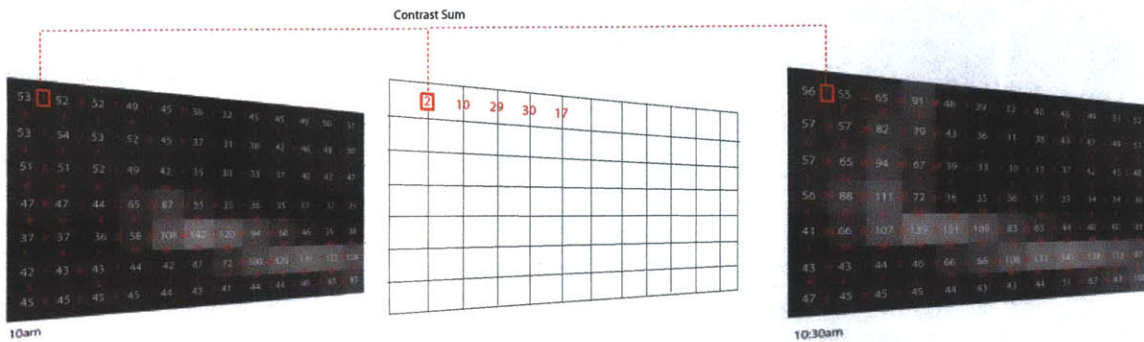


Figure 4.8 Cumulative Spatial Contrast Method Showing Two Separate Moments of Time a) & b) and the Accumulation of their Values c).

frame, representing a cumulative contrast sum across all 56 images. Figure 4.9 illustrates a full set of annual renderings (method of production described in section 5.2) for a hypothetical space located in Boston, MA. To compute annual spatial contrast, this set of renderings is imported into Matlab as an index and processed in a loop using the same code that was generated for the static spatial

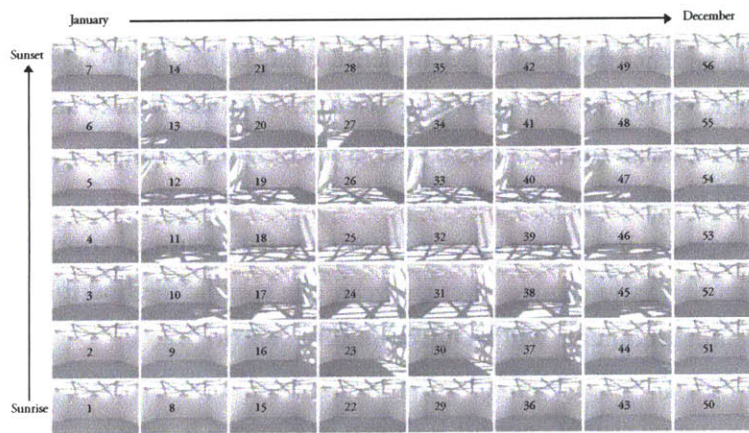


Figure 4.9: 56 Annual Images for Boston, MA (method of production explained in section 5.2)

contrast metric. This allows us to calculate spatial contrast for each of the 56 individual renderings and then layer that data accumulatively to visualize dynamic effects across the year. The full Matlab code can be found in Figure B.2, Appendix B. Each of the individual spatial contrast ratios is plotted onto a spatio-temporal map for the latitude and longitude of Boston

and represented alongside a false color image that shows the location and intensity of cumulative contrast. The full MATLAB code used to generate these temporal maps can be found in Figure B.4, Appendix B. Figure 4.10 illustrates three of these resulting spatial contrast representations (a, b & c) and indicates their location on the spatio-temporal map below (seen in d). The false-color image on the lower right (e) shows the cumulative sum of all 56 spatial contrast images to illustrate the location and intensity of annual contrast within the space. It is most useful in examples in which the orientation of light-emitting surfaces creates dramatic seasonal variations, such as those spaces represented by categories one through eight in the typological matrix. As most values produced by the annual spatial contrast metric were under 1% (from the maximum checkerboard represented in

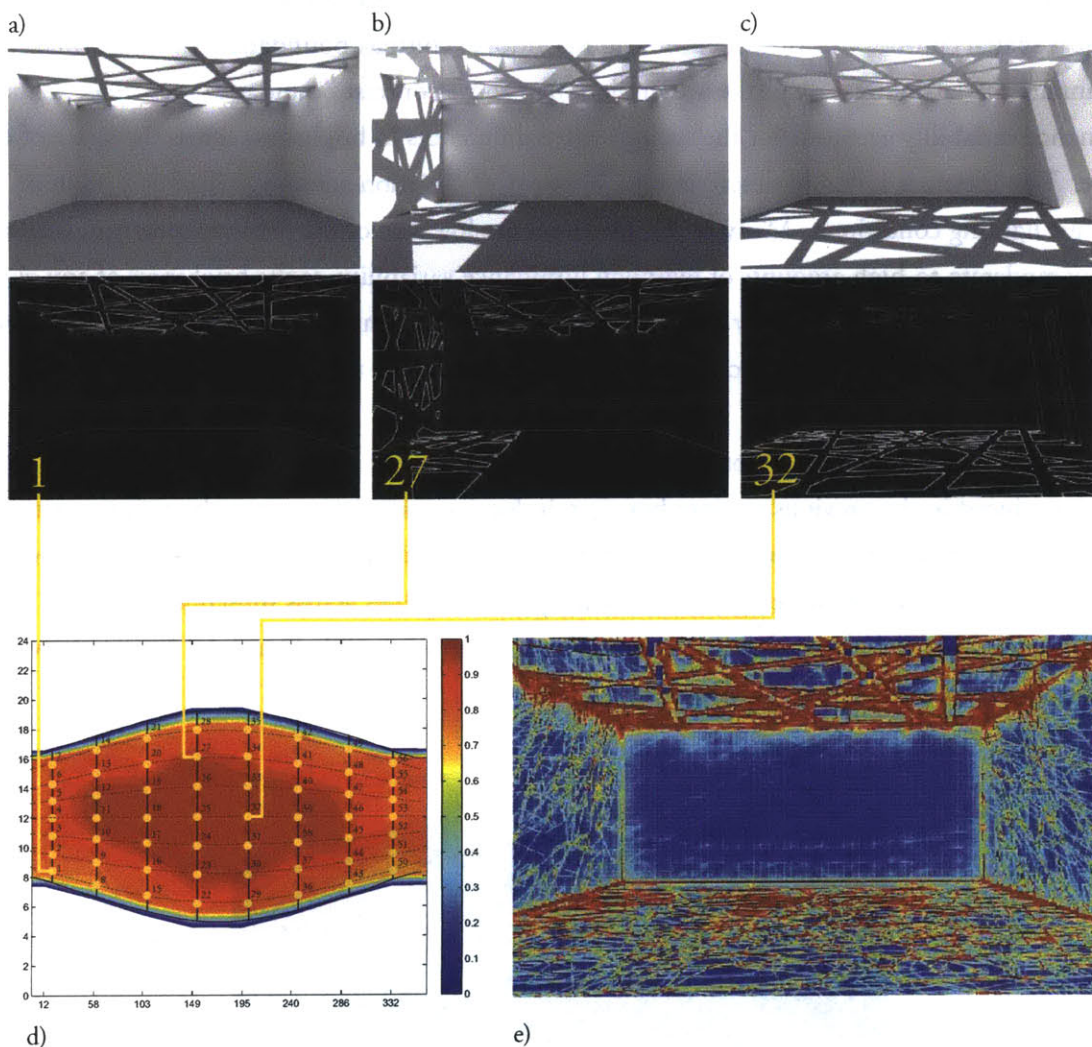


Figure 4.10: Annual Spatial Contrast

a) Rendering on January 13th at 10:33 b) Rendering on May 30th at 16:49 c) Rendering on July 15th at 12:50
d) Temporal Map Showing Overlay of 56 Plotted Moments with the Locations of a,b & c e) Cumulative Image of Annual Spatial Contrast

figure 4.4), the linear scale for this and all other maps was set from 0 to 1. Values between 0 and 0.33 are considered 'low,' between 0.33 and 0.66 are considered 'moderate,' and between 0.66 and 1 are considered 'high.' Any values over 1 are considered 'very high.' The map in figure 4.10 shows values between 0.6 and 1, all of which are 'high' in spatial contrast.

4.3.3 Annual Luminance Variability

The third and final metric that will be presented in this thesis describes a very different qualitative effect than the previous two. Annual luminance variability seeks to quantify the overall change in luminance levels across an architectural space due to annual variations in daylight. Whereas spatial contrast describes identifies compositional contrast boundaries within an image, and annual spatial contrast maps the accumulation of those contrast boundaries over time, annual luminance variability accounts for the accumulative differences in brightness across the space of each image. This metric is useful in describing the intensity of variation across a surface as a result of dynamic lighting conditions. Many of the spaces on the low side of the contrast spectrum may still display moderate-to-high amounts of temporal luminance variability, as the brightness of any given surface may transform dramatically while still maintaining smooth contrast gradients. This metric quantifies both subtle and dramatic degrees of light variation over time.

The quantitative method for this metric relies on the same set of 56 annual renderings that were introduced in the previous section; however, it does not calculate contrast boundaries within each image. Instead, annual luminance variability converts each image into a matrix of RGB values and then computes the absolute difference of each pixel as it varies across subsequent frames. Figure 4.11 illustrate how a single pixel can vary in brightness over time while Figure 4.12 shows how those differences can create a new matrix of resulting values.

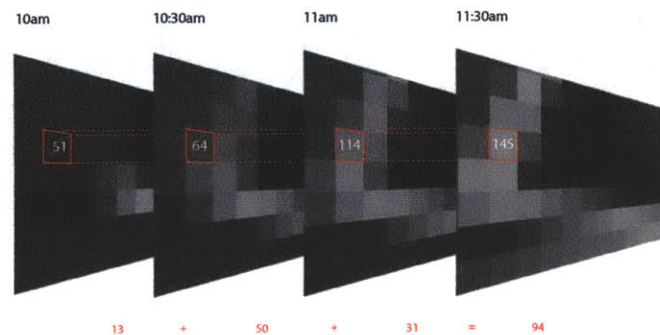


Figure 4.11: Variability in the Brightness of a Single Pixel Over Time (Pixels are Identified by a Value Between 0 and 255).

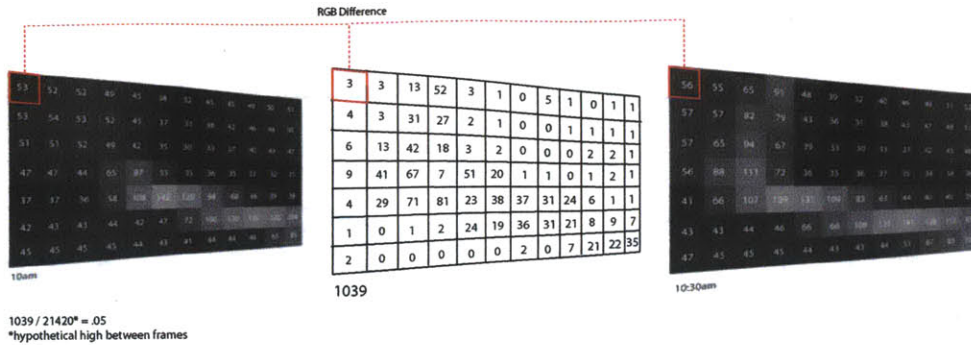


Figure 4.12: Luminance Variability Method (Pixels are Identified by a Value Between 0 and 255).

Figure 4.13 exemplifies how the absolute difference between four images produces a matrix of resulting values that sum these areas of change across a daily and monthly scale. The four images used to produce these values are represented in Figure 4.14, which shows each of the 56 annual moments (a) and the resulting 42 moments of ‘variation’ taken between neighboring points (b). It’s important

$$\text{abs} \left(\text{abs} \left(\begin{array}{c} 32 \\ \text{img1} \end{array} - \begin{array}{c} 31 \\ \text{img2} \end{array} \right) - \text{abs} \left(\begin{array}{c} 39 \\ \text{img3} \end{array} - \begin{array}{c} 38 \\ \text{img4} \end{array} \right) \right) = \begin{array}{c} 28 \\ \text{img5} \end{array}$$

Figure 4.13: Difference in Luminance Between Four Renderings. The Date and Time for Each of These can be Seen in Figure 4.14)

to reiterate that the 56 images we use to calculate annual luminance variability result in only 42 data points on the spatio-temporal map. This is due to the fact that one does not calculate the difference between sunrise and sunset of each subsequent daily interval or the beginning and end of each year. Therefore 7 daily intervals result in 6 daily points of total luminance variation and 8 seasonal intervals result in 7 seasonal points of total luminance variation (Figure 4.14). The value for annual luminance variability is represented by the total sum of these 42 intervals. Similar to the first two metrics presented in this chapter, the resulting cumulative variation cannot be compared to images of varied pixel density until it is converted into a relative value. In order to achieve this, the total sum of luminance variation across all 42 intervals is divided by the total pixel density of the input images. The full Matlab code can be found in Figure B.3, Appendix B.

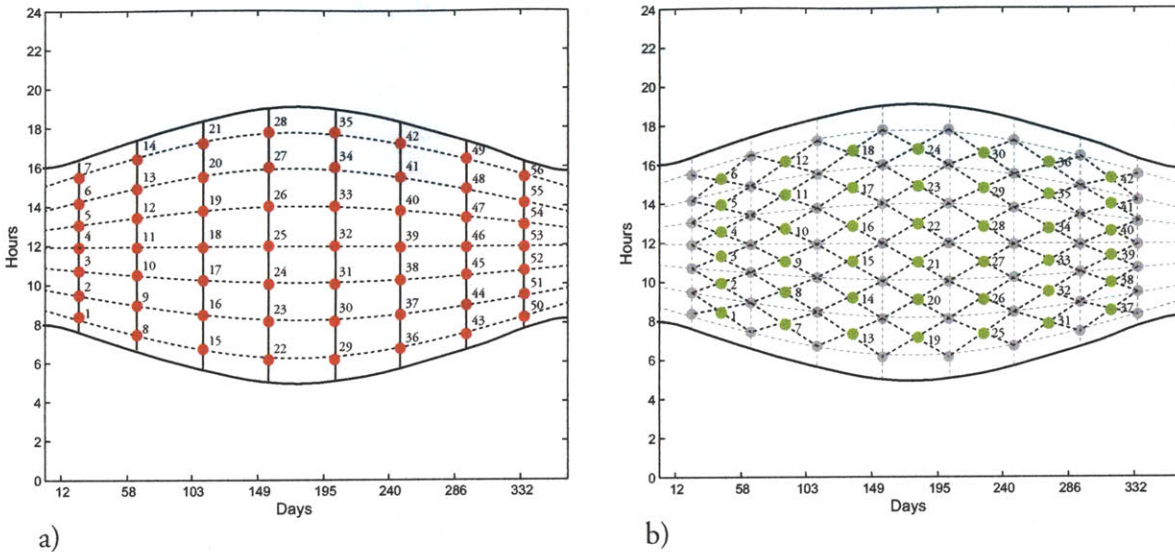


Figure 4.14: Spatio-Temporal Map Showing a) the Location of 56 Data Points for Spatial Contrast on the Left and b) 42 Data Points for Annual Luminance Variability on the Right

Figure 4.15 illustrates a full set of results for annual luminance variability; it contains three individual frames of variation (a,b & c), the spatio-temporal map with the sum of these changes at each of the 42 moments (d), and a cumulative image of these changes over time (e). This metric is useful in understanding when areas of brightness change within architectural space and whether that change is steady or abrupt. The image on the lower left (a) shows a low degree of luminance variability between renderings, while those to the right (b and c) show a high degree of cumulative variation. The temporal map (d) shows that these changes in luminance are most extreme in the summer when the sun is moving directly overhead. The maximum value for luminance variability at any one moment (otherwise understood as the absolute difference between four images) was found to be $8,000,000$ or 8×10^6 , which determined the linear scale for the each temporal map. Values between 0 and 2.6×10^6 were considered 'low' in luminance variability, values between 2.6×10^6 and 5.3×10^6 were considered 'moderate,' values between 5.3×10^6 and 8×10^6 were 'high.' Anything values exceeding 8×10^6 were considered 'very high.' The cumulative image (e) shows where these variations occur within space. These changes appear to be most extreme on the floor, as direct light is constantly moving across the roof, casting variable patterns down into the room. Some change can also be seen on the walls, with minimal variation occurring in the roof, where light is always bright and minimally variable.

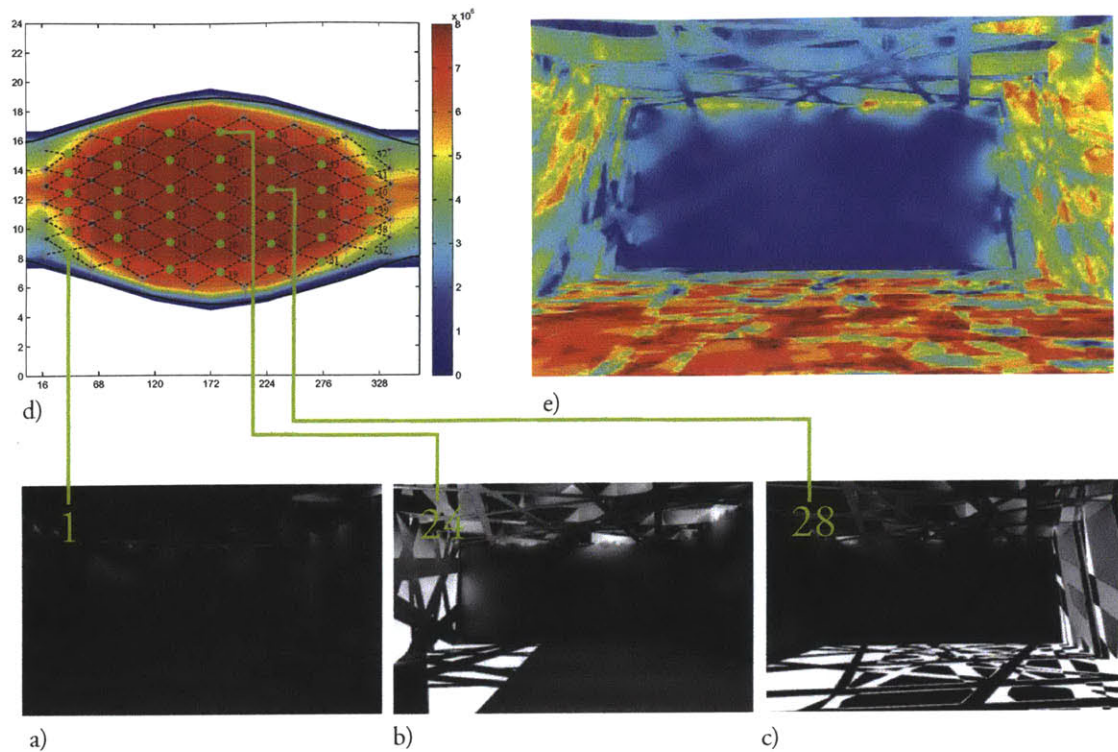


Figure 4.15: Annual Luminance Variability

a) Variation for New Data Point 1 (Taken Between Four Original Renderings 1,2,8 &9) **b)** Variation for New Data Point 24 (Taken Between Four Original Renderings 27,28, 34 & 35) **c)** Variation for New Data Point 28 (Taken Between Four Original Renderings 32,33, 39 & 40) **d)** Spatio-Temporal Map showing 42 point of Luminance Variability **e)** Accumulative Image of Annual Luminance Variability

4.4 Summary

The previous chapter categorized contemporary architecture into a matrix of contrast-driven daylight strategies. This matrix was then distilled down into a set of abstract typological models in order to understand the characteristics that define each category and its location within the gradient. This chapter introduced three new metrics that define the group of qualitative characteristics that emerged out of our intuitive categorizations. These metrics, referred to as spatial contrast, annual spatial contrast, and annual luminance variability represent three distinct, yet related aspects of perceptual performance and help to contribute to a more dynamic understanding of architectural space over time. The following chapter will apply these metrics to a set of typological case-study models to display their analytical capabilities across a range of architectural conditions.

Chapter 5

Application of Metrics to Case-Study Spaces

5.1 Introduction

In this chapter, we will apply each metric introduced in chapter four to a series of typological spaces to determine their relevance in quantifying and comparing spatial contrast, annual spatial contrast, and annual luminance variability. Although a total of eleven spaces were digitally modeled, rendered, and analyzed using each metric, four examples will represent a cross-section of results. We present the method for rendering a set of annual images as well as the established workflow for importing those images into Matlab and for outputting data for each metric in the form of cumulative images and temporal maps. The application of these metrics to a set of case-study spaces allows for a comprehensive understanding of their use and a comparative study of their results.

5.2 Production of Annual Image Sets

In order to analyze spatial contrast and luminance variability within each case study, a set of annual renderings or photographs must be produced that provide an accurate representation of each case's architectural qualities and daylight characteristics. Architects often use renderings to communicate the perceptual qualities of space within a proposed design, making them an ideal medium for the analysis of visual effects. Renderings give designers flexibility in choosing their desired camera angle and view direction to accommodate a variety of possible perspectives.

Figure 5.1 represents a workflow diagram showing three different methods for annual image production. The first method, Lightsolve, a daylight analysis software developed first at MIT and now continuing at EPFL, was originally preferred as the host program for this research because it produces 56 annual renderings as part of its goal-based analysis [Kleindienst, et al, 2008].

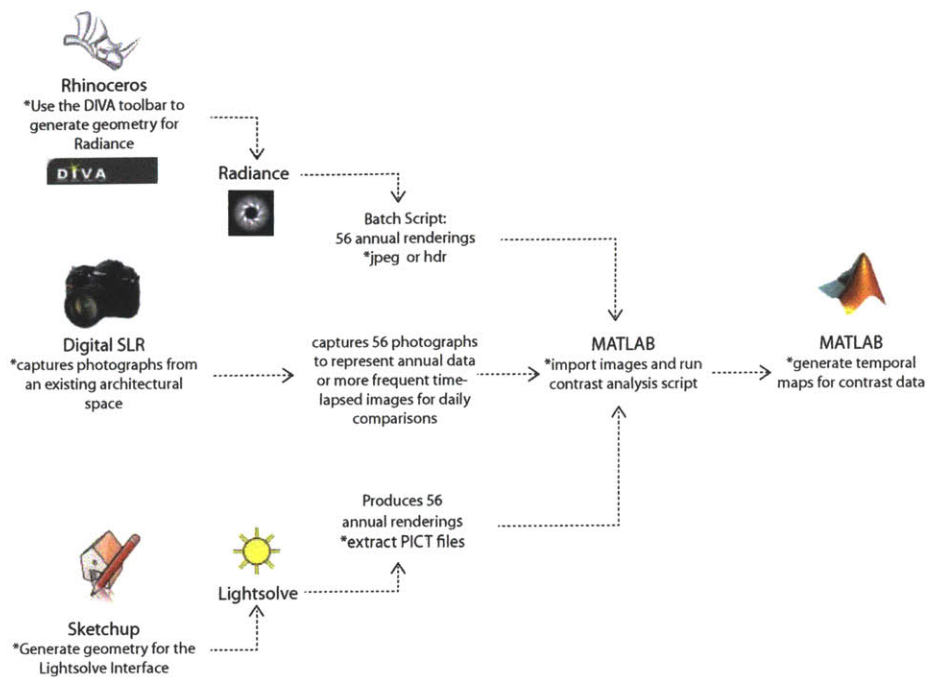


Figure 5.1: Workflow Diagram Showing the Potential of Various Modeling Softwares

These renderings are taken at symmetrical monthly and daily intervals and are produced for sunny, overcast, and turbid sky conditions to allow for climate-based analysis. The disadvantage of this program is that the current rendering engine associated with Lightsolve uses a single exposure across all 56 renderings and is thus incapable of generating a photorealistic set of images, which is essential to analyzing contrast.

Digital photographs provide a second means of input, although it is more difficult to capture annual sets because the accurate date and time for each image must be approximated. This can be done using a sundial under sunny sky conditions or a rotating table in an artificially lit environment. An example of this method will be presented in section 6.4.1.

The third method uses Radiance, an industry standard program that runs backwards ray-tracing to produce visually accurate climate-based renderings [Ward, 1994]. With the recent development of DIVA, a daylight analysis toolbar developed at the Harvard Graduate School of Design [<http://www.diva-for-rhino.com/>, 2009], it is now possible to export geometry from Rhinoceros 4.0 [<http://www.rhino3d.com/>, 2007], a popular nurbs-based geometric modeling program, directly to Radiance for analysis. The use of Rhinoceros, actively used in professional and academic studio environments, eliminates the need to model geometry within the Radiance environment, which is a notoriously inaccessible program for architects. Since the accuracy of

luminance values within each rendering is critical for contrast-based analyses, Rhinoceros and Radiance were selected as the more practical platform. The specific method for producing photo-realistic images is outside the scope of this thesis; however, the accuracy of rendered images is imperative to the comparison of results between each case-study.

In order to produce a set of annual renderings with consistent parameters, we modeled each case-study in Rhinoceros with the same floor area, ceiling height, and camera location so that results could be overlaid and compared (Figure 5.2). Cameras were positioned to face south and centered in the East-West direction, offset ten feet from the back wall (Figure 5.3), to ensure an even distribution of wall, floor, and ceiling surfaces within each view. The DIVA for Rhinoceros toolbar was then used

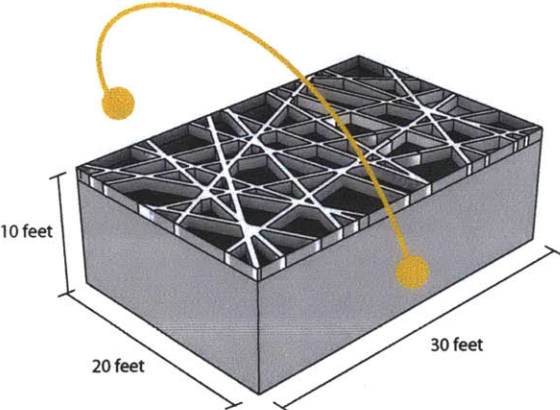


Figure 5.2: Basic Dimensions for Case Study spaces

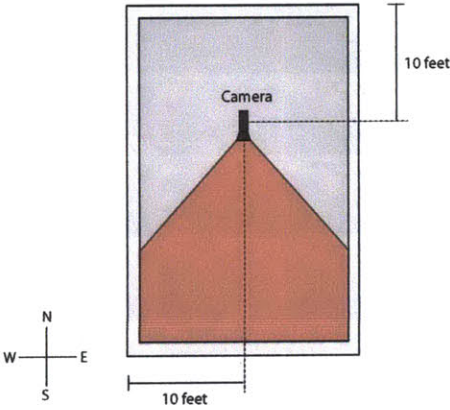


Figure 5.3: Camera Location in Plan

to export the camera view to Radiance with a vertical and horizontal viewport ratio set to -vv 40 and -vh 60. The specified materials for each surface were set to default reflectance values for floor, wall, and ceiling surfaces (0.3, 0.7, 0.9 respectively). The resolution of each image was rendered at ‘high

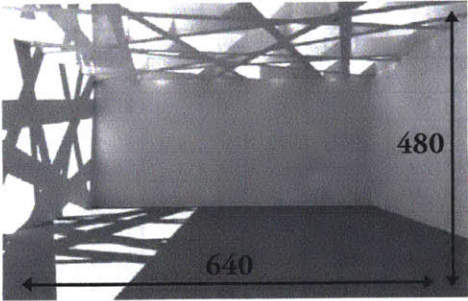


Figure 5.4: Example Rendering

quality’ to accommodate adequate detail with a 640 x 480 pixel aspect density (Figure 5.4). Although an individual rendering may be produced in Radiance using the DIVA toolbar, this thesis requires a set of 56 renderings for annual analysis. We determined this number via the same method used in the development of Lightsolve, which validates 56 periods over the year for which hourly values are interpolated to result in goal-based illuminance data

[Kleindienst, et al, 2008]. To automate this annual set, a Radiance batch script was used to generate a rendering for each date and time employing the same geometry and camera angle exported from Rhinoceros (Figure 5.5). Boston, Massachusetts was the location for all case-study renderings (Latitude 42 N, longitude 72W). The exact date and time for each rendering was established by sub-dividing the year into 8 symmetrical dates and each date into 7 symmetrical times from sunrise to sunset (Figure 5.6).

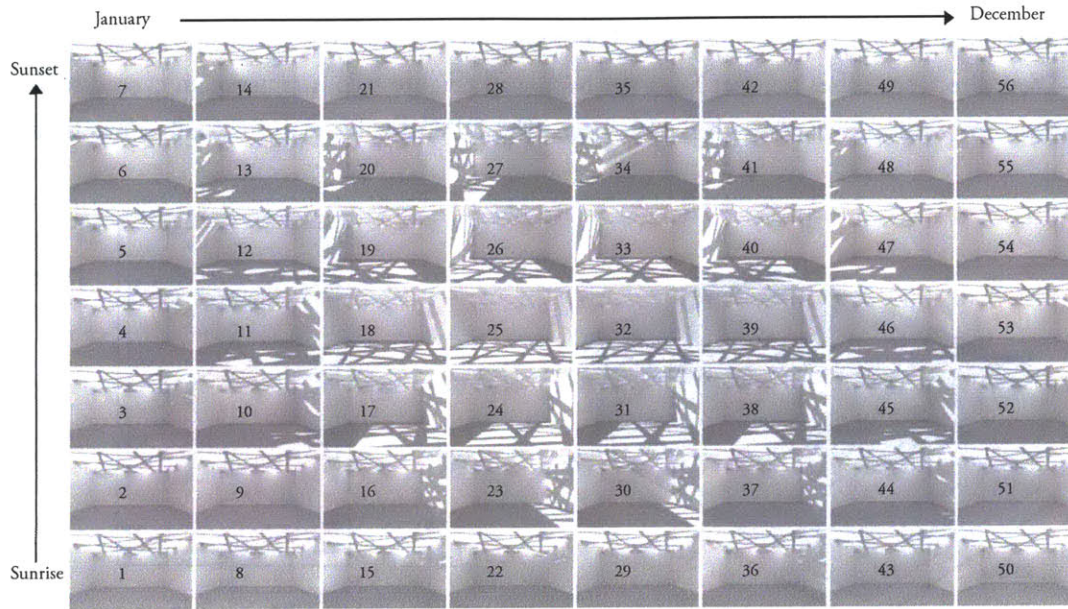


Figure 5.5: Batch Set of 56 Renderings and Location (see figure 5.6)

Date	Time	Date	Time	Date	Time	Date	Time				
1	1/13	7:52	15	4/14	7:03	29	7/15	6:25	43	10/14	7:43
2	1/13	9:12	16	4/14	8:57	30	7/15	8:33	44	10/14	9:18
3	1/13	10:33	17	4/14	10:51	31	7/15	10:41	45	10/14	10:54
4	1/13	11:53	18	4/14	12:45	32	7/15	12:50	46	10/14	12:29
5	1/13	13:13	19	4/14	14:39	33	7/15	14:58	47	10/14	14:04
6	1/13	14:34	20	4/14	16:33	34	7/15	17:06	48	10/14	15:40
7	1/13	15:54	21	4/14	18:27	35	7/15	19:14	49	10/14	17:15
8	2/28	7:09	22	5/30	6:15	36	8/29	7:03	50	11/28	7:30
9	2/28	8:45	23	5/30	8:24	37	8/29	8:57	51	11/28	8:50
10	2/28	10:21	24	5/30	10:33	38	8/29	10:51	52	11/28	10:11
11	2/28	11:57	25	5/30	12:42	39	8/29	12:45	53	11/28	11:32
12	2/28	13:33	26	5/30	14:50	40	8/29	14:39	54	11/28	12:52
13	2/28	15:09	27	5/30	16:59	41	8/29	16:33	55	11/28	14:23
14	2/28	16:45	28	5/30	19:08	42	8/29	18:27	56	11/28	15:33

Figure 5.6: 56 Annual Dates and Times for Radiance Batch Script for Boston, MA

Although these metrics were originally intended to look at dominant sky conditions and evaluate the effects of climate on annual contrast, we determined that the clearest comparisons were made under sunny skies with direct light penetration. When the spaces were rendered under overcast sky conditions, the amount of contrast was minimized and the temporal diversity virtually disappeared. In order to analyze the impacts of contrast over time, it was necessary to use a sky condition that allowed for maximized visual effects.

The radiance script used to generate all 56 renderings references the geometry from Rhino and then adjusts the date and time for each rendering, using the same sunny sky condition and image variables (Figure B.1, appendix B). Images produced by this batch script are reduced down from high-dynamic range (hdr) to jpeg format for speed and ease of processing. Although jpeg images have a narrower range of pixel information (0-255) than that of hdr images, the compression is relative and does not alter the results of each analysis which are quantified relative to their total pixel density. The date and time for each rendering can be adjusted for various latitudes to accurately describe even daily subdivisions. Once we have produced these annual sets of renderings, we can generate data for annual spatial contrast and annual luminance variability and map those effects over the year to see how they are affected by dynamic sun conditions.

5.3 Case Study Results

To calculate annual spatial contrast and annual luminance variability, each set of radiance renderings is imported into Matlab as an index so that individual images may be processed and data may be overlaid between images. The results of these metrics can be seen in their application to each of the following four typological models, category one (Direct and Exaggerated), category six (Partially Direct and Screened), category fourteen (Indirect and Dispersed), and category fifteen (Indirect and Diffuse). Category one represents a top-lit space with thickened asymmetrical mullions creating a dramatic penetration of sunlight across the walls and floor (Figure 5.7). Category six displays a louvered, side-lit daylight strategy that produces high spatial contrast and luminance variability in the winter, with less dramatic effects occurring during the summer when the sun is high in the sky (Figure 5.10). Category fourteen has a north-facing saw-tooth roof that minimizes contrast and variability with a daylight strategy that allows for minimal sunlight penetration (Figure 5.13). Category fifteen represents the low-contrast, low-variability end of the spectrum with a translucent glass roof that distributes an even and stable luminosity across the visual field (Figure 5.16).

1

Direct & Exaggerated Through Roof or Walls

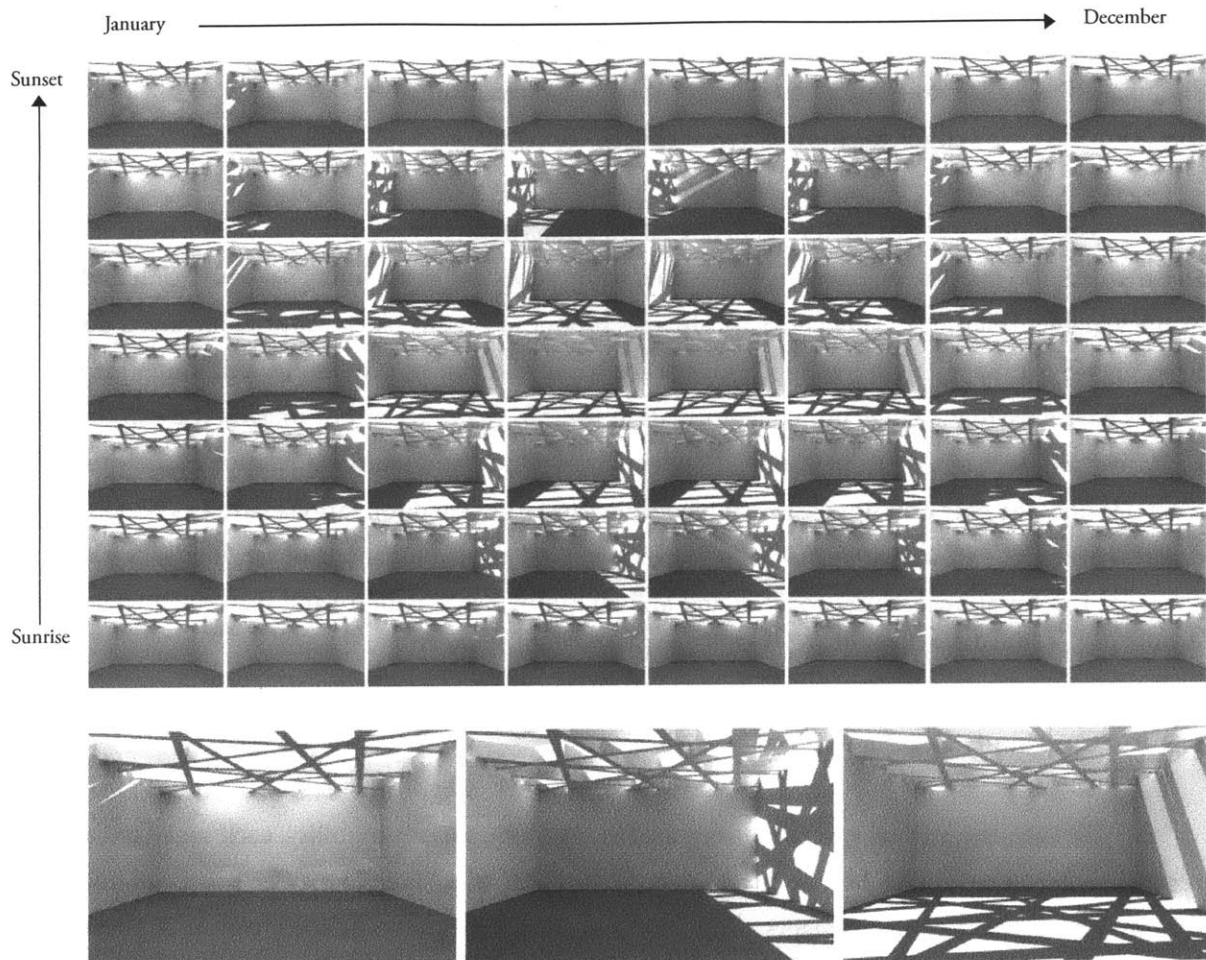
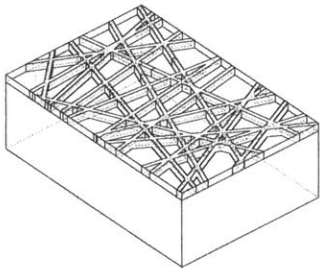


Figure 5.7: Annual Renderings



Category one, modeled to represent a highly contrasted and variable space, demonstrates a consistently high degree of spatial contrast across the year (Figure 5.7). The temporal map in Figure 5.8 shows a peak in spatial contrast (from 0.7 to 1) between 10 a.m. and 2 p.m. in the summer months when the sun is directly overhead. The temporal map of luminance variability in Figure 5.9 shows high peaks of variation in the spring and fall, ranging from 3×10^6 (low variability) to 8×10^6 (high variability). This is due to the changing altitude of the sun, which causes dramatic shifts in brightness within the space. In the image to the

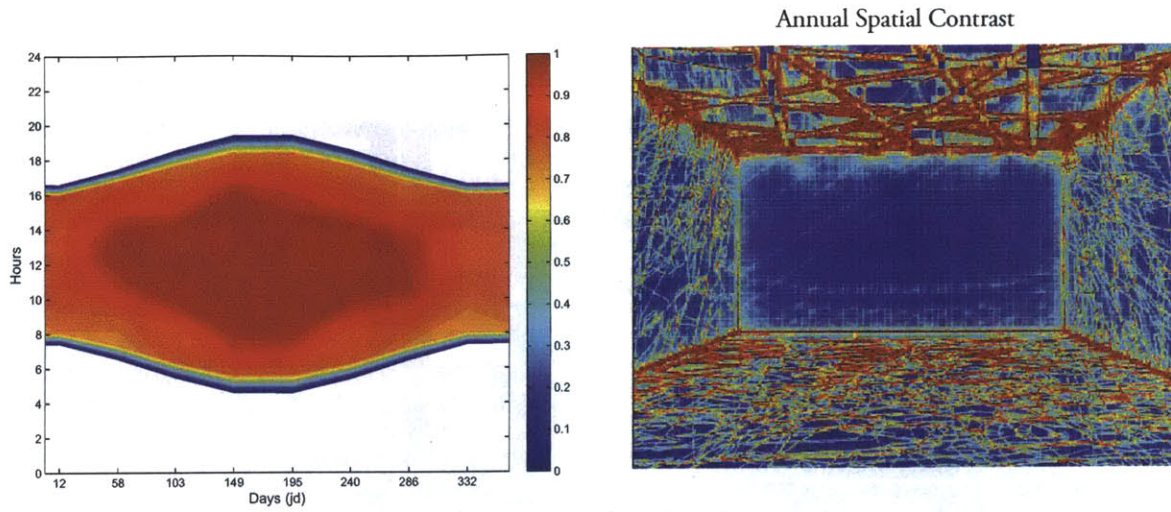


Figure 5.8: Annual Spatial Contrast (Temporal Map & Cumulative Image)

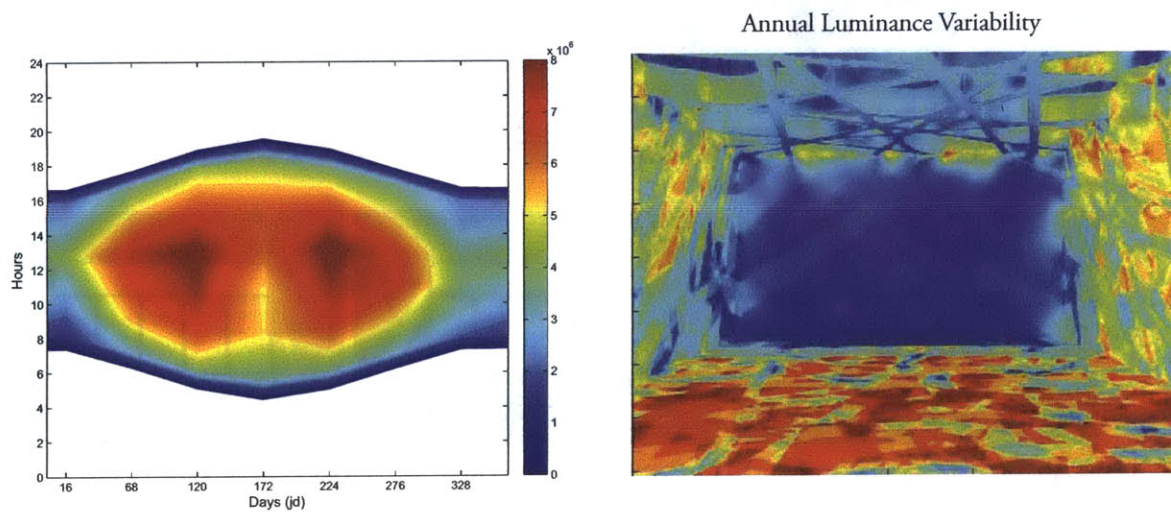


Figure 5.9: Annual Luminance Variability (Temporal Map & Cumulative Image)

right of Figure 5.8, thick red lines signify where spatial contrast is most consistent, highlighting the roof structure as the most redundant source with secondary accumulations on the floor and walls. The image to the right of Figure 5.9 depicts a cumulative view of luminance variation; here, the floor is the area that experiences the most dramatic change throughout the year. The cumulative effects shown in these two false-color images present an important distinction between metrics. Annual spatial contrast shows areas within the view where contrast accumulates, highlighting redundant textures and forms, whereas annual luminance variability shows areas within the image that experience the most variation, emphasizing areas of instability.

6

Partially Direct & Screened Through Walls

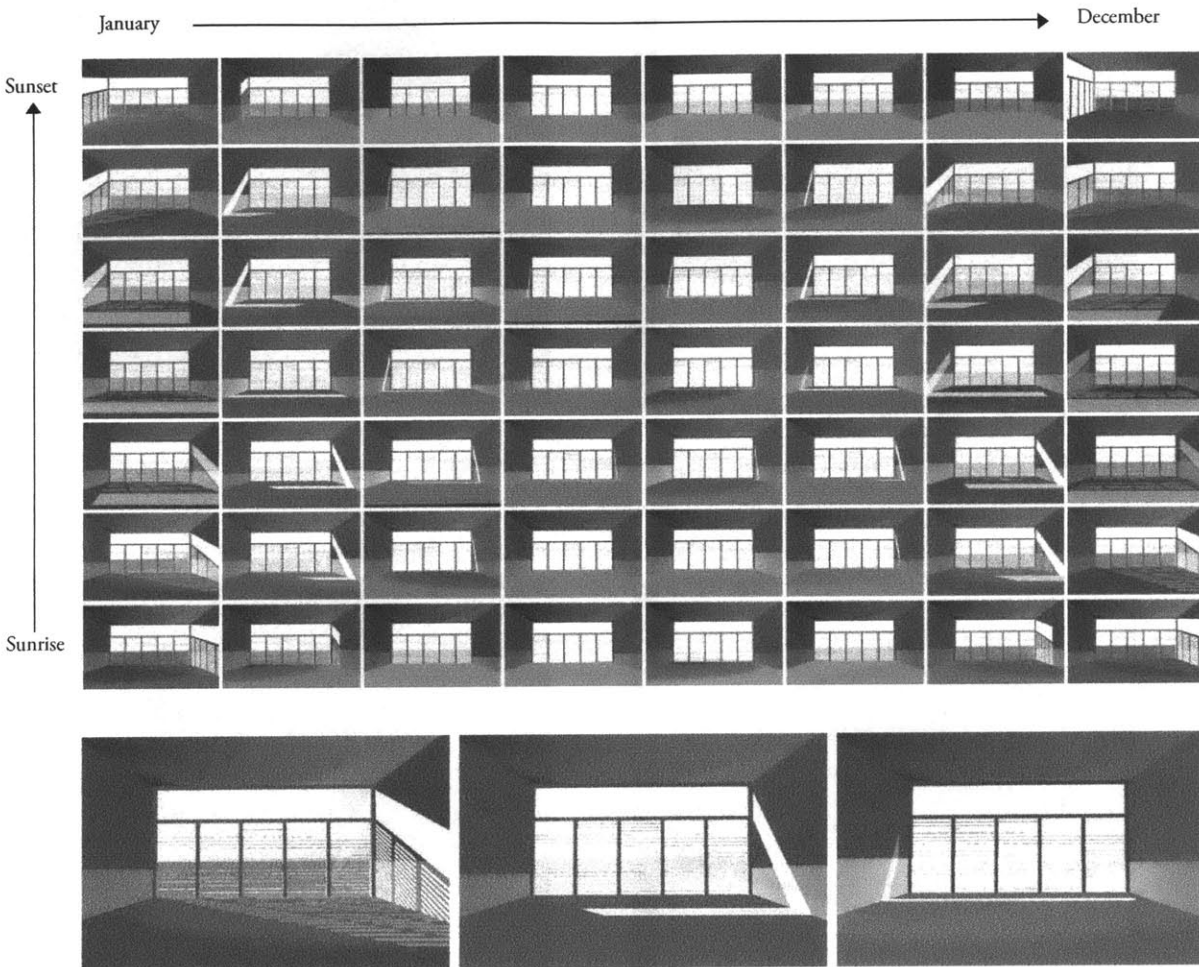
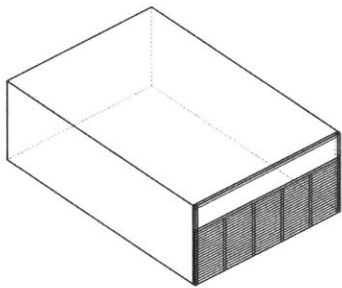


Figure 5.10: Annual Renderings



Category six represents a more traditional side-lit daylight strategy with a clear story window above and louvered screen below, creating varied effects across the year depending on solar altitude (Figure 5.10). Here, the results for annual spatial contrast and luminance variability depict more temporal variation, with a dramatic shift in contrast between the winter and summer months. The temporal map in Figure 5.11 shows high spatial contrast (0.7 to 1) between October and February, with moderate contrast over the rest of the year (0.3 to 0.6). The location of these effects can be seen in the false color image to the right

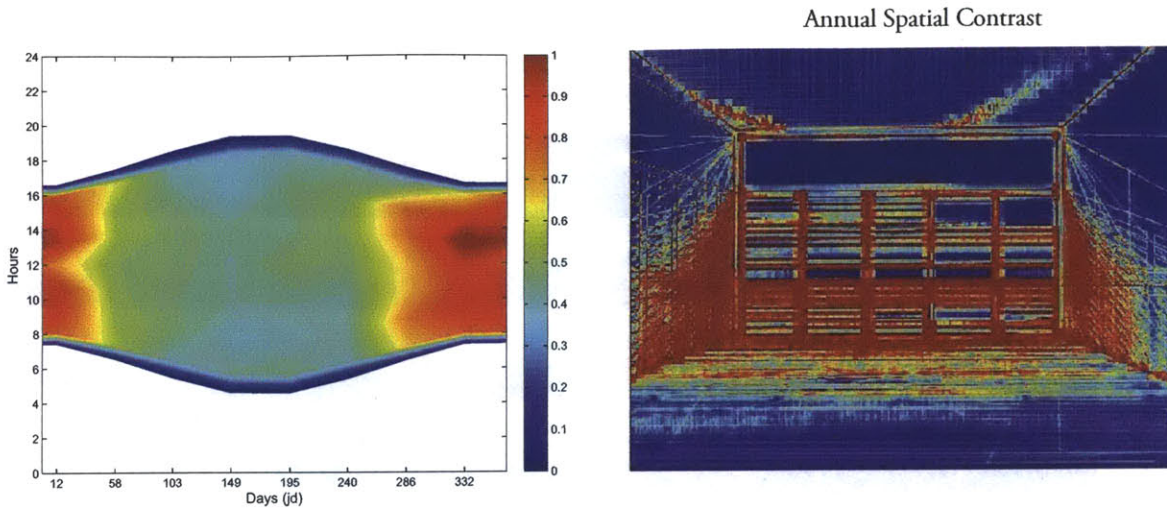


Figure 5.11: Annual Spatial Contrast (Temporal Map & Cumulative Image)

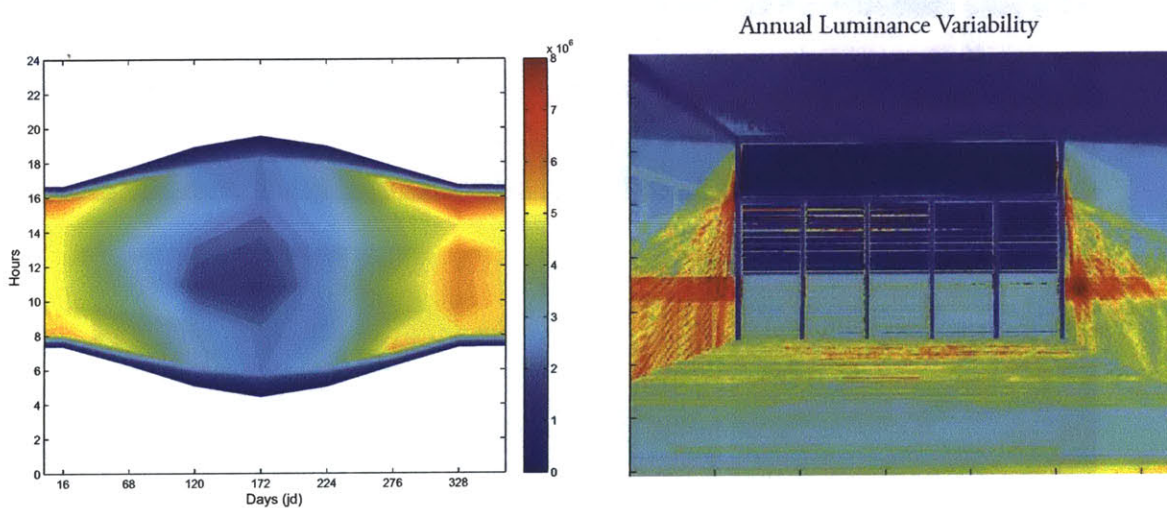


Figure 5.12: Annual Luminance Variability (Temporal Map & Cumulative Image)

of Figure 5.11, which shows the most dramatic accumulation through lines of contrast on the walls and floor closest to the louvers. Annual luminance variability, as seen in the temporal map in Figure 5.12, experiences similar changes in strength across the winter and summer months, but shows a concentration of these changes at sunrise and sunset, when the angle of the sun reaches furthest into the space. These variations range between 10×2^6 (low variability) to 10×7^6 (moderate-to-high variability) and occur most frequently on the walls and floor adjacent to the louvers.

14 Indirect & Dispersed Through Roof

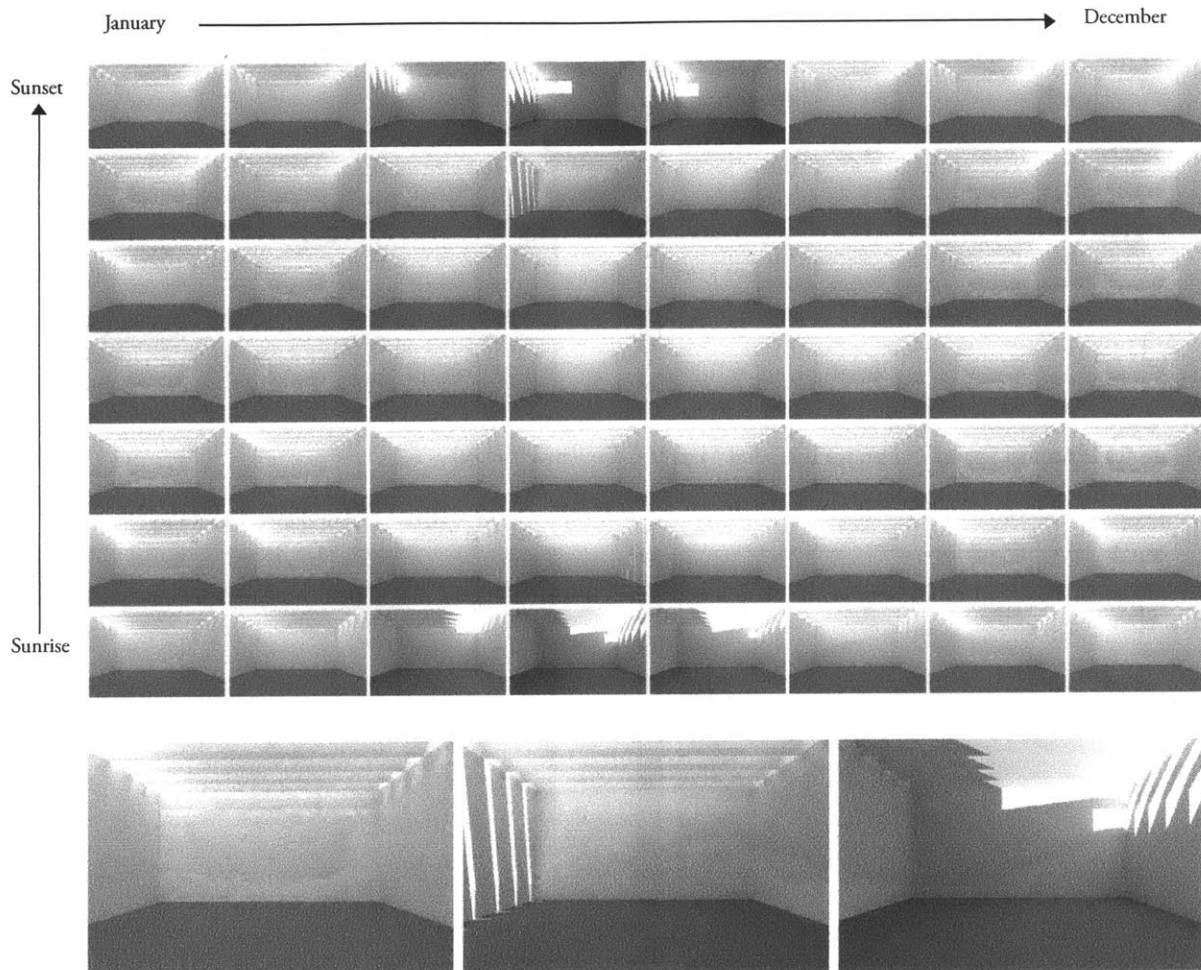
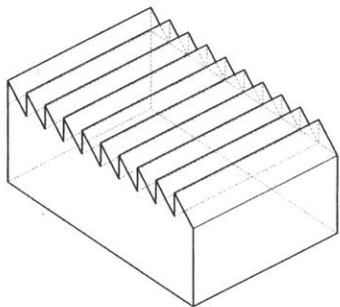


Figure 5.13: Annual Renderings



Category fourteen has a series of north-facing roof monitors that emit diffuse daylight down into the space. Across most of the year, category fourteen is a low-contrast space with selective light penetration, as seen through the renderings in Figure 5.13. The temporal map in Figure 5.14 shows the annual spatial contrast ranging from 0.1 to 0.4 (low to moderate). The annual luminance variability in this example is much more exciting, as it ranges from 8×10^6 (high) to 1×10^6 (low) in the early morning hours and then back again before sunset (Figure 5.15). This shift is due to the solar altitude

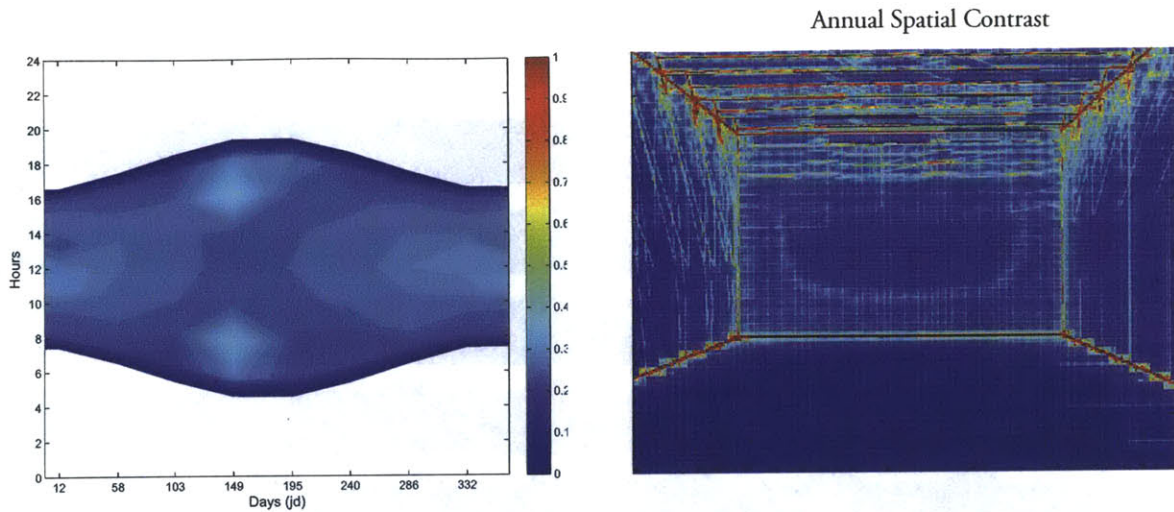


Figure 5.14: Annual Spatial Contrast (Temporal Map & Cumulative Image)

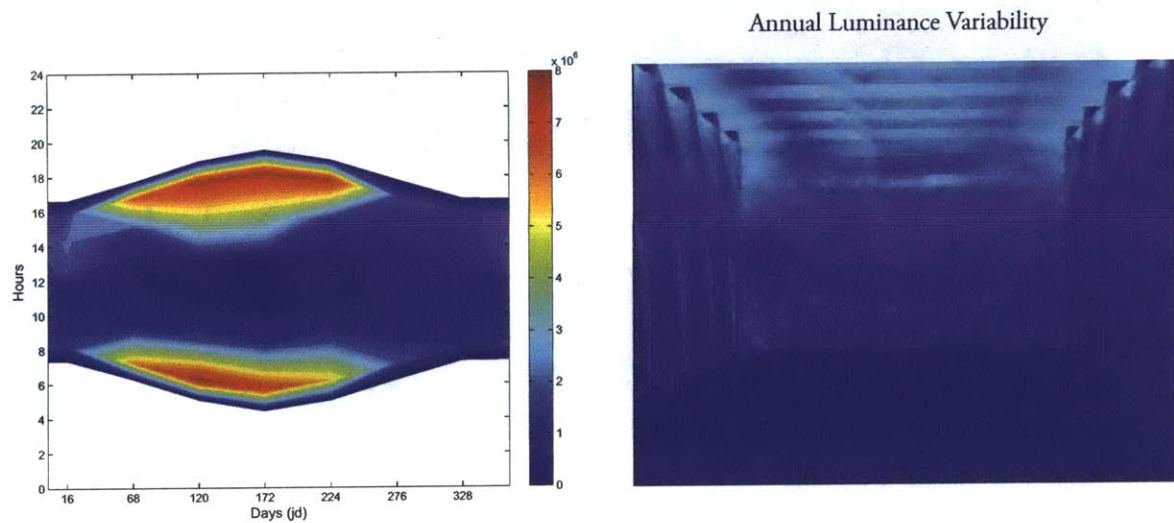


Figure 5.15: Annual Luminance Variability (Temporal Map & Cumulative Image)

and azimuth which allow direct sun penetration through the glass during select moments. This causes minimal spatial contrast across the year, with sharp peaks in luminance variability at sunrise and sunset in the spring and summer months. The image in Figure 5.14 depicts this contrast as it accumulates along the roof monitors. The image in Figure 5.15 shows minimal luminance variability on the floor and walls, with a moderate degree occurring across the ceiling.

15 Indirect & Diffuse Through Walls or Roof

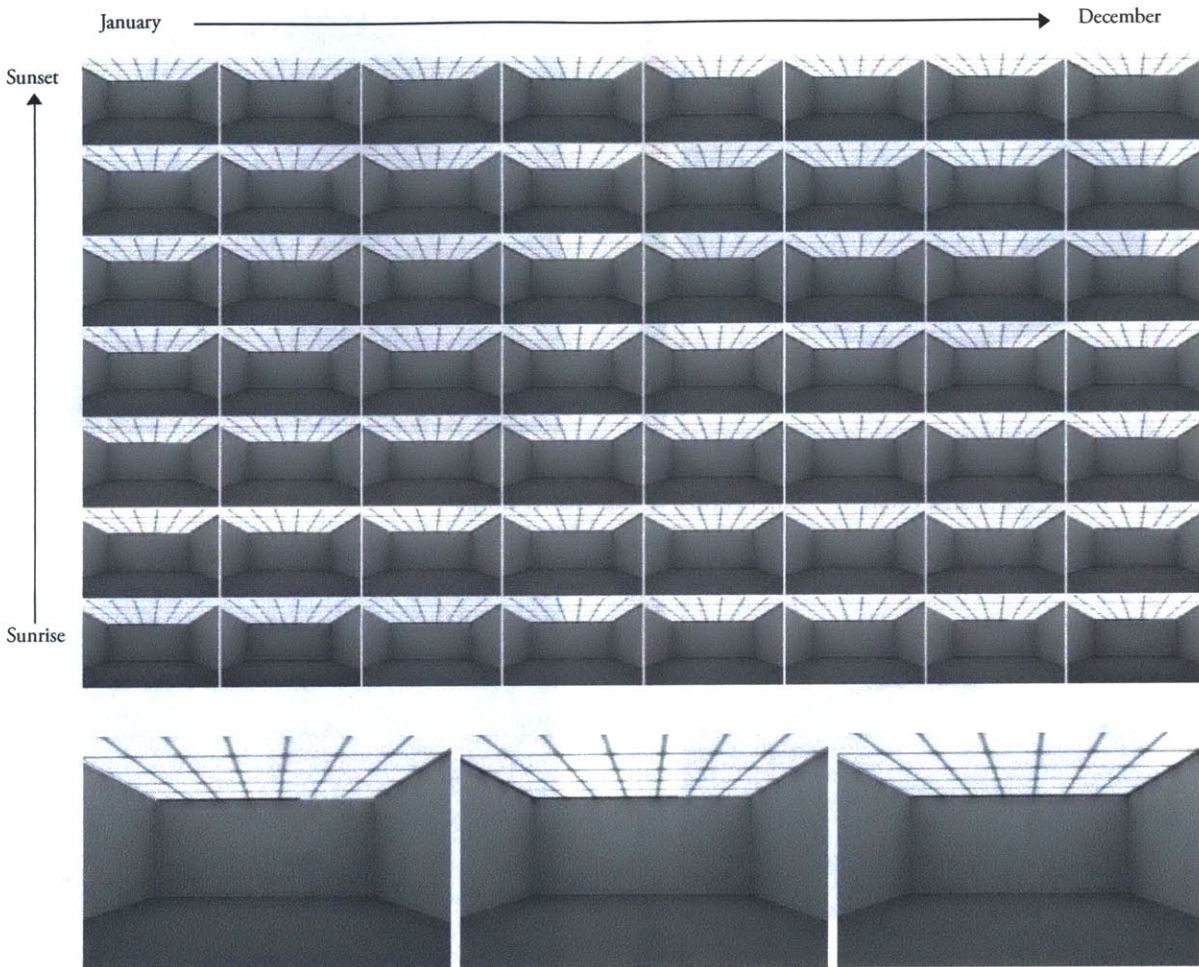
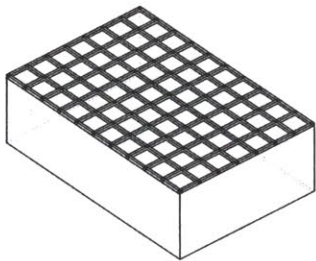


Figure 5.16: Annual Renderings



Category fifteen shows a space with almost no temporal variation, and minimal spatial contrast. The translucent roof glazing diffuses incoming light, creating a static internal effect that can be seen across the annual renderings (Figure 5.16). The dark shadows produced by the back-lit mullions generate some spatial contrast on the ceiling, evident in the image to the right of Figure 5.17. The temporal map to its left displays this contrast as a consistent value (between 0.2 and 0.3) across the year, with minimal daily or seasonal variation. The temporal map in Figure 5.18 shows static luminance across the year, with a range from 1×10^6 (low) to 2×10^6 (low). It

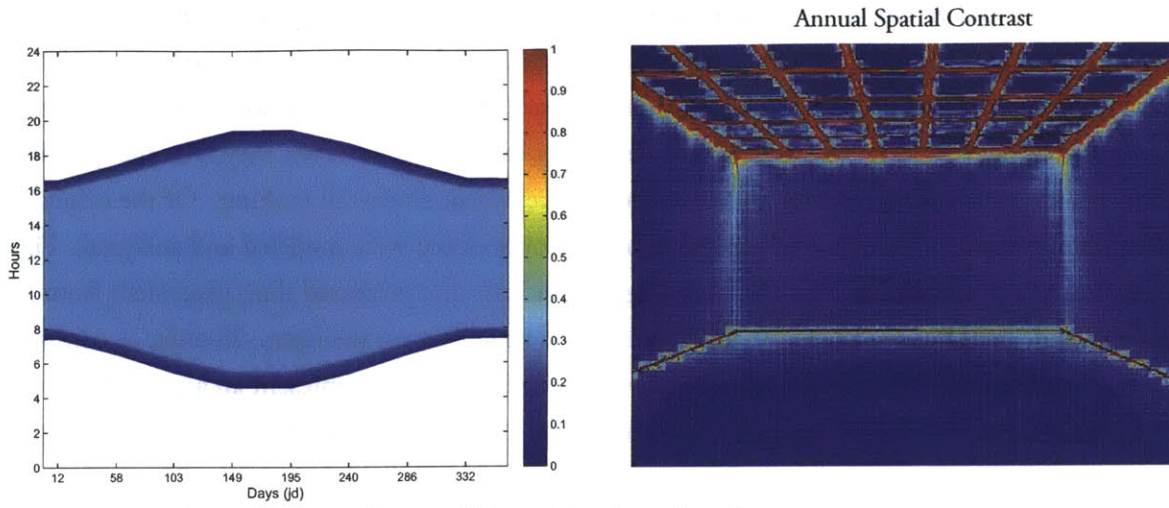


Figure 5.17: Annual Spatial Contrast (Temporal Map & Cumulative Image)

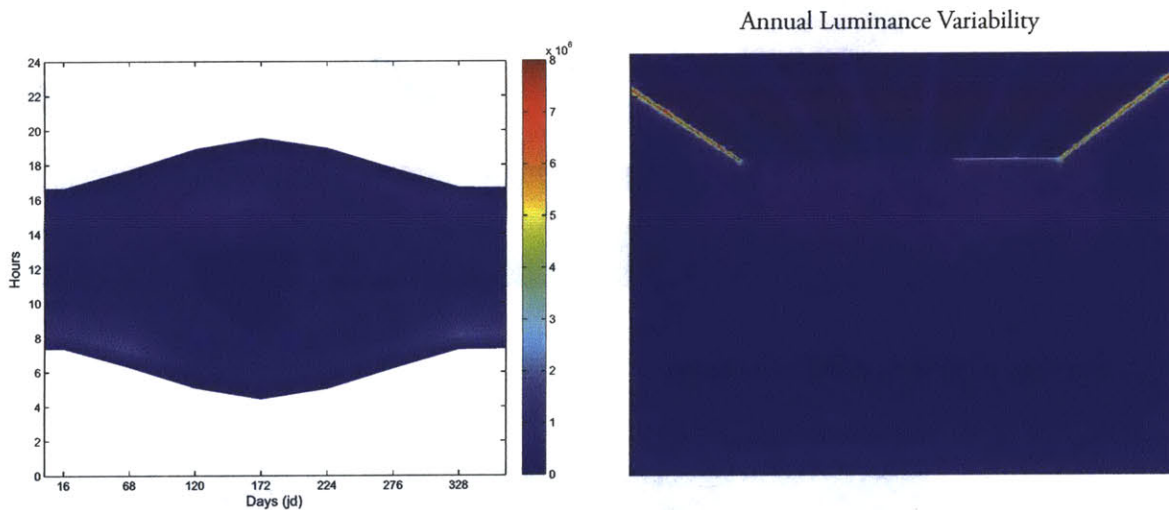


Figure 5.18: Annual Luminance Variability (Temporal Map & Cumulative Image)

is important to mention that this particular space was rendered in two different attempts with the first set of images representing sharp contrast between the mullions and glass, with peaks of high variability as the sun altered those shadows across the translucent glazing. This raises an important potential error within the production of images, which must represent an accurate view of the interior space. If the materials and/or surfaces do not render properly, the metrics cannot accurately calculate the degree of perceived contrast or variability and must be re-run. These results can be found at the end of Appendix B.

From this set of results, a clear gradient can be identified between the high and low ends of the contrast and variability spectrums. These four examples represent various combinations of annual spatial contrast and luminance variability, confirming the need for both metrics to depict the complexity of temporal conditions within each space. The results presented in this chapter are conclusive in their quantitative methods for describing each effect; however, they raise the question of how these numbers can or should be combined to represent an overall ranking. Of the original fifteen categories described in the typological matrix, only eleven were modeled and analyzed. Figure 5.19 shows these eleven case studies in the original gradient that predicted their placement from high contrast and variability on the left to low contrast and variability on the right. In order to compare the case studies, each metric was compressed into a single number to represent an accumulative sum of annual results. For annual spatial contrast, the total sum of spatial contrast across all 56 images

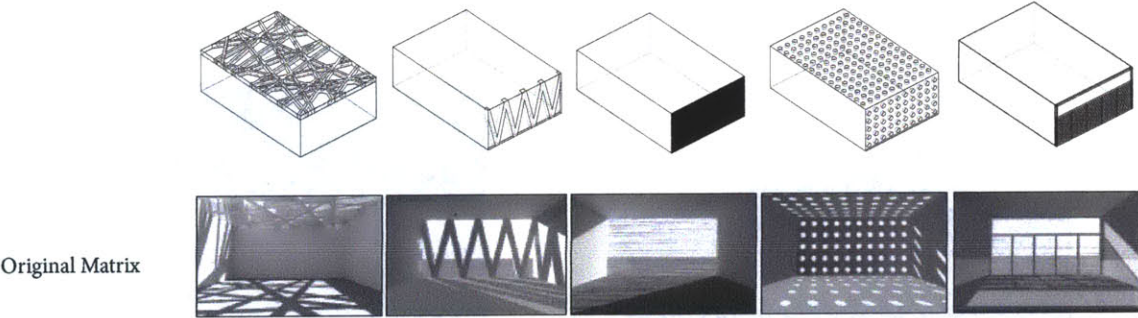


Figure 5.19: Original Gradient of Hypothesized Effects

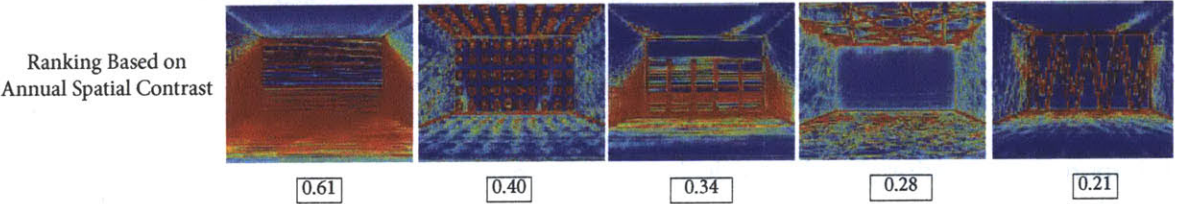


Figure 5.20: Reconfigured Matrix Based on Annual Spatial Contrast

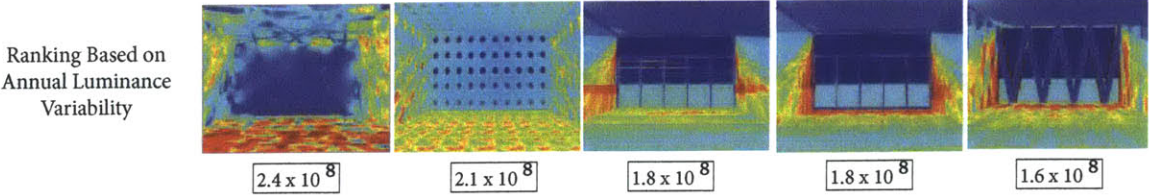
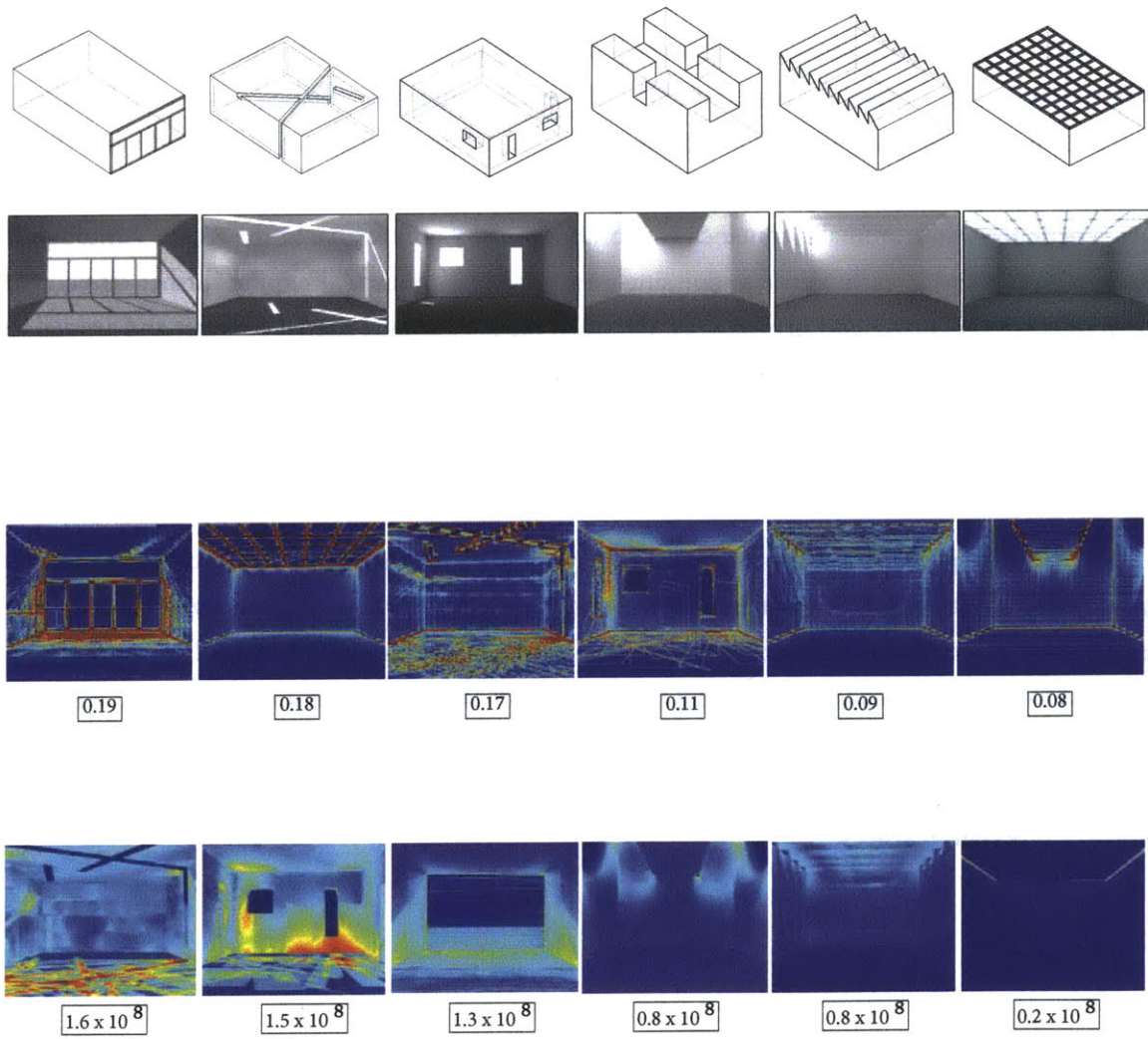


Figure 5.21: Reconfigured Matrix Based on Annual Luminance Variability

was divided by the total sum of spatial contrast across all 56 'maximum high' images (black and white checkerboards) to produce a single value. For annual luminance variability, the total sum was taken for all 42 moments and represented as one cumulative sum. The values that quantify the total sum for annual spatial contrast range between 0.07 and 0.61. Those that quantify the total sum for annual luminance variability range between 2.4×10^8 and 0.2×10^8 . Figure 5.20 shows the eleven case studies reconfigured to represent a new gradient specific to annual spatial contrast. This ranking organizes each space into a line from high annual spatial contrast on the left (0.61) to low annual spatial contrast on the right (0.007). Figure 5.21 shows the eleven case studies reconfigured to represent a gradient specific to annual luminance variability. This ranking organizes each value into a line from high annual luminance variability on the left (2.4×10^8) to low annual luminance variability on the right (0.2×10^8).



Although these values achieve a convincing gradient of effects, the number for total annual spatial contrast cannot be directly compared to the number for total annual luminance variability. In order to compare or combine these effects to recreate the original hypothesized matrix, (which represented a combination of the two annual metrics) one would need to validate the study across a wider range of typological examples to establish a true maximum and minimum for each metric, allowing for a weighted adjustment to the cumulative annual values. This would allow the two annual metrics to be combined and compared on a relative scale from high to low. That being said, the temporal maps, accumulative false-color images, and total annual values still represent an accurate ranking of each metric from one space to the next. They may also be compared in a relative gradient, as seen in Figures 5.20 and Figure 5.21. The numbers beneath each false-color image in Figure 5.20 may represent a different quantitative scale than those beneath each false-color image in Figure 5.21, but each space still receives a position in the line that ranks it from a relative high to a relative low across each metric. This allows us to make comparisons between temporal effects in each space. For example, we can say that the louvered space in category 6 represents a relatively high degree of both annual spatial contrast (0.34) and annual luminance variability (1.8×10^{-8}), while the screened space in category 4 shows a high degree of annual spatial contrast (0.61) and a low degree of annual luminance variability (1.3×10^{-8}). These numbers also allow us to confirm that category one experiences more annual luminance variability than any other space in the study. Although the clarity of representing each metric as one single and universal value will require further refinement, the results are conclusive and demonstrate the capabilities of annual spatial contrast and annual luminance variability in quantifying a set of temporal characteristics within daylight architecture.

5.4 Summary

This chapter applied annual spatial contrast and luminance variability metrics to a series of typological case study spaces to determine their adequacy in describing hypothesized effects. The results show a conclusive gradient for both spatial contrast and luminance variability, supporting the need for both metrics in representing the complexity of daylight variation over time. Although the value signifying annual effects varies in scale between each metric, the overall gradient of results, false-color representations, and temporal maps can be used to accurately quantify each effect across a group of typological spaces.

Chapter 6

Application of Metrics to Existing Architecture

6.1 Introduction

In the previous chapter, we applied spatial contrast, annual spatial contrast, and annual luminance variability metrics to a series of case-study models. The annual metrics were compared to show how they differ within each model and how those differences draw conclusions about when and where daylight changes over time. These results were then compared across the full spectrum of case studies to show how each metric adjusts the position of models within a gradient specific to its own analysis. This chapter will apply annual spatial contrast and luminance variability metrics to a pair of existing architectural spaces, Toyo Ito's 2002 Serpentine Pavilion and Louis Kahn's First Unitarian Church, in order to test their analytical capabilities with more detail and site specificity. The results will then be discussed alongside existing daylight metrics to provide a more holistic view of performance within each space. We will also take a look at a photographic method of image production through a physical model of the Louis Kahn Church.

6.2 Modeling Assumptions

Each architectural space was modeled in Rhinoceros and assigned default radiance materials for floor, wall, and ceiling surfaces (0.3, 0.7, 0.9 respectively). The camera view was selected to mimic an existing photograph of each space so that interior lighting conditions would be adequately represented through a single view. The location of each model was adjusted in Radiance, with Kahn's Church located in Rochester, NY (43 N, 77W) and Ito's Pavilion in London, UK (51 N, 10W). The rendering quality, view aspect ratio, and pixel resolution were set to high-quality ray-tracing, 40 x 60, and 480 x 640, respectively

2002 Serpentine Pavilion by Toyo Ito London, UK

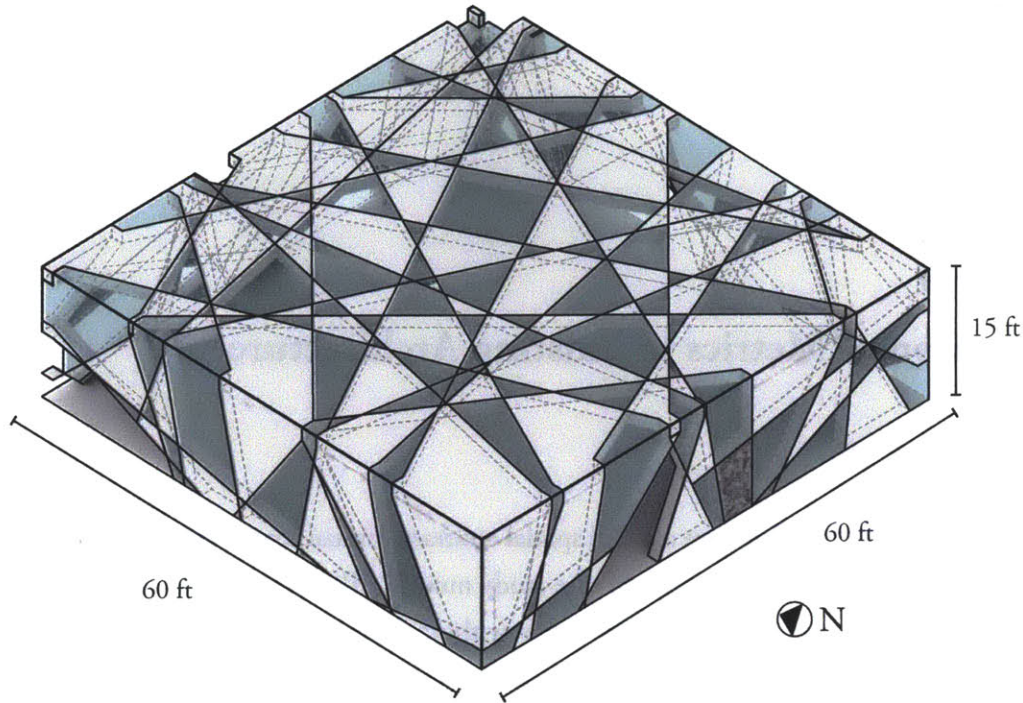


Figure 6.1: Axon of Serpentine Pavilio facing North-East

6.3 2002 Serpentine Pavilion

Toyo Ito's Serpentine Pavilion, constructed in Hide Park, London in 2002 is part of an ongoing commission instituted by the Serpentine Gallery for the exhibition of contemporary architecture. Each year, a prominent architect is selected to design and built a pavilion in which public activities such as film screenings, receptions, and lectures can take place. The design for the 2002 pavilion was an exquisite box of diagonal steel members with alternating glass and opaque white panels. The overall dimensions for the box were 60 ft. x 60 ft. x 15 ft. and were modeled from existing drawings of the building (Figure 6.1). The primary structure for the pavilion relied on a web of intersecting steel members, with secondary panels providing shear support (Figure 6.2). The leftover grid of openings were covered in glass to provide protection from the elements, while maintaining transparency. According to my matrix, this space falls into category one and represents a 'Direct and Exaggerated' daylight strategy. Due to the public program of this pavilion and its use as a semi-outdoor venue, there was little need to control direct sunlight within the space and variability was encouraged through asymmetry and transparency in the roof and walls.

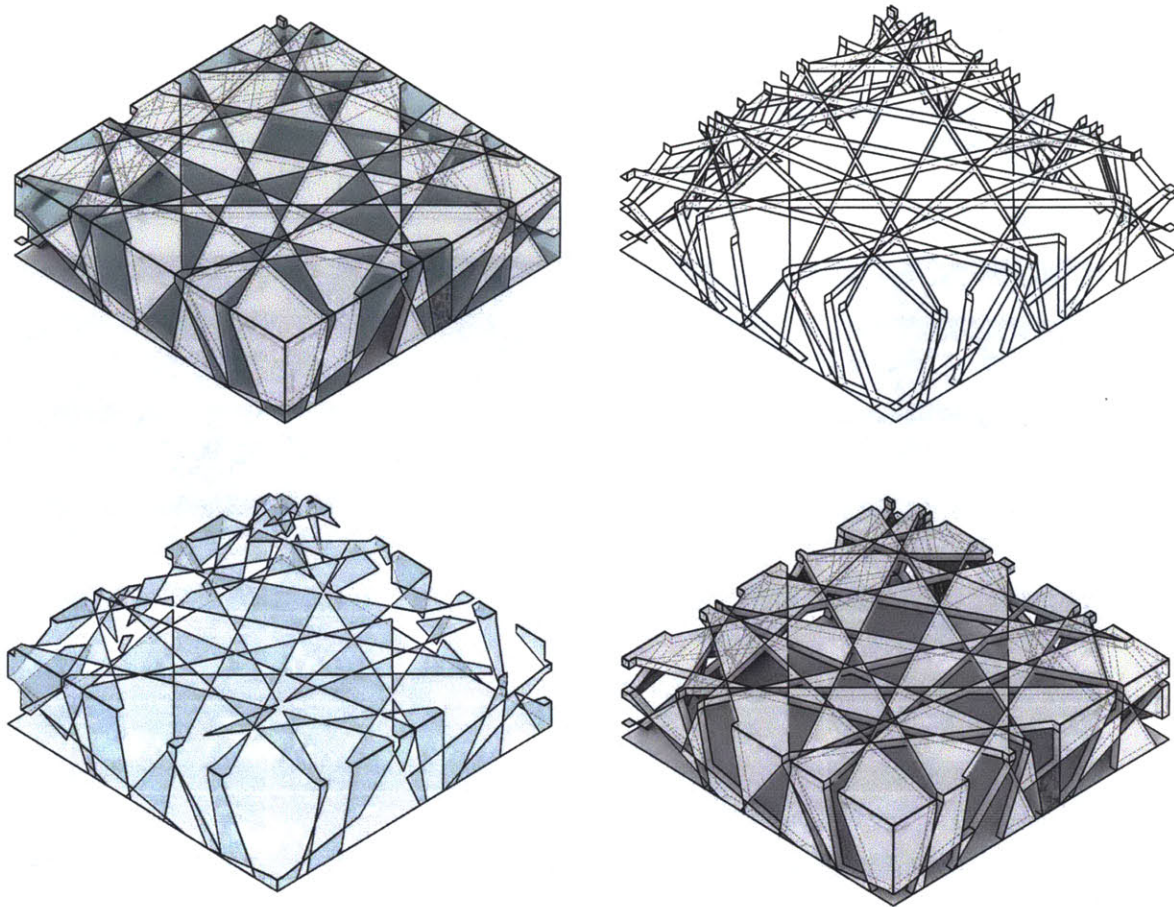


Figure 6.2: Exploded Axon of Serpentine Pavilion showing glazing, panels, and structure

The renderings in Figure 6.3 show a variable space with large patches of direct sunlight casting dynamic shadows across the floor. The photograph to the left of Figure 6.4 shows the southeast corner of the pavilion while the renderings to the right show how the camera angle for each rendering was adjusted to match it. The temporal maps and cumulative false-color images on the opposite page show the magnitude of this contrast and variation in luminance over time. The temporal map in Figure 6.5 shows high spatial contrast throughout the year (from 0.7 to 1), with a concentration from 10 a.m. to 4 p.m. during the summer months. The cumulative image to the right shows where this contrast occurs most frequently, highlighting lines of structure in the roof and resulting patterns across the floor. Figure 6.6 shows a more dynamic temporal map with peaks in luminance variability from 4×10^8 to 9×10^8 during the summer months and various degrees of change occurring throughout the rest of the year. The cumulative image to the right shows these variations occurring most frequently across the floor.

Serpentine Pavilion by Toyo Ito

London, UK

1 Direct & Exaggerated Through Walls or Roof

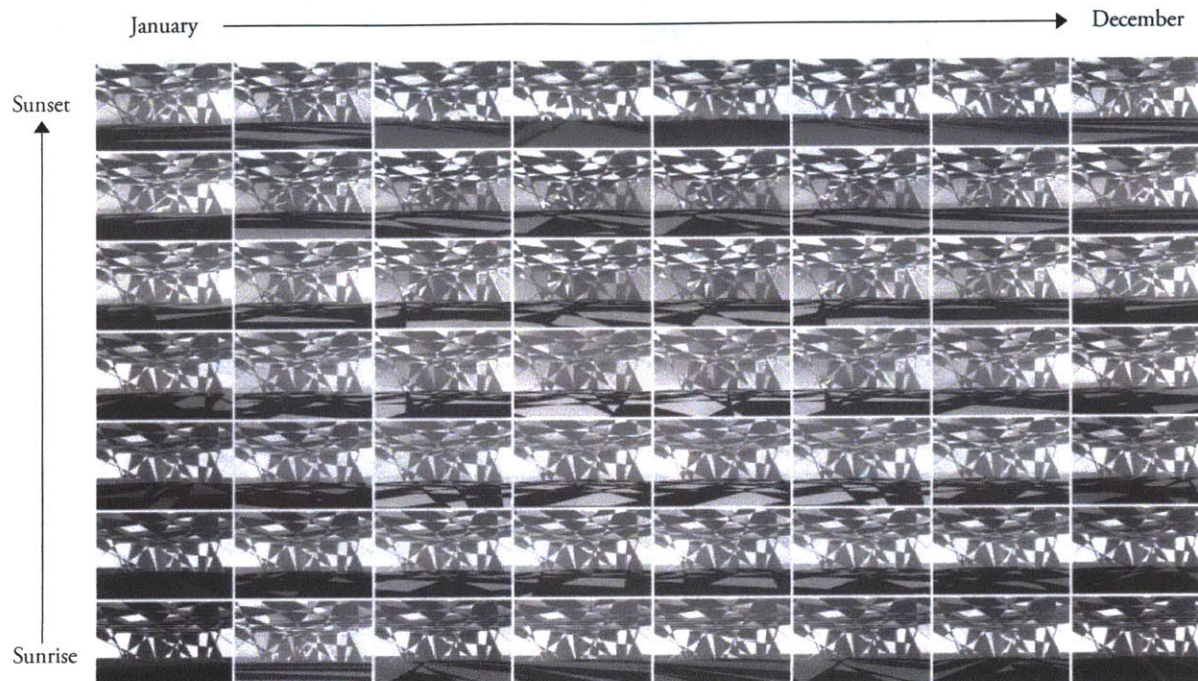


Figure 6.3: Annual Renderings

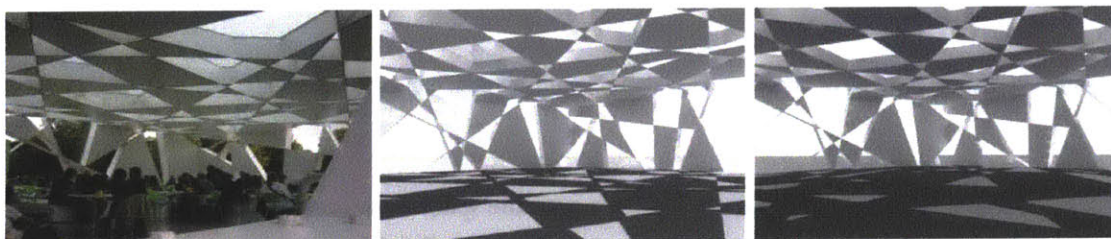


Figure 6.4: Photograph of Interior Space, Courtesy of Buzznet

Figure 6.7 shows a base-line analysis that was done to differentiate between accumulations of brightness across all 56 images, and the information that is revealed by each of the annual metrics shown above. This 'Annual Luminance Accumulation' took the sum of all pixel brightness within each image and plotted it across the temporal map on the left. The image to the right shows a simple accumulation of all 56 renderings, highlighting areas that are consistently bright. The temporal map on the left and the image on the right show how brightness accumulates across the year, while the metrics represented by figures 6.5 and 6.6 show how it changes, exposing the dynamic nature of daylight. Annual spatial contrast and luminance variability add more depth to our understanding of architecture over time.

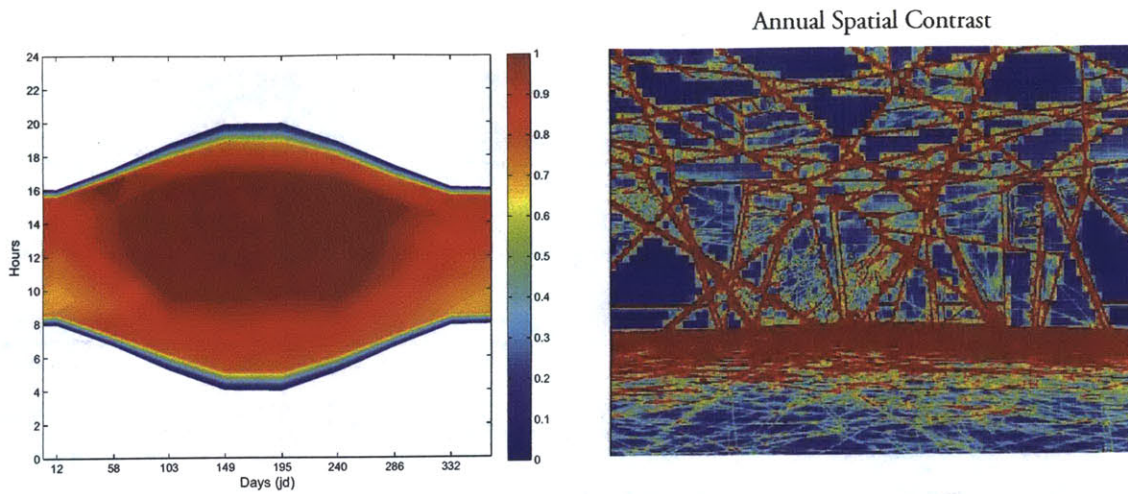


Figure 6.5: Annual Spatial Contrast (temporal map & cumulative image)

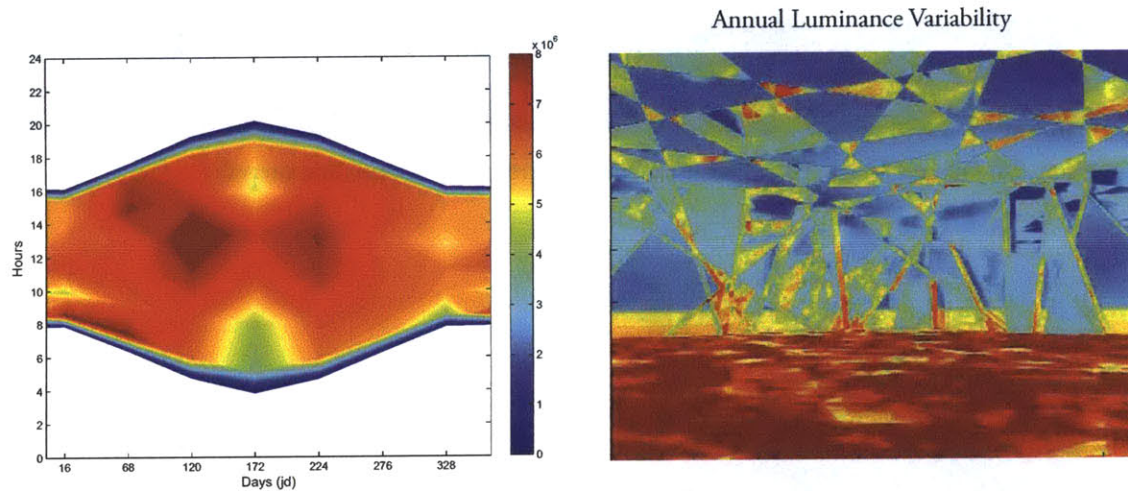


Figure 6.6: Annual Luminance Variability (temporal map & cumulative image)

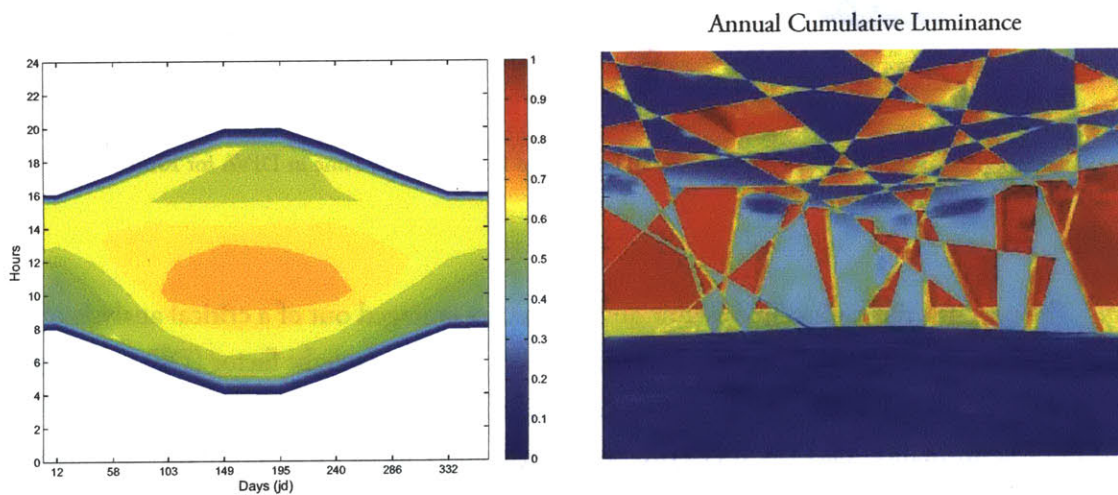


Figure 6.7: Annual Luminance Accumulation (temporal map & cumulative image)

Daylight Glare Probability Analysis

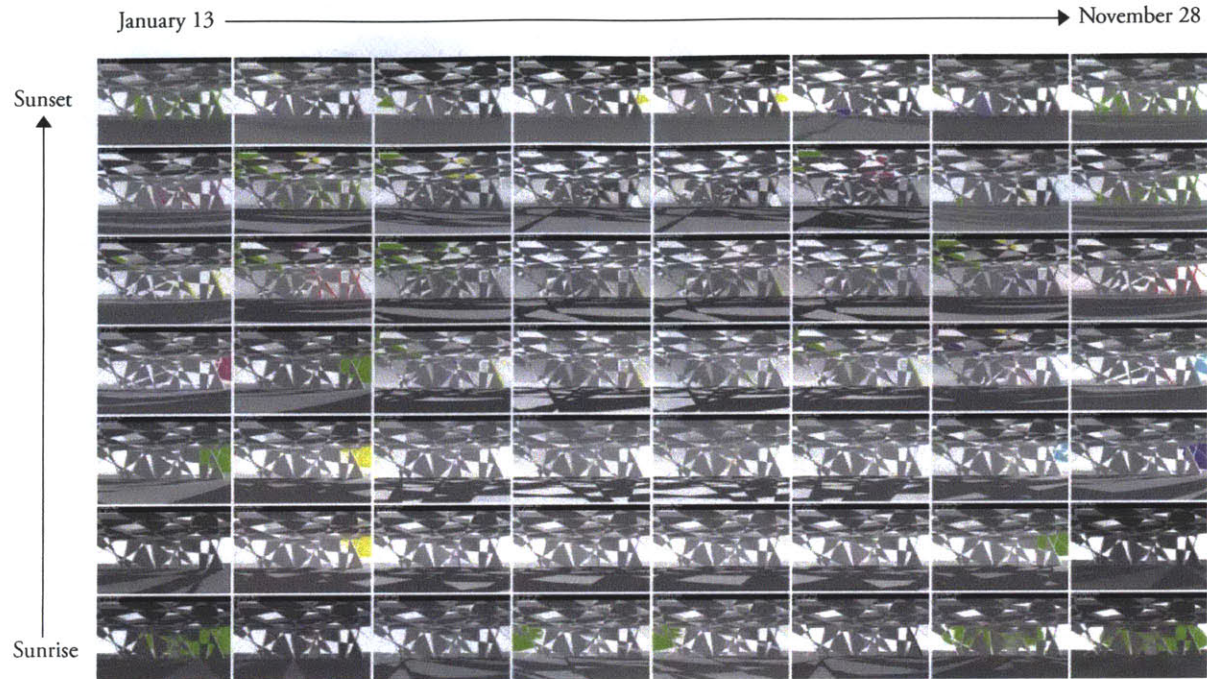


Figure 6.8: Annual Daylight Glare Probability Analysis across all 56 annual time intervals

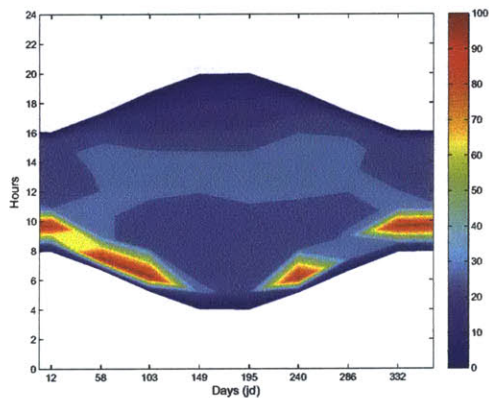


Figure 6.9: Temporal Map of DGP (0-100%), Calculated for each Date/Time in DIVA for Rhinoceros & DAYSIM and Plotted in Matlab.

The need for these visually dynamic annual metrics emerged out of a critical analysis of existing daylight metrics such as daylight glare probability (DGP), daylight factor (DF), and daylight availability (DA). Daylight Availability, in DIVA, is based on daylight autonomy but provides three indicators of performance; partially lit, daylit, and over lit space based on a minimum illuminance threshold. In order to differentiate the contrast-based metrics proposed by this thesis, DGP, DF, and

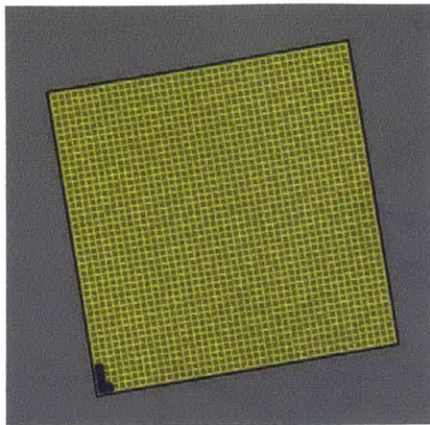


Figure 6.10: Daylight Factor, DIVA for Rhinoceros & DAYSIM

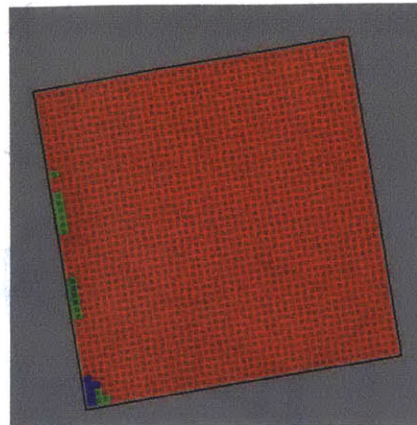


Figure 6.11: Daylight Availability (500 lux), DIVA for Rhinoceros & DAYSIM

DA analyses was run on both the Serpentine Pavilion and the First Unitarian Church to expose their limitations in describing temporal qualities of architecture and show how new metrics can be used as a compliment.

Figure 6.8 contains 56 individual DGP analyses, run in the DIVA for Rhinoceros toolbar. These values ,ranging between 0 and 100%, were plotted on the temporal map in Figure 6.9 to show how glare prediction varies across the year. This map shows distinct moments of high DGP in the early morning, with inconclusive (>20%) values across the rest of the year. The analysis tells us the Serpentine Pavilion has a high risk for glare-induced discomfort between 8 a.m. and 10 a.m. in the spring, fall, and winter months.

Figure 6.10 shows a daylight factor analysis, run in DIVA, with a sensor grid offset 2.5 ft. from the floor of the pavilion. The grid achieves a DF of 6% or higher everywhere in the space. Figure 6.11 contains a daylight availability analysis with a minimum threshold of 500 lux. The red squares, which cover the entire analysis grid, represent space that is considered to be ‘over lit’ for task-oriented activities. The DF analysis tells us that we have adequate light entering the space, while the DA tells us that it’s ‘over lit’ for recommended task-based levels. Given that the Serpentine Pavilion wasn’t designed to accommodate task-based activities, neither DGP, DF nor DA can effectively analyze the performance of its daylight strategy. Metrics like annual spatial contrast and annual luminance variability are more appropriate methods of analysis for the pavilion, which was designed to enhance visual effects as a dramatic exhibition space. Horizontal illuminance maps and glare-based metrics simply cannot communicate this information.

First Unitarian Church by Louis Kahn Rochester, NY USA

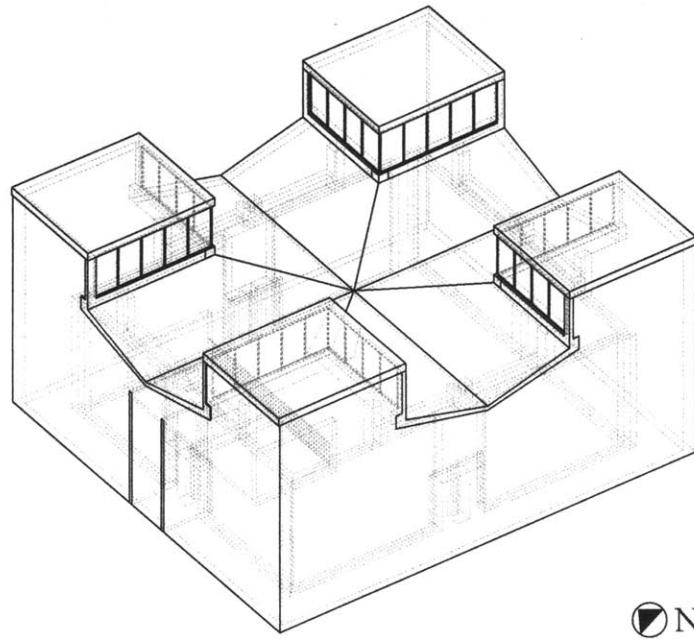


Figure 6.12: Axon of First Unitarian Church looking North

6.4 First Unitarian Church

Louis Kahn's First Unitarian Church was built in Rochester, NY in 1967. His intention was to design a space that represented the ideals of the United Universalists through essential qualities in material, structure, and light. In the brochure distributed to visitors of the church, Kahn was said to have designed the space to express "only what matters", with a central sanctuary surrounded by rooms devoted to education and spiritual inquiry. The concept for the plan was based on a question mark, with the center sanctuary surrounded by layers of circulation that allow for various degrees of participation and engagement. This is achieved through a multi-layered box, with internal and external concrete walls (Figure 6.12). The inner layer, a 15 ft. concrete masonry block wall, supports four branching concrete columns, which in turn carry the structure of the roof (Figure 6.13). The outer layer of the sanctuary is constructed from cast-in-place concrete and terminates in four 30-ft-high roof monitors with internally facing clerestory windows. These roof monitors emit mostly indirect light, which bounces off the outer concrete wall and down into the sanctuary. This creates smooth gradients of light in all four corners of the church. There is some spatial contrast present within the space, but the dominant visual effects are slowly changing luminance levels across the year.

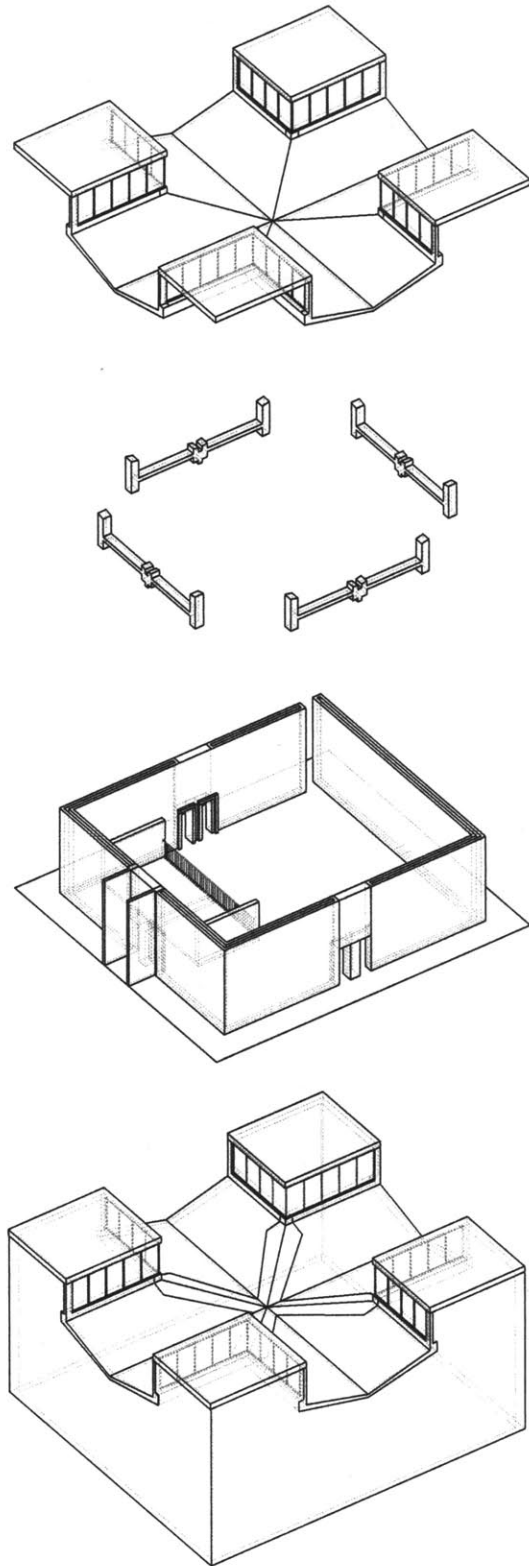


Figure 6.13: Exploded Axon of Church, showing roof, strcuture, interior, and exterior walls.

First Unitarian Church by Louis Kahn Rochester, NY USA

11 Spatial Indirect Through Walls or Roof

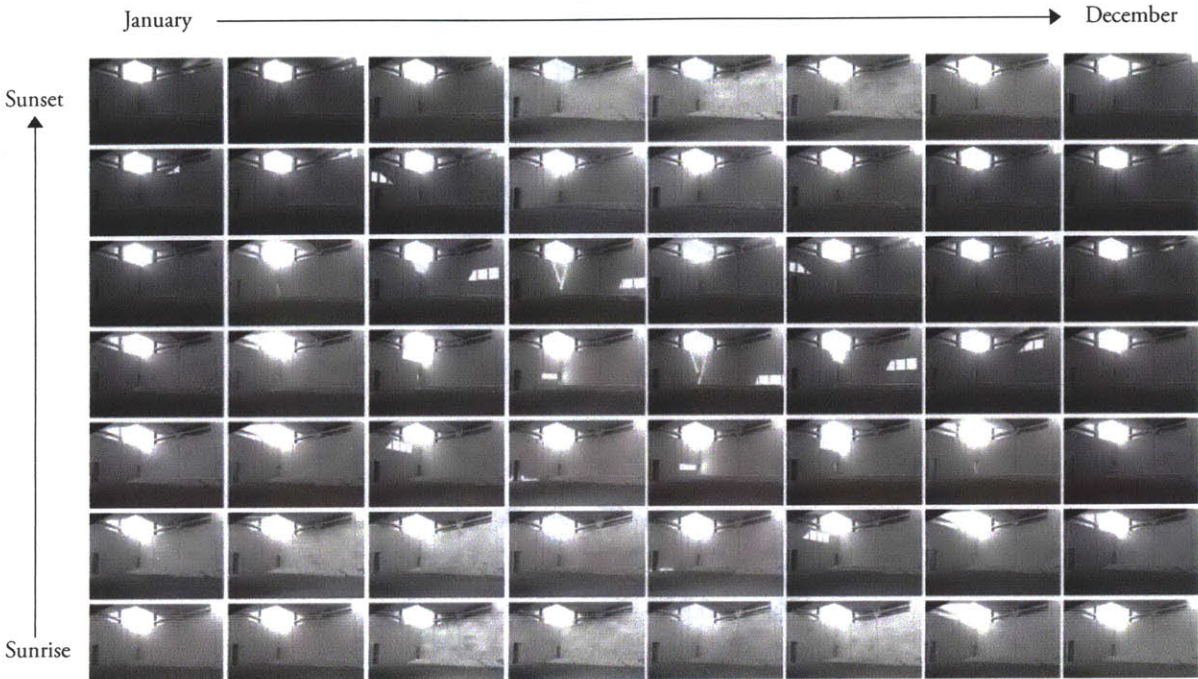


Figure 6.14: Annual Renderings

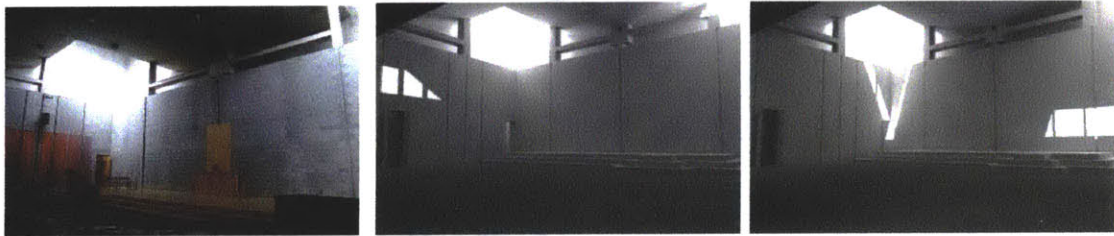


Figure 6.15: Photograph of Interior Space, Courtesy of Edanastas, flickr.com

The annual rendering set in Figure 6.14 shows incoming light distributed through a smooth gradient across the outer and inner concrete walls. The church interior can be seen through a perspective photograph in Figure 6.15, which served as precedent for the camera location in each annual rendering in the set. Figure 6.16 shows spatial contrast as moderate throughout the year, ranging from 0.3 to 0.5. Changes in light occur as the sun moves across the vertical monitors, creating large shifts in overall luminance. This variability can be seen in Figure 6.17, which shows sharp changes in the late afternoon and across the summer months. This temporal map is particularly engaging as it shows the range of luminous diversity within the church (from 2×10^8 to 8×10^8), while maintaining a relatively low degree of contrast. Figure 6.18 shows the baseline

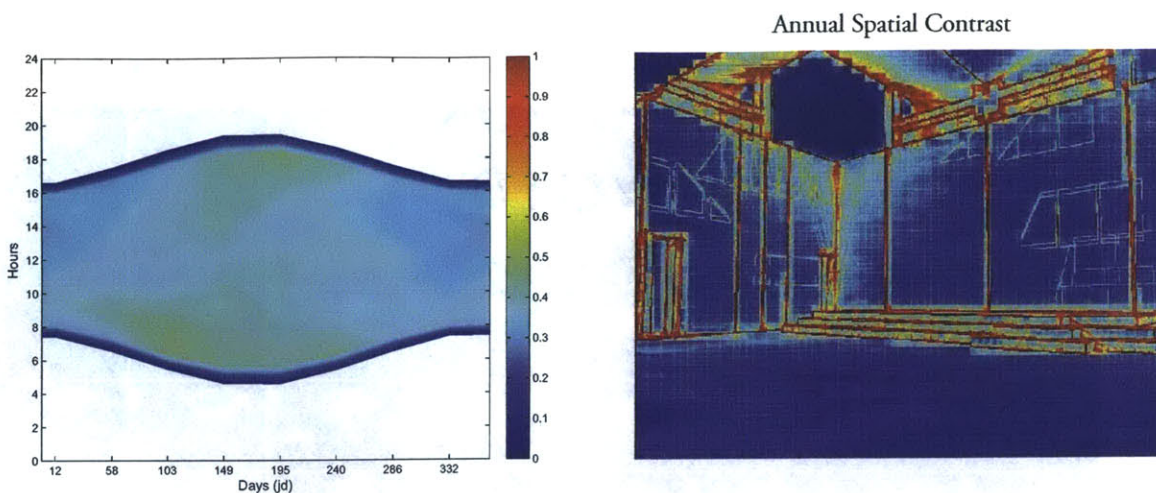


figure 6.16: Annual Spatial Contrast (temporal map & cumulative image)

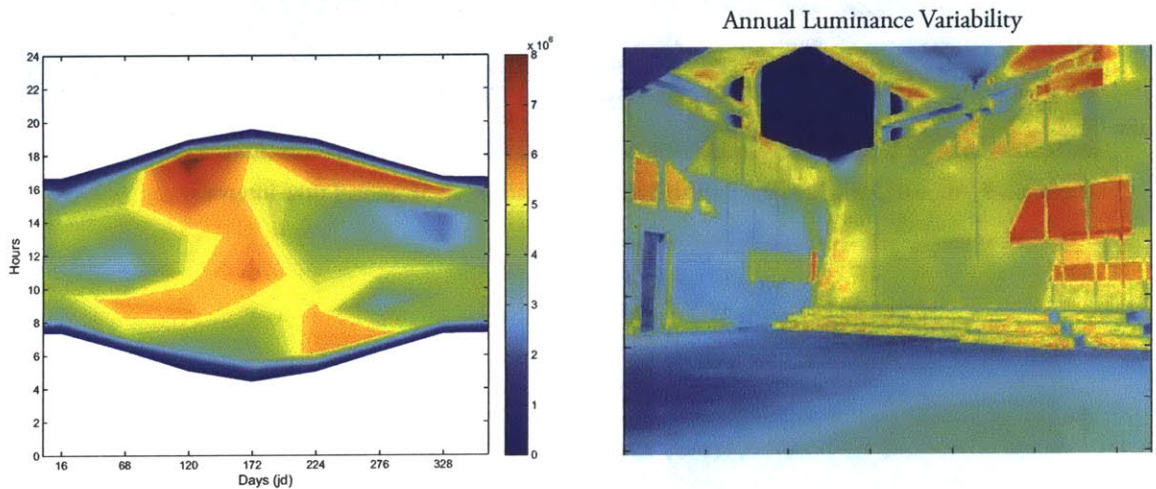


figure 6.17: Annual Luminance Variability (temporal map & cumulative image)

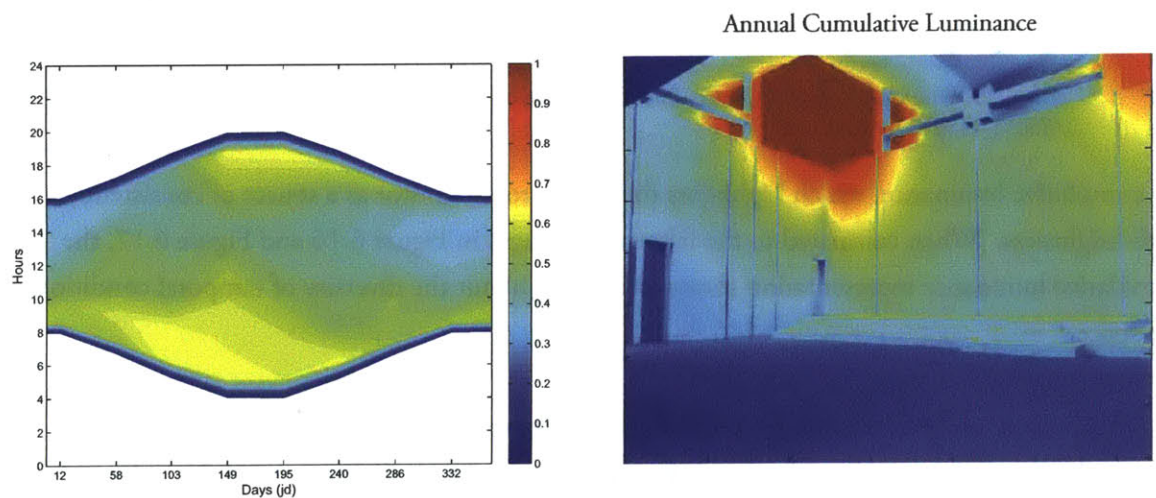


figure 6.18: Annual Luminance Accumulation (temporal map & cumulative image)

Daylight Glare Probability Analysis

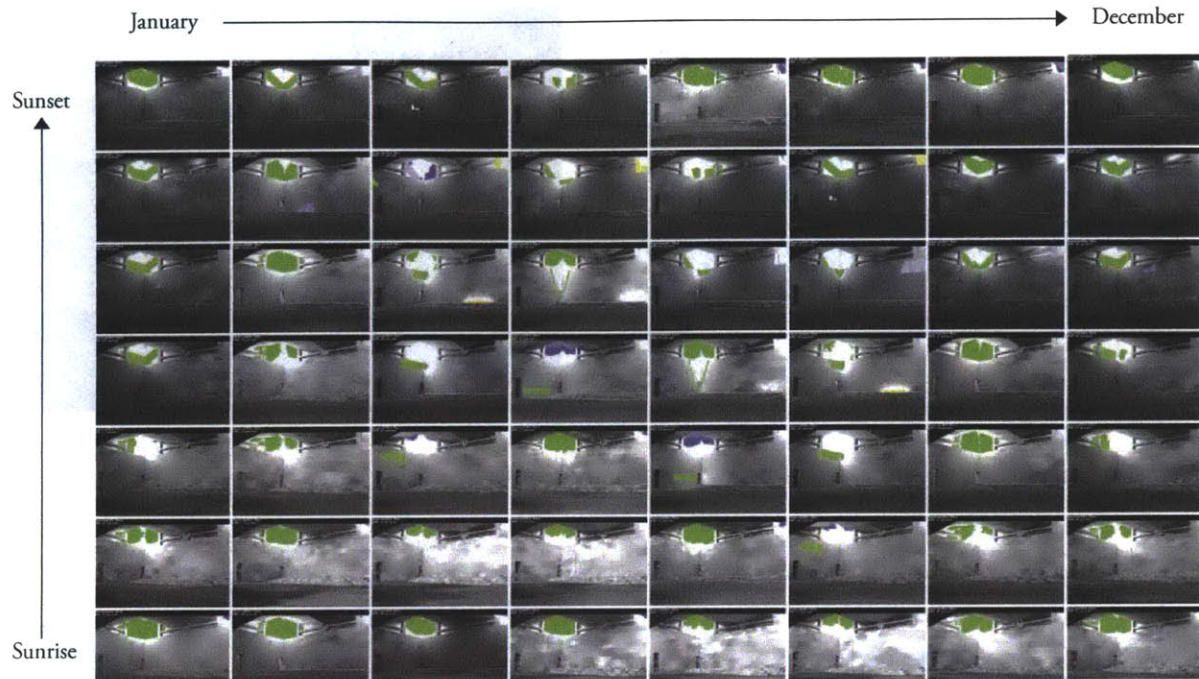


Figure 6.19: Annual Daylight Glare Probability Analysis Across all 56 annual time intervals

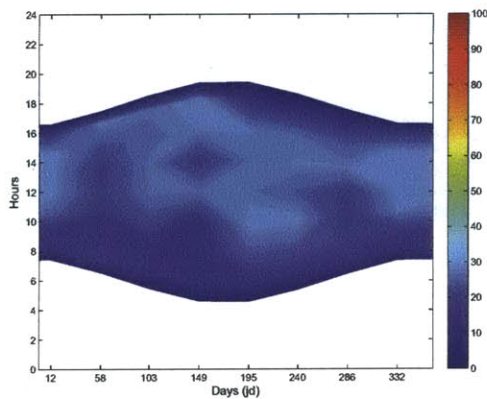


Figure 6.20: Temporal Map of DGP (0-100%), Calculated for each Date/Time in DIVA for Rhinoceros & DAYSIM, Plotted in MATLAB

for cumulative luminance, which highlights the corner roof monitor as a source of consistently high brightness. When compared to the false-color images in Figure 6.16 and Figure 6.17, the cumulative luminance representation shows us nothing about the diversity of temporal conditions in the space.

A DGP analysis was run for each of the 56 moments presented in figure 6.19 with a temporal map of the annual results shown figure 6.20. All the DGP results from this analysis fall between 10% and 30% and must be interpreted carefully, because DGP values below 20% have not

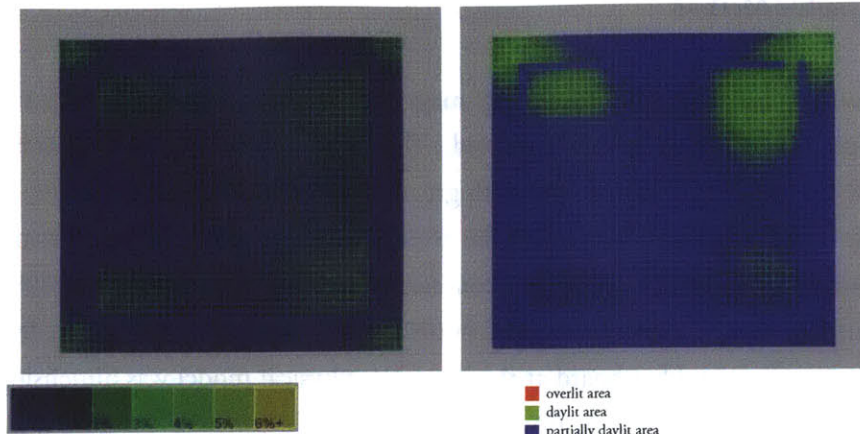


Figure 6.21: Daylight Factor, DIVA for Rhinoceros & DAYSIM

Figure 6.22: Daylight Availability (300 lux), DIVA for Rhinoceros & DAYSIM

been fully validated [Weinold & Christofferson, 2006]. In either case, the analysis tells us that there is a low probability of glare present within the space.

Figure 6.21 shows a DF analysis grid (with a 2.5 vertical offset) for the First Unitarian Church with values between DF 0 and DF 2%. The inner sanctuary receives perceptible light, but would not meet the recommendations set by most codes and standards. Figure 6.22 depicts a DA sensor grid (also offset 2.5 ft. from the floor) with a minimum illuminance threshold of 300 lux. The map shows that only two corners receive ‘daylit’ illumination across the year, while the majority of the space is only ‘partially lit’ from natural light.

If we were analyzing a classroom where we cared about the illuminance levels across a horizontal work surface, then these two metrics would be useful. Neither the Serpentine Pavilion nor the First Unitarian Church has programmatic uses that require horizontal task-based illumination and yet, we have few daylighting metrics that can account for anything else. DGP analyzes luminance within the field of view to predict glare-source discomfort, but this metric was developed for side-lit office environments [Weinold & Christofferson, 2006] and cannot provide relevant data for the programmatic use of a church. The First Unitarian Church is a perfect example of architecture that suffers under current performance-based daylight metrics. Kahn’s intent was to create a place of spiritual inquiry and personal reflection. Illumination was used to draw our attention upwards, but it was never designed to accommodate horizontal task-related activities that would necessitate a DF or DA analysis. The annual illuminance variability metric shown in figures 6.17 show how brightness varies across our field of view. This metric, which is based on the perspective of an occupant, measures perceptual effects within daylit architecture and gives us more relevant information about the performance of Kahn’s church.

6.4.1 The Photographic Method

To test a photographic method of capturing images for spatial contrast analysis, a scaled physical model of Louis Kahn's church was constructed. The $\frac{1}{2}'' = 1'-0''$ model, as seen in Figure 6.23, was constructed out of $\frac{1}{4}''$ black foam core with grey fiber board lining the outer and inner walls of the sanctuary. The foam core was used on the exterior of the model to block unwanted light, while the grey fiber board was selected to represent concrete with a surface reflectance of 40%. The floor of the Kahn church is treated with a semi-gloss finish and to mimic this material quality, a gel medium was painted onto the grey fiber board at the base. The physical model was dimensioned from the scaled Rhinoceros model used in section 6.4, complete with 'concrete' columns and

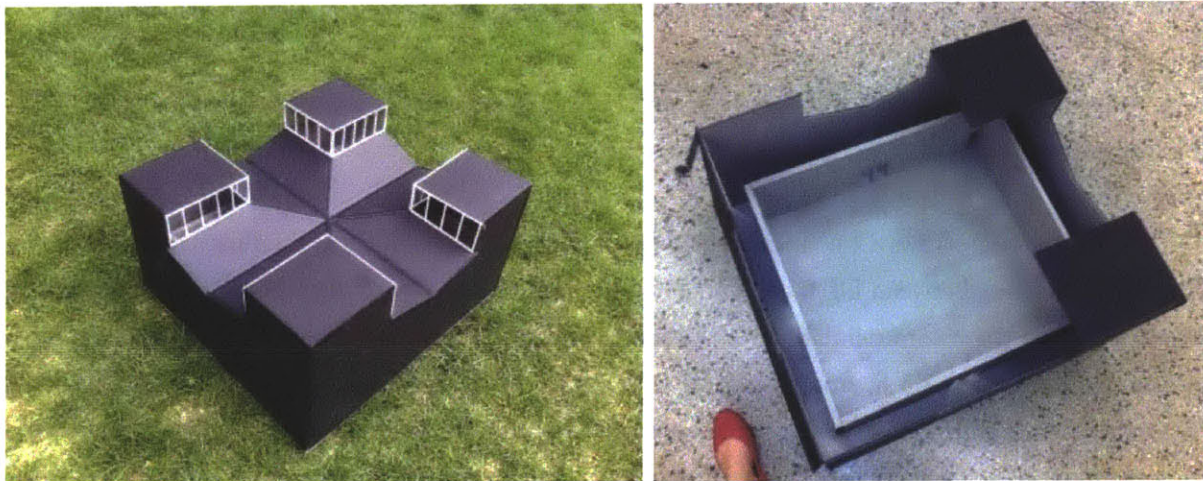


Figure 6.23: Scaled Physical Model of the First Unitarian Church ($\frac{1}{2}'' = 1'-0''$)

'wooden' stage. Figure 6.24 shows how the southeast corner of the model was modified to hold a camera, which was angled to match the renderings in the previous analysis. This was done to demonstrate the use of digital photographs and renderings as interchangeable mediums for image analysis. Both physical and digital models are capable of re-producing visual effects in architectural space and it was important to show that the methods introduced by this thesis were not entirely dependent on one method of image production.



Figure 6.24: Camera Hole Constructed in the Southeast Corner, Looking Northwest

Figure 6.25 shows two images; the photograph on the left (a) utilized a sundial to capture the interior space at 9 a.m. on April 14th, while the image on the right is a digital representation of spatial contrast, produced through Matlab. The spatial contrast for this image was 0.5 and matches that



a)

b)

Figure 6.25: a) Photograph Approximated for April 14 at 9am b) Spatial Contrast at 0.5

which was analyzed for rendering 16, seen in the lower left corner of the temporal map in Figure 6.16. Although local weather conditions did not allow for a full set of photographs to be captured from this model, the method still demonstrates the use of photographs as a legitimate input for spatial contrast analysis. To encourage the use of these metrics in the studio environment, it is necessary to provide flexible means of data input. Metrics that *require* complex digital models and time intensive computing can discourage designers from integrating daylight analysis into the culture of design and production. By showing multiple methods for image input, we can increase the adaptation of this metric to a variety of design environments.

6.5 Summary

This chapter demonstrated the successful application of annual spatial contrast and luminance variability metrics on a pair of existing architectural spaces. These spaces represent opposing ends of the contrast and variability spectrum with drastically different luminous effects. The Serpentine Pavilion produced high values in both annual spatial contrast and luminance variability, while the First Unitarian Church had moderate-to-low spatial contrast with fluctuating levels of luminance variability across the year. Each space was then analyzed for DGP, DF, and DA to compare the results of existing daylight metrics with those proposed by this thesis. The results support the need for a more objective use of existing metrics to accommodate a broader range of desired architectural effects. Annual spatial contrast and luminance variability were able to demonstrate the variability in perceptual effects over time, which contributes to a more holistic analysis of daylight in architectural space.

Chapter 7

Conclusion

7.1 Thesis Achievements

This thesis began with a critical look at existing daylight performance metrics through the lens of contemporary architecture. It established the need for new criteria that could account for the range of perceptual and temporal qualities present within designed space and position those criteria alongside existing metrics to provide a more holistic analysis. Through a survey of global contemporary architecture, a matrix of contrast-driven daylighting effects was established and a typological language emerged to describe each category. Using this typological study as context, three new metrics were intuitively identified and brought to light. These metrics, spatial contrast, annual spatial contrast, and annual luminance variability describe the complexity and temporal instability of daylit architecture over time.

In order to quantify each metric, digital images were used to read the luminance levels within a given view, providing a map of values that could be manipulated and analyzed. Although spatial contrast looks at the difference between luminance levels within a single image, annual spatial contrast and luminance variability map changes in contrast and brightness across 56 even increments throughout the year. This annual set of images allows the designer to identify the magnitude of spatial contrast and luminance variability at any given point in time as well as visualize these dynamic annual effects through spatio-temporal maps. When applied to the eleven case studies in chapter five, each metric produces a linear gradient of effects, demonstrating their ability to distinguish desired characteristics of contrast and temporal variation across the annual images.

The existing architectural spaces also produced conclusive results, showing the magnitude of annual spatial contrast and luminance variability within each view. When compared to existing daylight performance metrics such as daylight factor, daylight autonomy, and glare; these new annual, image-based metrics provide important quantitative information about the quality of space that has not, up until this thesis, been previously explored.

These new annual metrics communicate information about the temporal quality of space, giving architects a tool for comparing the magnitude of visual effects within architecture. The implications of this work are widespread, from a simple analytical tool for describing dynamic daylight conditions, to an objective approach that challenges the use of illuminance-based metrics in task and non-task oriented spaces. By establishing an intuitive gradient of possible daylight effects and producing a method for quantifying those effects over time, we are able to re-focus the discussion on environmental performance to include those perceptual qualities of light that are often disregarded in contemporary practice. This is critical to the successful integration of environmental analysis tools in the culture of the design environment as we must seek to define performance through both energy-conscious and aesthetic indicators.

7.2 Future Work

This thesis raises an important set of issues for architects and daylight designers. How do we leverage perceptual performance against those more established illuminance and glare-based metrics? To test the application of these new image-based metrics, they must be introduced into the architecture studio to determine their acceptance and/or use. From there, the metrics must be applied to a broader set of architectural spaces to determine a reasonable maximum and minimum scale for each method so that accumulative values represent something more tangible than 8×10^8 . This will allow for a more comprehensive understanding of the values represented by each metric, allowing for their widespread use.

Other areas of future work include a refinement of the quantitative methods for calculating spatial contrast. The current method takes an accumulative difference between neighboring pixels to produce a set of boundary conditions within the image. Although this accounts for a fine level of detail in luminance variation, it does not account for larger areas of contrast that are perceived on a macro scale. A look into contemporary methods of computation, including pattern recognition, may produce a multi-scale approach to quantifying spatial contrast. This research might combine work that is being done in cognitive sciences to explore new methods for characterizing the light we perceive.

Lastly, it's important to propose the integration of these metrics into daylight analysis software so that perceptual performance may be observed alongside illuminance and glare-based methods to provide a more holistic view of space. The Lightsolve project, created at MIT and currently under development at EPFL, would be ideal for the adaptation of this metric as it already generates renderings alongside goal-based illuminance data. If the rendering engine associated with Lightsolve adapted dynamic tone-mapping to produce more photo-realistic images, then the metrics could integrate quite smoothly. This would allow architects to gain useful information about illuminance, glare, contrast, and temporal variability through a single digital model.

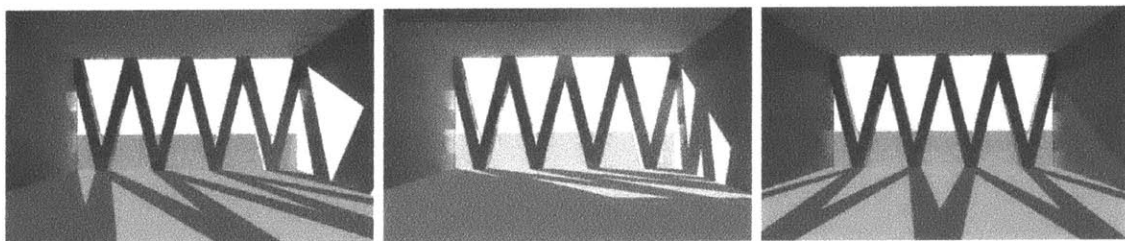
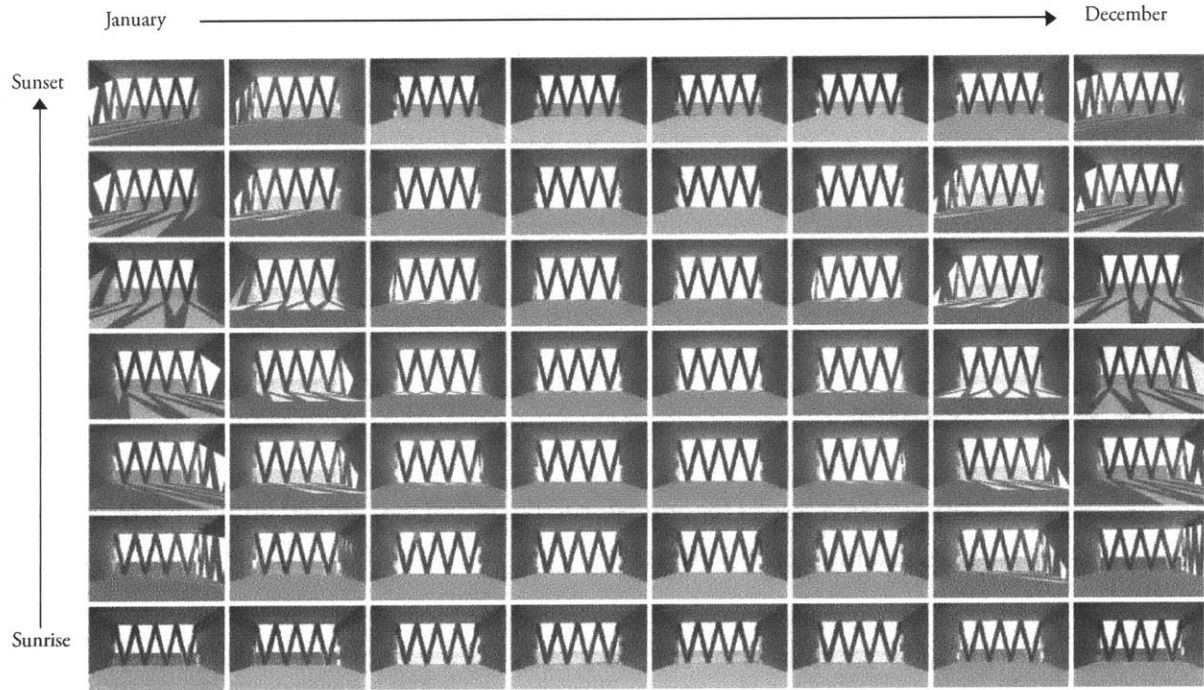
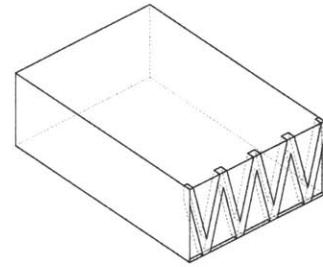
Appendix A

Case Study Results

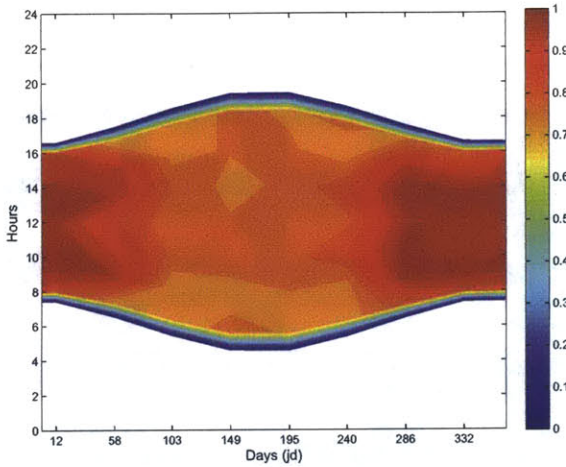
This appendix contains rendered results for annual spatial contrast and annual luminance variability for the case study spaces summarized in Chapter 5.

3

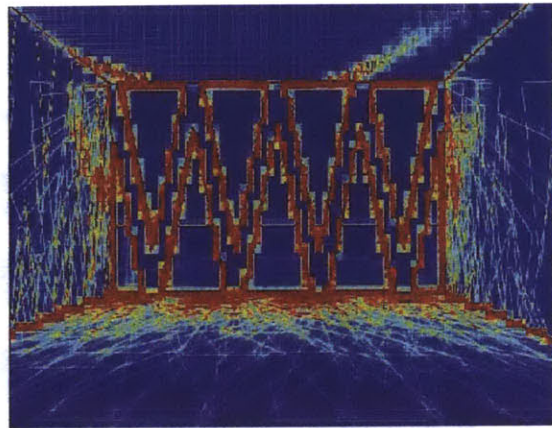
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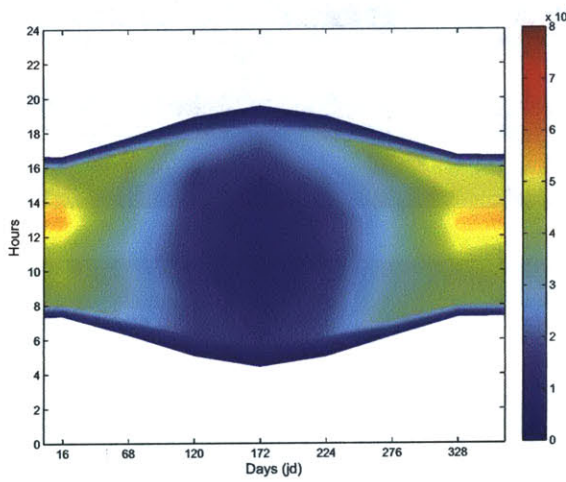
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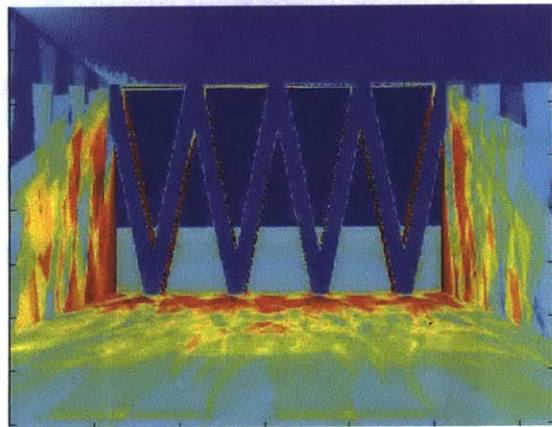
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Annual Spatial Contrast (Temporal Map & Cumulative Image)



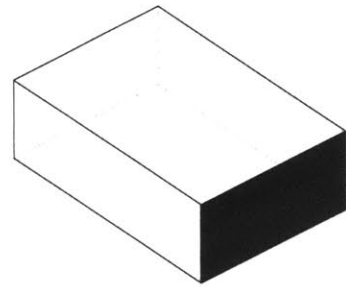
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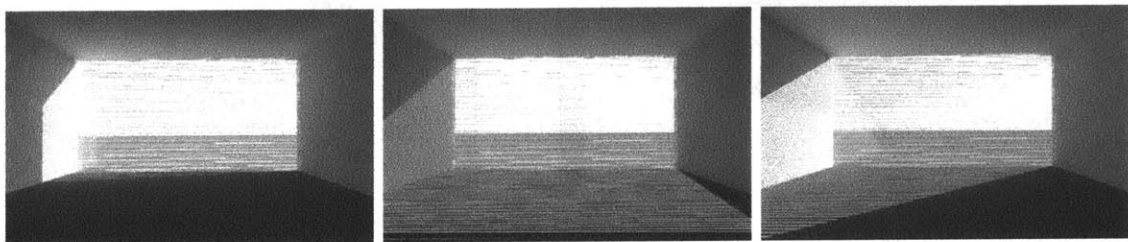
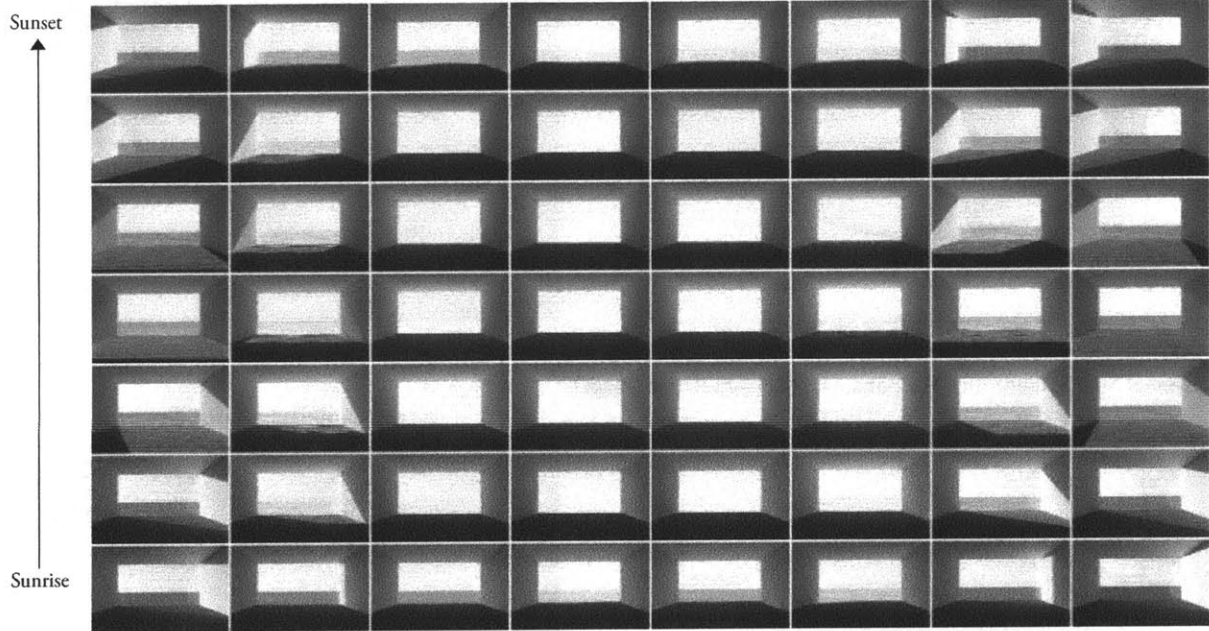
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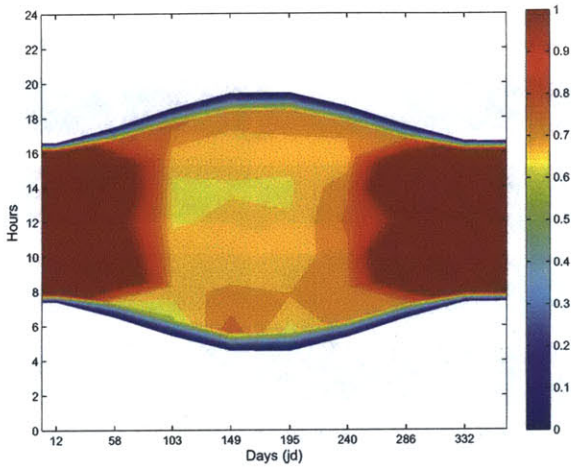
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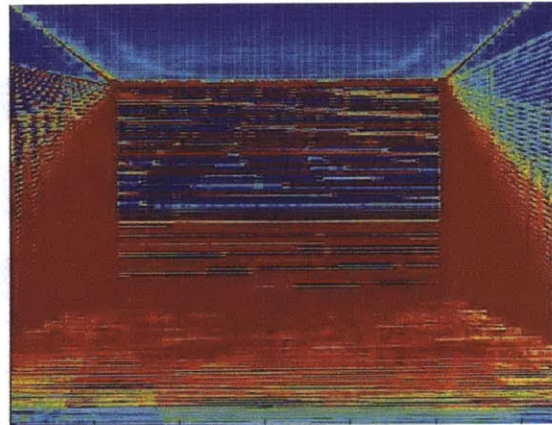
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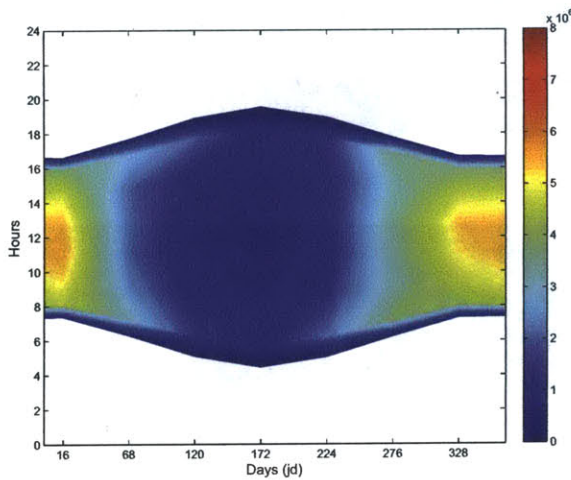
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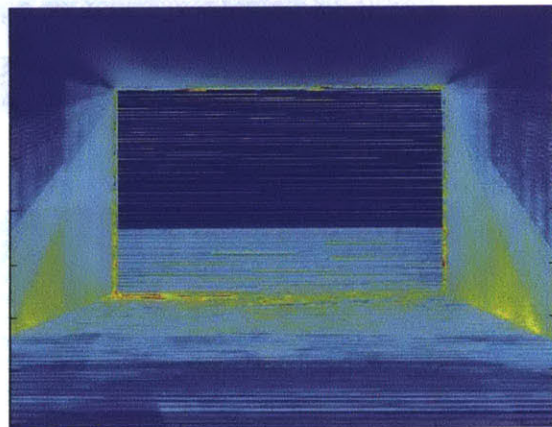
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Annual Spatial Contrast (Temporal Map & Cumulative Image)



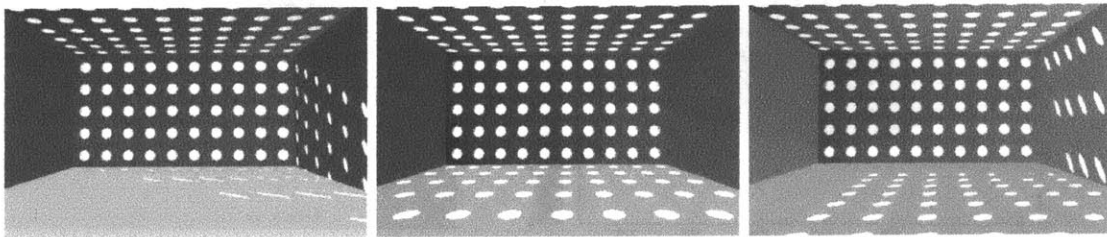
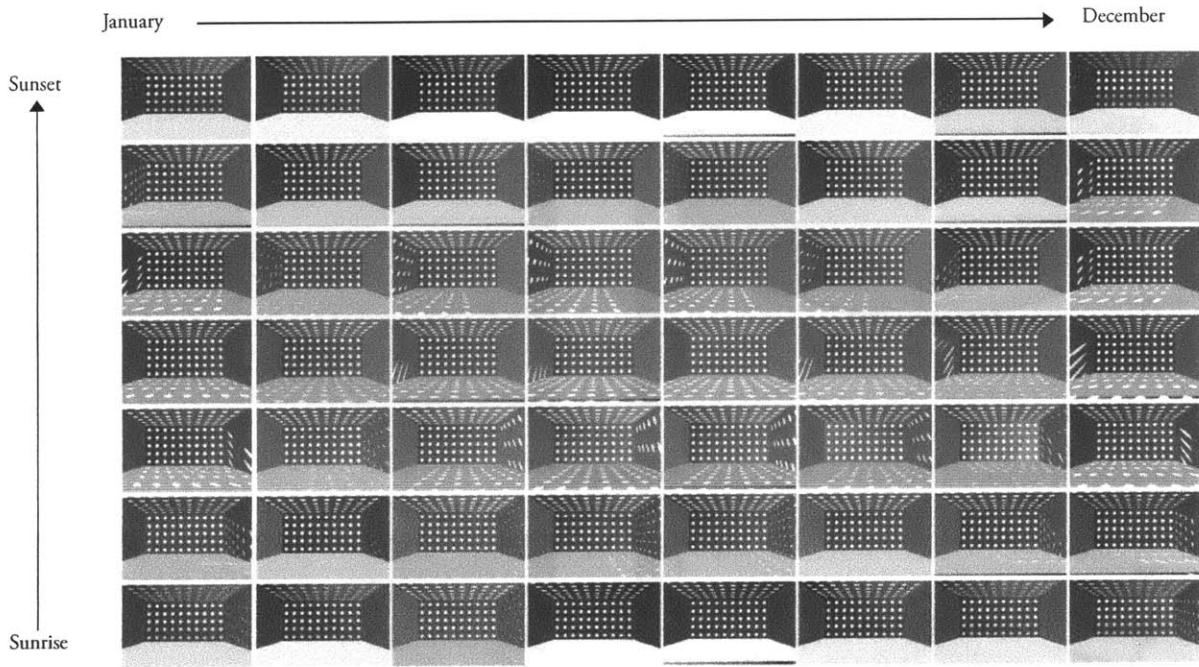
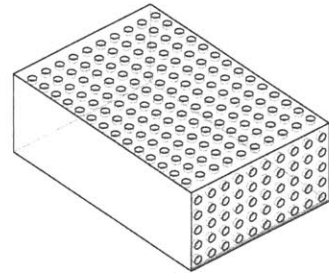
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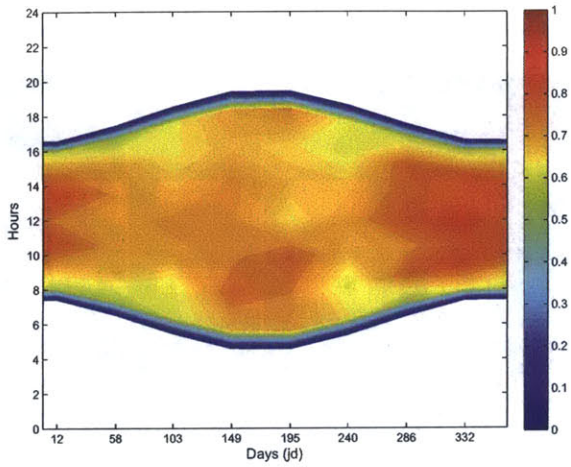
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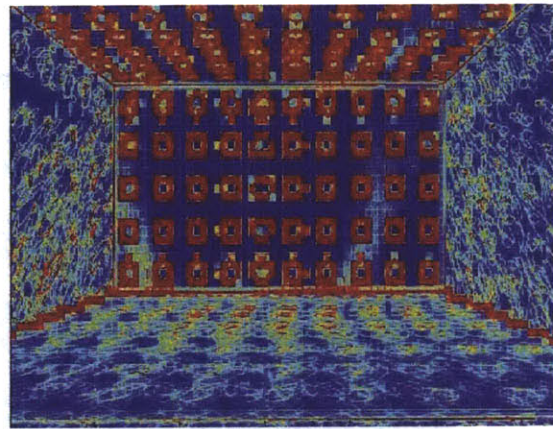
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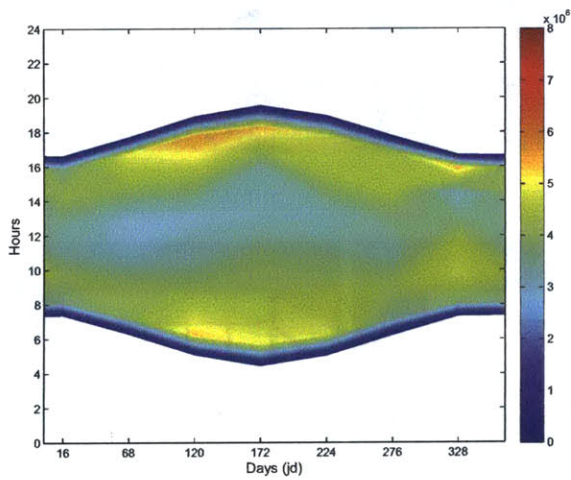
Annual Renderings



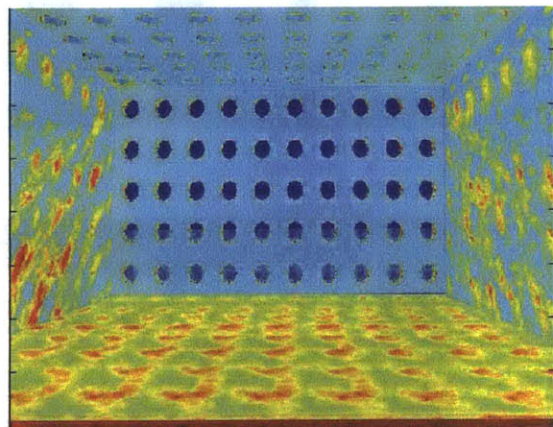
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Annual Spatial Contrast (Temporal Map & Cumulative Image)



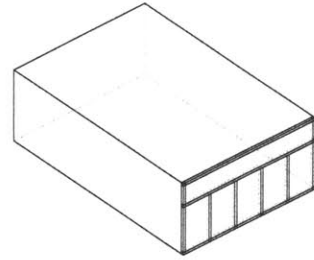
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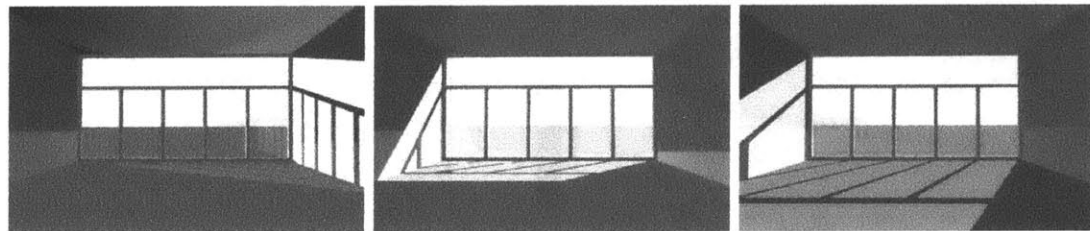
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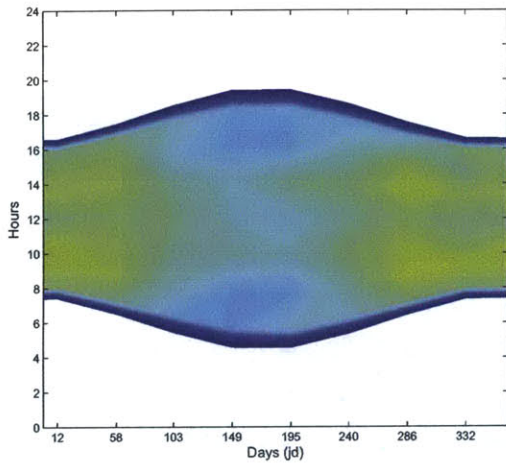
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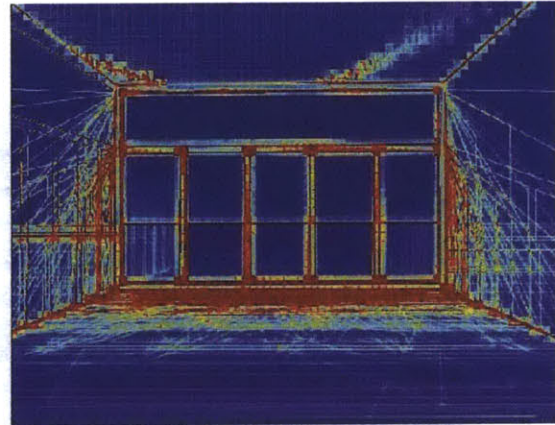
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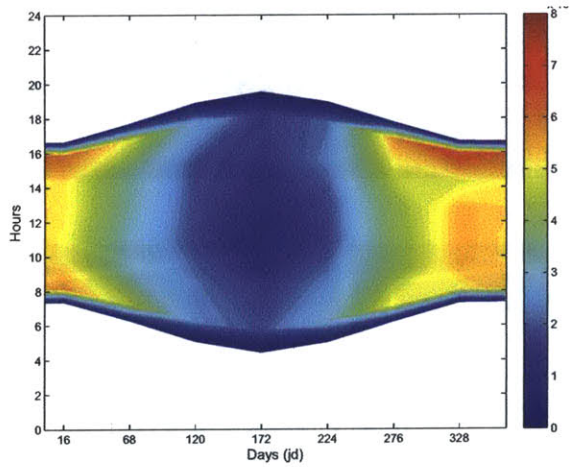
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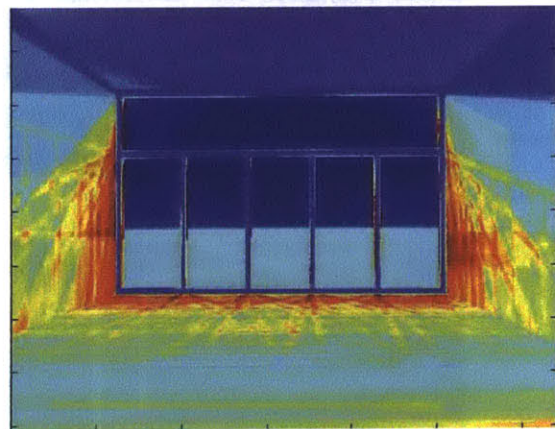
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Annual Spatial Contrast (Temporal Map & Cumulative Image)



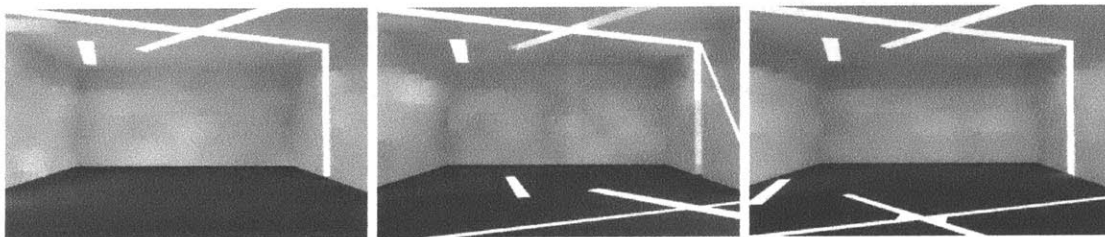
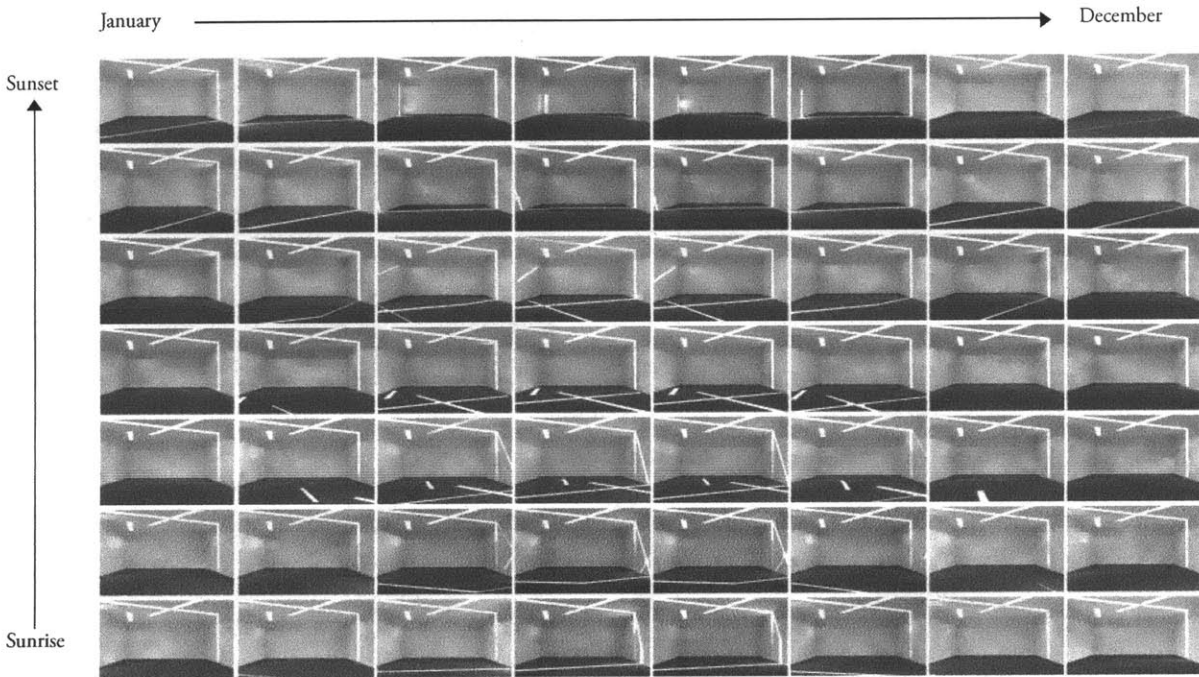
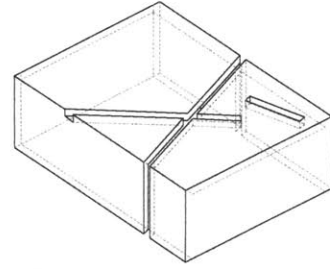
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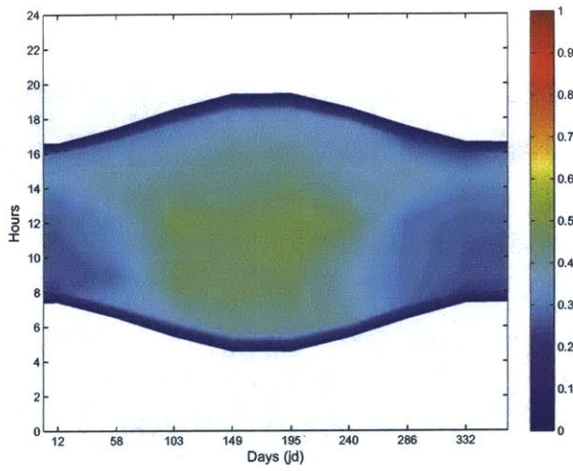
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8

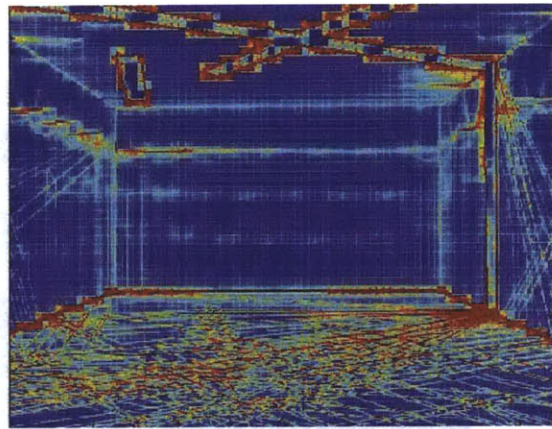
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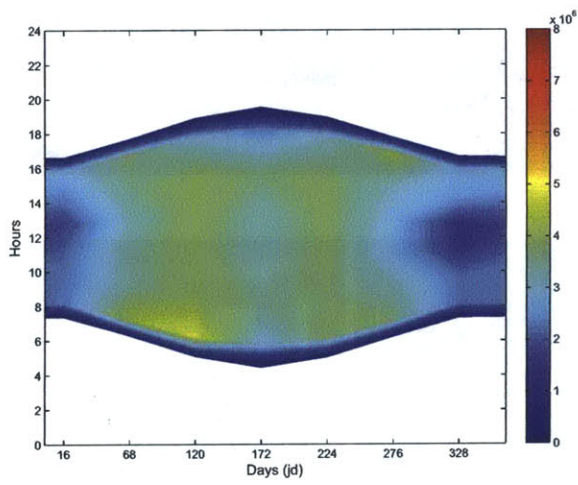
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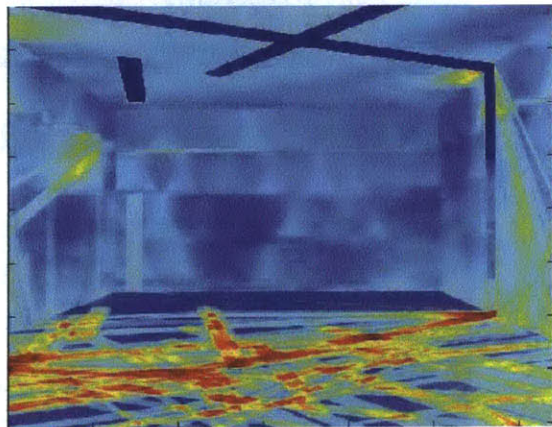
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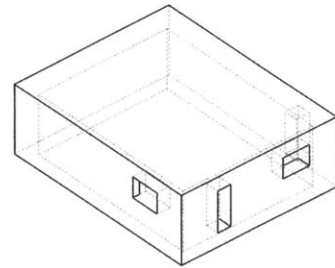
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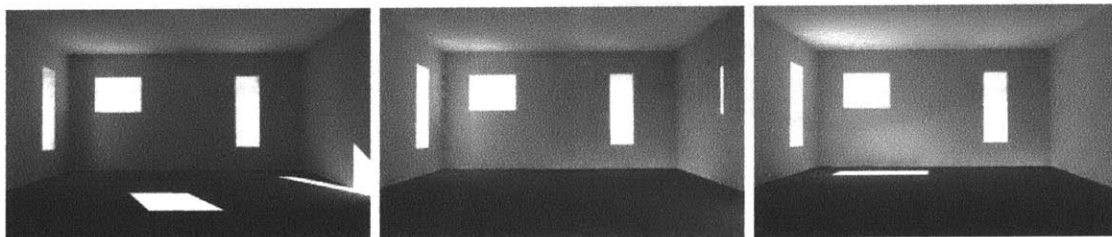
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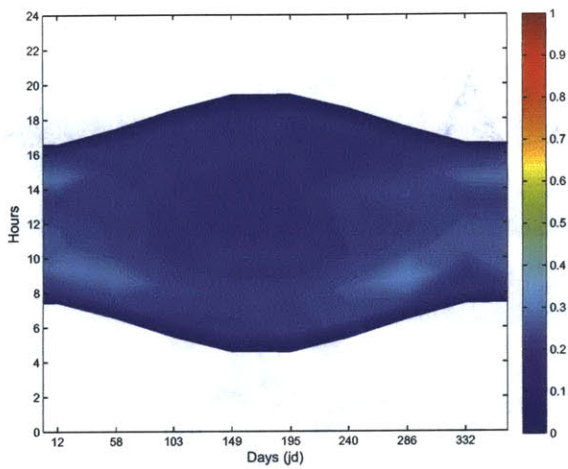
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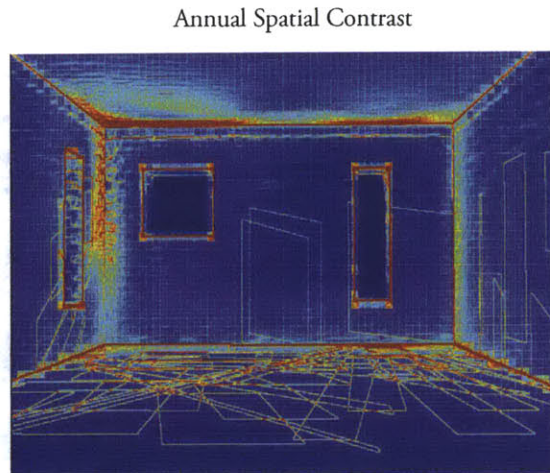
10 Partially Direct & Partially Indirect Through Walls or Roof



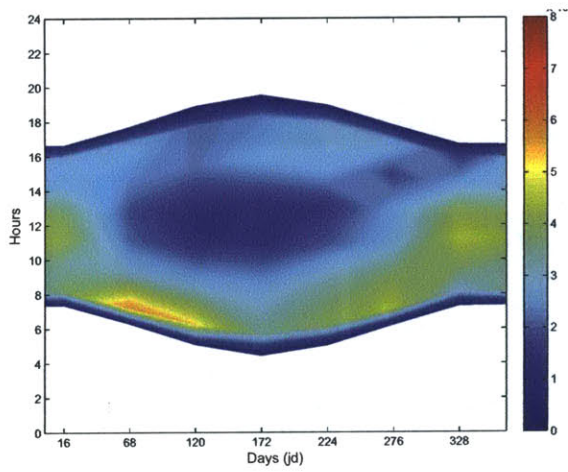
Annual Renderings



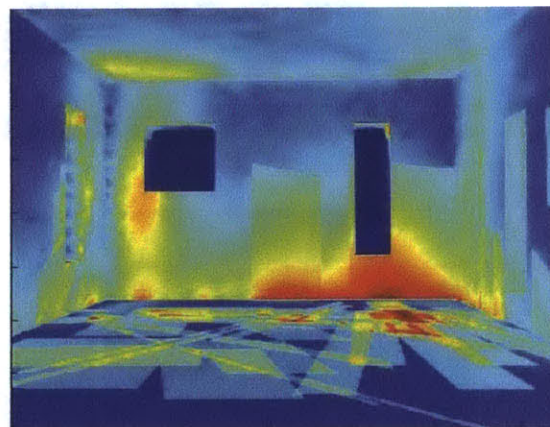
Annual Spatial Contrast (Temporal Map & Cumulative Image)



Annual Spatial Contrast



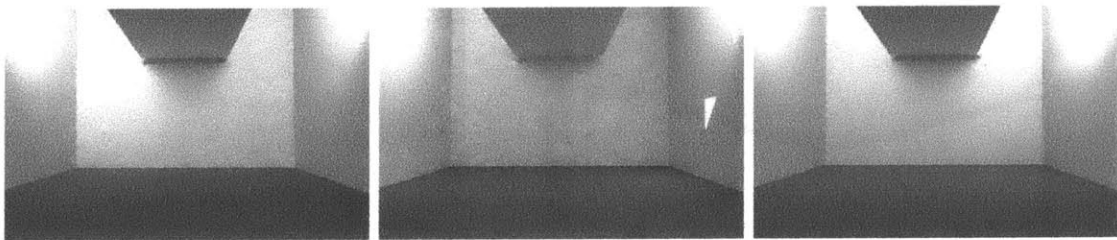
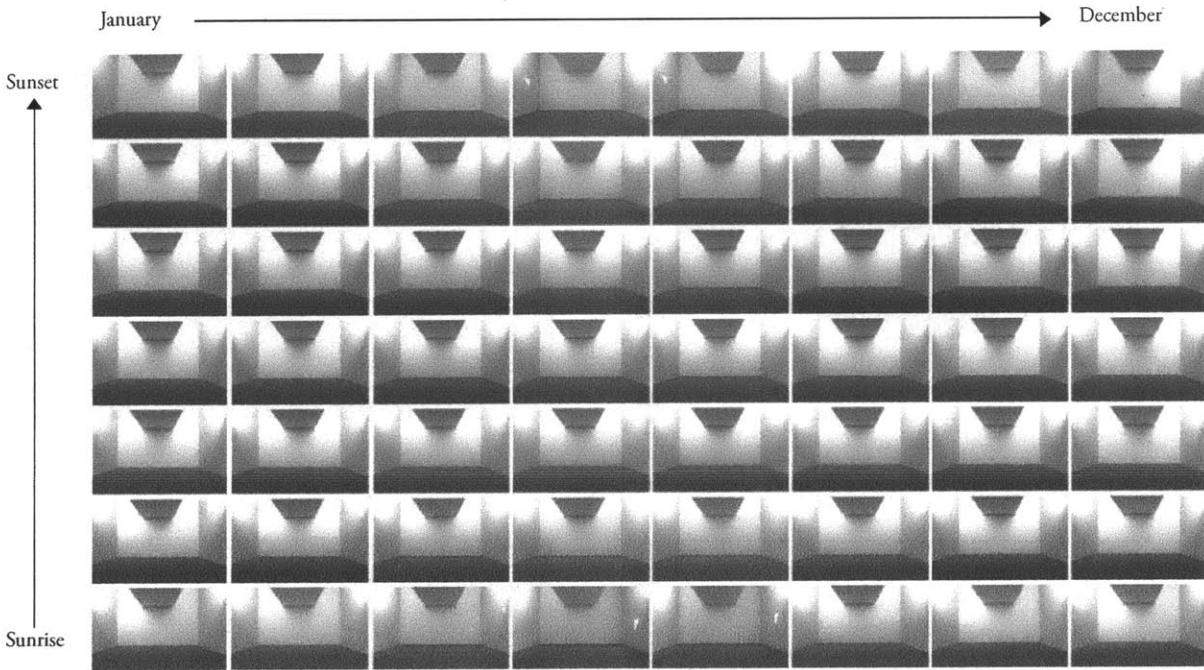
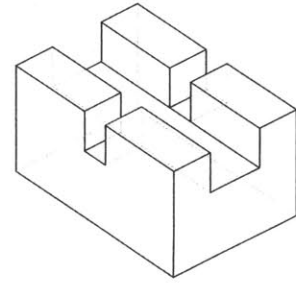
Annual Luminance Variability (Temporal Map & Cumulative Image)



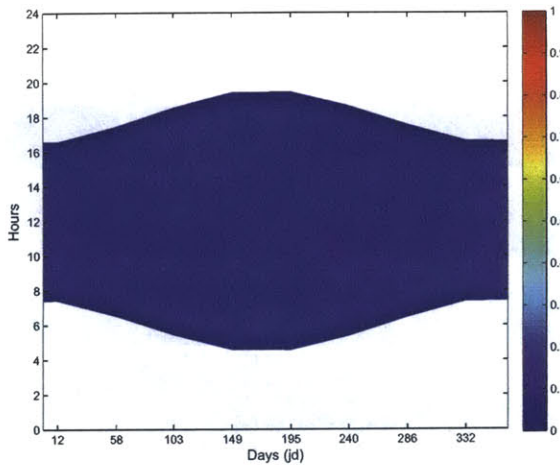
Annual Luminance Variability

11

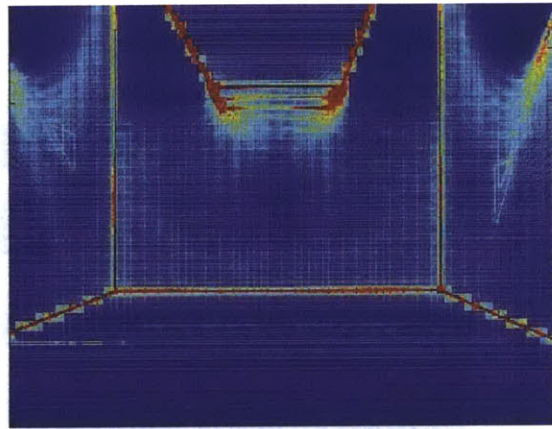
Spatial Indirect Through Walls or Roof



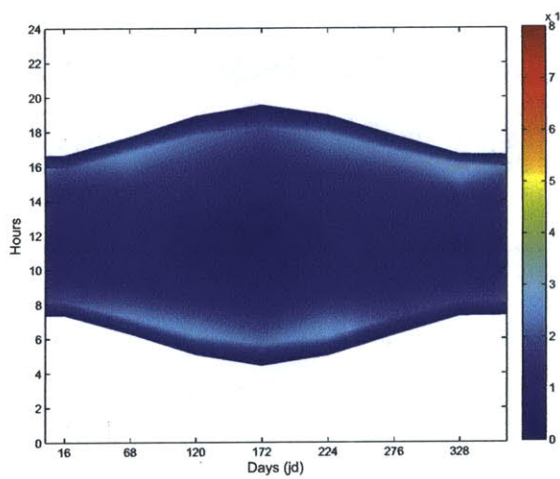
Annual Renderings



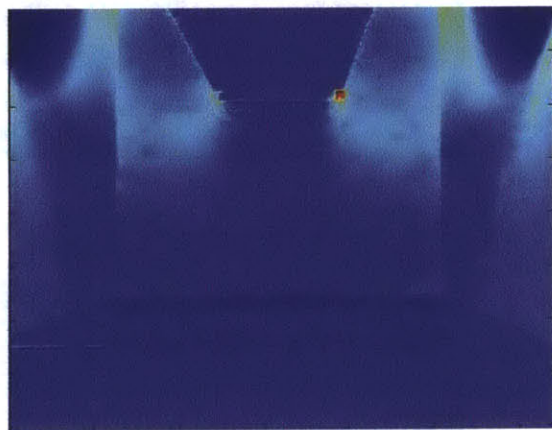
Annual Spatial Contrast



Annual Spatial Contrast (Temporal Map & Cumulative Image)



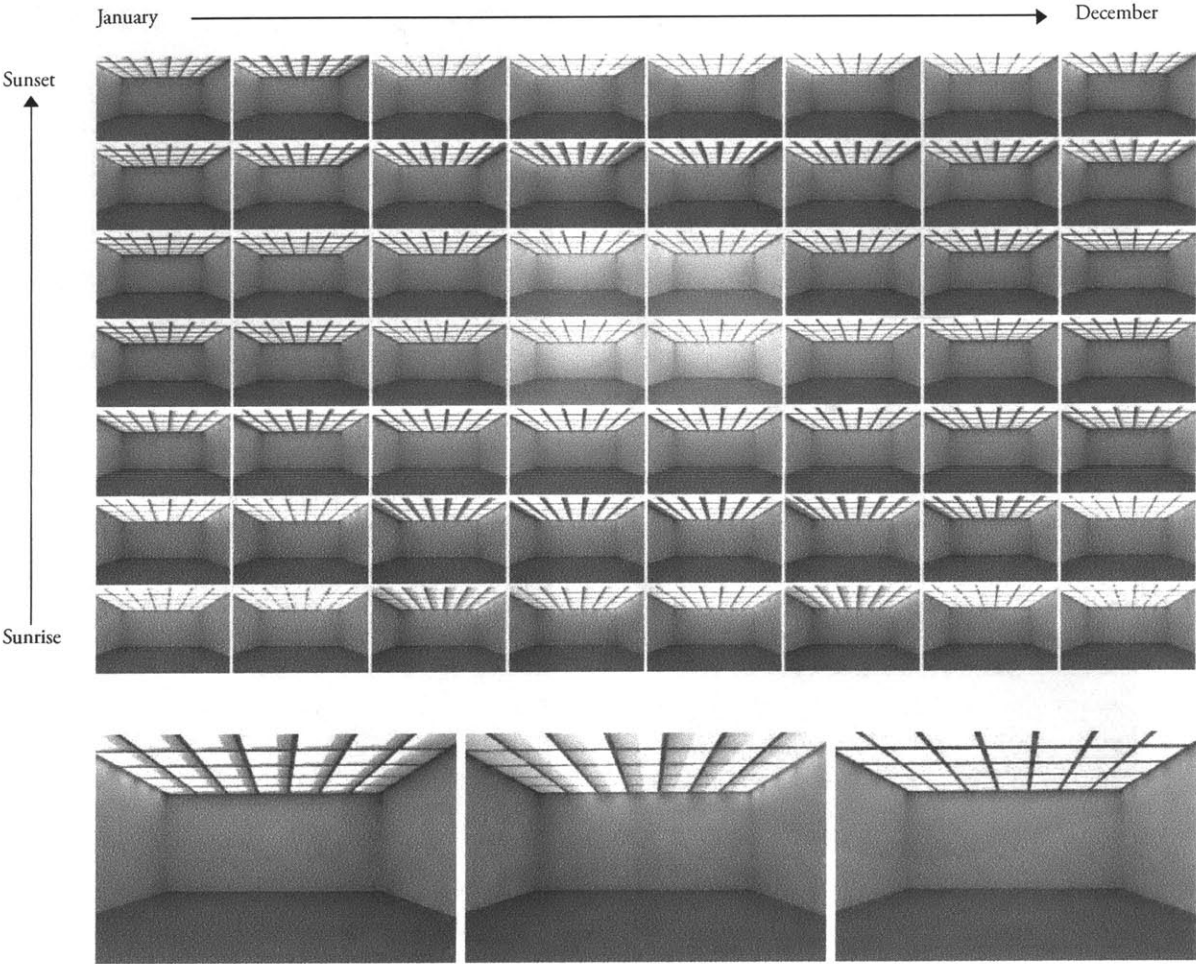
Annual Luminance Variability



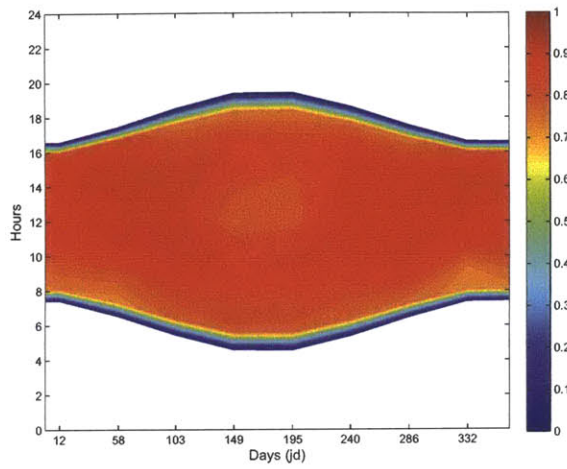
Annual Luminance Variability (Temporal Map & Cumulative Image)

Source of Error

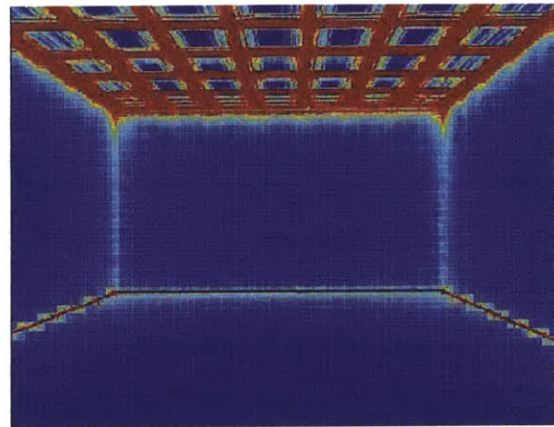
15 Indirect & Diffuse Through Walls or Roof



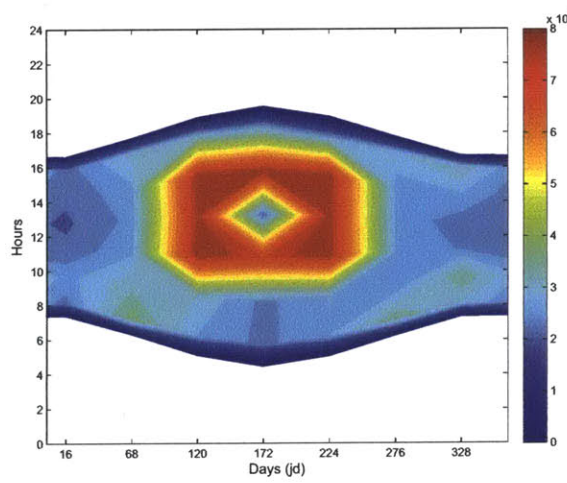
Annual Renderings



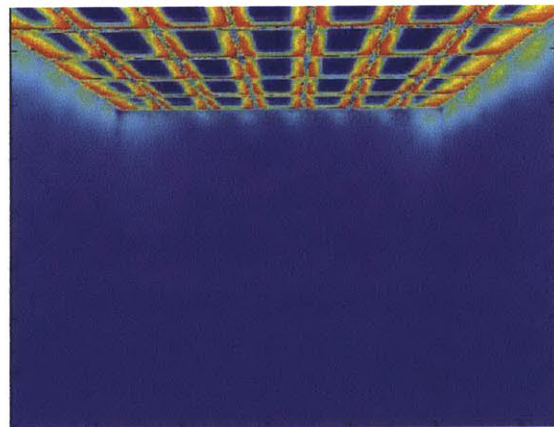
Annual Spatial Contrast



Annual Spatial Contrast (Temporal Map & Cumulative Image)



Annual Luminance Variability



Annual Luminance Variability (Temporal Map & Cumulative Image)

Appendix B

Radiance & Matlab Code

This appendix contains full and partial scripts that were used to automate various parts of this thesis.

Batch Script for Radiance

```
fileprefix = filename  
lat = 42  
long = 72  
timezone = gmt -5
```

```
RAYPATH=$RAYPATH:/cygdrive/c/Radiance/bin:/cygdrive/c/Radiance/lib
```

```
mkdir 1\ 13\ 7\ 52  
cd 1\ 13\ 7\ 52  
cp ../${fileprefix}.rad .  
cp ../${fileprefix}material.rad .  
  
echo '# Sky Definition' >>${fileprefix}_sky.rad  
echo !gensky 1 13 7 +s -a $lat -o $long -m $timezone >>${fileprefix}_sky.rad  
  
echo skyfunc glow sky_mat >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 4 >>${fileprefix}_sky.rad  
echo 1 1 1 0 >>${fileprefix}_sky.rad  
echo sky_mat source sky >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 4 >>${fileprefix}_sky.rad  
echo 0 0 1 180 >>${fileprefix}_sky.rad  
echo skyfunc glow ground_glow >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 4 >>${fileprefix}_sky.rad  
echo 1 .8 .5 0 >>${fileprefix}_sky.rad  
echo ground_glow source ground >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 0 >>${fileprefix}_sky.rad  
echo 4 >>${fileprefix}_sky.rad  
echo 0 0 -1 180 >>${fileprefix}_sky.rad  
  
oconv ${fileprefix}material.rad ${fileprefix}_sky.rad ${fileprefix}.rad > ${fileprefix}.oct  
  
rpict -t 15 -vrv -vp 9.307 29.066 3.278 -vd 0.2099999999999999 -13.353 0.28 -vu 0 0 1 -vh 32 -vv 26 -vs 0  
-vl 0 -af 1_01.amb -x 1280 -y 960 -dp 2048 -ar 186 -ms 0.57 -ds .2 -dt .05 -dc .75 -dr 3 -sj 1 -st .01 -ab 8  
-aa .075 -ad 2048 -as 1024 -av 0.01 0.01 0.01 -lr 12 -lw .0005 -ps 2 -pt .08 -vv 40 -vh 60 ${fileprefix}.oct >  
${fileprefix}_1_13_7_52.unf  
pfilt -r .6 -x /2 -y /2 ${fileprefix}_1_13_7_52.unf > ${fileprefix}_1_13_7_52.pic  
ra_tiff ${fileprefix}_1_13_7_52.pic ${fileprefix}_1_13_7_52.jpg  
  
rm ${fileprefix}_1_13_7_52.unf  
rm ${fileprefix}.rad  
rm ${fileprefix}material.rad  
cd ..
```

Figure B.1: Cygwin Shell Script for Batch Radiance Renderings (Adapted From a Script Written by Alstan Jakubiec, Harvard GSD)

Annual Spatial Contrast Metric

Developed by Siobhan Rockcastle (contributions by Shreya Dave)

November 4, 2010

```
cd('folder_path');
FS = dir('*.jpg');

for qd = 1:length(FS)
    str = strcat(int2str(qd), '.jpg');
    eval('Z=imread(str);');

A1 = rgb2gray(Z);
A = double(A1) + 1

    % Compute the row difference matrix
for i = 2:size(A,1)
    B(i-1,:)=abs(A(i,:)-A(i-1,:));
end

    % Compute the column difference matrix
for j = 2:size(A,2)
    C(:,j-1)=abs(A(:,j)-A(:,j-1));
end

    % Combine the two matrices into average matrices
for k=1:size(B,1)
    for l=1:size(B,2)-1
        D1(k,l)=sum(B(k,[l l+1]))/2;
    end
end

for m=1:size(C,2)
    for n=1:size(C,1)-1
        D2(n,m)=sum(C([n n+1], m))/2;
    end
end

for o=1:size(D1,1)
    for p=1:size(D1,2)
        D(o,p)=(D1(o,p)+D2(o,p))/2;
    end
end

D=round(D);

    % Sum the matrices
ContrastSum=sum(sum(B))+sum(sum(C));

%imtool(A, [0 255])
%imtool(D, [0 100])

    % Make reference matrix to create a ratio
```

```

for p = size(A,1)
    for q = size(A,2)
        T=repmat(kron(eye(2),255*ones(1)),p/2,q/2);
    end
end

for r = 2:size(T,1)
    F(r-1,:)=abs(T(r,:)-T(r-1,:));
end

    %Compute the colum difference matrix for maxSum

for s = 2:size(T,2)
    G(s-1,:)=abs(T(:,s)-T(:,s-1));
end

MaxSum=sum(sum(F))+sum(sum(G));

    % Take a ratio of ContrastSum over maxSum

ContrastRatio(qd)=100*(ContrastSum/MaxSum);

eval(['D' num2str(qd) '= D;']);

end

ContrastImage = (D1+D2+D3+D4+D5+D6+D7+D8+D9+D10+D11+D12+D13+D14+D15+D16+D17+D18+D19);
+(D20+D21+D22+D23+D24+D25+D26+D27+D28+D29+D30+D31+D32+D33+D34+D35+D36+D37+D38+D39);
+(D40+D41+D42+D43+D44+D45+D46+D47+D48+D49+D50+D51+D52+D53+D54+D55+D56);

imagesc(ContrastImage, [0 200]);figure(gcf);

    % Reorder the matrix for excel sheet

X = ContrastRatio;
reorder = [X(1,1) X(1,2) X(1,3) X(1,4) X(1,5) X(1,6) X(1,7);
    X(1,8) X(1,9) X(1,10) X(1,11) X(1,12) X(1,13) X(1,14);
    X(1,15) X(1,16) X(1,17) X(1,18) X(1,19) X(1,20) X(1,21);
    X(1,22) X(1,23) X(1,24) X(1,25) X(1,26) X(1,27) X(1,28);
    X(1,29) X(1,30) X(1,31) X(1,32) X(1,33) X(1,34) X(1,35);
    X(1,36) X(1,37) X(1,38) X(1,39) X(1,40) X(1,41) X(1,42);
    X(1,43) X(1,44) X(1,45) X(1,46) X(1,47) X(1,48) X(1,49);
    X(1,50) X(1,51) X(1,52) X(1,53) X(1,54) X(1,55) X(1,56);]

TotalAnnual = sum(sum(reorder))

    %Write the contrast ratio to an excel sheet
xlswrite('yourfileherecontrast.xls',reorder,'titleworksheet');

```

Figure B.2: Matlab Script for Calcularing Annual Spatial Contrast (written by Siobhan Rockcastle & Shreya Dave)

Annual Luminance Variability

Developed by Siobhan Rockcastle

February 11, 2011

```
cd('folder_path');
```

```
% convert each jpeg into a two-dimensional grayscale matrix
```

```
A1 = imread ('1.jpg');  
Z1 = rgb2gray(A1);  
B1 = double(Z1) + 1;
```

```
A2 = imread ('2.jpg');  
Z2 = rgb2gray(A2);  
B2 = double(Z2) + 1;
```

```
A3 = imread ('3.jpg');  
Z3 = rgb2gray(A3);  
B3 = double(Z3) + 1;
```

```
A4 = imread ('4.jpg');  
Z4 = rgb2gray(A4);  
B4 = double(Z4) + 1;
```

```
A5 = imread ('5.jpg');  
Z5 = rgb2gray(A5);  
B5 = double(Z5) + 1;
```

```
A6 = imread ('6.jpg');  
Z6 = rgb2gray(A6);  
B6 = double(Z6) + 1;
```

```
A7 = imread ('7.jpg');  
Z7 = rgb2gray(A7);  
B7 = double(Z7) + 1;
```

```
A8 = imread ('8.jpg');  
Z8 = rgb2gray(A8);  
B8 = double(Z8) + 1;
```

```
A9 = imread ('9.jpg');  
Z9 = rgb2gray(A9);  
B9 = double(Z9) + 1;
```

```
A10 = imread ('10.jpg');  
Z10 = rgb2gray(A10);  
B10 = double(Z10) + 1;
```

```
A11 = imread ('11.jpg');  
Z11 = rgb2gray(A11);  
B11 = double(Z11) + 1;
```

```
A12 = imread ('12.jpg');  
Z12 = rgb2gray(A12);  
B12 = double(Z12) + 1;
```

```
A13 = imread ('13.jpg');  
Z13 = rgb2gray(A13);  
B13 = double(Z13) + 1;
```

```
A14 = imread ('14.jpg');  
Z14 = rgb2gray(A14);  
B14 = double(Z14) + 1;
```

```
A15 = imread ('15.jpg');  
Z15 = rgb2gray(A15);  
B15 = double(Z15) + 1;
```

```
A16 = imread ('16.jpg');  
Z16 = rgb2gray(A16);  
B16 = double(Z16) + 1;
```

```
A17 = imread ('17.jpg');  
Z17 = rgb2gray(A17);  
B17 = double(Z17) + 1;
```

```
A18 = imread ('18.jpg');  
Z18 = rgb2gray(A18);  
B18 = double(Z18) + 1;
```

```
A19 = imread ('19.jpg');  
Z19 = rgb2gray(A19);  
B19 = double(Z19) + 1;
```

```
A20 = imread ('20.jpg');  
Z20 = rgb2gray(A20);  
B20 = double(Z20) + 1;
```

```
A21 = imread ('21.jpg');  
Z21 = rgb2gray(A21);  
B21 = double(Z21) + 1;
```

```
A22 = imread ('22.jpg');  
Z22 = rgb2gray(A22);  
B22 = double(Z22) + 1;
```

```
A23 = imread ('23.jpg');  
Z23 = rgb2gray(A23);  
B23 = double(Z23) + 1;
```

```
A24 = imread ('24.jpg');  
Z24 = rgb2gray(A24);  
B24 = double(Z24) + 1;
```

```
A25 = imread ('25.jpg');  
Z25 = rgb2gray(A25);  
B25 = double(Z25) + 1;
```

```
A26 = imread ('26.jpg');  
Z26 = rgb2gray(A26);  
B26 = double(Z26) + 1;
```

```
A27 = imread ('27.jpg');  
Z27 = rgb2gray(A27);  
B27 = double(Z27) + 1;
```

```
A28 = imread ('28.jpg');  
Z28 = rgb2gray(A28);  
B28 = double(Z28) + 1;
```

```
A29 = imread ('29.jpg');  
Z29 = rgb2gray(A29);  
B29 = double(Z29) + 1;
```

```
A30 = imread ('30.jpg');  
Z30 = rgb2gray(A30);  
B30 = double(Z30) + 1;
```

```
A31 = imread ('31.jpg');  
Z31 = rgb2gray(A31);  
B31 = double(Z31) + 1;
```

```
A32 = imread ('32.jpg');  
Z32 = rgb2gray(A32);  
B32 = double(Z32) + 1;
```

```
A33 = imread ('33.jpg');  
Z33 = rgb2gray(A33);  
B33 = double(Z33) + 1;
```

```
A34 = imread ('34.jpg');  
Z34 = rgb2gray(A34);  
B34 = double(Z34) + 1;
```

```
A35 = imread ('35.jpg');  
Z35 = rgb2gray(A35);  
B35 = double(Z35) + 1;
```

```
A36 = imread ('36.jpg');  
Z36 = rgb2gray(A36);  
B36 = double(Z36) + 1;
```

```
A37 = imread ('37.jpg');  
Z37 = rgb2gray(A37);  
B37 = double(Z37) + 1;
```

```
A38 = imread ('38.jpg');  
Z38 = rgb2gray(A38);  
B38 = double(Z38) + 1;
```

```
A39 = imread ('39.jpg');  
Z39 = rgb2gray(A39);  
B39 = double(Z39) + 1;
```

```
A40 = imread ('40.jpg');  
Z40 = rgb2gray(A40);  
B40 = double(Z40) + 1;
```

```
A41 = imread ('41.jpg');  
Z41 = rgb2gray(A41);  
B41 = double(Z41) + 1;
```

```
A42 = imread ('42.jpg');  
Z42 = rgb2gray(A42);  
B42 = double(Z42) + 1;
```

```
A43 = imread ('43.jpg');  
Z43 = rgb2gray(A43);  
B43 = double(Z43) + 1;
```

```
A44 = imread ('44.jpg');
Z44 = rgb2gray(A44);
B44 = double(Z44) + 1;
```

```
A45 = imread ('45.jpg');
Z45 = rgb2gray(A45);
B45 = double(Z45) + 1;
```

```
A46 = imread ('46.jpg');
Z46 = rgb2gray(A46);
B46 = double(Z46) + 1;
```

```
A47 = imread ('47.jpg');
Z47 = rgb2gray(A47);
B47 = double(Z47) + 1;
```

```
A48 = imread ('48.jpg');
Z48 = rgb2gray(A48);
B48 = double(Z48) + 1;
```

```
A49 = imread ('49.jpg');
Z49 = rgb2gray(A49);
B49 = double(Z49) + 1;
```

```
A50 = imread ('50.jpg');
Z50 = rgb2gray(A50);
B50 = double(Z50) + 1;
```

```
A51 = imread ('51.jpg');
Z51 = rgb2gray(A51);
B51 = double(Z51) + 1;
```

```
A52 = imread ('52.jpg');
Z52 = rgb2gray(A52);
B52 = double(Z52) + 1;
```

```
A53 = imread ('53.jpg');
Z53 = rgb2gray(A53);
B53 = double(Z53) + 1;
```

```
A54 = imread ('54.jpg');
Z54 = rgb2gray(A54);
B54 = double(Z54) + 1;
```

```
A55 = imread ('55.jpg');
Z55 = rgb2gray(A55);
B55 = double(Z55) + 1;
```

```
A56 = imread ('56.jpg');
Z56 = rgb2gray(A56);
B56 = double(Z56) + 1;
```

```
%find the absolute differences between matrices (c=times, r=days)
```

```
c1 = sum(sum(abs(B2 - B1)));
c2 = sum(sum(abs(B3 - B2)));
c3 = sum(sum(abs(B4 - B3)));
c4 = sum(sum(abs(B5 - B4)));
c5 = sum(sum(abs(B6 - B5)));
```

```

c6 = sum(sum(abs(B7 - B6)));

c8 = sum(sum(abs(B9 - B8)));
c9 = sum(sum(abs(B10 - B9)));
c10 = sum(sum(abs(B11 - B10)));
c11 = sum(sum(abs(B12 - B11)));
c12 = sum(sum(abs(B13 - B12)));
c13 = sum(sum(abs(B14 - B13)));

c15 = sum(sum(abs(B16 - B15)));
c16 = sum(sum(abs(B17 - B16)));
c17 = sum(sum(abs(B18 - B17)));
c18 = sum(sum(abs(B19 - B18)));
c19 = sum(sum(abs(B20 - B19)));
c20 = sum(sum(abs(B21 - B20)));

c22 = sum(sum(abs(B23 - B22)));
c23 = sum(sum(abs(B24 - B23)));
c24 = sum(sum(abs(B25 - B24)));
c25 = sum(sum(abs(B26 - B25)));
c26 = sum(sum(abs(B27 - B26)));
c27 = sum(sum(abs(B28 - B27)));

c29 = sum(sum(abs(B30 - B29)));
c30 = sum(sum(abs(B31 - B30)));
c31 = sum(sum(abs(B32 - B31)));
c32 = sum(sum(abs(B33 - B32)));
c33 = sum(sum(abs(B34 - B33)));
c34 = sum(sum(abs(B35 - B34)));

c36 = sum(sum(abs(B37 - B36)));
c37 = sum(sum(abs(B38 - B37)));
c38 = sum(sum(abs(B39 - B38)));
c39 = sum(sum(abs(B40 - B39)));
c40 = sum(sum(abs(B41 - B40)));
c41 = sum(sum(abs(B42 - B41)));

c43 = sum(sum(abs(B44 - B43)));
c44 = sum(sum(abs(B45 - B44)));
c45 = sum(sum(abs(B46 - B45)));
c46 = sum(sum(abs(B47 - B46)));
c47 = sum(sum(abs(B48 - B47)));
c48 = sum(sum(abs(B49 - B48)));
c49 = sum(sum(abs(B43 - B49)));

c50 = sum(sum(abs(B51 - B50)));
c51 = sum(sum(abs(B52 - B51)));
c52 = sum(sum(abs(B53 - B52)));
c53 = sum(sum(abs(B54 - B53)));
c54 = sum(sum(abs(B55 - B54)));
c55 = sum(sum(abs(B56 - B55)));

r1 = sum(sum(abs(B8 - B1)));
r2 = sum(sum(abs(B15 - B8)));
r3 = sum(sum(abs(B22 - B15)));
r4 = sum(sum(abs(B29 - B22)));
r5 = sum(sum(abs(B36 - B29)));
r6 = sum(sum(abs(B43 - B36)));
r7 = sum(sum(abs(B50 - B43)));

```

```

r9 = sum(sum(abs(B9 - B2)));
r10 = sum(sum(abs(B16 - B9)));
r11 = sum(sum(abs(B23 - B16)));
r12 = sum(sum(abs(B30 - B23)));
r13 = sum(sum(abs(B37 - B30)));
r14 = sum(sum(abs(B44 - B37)));
r15 = sum(sum(abs(B51 - B44)));

r17 = sum(sum(abs(B10 - B3)));
r18 = sum(sum(abs(B17 - B10)));
r19 = sum(sum(abs(B24 - B17)));
r20 = sum(sum(abs(B31 - B24)));
r21 = sum(sum(abs(B38 - B31)));
r22 = sum(sum(abs(B45 - B38)));
r23 = sum(sum(abs(B52 - B45)));

r25 = sum(sum(abs(B11 - B4)));
r26 = sum(sum(abs(B18 - B11)));
r27 = sum(sum(abs(B25 - B18)));
r28 = sum(sum(abs(B32 - B25)));
r29 = sum(sum(abs(B39 - B32)));
r30 = sum(sum(abs(B46 - B39)));
r31 = sum(sum(abs(B53 - B46)));

r33 = sum(sum(abs(B12 - B5)));
r34 = sum(sum(abs(B19 - B12)));
r35 = sum(sum(abs(B26 - B19)));
r36 = sum(sum(abs(B33 - B26)));
r37 = sum(sum(abs(B40 - B33)));
r38 = sum(sum(abs(B47 - B40)));
r39 = sum(sum(abs(B54 - B47)));
r40 = sum(sum(abs(B5 - B54)));

r41 = sum(sum(abs(B13 - B6)));
r42 = sum(sum(abs(B20 - B13)));
r43 = sum(sum(abs(B27 - B20)));
r44 = sum(sum(abs(B34 - B27)));
r45 = sum(sum(abs(B41 - B34)));
r46 = sum(sum(abs(B48 - B41)));
r47 = sum(sum(abs(B55 - B48)));

r49 = sum(sum(abs(B14 - B7)));
r50 = sum(sum(abs(B21 - B14)));
r51 = sum(sum(abs(B28 - B21)));
r52 = sum(sum(abs(B35 - B28)));
r53 = sum(sum(abs(B42 - B35)));
r54 = sum(sum(abs(B49 - B42)));
r55 = sum(sum(abs(B56 - B49)));

Time = [c1 c2 c3 c4 c5 c6; c8 c9 c10 c11 c12 c13; c15 c16 c17 c18 c19 c20; c22 c23 c24 c25 c26 c27; c29 c30 c31 c32 c33 c34;
c36 c37 c38 c39 c40 c41; c43 c44 c45 c46 c47 c48; c50 c51 c52 c53 c54 c55];

Seasons = [r1 r9 r17 r25 r33 r41 r49; r2 r10 r18 r26 r34 r42 r50; r3 r11 r19 r27 r35 r43 r51; r4 r12 r20 r28 r36 r44 r52;
r5 r13 r21 r29 r37 r45 r53; r6 r14 r22 r30 r38 r46 r54; r7 r15 r23 r31 r39 r47 r55];

% Combine the two matrices into average matrices

for k=1:size(Seasons,1)
    for l=1:size(Seasons,2)-1
        D1(k,l)=sum(Seasons(k,[l l+1]))/2;
    end
end

```



```

    end
end

for m=1:size(Time,2)
    for n=1:size(Time,1)-1
        D2(n,m)=sum(Time([n n+1], m))/2;
    end
end

for o=1:size(D1,1)
    for p=1:size(D1,2)
        D(o,p)=(D1(o,p)+D2(o,p))/2;
    end
end

D=round(D);

xlswrite('yourfilehere2.xls',D,'titleworksheet');

%take the cumulative differences between all frames

C =
    abs(B2 - B1) + abs(B3 - B2) + abs(B4 - B3) + abs(B5 - B4) + abs(B6 - B5) + abs(B7 - B6) + abs(B9 - B8) + abs(B10 - B9);
    + abs(B11 - B10) + abs(B12 - B11) + abs(B13 - B12) + abs(B14 - B13) + abs(B16 - B15) + abs(B17 - B16) + abs(B18 - B17);
    + abs(B19 - B18) + abs(B20 - B19) + abs(B21 - B20) + abs(B22 - B23) + abs(B24 - B23) + abs(B25 - B24);
    + abs(B26 - B25) + abs(B27 - B26) + abs(B28 - B27) + abs(B30 - B29) + abs(B31 - B30) + abs(B32 - B31);
    + abs(B33 - B32) + abs(B34 - B33) + abs(B35 - B34) + abs(B37 - B36) + abs(B38 - B37) + abs(B39 - B38);
    + abs(B40 - B39) + abs(B41 - B40) + abs(B42 - B41) + abs(B44 - B43) + abs(B45 - B44) + abs(B46 - B45);
    + abs(B47 - B46) + abs(B48 - B47) + abs(B49 - B48) + abs(B51 - B50) + abs(B52 - B51) + abs(B53 - B52);
    + abs(B54 - B53) + abs(B55 - B54) + abs(B56 - B55);

F =
    abs(B8 - B1) + abs(B15 - B8) + abs(B22 - B15) + abs(B29 - B22) + abs(B36 - B29) + abs(B43 - B36) + abs(B50 - B43);
    + abs(B1 - B50) + abs(B9 - B2) + abs(B16 - B9) + abs(B23 - B16) + abs(B30 - B23) + abs(B37 - B30) + abs(B44 - B37);
    + abs(B44 - B37) + abs(B51 - B44) + abs(B2 - B51) + abs(B10 - B3) + abs(B17 - B10) + abs(B24 - B17) + abs(B31 - B24);
    + abs(B38 - B31) + abs(B45 - B38) + abs(B52 - B45) + abs(B3 - B52) + abs(B11 - B4) + abs(B18 - B11) + abs(B25 - B18);
    + abs(B32 - B25) + abs(B39 - B32) + abs(B46 - B39) + abs(B52 - B45) + abs(B4 - B53) + abs(B12 - B5) + abs(B19 - B12);
    + abs(B26 - B19) + abs(B33 - B26) + abs(B40 - B47) + abs(B54 - B47) + abs(B5 - B54) + abs(B13 - B6) + abs(B20 - B13);
    + abs(B27 - B20) + abs(B34 - B27) + abs(B41 - B34) + abs(B48 - B41) + abs(B55 - B48) + abs(B6 - B55) + abs(B14 - B7);
    + abs(B21 - B14) + abs(B28 - B21) + abs(B35 - B28) + abs(B42 - B35) + abs(B49 - B42) + abs(B56 - B49) + abs(B7 - B56);

ContrastImage = C + F;
Ctotal = sum(sum(C));
Ftotal = sum(sum(F));
[Rows, Columns] = size(B1);
TPixels = (Columns * Rows)*100;

Ratio = Ctotal + Ftotal/TPixels;

imshow(ContrastImage, [0 4000]);
imagesc(C, [0 2000]);figure(gcf);

```

Figure B.3: Matlab Script for Calculating Annual Luminance Variability (Written by Siobhan Rockcastle)

Temporal Map Maker

Developed by Sian Kleindienst

```
%DATA VARIABLES
city = 'Boston';
%Latitude of your location
lat = 42.35;
%Longitude of your location
lon = 71.09;
%Longitude of the time zone of your location
tz = 75;
%The filename of your excel data file
excelfile = 'yourfileherecontrast.xls';
%The worksheet name of your data file
worksheetname = 'titleworksheet';

%GRAPH VARIABLES
col = 'jet';
%some choices: 'jet', 'gray', Option rangejet: use without quotes, and run,
rangejetmap" in MATLAB first, after setting ranges.

%background color RGB for DARK BLUE background
backcol = [0 0 0.5625];
%backcol = [0 0 0]; background color RGB for BLACK background
%The number you want at the top of the colorscale
sat = 1;
%title on graph output
titl = [city ': Roof Monitors'];

Etot=xlsread(excelfile, worksheetname);

di = size(Etot)
%#Daily intervals
Di = di(2);
%#Yearly intervals
Yi = di(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Divide time into lightsolve dynamic moments specified in "day_logics.doc"
% then create useful matrixes and lists corresponding to these moments
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%calculate all the limiting hours over the year:
for j=1:365
    %calculate the declination (in degrees)
    n = j * (2 * pi) / 366;
    dec(j) = 0.33281 - 22.984 * cos(n) + 3.7872 * sin(n) - 0.3499 * cos(2 * n) + 0.03205 * sin(2 * n);
    - 0.1398 * cos(3 * n) + 0.07187 * sin(3 * n);
    %calculate the Equation of Time
    eqt(j) = -0.00037 - 0.43177 * cos(n) + 7.3764 * sin(n) + 3.165 * cos(2 * n) + 9.3893 * sin(2 * n);
    - 0.07272 * cos(3 * n) + 0.24498 * sin(3 * n);
    %determine the time of sunrise
    srt(j) = 12 - ((acos(-tan(dec(j)) * pi / 180) * tan(lat * pi / 180)) / 15) * 180 / pi);
    %determine the time of sunset
    sst(j) = 12 + ((acos(-tan(dec(j)) * pi / 180) * tan(lat * pi / 180)) / 15) * 180 / pi);
    %determine the length of the day
    dj(j)=sst(j)-srt(j);
    %define the half time interval for each day
```

```

it(j)=dj(j)/(Di*2);
% determine the hours that limit these intervals
for h= 1:(Di+1)
    lim(j,h)=srt(j)+(h-1)*2*it(j);
end
end

%make a matrix of the limits of the yearly interval:
yearlim(1) = -10; %Start the interval divisions on Dec 21...
%...Then add the number of days in each interval according to Yi
for y=2:(Yi+1)
    yearlim(y) = yearlim(1)+floor((y-1)*365/Yi);
end

%yearlim; create "numj" - a list of the interval mid-point julian dates. These are the Yi representative days of the year. (usually 8); cre-
ate "mois" and "jour", a list of the month and day associated with the numj julian date

for y=1:Yi
    numj(y) = floor((yearlim(y+1)-yearlim(y))/2 + yearlim(y));
    if (numj(y) < 1)
        numj(y) = numj(y) + 365;
    end
    if and(numj(y)>=1,numj(y)<32)
        mois(y) = 1;
        jour(y) = numj(y);
    elseif and(numj(y)>=32,numj(y)<60)
        mois(y) = 2;
        jour(y) = numj(y) - 31;
    elseif and(numj(y)>=60,numj(y)<91)
        mois(y) = 3;
        jour(y) = numj(y) - 59;
    elseif and(numj(y)>=91,numj(y)<121)
        mois(y) = 4;
        jour(y) = numj(y) - 90;
    elseif and(numj(y)>=121,numj(y)<152)
        mois(y) = 5;
        jour(y) = numj(y) - 120;
    elseif and(numj(y)>=152,numj(y)<182)
        mois(y) = 6;
        jour(y) = numj(y) - 151;
    elseif and(numj(y)>=182,numj(y)<213)
        mois(y) = 7;
        jour(y) = numj(y) - 181;
    elseif and(numj(y)>=213,numj(y)<244)
        mois(y) = 8;
        jour(y) = numj(y) - 212;
    elseif and(numj(y)>=244,numj(y)<274)
        mois(y) = 9;
        jour(y) = numj(y) - 243;
    elseif and(numj(y)>=274,numj(y)<305)
        mois(y) = 10;
        jour(y) = numj(y) - 273;
    elseif and(numj(y)>=305,numj(y)<335)
        mois(y) = 11;
        jour(y) = numj(y) - 304;
    elseif and(numj(y)>=335,numj(y)<365)
        mois(y) = 12;
        jour(y) = numj(y) - 334;
    end
end
end

```

% "numja" is numj with it's last entry repeated at the beginning and its first entry repeated at the end... needed for graphing purposes

```
numja = [(numj(Yi)-365) numj (numj(1)+365)];
numjb = [numj(Yi) numj numj(1)];
```

%make a matrix "mom" of hour moments for each day/time of interest

```
for i=1:Yi
    for h= 1:Di
        mom(i,h)=lim(numj(i),h)+it(numj(i));
    end
end
```

%make a list of "sunrise" and "sunset" moments corresponding to "numja" jd

```
for i=1:(Yi+2)
    sunrise(i)=srt(numjb(i));
    sunset(i)=sst(numjb(i));
end
```

% GET DATA

```
moments=mom;
Etot=xlsread(excelfile, worksheetname);
```

% CREATE MATRICES OF DATA TO BE USED IN GRAPHING

% Create extra columns for graphing matrices so in order to have data beyond the edge of the graph. (like numja's relationship to numj)

```
for h=1:Di
    X(1,h) = (numj(Yi)-365);    %1st column, negative jd
    X((Yi+2),h) = (numj(1)+365); %last column, jd beyond 365
    mom1(1,h) = moments(Yi,h); %1st column, repeat last jd moments
    mom10(1,h) = moments(1,h); %last column, repeat first jd moments
    Etot1(1,h) = Etot(Yi,h);    %1st column, repeat last illums
    Etot10(1,h) = Etot(1,h);    %last column, repeat first illums
end
```

% Concatenate extra columns onto base matrices

```
momentsa = vertcat(mom1,moments,mom10);
Etota = vertcat(Etot1,Etot,Etot10);
% Add rows for sunrise and sunset times to moment matrix
momentsb = horzcat(sunrise',momentsa,sunset');
% Add rows of "0" illuminance at sunrise and sunset moments to Etot matrix
Etotb = horzcat(zeros((Yi+2),1),Etota,zeros((Yi+2),1));
% X: Create a matrix of julian dates for each moment (same for same day)
for j=1:Yi
```

```
    for h=1:(Di+2)
        X(j+1,h) = numj(j);
    end
end
```

% Fill in the corners of the X matrix, left empty by adding columns shorter than base matrix

```
X(1,(Di+1)) = (numj(Yi)-365);
X(1,(Di+2)) = (numj(Yi)-365);
X((Yi+2),(Di+1)) = (numj(1)+365);
X((Yi+2),(Di+2)) = (numj(1)+365);
```

% Make the upper limit of the graph the saturation lux

```

for j=1:(Yi+2)
    for h=1:(Di+2)
        if Etorb(j,h)>sat
            Etorb(j,h)=sat;
        end
    end
end
end

% GRAPH THE DATA: contour graph (X = xcoord, momentsb = ycoord, Etorb = zcoord, 25 = # contours)

figure
contourf(X,momentsb,Etorb,25);
xlim([1 365]);
ylim([0 24]);
caxis([0 sat]);
colormap(col);

%caxis([0 70000]);
colorbar;
set(gca,'color',backcol);
set(gca,'Title',text('String',titl,'fontsize',14))
xlabel('Days (jd)','fontsize',12);
ylabel('Hours','fontsize',12);
set(gca,'ytick',[0 2 4 6 8 10 12 14 16 18 20 22 24],'fontsize',10);
set(gca,'xtick',numja);

%set(gca,'XTickLabel','04/12|17/01|26/02|13/04|29/05|14/07|29/08|15/10|04/12|17/01')
children=get(gca,'children');
set(children,'linestyle','none');

```

Figure B.4: Matlab Script for Mapping Temporal Data (Written by Sian Kleindienst and Altered by Siobhan Rockcastle)

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