# Improving Design Decision-Making through a Re-Representation Tool for Visual Comfort Consideration in Dynamic Daylit Spaces

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Doctor of Philosophy in Architecture Design Research

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#### ABSTRACT

Light and architectural design are inseparable. Light plays a significant role in the perception of the place. One of the main reasons a good number of today's buildings are unsuccessful regarding visual conditions and comfort is because they are only focused on function and structure without considering the quality of the place. Design for spaces often does not fully consider the setting where the building is placed. This connection with the surrounding environment can turn the space into a place where an occupant feels his existence and sense of dwelling while being at peace. Daylight is one aspect that can enhance the sense of place and influence the personal interpretations and impressions that last long after leaving the place. Today, architects are being asked to consider low-energy design with daylighting in their designs. In response to this, there is growing interest in the study of visually disturbing effects such as glare and poor visual comfort that can adversely impact the sense of dwelling.

While several studies on visual comfort have been conducted, very little research addressed movement through space and the time-dependency of daylighting. Concern for daylight control is needed in buildings especially museums and art galleries because of their exhibits' sensitivity to light. To address the dynamic daylight conditions, this research proposes a framework for an innovative approach to improving design decision-making by evaluating visual comfort during the early stages of design, which can alter the design process. A framework-based prototype has been designed for this research that uses Grasshopper and its sub-components to interface with Radiance and Daysim. In addition to quantitative outputs, special re-representation is used for qualitative analysis to support design decision-making. Through logical argumentation, prototyping, immersive case study, and member impressions via a Delphi panel, an interpretive approach is used to demonstrate the enhancement in design decision-making that occurs when one considers dynamic daylighting. The research outcomes are expected to provide researchers, designers, and decision makers with a new approach to designing and re-imagining spaces to improve visual comfort and the quality of the place.



All your blessings are from the Lord

To my father who could not see this dissertation completed.... I know you are proud of me now

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# **1 CHAPTER 1: INTRODUCTION**

"We were born of light. The seasons are felt through light. We only know the world as it is evoked by light... Natural light is the only light, because it has mood... it puts us in touch with the eternal. It is the only light that makes architecture."- Louis Khan (Cen, 2007)

# **1.1 Introduction**

Daylighting can play a major role in resource conservation and contribute to higher levels of productivity, health, and comfort for building occupants. As suggested by Kleindienst and Andersen (2009) in their study on student performance in classrooms, views to the outside provided by daylighting have a strong effect on psychological and physical wellbeing. Daylighting can create a sense of being in a place (or space phenomenon), where feelings of awareness and dwelling have desirable effects (Haddad, 2010). Daylighting can participate in this phenomenological experience. While daylight is desirable in most living or working spaces, its dynamism can cause visual discomfort. The phenomenon of discomfort glare is recognized as one of the most common visual problems that has not been fully quantified nor understood. Several visual discomfort studies were based on light measurements combined with psychophysical assessment. Many of these studies have not considered the time and space dynamics of the daylight condition, nor the representation and re-imagining of these dynamics especially in the early stages of the design process.

#### **1.2 Problem Statement**

A goal of the architect is to design comfortable, high-quality spaces. Richard Rogers echoes this opinion, stating "My passion and great enjoyment for architecture, and the reason the older I get, the more I enjoy it, is because I believe we - architects - can affect the quality of life of the people" (Nabil and Mardaljevic, 2006). However, visual discomfort and glare can distract architects from achieving this objective. Although there have been many studies on visual comfort, several issues exist when implementing a consideration of daylight into the design process. This is compounded by the fact that many lighting analysis tools are not applicable during the early stages of the design process. Moreover, many of the tools that are available tend

to be accessible only to professionals and they often require specialized computing and programming skills.

Furthermore, most existing tools do not consider two important dynamic issues: time and space. Because the position of the sun changes with time of day and day of the year, the daylight situation is time dependent. For a given space the daylight condition may be acceptable for one moment in time and completely unacceptable at another. Typically daylight analysis is static. In terms of space, the perception of the quality of space and potential for glare depends on one's location and view angle. As one moves through space such as a transitional space, the lighting condition may be acceptable at one location but not at another. These shortcomings will be addressed through this research.

#### **1.3 Research Objective**

The main objective of this research is to improve design decision-making through the development and demonstration of a prototypical representation tool that considers visual comfort and glare. A new prototypical tool for visual comfort evaluation that considers time and space dynamics in daylit spaces was developed to help designers make better-informed decisions. To achieve this objective, a shift in the design process is proposed to evaluate visual comfort through the development and implementation of a prototype tool. An immersive case study approach was used to determine how the proposed prototype affects design decision-making in two types of spaces.

As transition spaces in buildings such as museums are necessary for glare control, one case study examined the visual comfort of a passageway adaptation between multiple gallery spaces. Through this case study, the tool was used and the interpretations and impressions of the researcher and a purposeful sample of members of the design community were collected and coded to determine the efficacy of decision support. Furthermore, the proper integration and control of daylighting in office spaces can provide the increase the workers productivity by providing them with the best spectrum of light for the eye. Consequently, the second case study examined visual comfort in a typical office space. After the completion of the case studies, some professionals were asked to evaluate the prototype tool regarding design decision support. The tool was modified following each round of feedback.

The research makes a contribution to normative theory by developing and demonstrating an improvement in the design decision-making process.

# 1.4 Research Methodology

To meet the research objectives, a qualitative method was adopted with two quantitative tasks. This research was conducted in multiple stages that included logical argumentation, prototyping, immersive case study, Delphi, and member check. The research aimed to demonstrate the improved efficacy of design decision-making through the implementation of the prototypical tool as shown in Figure 1-1.



**Figure 1-1: Design triangulation** 

The research was carried out in eight stages. 1) First, the research started with the review of the literature to identify the current state-of-the-knowledge in visual comfort, glare, and light analysis as well as typical design procedures for daylighting. 2) As a second step, logical argumentation was applied using an interpretation of the literature review; the researcher examined the selected visual comfort indexes and thresholds for decision-making. 3) During the same stage, a preliminary survey questionnaire was developed and administered; this instrument aimed at examining the difficulties and problems with daylighting analysis software, and at collecting suggestions for improvements. 4) Next, a prototype for decision support tool was developed from stages 1-3. The prototyping process started with the development of the first prototype that was tested by a small group of participants (5 members). Following this, a second iteration of the prototype was developed. 5) Through this iterative process, the prototype was then applied and tested through two immersive cases studies. The researcher kept track of the impressions and the process of using the tool, which helped the researcher to capture thoughts from the participants as well as herself by keeping a journal and being self-reflective. 6) As an

attempt towards triangulation, the museum case study results and analysis were shared with a group of purposefully selected members of the design community (3 members). The feedback collected from the interviews was coded into themes. 7) To ensure the trustworthiness of the tool outputs, a reliability and validity check took place on the tool outputs from the museum case study. 8) Finally, a Delphi approach was applied to the office space case study to quantify the impressions of the participants concerning the value in supporting decision-making. In this approach, a group of members (6-10) applied to the tool and their impressions were collected.

#### **1.5 Research Contributions**

The application of the prototype testing in the course of a case study attempted to address questions such as the following:

- How can informing designers about dynamic visual discomfort conditions early in the design process affect their decision-making?
- Can the process of reimagining the space change the way architects design spaces?
- For architects what are the most informative types of outputs (numerical, graphical or visual)?

By answering these questions, the proposed research tool may alter the design process in several ways. In general, 3D modeling comes as a late stage in the design process, and many times only for presentation purposes. However, the new tool combines shifting 3D modeling with daylighting analysis in the early stages of the design process. This allows the lighting conditions and potential problems to be understood particularly as they relate to glare. Also, one of the main research contributions is proposing a shift in the normative theory of design decision-making. The tool can also support better communication among the design team members and between the designer and the client through the 3D representation of the space.

#### **1.6** Assumptions and Limitations

Aside from visual comfort being a subjective preference that differs from one person to another based on many factors, there are assumptions and limitations in the proposed methodology.

#### 1.6.1 Methodological Limitations

- The researcher is the primary tool for carrying out this research, which may cause bias in the interpretation of results. However, bias minimization techniques and user feedback were used through the prototyping process to minimize potential bias.
- There is not agreed upon metric for visual comfort evaluation. The metrics most often used for glare analysis; while some were used for visual comfort analysis. Hence, multiple metrics were utilized in the analysis of visual comfort for the prototype.

# 1.6.2 **Prototype Limitations**

- The prototype was applied to a limited number of immersive case studies.
- To generate results quickly and due to limits in computational speed, compromises were made in the simulation procedures.
- The prototype has some limited accuracy and does not address the full range of perceptual and cognitive response to stimulation.
- The prototype simulations were based on metrics that in themselves have assumptions and limitations.
- Typically prototype testing is used to reduce the risk that a design may not perform as intended. However, prototypes generally cannot eliminate all risk.
- Multiple factors were not considered when setting thresholds and guidelines including occupants age, gender, visual disabilities, multiple eye directions and other possible non-visible discomfort effects including acoustics, thermal comfort, and mood.
- For all these reasons, judgment is required in the implementation of the results.

# 1.6.3 **Outcomes Limitations**

- Simulation software have their limitations. Research findings showed that in general computer simulation software for daylighting underestimate illuminance values. The difference between measured and simulated illuminance values especially under the direct sun is between 5-10% (Wynekoop and Walz, 2000, Fraguada, 2015).
- The transition passing of data from one software subcomponent to another from may create approximations errors.

- As previously mentioned, the researcher was the primary instrument in the research. Which may introduce bias into the research.
- The case study outcomes are based on selected days and hours of the day and do not represent a full year simulation—which may result in some discomfort conditions not being identified.

#### **1.7 Dissertation Layout**

To achieve the research goal, this study is organized into nine chapters, each with its own objective and methodology (as summarized in Figure 1-2). The description of each subsequent chapter is given below.

**Chapter 2**: This chapter presents the key definitions and summarizes the literature and previous research findings.

Chapter 3: This chapter presents the proposed research design and methodology.

**Chapter 4**: This chapter presents: 1) a description of the prototypical tool: the logical argumentation for the selected visual discomfort metrics, and the hardware and software configuration; 2) version two of the prototype along with member feedback with corresponding, coding, and themes.

**Chapter 5**: This chapter describes the immersive case study and detailed explanation of the collaborative design effort.

**Chapter 6**: This chapter presents the reliability and validation study of the tool when compared with in-situ measurements.

**Chapter 7**: This chapter discusses the impressions of members of the design community (Delphi), where designers and decision makers were asked to share their impressions of the tool and its usefulness in improving the design decision-making process.

**Chapter 8**: This chapter presents the results and findings from previous chapters, as various criteria were used to test the trustworthiness of the research findings.

Chapter 9: This chapter represents conclusions, research continuation, and anticipated future work recommendations.



Figure 1-2: Dissertation Layout

Generally, the phenomenology of human existence, including joy and a sense of dwelling, can be achieved by the powerful connection with the outside environment. One way to realize this is when the dynamic natural light is present and evokes feelings of comfort and satisfaction with the visual environment. However, because daylight is dynamic, there may be times when the lighting condition is acceptable and other times when it is not and similarly from one location to another. These dynamics are not usually accounted for in the early stages of the design process. Therefore, a prototype tool is needed to alter the design process and help the architect make informed design decisions as presented in the following chapters.

# **2** CHAPTER 2: LITERATURE REVIEW

"Architecture should speak of its time and place, but yearn for timelessness."- Frank Gehry (Gehry, 2016)

#### 2.1 Introduction

Dynamism and constant change are two elements that can characterize daylighting in buildings and spaces. Conversely, such dynamism can create unwanted lighting conditions such as discomfort and glare. This discomfort may affect the performance of building occupants such as workers or students. Consequently, designing for daylighting requires a proper understanding of such dynamism. However, the evaluation of daylighting is not well addressed in the early stages of design. This is in part because of the lack of user-friendly tools to perform the analysis and the difficulty in understanding the output from such tools by non-daylighting professionals.

As mentioned in Chapter 1, this dissertation aims to evaluate visual comfort to help designers make better-informed decisions. To help achieve this goal, a prototypical tool was developed. The development of this tool requires an understanding of issues such as daylight, glare, and currently available design support tools. Therefore, this chapter begins with key definitions and issues associated with daylight and glare. It then moves to the various classifications of visual comfort. A comparison of these methods and limitations is then presented, followed by a review of previous research related to daylighting, visual comfort analysis, and glare.

#### 2.2 Daylighting Phenomena

Juhani Pallasmaa argues that architecture is an unknown structure with a proposition about an ideal human situation, the image of a better world, stating "I see the task of architecture as the defense of the authenticity of human experience "(Osterhaus, 2002, Ong, 2013). Pallasmaa also believed that multisensory experience should support every phenomenological interpretation (Pallasmaa, 1991). More importantly, he also argued that human perception is dynamic and multisensory; in perception, all the senses including vision, hearing, touching and smelling the space have a role in creating a special sensation (Yin, 2011). The term "spatial sensation" was defined by Marshall (1996) as "the ability to comprehend three-dimensional spaces with the help

of the senses, and as the ability to create spatial ideas and concepts that are subsequently formed into a more tangible shape such as in architecture, sculpture or dance". Yin's (2011) concept of spatial sensation is illustrated in Figure 2-1.



Figure 2-1: Vision and human perception (Yin, 2011)

In order to create a link between "vision" and "creating a sense of place," the design process often does not have a definite and identifiable end, which may be affected by uncertainties of the future and require additional experience and judgment. Zeisel describes the architectural design process in three stages: imaging, presenting and testing—where imaging takes us into the realm of thinking and creativity, presenting is the process of drawing the ideas and represents the central role of the design process, and finally testing it (Creswell, 1999). This pertains to the design process as designers can build their designs virtually (imaging) before construction (presenting). Once built, virtual models of designs are much more flexible than other forms of representation to allow the building form to be developed and improved dynamically and rapidly (Jung, 2014, Toplak and Stanovich, 2003). Since vision is the most developed of our senses, it is important to control glare and patterns of contrast should be appropriate (Yin, 2011). Important aspects of how daylighting can inform the design process are explained in the following section.

#### 2.2.1 **Daylighting and Architecture Quality**

Daylighting offers a better sense of spirituality, openness, and freedom from prison-like windowless spaces. Humans are affected both psychologically and physiologically by the different spectrums provided by the various types of light. Daylighting has been associated with improved mood, lower fatigue, and less eye exhaustion. One study also found an increase in workers' productivity when working in a daylit office regardless of gender, position, or task

(Osterhaus, 2004). In another study, improvement was observed in patients' health when offered more daylighting and connection to the outside environment in healthcare facilities. Such improvement supports "The Biophilia hypothesis," which concludes that humans have a biological need to contact with nature, which could not be fulfilled by electric lighting alone (Edwards and Torcellini, 2002).

Many motivations inspired designers to incorporate more natural lighting. However, it is important to remember that daylighting as a science should not become more important than the architectural quality resulting from the visually inspiring daylighting design (Steemers, 1994). Therefore, designers should take the following into consideration. 1) Change and variety: a continuous human desire for change as experienced through the changes in the seasons, the weather, and the time of day. 2) Rendering: the direction of natural light provides shadow patterns, which inform the appearance of objects and surfaces. In other words, objects have more depth and appear more natural. 3) Orientation: orientation is important to situate the building in its surroundings and dynamic changes. 4) Sunlight effect: sunlight has a beneficial effect, as sunlight penetration is critical and acceptable to certain limits because of its dynamism. 5) Color: natural color may vary throughout the day, but it is the standard by which all color is judged; there is no artificial source which can match it. 6) View: access to an outside view is an important feature that can influence the productivity and performance of the occupants (Steemers, 1994).

#### 2.2.2 Museum Spaces Daylighting

In addition to offices and hospitals, museums represent excellent case studies for understanding the impact of daylighting on human experience within a space. Previous case studies on the subject examined different museums with the goal of ensuring adequate lighting conditions on various artifacts while assuring visual comfort for visitors. These studies have shown that most museum visitors prefer seeing exhibits under daylight conditions. Chauvel, Collins, Dogniaux, and Longmore (1982) examined visual comfort and lighting quality in three daylit San Francisco art museums. The main goal of their study was to present snapshots of the daylighting conditions inside the museums spaces during a particular month.

Ward (1992) examined two important Lisbon Art Museums, Arte Antiga Museum and Gulbenkian Museum. The study aimed at improving our understanding of the relationship between lighting characteristics and visitor satisfaction within a museum space. The study showed that the visitors appreciated the outside view and daylight presence in the spaces, while their ability to see the artifacts was not affected.

More recently, Oliveira and Steemers (2008) investigated three daylit museums using simulation software. This study suggested recommendations including adding exterior shading devices and louvers and reducing the overall illuminance on display areas. Another study by Betran (2004) compared different daylighting conditions in three well known daylit art museums: the Modern Art Museum by Tadao Ando, the Kimbell Art Museum by Louis Kahn, and the Amon Carter Museum by Philip Johnson (Figure 2-2). The results of this comparison are summarized below.



Figure 2-2: A-Modern Art Museum; B-Kimbell Art Museum; C- The Amon Carter Museum

Of the three, the Kimbell Art Museum represented the most successful lighting distribution. The comparison showed good direct sun control in the Kimbell Museum, while direct sun penetration occurred in the other two museums. The study also suggested changes to the daylighting problem in the Modern Art Museum and the Amon Carter Museum. While a near uniform illuminance was found in the Kimbell Museum, a wide range of illuminance values was found in the other two causing high contrast and damage to the artifacts.

#### 2.2.2.1 Form, light, and shadow in a museum

The Helsinki Museum of Contemporary Art designed by Steven Holl is one example of the connection between architectural form, light, and shadow to create poetic spatiality. The emotional and imaginative experience of the museum spaces is the result of the quality of the visual environment, as shown in Figure 2-3 (Osterhaus, 2002). This is one successful example of

how museums can represent ideal case studies for understanding the importance of daylighting conditions during the design process.







Figure 2-3: Contemporary art museum

# 2.2.3 Transitional Spaces

The human eye can adjust to a significant range of light levels—the process by which the eye adapts to varying quantities or colors of light (Wilson, 2006)—it is best if this is done without causing discomfort from high contrast. For this reason, transitional and circulation spaces are included in the design of most non-residential buildings. The percentages of areas for these spaces may vary between ten to forty percent of the total floor area for different building types (REA, 2010, Roudsari and Pak, 2013). Previous research findings have shown that although people do not stay in transitional spaces for extended periods, the visual condition in these spaces can strongly affect task performance and comfort during one's stay in the building (Betran et al., 2004). Transitional spaces are needed for eye adaptation, especially when moving through unusual lighting conditions. There are three definitions of transitional spaces:

• **Transitional spaces in the visual field:** Defined in the IESNA Handbook as the spaces where the time required to adapt to a change in retinal illumination depends on the magnitude of the change, including different light photoreceptors, the direction of the change, the transition time, and the visitor age. Usually, adaptation occurs within one second if the change in luminance is in the range of 100:1 (Steffy, 2002, Rea, 2000).

- **Transitional spaces in the architecture context:** Defined as the architectural areas situated between two or more environments and acting as buffer spaces (Kwong et al., 2009). They are typically secondary rather than directly occupied spaces. Examples of such spaces are a foyer, entrance lobby, atriums, lift lobby, and passageway. These spaces are significant in exceptionally-lit buildings like museums and art galleries where light distribution is a key factor for the protection of artifacts and visual comfort. This is the primary type of transitional space that will be studied in this research.
- **Transitional spaces in the phenomenological context:** Defined as the spaces where we find transitional objects and transitional phenomena. They represent the relationship between two sets of a phenomenon that are separated by a time interval. (Winnicott, 1971, p.12)

The visual conditions of transitional spaces need to be considered when trying to avoid daylight visual discomfort and accommodate visual adaptation in the design process. Consequently, the study of visual comfort in transitional spaces is critical, especially in buildings with acute lighting conditions like museums where contrast from dark to light (or vice-versa)—depending on the exhibition type—is often acute. In addition to daylighting quality, transitional spaces can increase the harmony between the interior and the outdoor environment, often experienced from macro to micro levels (REA, 2010, Roudsari and Pak, 2013). Accordingly, there is a need to study transitional spaces for the overall space to function properly regarding light quality.

#### 2.2.4 Daylighting, Space, and Time

According to Martin and McIntyre (1994), the task of architecture should be timeless; it should reflect materials and eternalize ideas and images of ideal life. It should allow us to settle and dwell in any cultures and times. In history good, examples of daylighting as essential to the design process can also be seen in the Parthenon, particularly in the articulation of the entrance and exit and the framing of views from the inside-out and outside-in; all contribute to a dynamic experience as shown in the plan and the rebuilt model in Figure 2-4 (Rea, 2000).



Figure 2-4: Parthenon plan view and rebuilt model (Rea, 2000, Linney, 2008)

In Islamic architecture, the use of light within an architectural space took place using light from the sun and moon and shadows. Walls, windows, domes, patios ornaments and other architecture elements were used with natural light to enrich the sensory experience and perception of the spaces (Carlucci et al., 2015) as shown in Figure 2-5 (Carlucci et al., 2015).



A-Hagia Sophia dome light in Istanbul

**B-Light and shadow in Islamic window (Mashrabeya)** 

Figure 2-5: Natural light and shadow transition in Islamic architecture

In today's architecture, the sensory experiences are finely tuned in the work of Glenn Murcut, Steven Holl, and Peter Zumthor, where architecture, space, and time are all fused into one single experience—the sense of being (Phillips, 2004).

# 2.2.4.1 Space-time couple in Glenn Murcutt's architecture

Murcutt is often quoted as saying "touch the earth lightly," which guided him design buildings that fit into the landscape. His works are economical and multi-functional; his primary materials

are glass, stone, timber and steel. More importantly, Murcutt always gives attention to the environment. As a first stage of designing, he examines the site and its surrounding effects including wind direction, water movement, temperature, and light. He designs architecture elements such as a verandah or porch to function as a transitional space to separate light from dark, outside and inside, public and private, hot and cool, etc. He creates balance for his buildings with nature: structural balance from trees, airflow balance from birds' wings, and most importantly light balance. He pays careful attention to details and edges by looking at how things meet in with nature. For example, his buildings meet the site as lightly as a tree meets the ground as shown in Figure 2-6 (Martin and McIntyre, 1994).



A- Magney House

B- Walsh House

#### Figure 2-6: Glenn projects examples

#### 2.2.4.2 Space-time couple in Peter Zumthor's architecture

Another example of this space-time couple can be seen in the works of Peter Zumthor. Zumthor knows the importance of having inspiring surroundings and believes that environments should maintain sensory qualities and atmosphere. This belief is expressed in his Therme Vals, where he engaged enjoyable atmosphere from the light composition and "presence" of the materials (Figure 2-7). Zumthor described this architectural atmosphere as "this singular density and mood, this feeling of presence, well-being, harmony, and beauty...under whose spell I experience what I otherwise would not experience in precisely this way."



A- Art Museum Kolumba

**B-Therme Vals** 

#### Figure 2-7: Examples from Peter Zumthor's works

#### 2.2.4.3 Space-time couple in Steven Holl's architecture

A final example of the space-time relationship in design can be seen in the works of Steven Holl's. Holl believes that the reading of time through architecture is only possible spatially. Moreover, he believes that time and memory conditions our experience of space. Phenomenology of dwelling is one major approach that Holl's embraces. He interprets space and time as two connected realms which intermingle and depend on the perceptual experiences of body-subject, Figure 2-8. Holl describes this as "the moving body through time" (Guha et al., 2004).



Figure 2-8: Spatiality of time in Holl's architecture
The works of Holl and Zumther delivered spiritual and pleasant feelings to their buildings occupants while depending on dynamic patterns of light and shadows. This inspired the basic concept of the research and clarified the theory that daylighting can help the designer achieve spaces that are environmentally efficient, comfortable with an enriched sense of space.

# 2.3 The Visual System

Vision is part of the complicated network of the human sensory system. Our eyes are remarkable sense organs that allow us to appreciate all the beauty of the world around us, to read and expand knowledge, and to communicate our thoughts and needs with each other through visual expression. Many aspects of the visual system need to be considered to implement daylighting strategies into the design process.

### 2.3.1 Visual Adaptation

Visual adaptation is the ability to accommodate different brightness levels. It is influenced by all areas of the field of view. There are two types of light receptors in the visual system: rods and cones. Rods are more sensitive to light than cones. Rods are responsible for low-light vision while cones are responsible for detailed vision. In other words, rods are more sensitive to low light and cones are responsible for visual acuity in brighter conditions. Cone adaptation is fairly rapid, but rod adaptation is more profound when the eyes are fully adapted to low light. Pigment regeneration (i.e. adaptation time) takes about six minutes for cones and thirty minutes for rods. Rods and cones adaptation curves are shown in Figure 2-9.







Figure 2-9: Rods and cones (Parpairi et al., 2002, Chakravarti et al., 1998)

From the above curve in Figure 2-9(a), there is a rapid decrease in the threshold of the ones' ability to adapt, after which it declines more slowly. After five to eight minutes, the second mechanism of vision comes into play, where another rapid decline in the threshold of the rods' ability to adapt takes place, followed by another gradual decline. The curve reaches its minimum (absolute threshold) at about  $10^{-5}$  cd/m<sup>2</sup> after about forty minutes in the dark.

Although measured brightness (or luminance) would be the same on two surfaces, one surface could appear brighter due to background brightness adaptation. Visual adaptation becomes difficult, and visual discomfort occurs if the brightness changes too rapidly as shown in Figure 2-10 (Nabil and Mardaljevic, 2006).



#### 2.3.2 The Visual Field of View

The range of visual abilities is not uniform across a natural field of view; it extends vertically 130 degrees and horizontally more than 1 20 degrees when using both eyes. Figure 2-11 shows the human visual fields (Rea, 2000). Figure 2-11(b) shows a standard, normal, optimum and maximum line of sight in addition to the limit of the visual field.



Figure 2-11: typical visual field, B- visual comfort typical angles

# 2.4 Visual Comfort and Glare

Visual comfort is defined as the state of mind that expresses satisfaction with the visual environment. It is a human need that can affect task performance, health, safety, mood and atmosphere (Park et al., 2003). Visual comfort problems are often experienced in our lives every day, in offices, movie theaters, libraries, or when entering and exiting a building. Visual comfort has two dimensions:

- a. The quantitative (measurable): Where enough light can provide the required visibility.
   If the occupants can clearly and correctly see the visual environment, they may be satisfied with it.
- b. The qualitative (immeasurable): Which is the elimination of disturbing effects related to the lighting. A visually comfortable space has minimal disturbing effects (Osterhaus, 2009).

Many studies have been conducted to evaluate visual comfort. As an example, visual comfort in offices was investigated by Osterhaus (2009) using a case study approach. This research concluded that prediction methods are of limited use in daylit situations. It also concluded that no efficient systems that combine daylighting and electric lighting were provided. The research findings suggested ways to better integrate computer workstations in daylit offices. Many studies focused on the required conditions for visual comfort in educational buildings. The results of these studies showed a positive relationship between increased daylighting and improved test scores and better student performance.

Furthermore, a visual comfort simulation tool for artificially lit buildings was presented in the paper entitled "A Hypertextual Tool for Comfort" (Filippi et al., 2000). The results of this study found that the tool could assist users in validating the lighting condition of existing design measurements and calculations. In addition, a study entitled "Animated Building Performance Simulation" investigated possible ways to link 3D modeling tools with advanced daylighting simulation tools. This tool represented a step towards the integration of the parametric design process with the performance analysis (Pointer, 1986).

The study conducted by Reinhart and Wienold (2010) investigated daylighting analysis based on climatic metrics, glare analysis, and occupant comfort. Glare is defined as the difficulty seeing in the presence of bright light resulting from a direct or reflected light source in the visual field. It is typically expressed as the ratio of the size, location and luminance of glare sources in a field of view when compared with the average luminance not inclusive of the glare source (Berkeley, 2012, CIE., 1983, Chauvel et al., 1982). In general, there are two types of glare:

- **Disability glare:** Glare that can result from light scattering within the eye, which can decrease visual performance and visibility (especially when accompanied by discomfort glare).
- **Discomfort glare**: Glare caused by high luminances in the visual field causing discomfort. The degree of discomfort glare depends on the size, luminance and position of glare sources; background luminance is also a factor. This is the primary source of glare that will be considered in this research.

In general, Reinhart and Wienold's (2010) research explored computer-based daylighting analysis capabilities to predict daylight availability, occupant comfort, occupant behavior, and energy use. Also, this research explored the issues in multiple simulation software operations and long simulation time. Identifying suitable daylighting performance metrics thresholds was an unresolved issue in this research.

### 2.4.1 Visual Comfort Analysis and Glare Analysis in the Design Process

In an attempt to investigate the visual comfort effectiveness in the design process, Thomson (2000) studied the daylighting analysis (including visual comfort) position in the design process using four different case studies. The study investigated the impact of four possible design stages of the daylighting analysis on glare penetration. The four examined design stages were 1) Late Schematic, 2) Early Schematic, 3) Middle Developed Design, and 4) Start of Concept Design. The study summary and daylighting analysis outcomes are shown in Table 2-1.

Project	Building	Daylighting	Outcomes
	Function	Analysis Stage	
Project1	Hospital	Late Schematic	Only changes were applied to glazing and shading
		Design	selections.
Project2	Academic	Early Schematic	The modeling results impacted façade options,
		Design	including form, glazing, and shading in addition to
		-	interior furniture.
Project3	Commercial	Middle of Developed	No changes were applied to the design; only glazing
-		Design	properties were modified. Building failed to meet the
		-	LEED requirements.
Project4	Laboratory	Start of Conceptual	Changes were able to impact building form, glazing,
		Design	shading, and façade. Building successfully met the
		Ŭ	LEED requirements.

Table 2-1: Case study summary and outcomes

The results of this research recommended the early contribution of glare analysis in the design process (i.e. Start of Concept Design or Early Schematic), which can lead to a positive impact on the occupants' comfort within the built environment.

# 2.5 Visual Comfort Evaluation Methods

From the literature, there are eight calculation methods used to evaluate lighting conditions and visual comfort. The eight methods are: 1) the Illuminating Engineering Society of North America (IESNA) method, 2) the Glare Index, 3) the Brightness Ratio, 4) the Unified Glare Rating, 5) the

Radiance method or Glare perception, 6) the Daylight Glare Probability (DGP), 7) the Daylight Autonomy, and 8) the Useful Daylight Illuminance, as shown in Figure 2-12 and explained in the following subsections:



Figure 2-12: Visual comfort evaluation methods

# 2.5.1 The IESNA Method (Visual Comfort Probability-VCP)

The IESNA method—also referred to as Visual Comfort Probability (VCP)—is a metric used to rate lighting scenes. It is defined as the percentage of people that will find a certain scene (i.e. viewpoint and direction) comfortable with regards to visual glare (Jakubiec and Reinhart, 2011). The IESNA Handbook stated that discomfort glare is not a problem when the following conditions are satisfied: the visual comfort probability (VCP) is 70% or more at the given view angles (varying from 60 to -60 degrees), with 0 representing the center of the field of view. Also, the ratio of the maximum luminance to the average luminaire luminance should not exceed 5:1 at 45°, 55°, 65°, 75°, and 85° from the lowest point for crosswise and lengthwise viewing (Design-Lab, 2010). The IESNA advises that direct solar exposure illuminance that exceeds 1,000 Lux will cause discomfort (Dushkes, 2012).

The limitations of the IESNA method (and the visual comfort probability method) are:

- A fixed initial illuminance of 1,000 Lux (100 Foot-Candle) is used.
- Predetermined room surface materials properties are used.
- The VCP rating applies to lighting fixtures with the viewer in a specific location and looking in a particular direction. In other words, a fixed observation point is placed at 1.2 meters (4 ft.) horizontally from the center of the rear wall and 1.2 meters (4 ft.) above the

floor with a horizontal line of sight looking directly forward. A limited field of view angle - 53° from the line of sight of the observer is defined.

#### 2.5.2 **The Glare Index**

The Glare Index is a unitless index of visual comfort. Factors affecting the glare index include the size and relative position of the openings, sky, and interior luminance. It can be calculated via computer software such as RADIANCE and DAYSIM using the IESNA Handbook equations (Araji et al., 2007).

The Daylight Glare Index is a derivative method, but for daylighting (Equation 2-1).

$$DGI = 10 \log_{10} 0.48 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \Omega_s^{0.8}}{L_b + 0.07 \,\omega_s^{0.5} \,L_s}$$
(Equation 2-1)

Where Ls is Luminance of the source,  $\omega$ s is the solid angle of the source,  $\Omega$ s is the modified solid angle, Lb is the background luminance  $\Rightarrow$  adaptation luminance, and P is the Position Index.

If DGI > 31: Intolerable, < 18: Barely Perceptible.

Although the DGI is one of the main indexes for the daylight glare evaluation, especially for sources with non-uniform luminance, some previous research opposed using DGI as a reliable glare index for the following reasons:

- Instrumental limits: Including difficulties calculating luminance values and solid angle
   (ω) are evaluated using diagrams, which are only valid when the line of sight is
   perpendicular to the window and passing through one of the lower corners and does not
   apply to all cases. However, computer simulation tools can overcome this limitation.
- **Interpretative limits**: The simplification of the window plane uniformity zoning (e.g. sky, obstructions, and ground) could lead to conflicting or simplified results.
- **Conceptual limits**: The background is not properly considered in the DGI formula. The solid angle of the background is not considered, apart from its luminance level.
- Evaluation limits: Some researchers showed that DGI sometimes overestimated glare when compared with other metrics especially under clear sky conditions (Institution, 2015).

### 2.5.3 The Luminance Ratio Method

This method compares the measured brightness or "luminance" of points in the visual field. According to ISO standards, contrast ratios above three are necessary to preserve readability. More contrast is suggested for low luminance values "below 10 Candela/m2" (Dushkes, 2012). Previous research applied several luminance ratio methods:

• Central: Adjacent: Non-adjacent: Osterhaus (2002) claimed that the visual field has to be subdivided into zones, and identified three: the central zone, where the visual task takes place; the adjacent zone delimited by a cone of 60°; and the non-adjacent zone, delimited by a wider cone of 120° as shown in Figure 2-13. Osterhaus identified the ratio between the three zones as "1:3:10." This ratio is based on the idea that the luminance in the visual field of someone who is doing a static task must remain within reasonable ratios to prevent glare (Newsham and Veitch, 2001).



Figure 2-13: Field of view

- Maximum to minimum: The occupants' preferred maximum to minimum luminance ratio in the field of view was investigated in several studies, ratios of 1:5, 1:10 and 1:20 were previously declared (Carlucci et al., 2015).
- Mean luminance: A digital video photometer was used in previous research to look at a grid of squares of approximately 1° (15 x 15 pixels) in size. The mean luminance of each square in the field of view was measured, and the maximum square to the minimum square was compared. From their results, Loe et al. (1994) suggested that the maximum-to-minimum luminance ratio in the field of view be between 10 and 50.

- **Relative maximum luminance RML:** Tuaycharoen and Tregenza (2007) applied the Relative maximum luminance to test discomfort glare from windows using the following formula: RML= maximum luminance of glare source/mean luminance of glare source.
- Lambert's Law: In research conducted by Araji and Bobekry (2007), based on Lambert's cosine law (i.e. a surface obeying the law has the same luminance in every direction), illuminance ratio replaced luminance ratio to evaluate visual comfort. Physical illuminance values were measured from a scale model with readings taken using light sensors. These sensors were placed on fixed stationary points situated along a path in the study model. The common luminance ratio thresholds were used to compare the illuminance collected from the scale model sensors as shown in Table 2-2.

Display Effect	Subjective apparent brightness ratio
Subtle	2.5:1
Moderate	5:1
Strong	7:1
Dramatic	10:1

Table 2-2: Brightness ratio threshold and display effect (Araji et al., 2007)

The luminance ratio method was based on some assumptions, which produced limitations to the applied experience:

- To obtain numerical values, illuminance was used instead of luminance in previous research based on Lambert's law.
- A linear relationship was assumed between horizontally diffused illuminance and adaptation luminance, which can generate some inaccuracy in the results.
- An artificial sky was used, which means only overcast sky conditions were considered.

#### 2.5.4 Unified Glare Rating

UGR is defined as the log of the glare from the lamps in the visual field divided by the background visible light from the room (Cavazza et al.) (Equation 2-2).

UGR= 8 log 
$$\left[\frac{0.25}{L_b}\sum \left(\frac{L^2\omega}{p^2}\right)\right]$$
 (Equation 2-2)

Where L is the luminance,  $\omega$  is the solid angle between viewer eye and the luminaire, p is the Guth index and  $L_b$  is the background luminance. Glare increases with brighter lamps and lower

background lighting and decreases with dimmer lamps and more background luminance (Park et al.).

If UGR < 10: Glare is insignificant and can be ignored.

If UGR > 31: Glare is intolerable (Rea, 2000). A detailed glare threshold and criterion is shown in Table 2-3.

Glare criterion	UGI
Just imperceptible	10
Perceptible	16
Just acceptable	19
Unacceptable	22
Just Uncomfortable	25
Uncomfortable	28
Just Intolerable	31

Table 2-3: UGR threshold and criterion (Rea, 2000)

The glare calculation is based on artificial lighting from ceiling fixtures only, which is a limitation when using this method for evaluating glare from daylighting.

### 2.5.5 The Daylight Factor

The daylight factor was originally developed to examine overcast conditions, which is considered a limitation when examining clear sky and direct sun conditions (Weinold and Christoffersen, 2005). The DF is the ratio of the internal light level to the external light level (Equation 2-3) and can be expressed as:

$$DF = (Ei/Eo) \times 100 \%$$

#### (Equation 2-3)

Where *Ei* is illuminance due to daylight at a point on the indoor working plane and *Eo* is outdoor illuminance on a horizontal plane from the clear hemisphere of an overcast sky.

DF thresholds depend on the building function; they can be categorized into:

- Under 2: Not adequately lit artificial lighting will be required.
- Between 2 and 6: sufficiently daylit.
- Over 5: Well lit artificial lighting not required except at dawn and dusk but glare and solar gain may cause problems.

#### 2.5.6 The Daylight Glare Probability

The DGP is an empirical approach based on the vertical eye illuminance, the glare source luminance, its solid angle, and its position index (Harvard, 2006). DGP calculation considers the overall brightness of the view, the position of glare sources, and visual contrast. This method shows a strong connection to the user response concerning glare sensitivity when compared to other existing glare models. The DGP can be calculated from the following equation (Equation 2-4).

DGP = 
$$5.87 X 10^{-2} E_{v} + \frac{9.18 X 10^{-2} \log(1 + \sum L_{si}^{2} \cdot \omega_{si})}{[(E_{v}^{c4} \cdot P_{vi}^{2}) + 0.16]}$$
  

$$\hat{1}$$

Term1 Term2 (E	quation 2-4)
----------------	--------------

Where  $E_v$  is vertical illuminance at eye level (Lux), Ls is the luminance of the source (Cd/m<sup>2</sup>),  $\omega$  is the solid angle of the source (Cormode et al.), and P is the Guth position index.

For Term 1: the measurable visual comfort aspects depend on the vertical eye illuminance (which may be calculated using DAYSIM software), and Term 2 includes visual comfort aspects that depend on the detected glare sources: solid angle and position index, size, and luminance can only be calculated from an image rendering.

A simplified method to calculate the DGP was presented by Wienold (2009). This method shows a reasonable glare perception judgment when considering only vertical space illuminance at eye level and neglecting other illuminance directions. Therefore, a simplified DGP (DGPs) was found (Weinold and Christoffersen, 2005) (Equation 2-5).

DGPs = 
$$6.22 X 10^{-5} E_v + 0.184$$
 (Equation 2-5)

Analysis of the DGPs-values and the glare rating categories of the user glare discomfort assessments are presented in Table 2-4.

95%- confidence interval						
Glare Rating	Avg	Lower limit	Upper limit			
Imperceptible	0.33	0.314	0.352			
Perceptible	0.38	0.356	0.398			
Disturbing	0.42	0.390	0.448			
Intolerable	0.53	0.464	0.590			
Avg	<u>0.39</u>	0.314	0.352			

 Table 2-4: Analysis of the DGPs-values and the glare rating categories of the user assessments (Kensek and Suk, 2011a)

#### 2.5.6.1 Daylight glare probability low light correction

One of its limitations is that DGP is not defined for values smaller than 0.2 or if the vertical illuminance is below 320 Lux. Based on the user assessment, a correction factor was applied to the existing DGP equation to extend the usability range were the illuminance curve is between 0 and 300 Lux (Figure 2-14)



• Method limitation: The influence of individual glare sources was neglected. Hence, the DGPs can only be applied if no direct sun or high reflection hits the eye of the observer (Jakubiec and Reinhart, 2011).

#### 2.5.7 Daylight Autonomy

The DA predicts the percentage of daylight hours where the illuminance meets or exceeds the desired task illuminance level. Continuous daylight autonomy (cDA) is similar to DA; the only difference is that cDA considers partial credit for daylight levels below a user-defined threshold in a linear fashion (Chatzikonstantinou, 2015).

• Method limitations: DA is considered a quantitative measure only. It does not give partial credit for daylight levels below the user-defined Lux threshold which may cause an overestimation of electric lighting energy use (Chatzikonstantinou, 2015).

### 2.5.8 Useful Daylight Illuminance

Useful daylight illuminances (UDI) are defined as the illuminances that fall within the range 100-2,000 Lux (Figure 2-15).



Figure 2-15: Visual acuity as a function of illuminance (Chakravarti et al., 1998)

This range is based on data from comprehensive field studies of occupant behavior under daylit conditions. It can be explained as follows:

- Useful illuminance range (100–2000 Lux);
- Insufficient illuminance (less than 100 Lux);
- Extreme illuminance (greater than 2000 Lux)

In order for a space to meet the UDI thresholds, the percentage of its floor area that meets the UDI criteria should be at least 50% of the time. The UDI helps to communicate the significant

characteristics of climate-based analyses gained from daylight autonomy in addition to considering daylighting dynamism and human factors. The UDI approach provides a simple assessment of daylight and solar penetration using realistic, climate-based conditions (Pesudovs et al., 2002).

Index values were related for DGI and UGR to discomfort probability (for DGP) and comfort probability (for VCP) to Hopkinson's (1950) categorical rating scheme for discomfort glare as shown in Table 2-5 (Evans, 1981, Nazzal, 2005, Plympton et al., 2000).

	DGP	DGI	UGR	VCP
Imperceptible	<0.35	<18	<13	80-100
Perceptible	0.35-0.40	18–24	13–22	60-80
Disturbing	0.40-0.45	24-31	22-28	40-60
Intolerable	>0.45	>31	>28	<40

Table 2-5: Glare index values relation

In the research by Kensek and Suk (2011b), various glare indexes were compared using multiple simulation tools with major differences under overcast and clear sky conditions as shown in Figure 2-16. The results of this research showed variation in the output from different simulation tools which should be considered as a limitation of any research using these tools (Kensek and Suk, 2011b).



Figure 2-16: illuminance output using different software

Although the visual comfort evaluation tools can provide the designer with lighting analysis data during the design process. The success of the assessment rests in the careful balance of art and

science and how the designer can use the provided evaluation data to make better design decisions.

## 2.6 Architectural Design Process

A design process is a series of activities made by the designer to refine the design through problem solving (Buchenau and Suri, 2000). There are multiple strategies used by designers to arrive at solutions to problems depending on the designers' skills, knowledge, and nature of the project. An example of the typical stages of the design process includes a design brief, analysis, research, specification, problem solving, development, implementation, evaluation, and conclusion.

Many design methodologists and designers believe that the act of designing itself is not and will not be a scientific activity. According to Yanow and Schwartz-Shea (2006), "Science is analytic; the design is constructive" (p.121). However, other methodologists like Stiles (1959) state that "the study of designing may be a scientific activity; that is, design as an activity may be the subject of the scientific investigation". Although some remaining confusion exists between concepts of science and a science of design, the science of design should be understood as a group of sub-disciplines having design as their common interest (Blake et al.). Different stages of the design process are described in the following sections.

#### 2.6.1 Design Ideation Representation and Visualization in Architecture Research

The ability of the designer to imagine objects in the real world is a fundamental element of making good designs (Duncan, 1995). Architectural design ideas form in multiple stages as shown in Figure 2-17. As expected, when designers imagine their designs, they have an ideal mental image with no discomfort conditions. Therefore, there are two problems associated with the imaging process: 1) Since the mental image is idealized, no confounding or discomfort that can occur in reality. 2) The mental image is fixed and does not include time nor space dynamics. The result may be an as-built space that does not conform to the mental image, and the resulting design may not be a "place" as suggested by Norberg-Schultz (Schultz, 1971).



Figure 2-17: Design ideation

## 2.6.2 **Decision Making**

Decision-making can be defined as "the process resulting in the selection of a course of action among several alternative possibilities" (Hasson et al., 2000). It represents a problem-solving activity terminated by a proposed satisfying solution (Rowe and Wright, 1999).

An important part of science-based professions is logical decision-making where professionals apply their knowledge to make educated decisions. Decision-making can be done individually or through a group decision-making "Delphi technique." A general set of guidelines are considered when making a decision, including: 1) establishing the objectives, 2) classifying and ordering objectives in the order of importance, 3) developing alternative actions, 4) evaluating alternatives against objectives, 5) selecting the alternative that satisfies objectives, and 6) evaluation of the selected alternative for possible consequences.

# 2.6.2.1 Information processing for decision-making

Decisions are often made based on the orderly processing of information. Information processing may be sequential (where a single task is completed before starting another) or parallel (where multiple operations take place at the same time). Several proposed models/theories also describe the way in which we process information including deep and surface processing. In deep information processing, the researcher analyzes the information regarding its meaning and importance. In surface processing, the researcher processes the information only regarding its surface structure. For decision-making, deep processing can generate better results, as it encodes the meaning of the processed data and relates them to other data with similar meaning for a meaningful analysis.

# 2.7 Daylighting Analysis: Decision Support Tools

Daylighting design decision support tools are defined as tools made to help the designer make decisions regarding daylighting with features including:

- Controlling the penetration of the sun rays and visualization of possible sunlight penetration.
- Estimation of daylight factors in a daylit space using the specific daylight control system.
- Visualization of the building and outside surroundings.
- Evaluation of visual comfort indicators and detection of possible glare sources.
- Prediction of expected energy savings when using daylighting (Rogers, 2007).

Design tools play a significant part in the decision-making process throughout the sequence of decisions starting from formulation of the daylighting concepts to final implementation of daylighting strategies and innovative techniques in real building daylight. Examples of daylighting design tools are Physical Modeling and Computer-Based, which are discussed in the following sections.

# 2.7.1 Physical Modeling-Based Daylighting Decision Support Tools

These tools are used by architects and other building professionals to generate models that are close to reality (Rogers, 2007). Some of these methods (explained in Appendix A) can be summarized as follows: 1) mirror box cloudy sky simulator, 2) scanning sky simulator, 3) indoor and outdoor heliodons (a device for adjusting the angle between a flat surface and a beam of light to match the angle between a horizontal plane at a specific latitude and the solar beam) (Kumaragurubaran, 2012, AIA, 2012), and 4) artificial sky (which is similar to the mirror-box sky in that it simulates overcast sky conditions and feature no heliodon) (Buchenau and Suri, 2000).

# 2.7.1.1 Limitations for physical modeling-based tools

- Due to proximity, both simple and complex artificial skies have geometric modeling errors that require some calculation analysis to overcome some of their limitations (Creswell, 1999).
- Due to the finite dimensions, horizon errors may occur because of the ratio between the model size and the dome size; adjustment factors are needed to overcome this error.
- The artificial light used in the procedures outputs can change with temperature and age, dirt accumulation and applied voltage that may affect the illuminance outputs (Mitroff and Turoff, 2002).

# 2.7.2 Computer-Based Daylighting Decision Support Tools

These tools can investigate different daylighting settings based on detailed virtual models. They are used for advanced daylighting systems and can provide a range of outputs including images, visual comfort calculations and building performance with energy savings expectations. Some of these methods are:

- Radiosity Software (AGI32, Autodesk VIS, Lumen Designer/Lumen Micro)
- Forward Raytracing Engines (TracePro, Photopia)
- Backward Raytracing (Radiance and its interfaces: Desktop Radiance, Rayfront, Ecotect, Adeline, DAYSIM, SPOT, IES VE) (Morris, 1992).

# 2.7.2.1 Limitations for computer-based based tools

- One major limitation of the daylighting computer simulations is in creating the geometry and simulation of properties of materials (e.g. windows have to be modeled as surfaces with zero thickness). This may require complexity in the model with more time and effort.
- Complex and detailed models may produce larger files and need greater computing capabilities.
- Some 3D modeling software involve translation or sub-components, which require many steps to transfer to an input file for the daylighting simulation tool.
- Some daylighting tools can work with one 3D-modeling software but not others (Kota et al., 2014).
- Some simulation tools consider illuminance from only one direction (e.g. vertical illuminance) and not all directions, which can affect accuracy.
- Several tools do not take into account internal obstructions (furnishing, occupants, etc.), and bidirectional transmissions (Hasson et al., 2000).

# 2.7.2.2 Validation of Computer-based tools

Much previous research aimed to validate RADIANCE and compare the output with different simulations software and in-situ illuminance and luminance measurements. Research conducted by Bellia et al. (2015) compared computer simulations with in-situ illuminance measurements

for a building atrium under overcast and clear sky conditions. Hourly illuminance simulations using RADIANCE were compared with in-situ field measurements. Comparisons of in-situ and simulated measurements are shown in Figure 2-18.



Figure 2-18: Simulated Vs measured illuminance under overcast and clear sky (Bellia et al., 2015)

The research findings showed good agreement in the distribution pattern between the measured and simulated illuminance values for both clear and overcast sky conditions. Instantaneous differences between measured and simulated illuminance values varied from 9% to 19% at any time from 9 AM to 3 PM. The maximum differences occurred under overcast sky conditions. The study showed that the simulation had the potential to model the geometry, openings treatments, and materials properties accurately.

In other research conducted by Au1 and Donn (2005a), the acceptability of computer simulation was examined using High Dynamic Range (HDR) photography. The research outcomes showed that computer simulations were useful in analyzing the daylighting conditions in the building. From the above, it can be concluded that computer simulated daylighting analysis can generate trusted outputs although the difference between simulated and field measured values need to be considered as part of the limitations.

# 2.8 Chapter Conclusion

The literature review discussed some key points including the daylighting phenomena and its dynamism role in creating architecture quality. Some key characteristics of the visual system were examined including the field of view, and visual adaptation. Also, visual comfort and its main evaluation methods were presented. This chapter also examined the architectural design process, types of information processing, and key factors for decision-making.

The literature review shows that few studies have examined visual comfort under daylighting conditions and fewer still considered the design process and how design decisions are made for visual comfort. Previous research gaps were found to include considerations for visual comfort in the early stages of the design. Furthermore, the spatial and time dynamism of daylighting are important factors when designing for daylighting and also not typically considered in the early stages of design. Moreover, studies of visual comfort in transitional spaces are important when trying to avoid visual discomfort and accommodate visual adaptation; especially in buildings with acute lighting conditions like museums where adaptation is a key factor.

Finally, the literature review discussed daylighting analysis decision support tools and their limitations. From this chapter, it could be concluded that a shift in the design process and how design decisions are made to avoid visual discomfort is desirable as shown in Figure 2-19.



Figure 2-19: Literature review summary

# **3 CHAPTER 3: METHODOLOGY OVERVIEW**

"A profound design process eventually makes the patron, the architect, and every occasional visitor in the building a slightly better human being"- Pallasmaa (Dushkes, 2012.)

## 3.1 Introduction

Architecture is experienced mentally through vision; our eyes perceive an object before we physically touch it. Moreover, light reveals form, space, texture, and color, all of which are fundamental architectural considerations. The integration of daylighting in the design is usually associated with visual discomfort and glare problems. Designers started to give more attention to visual comfort inside spaces while trying to obtain high quality daylighting that sometimes exceeded that which is provided by electric lighting. Generating a sufficient lighting environment to maintain human health and productivity is a challenge, especially with energy efficient lighting. This research aims to help designers and decision makers achieve space quality through visual comfort evaluation.

This chapter aims to provide an overview of the research design and used methods. It describes the main phases of the research in addition to the limitations and possible impacts on the design process. The research relies on an interpretive approach primarily, it seeks to collect and analyze data from parts of a phenomenon for the following tasks: 1) logical argumentation: including an argument for the main visual comfort metrics and thresholds, software engines, 2) prototyping: including iterative development of the tool and member checking, 3) immersive case study: including evaluation and the interpretation of decision support impressions while using the tool for both the members and the researcher, and 4) quantitative analysis including two phases: a reliability and validity check and a Delphi questionnaire (as shown in Figure 3-1 and will be discussed in details in the following sections).



Figure 3-1: Research method overview

# 3.2 Quantitative and Qualitative Research Method Overview

There are fundamental differences in quantitative and qualitative methods; one is looking for causes while the other is looking for happenings. Quantitative research looks for explanations and control, while qualitative research attempts to understand the complex interrelationships and the human experience. A mixed methods approach is one in which the researcher tends to base knowledge claims on rational grounds (Evans, 1981). In general, qualitative methods generate information only on the particular cases studied, while general conclusions are only propositions. On the other hand, the quantitative method can be used to produce efficient support for the research hypotheses (Kota et al., 2014). According to Linda Groat, "qualitative researchers study things in their natural settings, attempting to make or interpret sense phenomena regarding the meanings people bring to them" (Parpairi et al., 2002). The primary goal of qualitative research is to obtain a systematic, all-encompassing, integrated overview of the context under study (Bellia et al., 2011).

The goal of this research is to provide evidence of improved design decision-making through the development and demonstration of a new re-representation tool for glare assessment. Therefore, the proposed research will follow a qualitative research approach for its ability to connect with life situations and examine initial conditions. Using a qualitative approach, the researcher's knowledge claims were based on individuals' experiences, observations, feedback collection, phenomenology, grounded theory studies, and case studies. The researcher was considered the primary tool in this research; she made the observations and realized her consciousness. The researcher collected open-ended data with the intent of developing themes from these data while seeking patterns of expected relationships in order to develop a re-representation of the prototype tool (Kota et al., 2014).

Although quantitative research does not fully understand the usefulness of studying small samples, quantitative analysis is considered useful in this research in order to 1) check the prototype outputs' reliability and validity through the comparison between the in-situ measurements and the simulated data, 2) for data triangulation, and 3) analyze the consensus of member impressions through a Delphi questionnaire. This method was supplemented with a quantitative statistical analysis via 1) the validity and reliability check of the prototype outputs measurements (in-situ and simulated luminance and illuminance values) and 2) the Delphi analysis of the participants' feedback.

# 3.3 Prototyping Overview

Prototyping is defined as a scenario-based simulation that allows the researcher to experience chosen aspects of a potential product. It allows for modeling, simulating, evaluating and testing with a high fidelity that can support design decision-making (Boyce and Gutkowski, 1995, Wang, 2002).

In this research, prototyping signified a re-representation tool for visual comfort assessment. To achieve a successful prototype, the researcher needed to identify and follow an explicit goal during the prototyping process—the primary objective of the prototype was to improve decision-

making especially in the early stages of the design process where decisions are often more impactful. The prototyping process informed the qualitative method through observations and interviews of the member group. Feedback was used to enhance the tool interface, ease of use, and user support (through help menus). Also, members' feedback and suggestions were used for future tool development and understandability.

The prototyping stages included: 1) Logical argumentation to investigate the evaluation metrics, 2) a preliminary survey questionnaire on daylighting software, 3) creating the first prototype based on the initial questionnaire, the literature review, and initial hypothesizes, 4) asking members to provide their opinion on the prototype, 5) using members feedback to create a modified second version of the prototype.

### 3.3.1 Logical Argumentation

The development of the re-representation prototype tool also relied on the evaluative metrics that are selected based on logical argumentation. Also, logical argumentation will be used to determine the most appropriate hardware and software structure for the prototype.

The foundation of a logical argument is its intention, or the proposition is either true or false (i.e. accurate or inaccurate). For a logical argument to be valid, it needs to follow three stages: premises, inference, and conclusion.

**A. Premises:** Premises are the necessary propositions for the argument to continue. They are the evidence (or reasons) for accepting the argument and its conclusions, and they need to be stated clearly. They are indicated by phrases such as "because," "since," "obviously," etc.

**B. Inference:** The inference is the process of using the arguments to obtain further propositions. The accepted proposition is used to derive a new proposition. They are indicated by phrases such as "implies that" or "therefore."

**C. Conclusion:** The conclusion is the final stage of inference. It affirms the argument on the basis of the premises and the inference. Conclusions are often indicated by phrases such as "therefore," "it follows that," "we conclude," etc. (Bellia et al., 2011, Budde et al., 1992).

In this research, the logical argumentation is premised on the literature review, where the main goal is to argue for the selection of thresholds for design criteria and decision support metrics for visual comfort.

### 3.3.1.1 Used metrics argument

From the literature review, it was found that some of the methods used for visual comfort evaluation were based on questionnaires (IESNA or VCP) while others were presented with artificial lighting in mind (UGR method). Several other methods used preset illuminance values and materials properties.

It was concluded that no single metric could adequately address all of the factors involved in a successful daylighting system. Consequently, Useful Daylight Illuminance and Illuminance distribution were used as illuminance evaluation metrics. The DGP, DGI, and luminance ratio were used for luminance image evaluation. Also, visual renderings were employed in this research for visual representation and re-imagination of the examined space.

### 3.3.2 Initial Daylighting Software Questionnaire

A survey questionnaire is defined as "a list of research questions asked to respondents and designed to extract accurate information" (SareyKhanie et al.). It aims at: 1) collecting the appropriate data, 2) making data comparable to analysis, and 3) minimizing bias in composing and asking questions.

As an initial step towards the prototyping process, a survey questionnaire on daylighting software was initiated. It collected opinions from a variety of members including architects, daylighting professionals, researchers, contractors, and engineers. It focused on the difficulties facing users of the existing daylighting analysis tools, preferred forms of outputs, and suggestions towards daylighting analysis tool improvements. It also examined the design stage where such tools would be best implemented.

### 3.3.3 **Prototype Initial Version (Version1)**

From the literature review, the logical argumentation findings and the daylighting survey results the researcher developed the initial version of the prototype (Version1). This version of the prototype followed a proscriptive method, where the designer is not involved in the analysis procedure. Also, the designer is not obligated to follow a particular path by offering a solution. The designer is more concerned with the final results to support his/her decisions and solutions; it has the advantage of being understandable.

#### 3.3.4 Member Checking

Member checking is a technique used by researchers to help improve the accuracy and credibility of the research where the research interpretation and a summary report is given to the members to check the accuracy of the work. Members comments and feedback are used to check for the interpretation feasibility (Cottam et al., 2004). There is a set of questions to answer when applying the member check technique: 1) What is being checked? 2) With whom are you checking? 3) Who is checking whom? 4) How would you interpret agreement? 5) What follows if "they" agree? 6) How does one interpret disagreement? 7) What was it they responded to? 8) How partial was the interpretation? (Cottam et al., 2004).

In this research, member check took place during the interview process to increase the credibility and validity of the qualitative study. During the interview, the researcher summarized the information collected from the interview then asked the participant to determine accuracy. The member checking results were shared with the participants where they were given the opportunity to agree or disagree that the summary reflected their views, feelings, and experiences.

#### 3.3.4.1 Analysis of the Member Check

Coding is defined as an interpretive method used to arrange and to produce interpretations of the data in a qualitative method using codes or labels (West and Cannon, 1988). There are three types of coding including: 1) open coding, 2) axial coding, and 3) selective coding (Appendix A). In this research, hermeneutic strategy was used as a first step to analyze members and researcher impressions followed by open-coding.

The hermeneutic method was used for data ordering according to the researcher's theoretical position and by comparing one text with another, which allowed the researcher for a deep understanding of the process, given the reinterpretation of the parts. Afterwards, Open Coding

method was applied where the researcher read the data to distinguish segments. Each one was labeled with a "code," and then words and phrases were labeled in the transcript to inform the research objectives.

#### 3.3.5 **Prototype Working Version (Version2)**

Based on the member check results the researcher developed the second version of the tool. The tool environment remained proscriptive; where inappropriate actions are prohibited, while not limiting the means or order in which tasks are performed. This maintained the creativity and control of the designers over their design decisions.

#### 3.4 Immersive Case Studies Overview

Yin (2013) defines the scope of a case study as "an empirical inquiry that: investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (p.12). The purpose of a case study method was described by Yin's typology (Appendix A) into descriptive, explanatory, and exploratory or combined. A case study can be: 1) quantitative, where the main focus is on numeric data, and results are sets of statistical analysis and conclusions for this particular case or 2) qualitative, where the primary characteristic is to focus on a single or multiple cases which are studies in their original settings including their surrounding dynamics.

In this research, the case study followed a qualitative approach where a case design problem and observed data were recorded and examined then conclusions were drawn. It was used as a demonstration of how the tool fits in the main process. Moreover, the case study in the research represented a combined (descriptive and explanatory) approach where theory development is an essential guide while the open-ended and broad focus of the case study was recognized.

#### 3.4.1 Case Study Selection

The case study method is considered useful in this research as it enables designers to reconsider their design proposals through representation. The purpose of the case studies was to examine the tool impact on the design decision-making, especially when visual discomfort evaluations occur early in the design process. To achieve this goal, some desirable characteristics of the examined space are required, including 1) a partially or entirely daylit space and 2) a transitional space that could be an entrance, lobby, a corridor, or a staircase for adequate light adaptation. In this research, two case studies were used to examine visual comfort in daylit interior spaces. They aimed at understanding how decisions are made through the utilization of the tool.

The first case study was a typical daylit office space. The case study evaluation results were shared with a group of professionals using a Delphi process (section 3.6). Feedback from these professionals was collected and served as a source for reliability and validity of the tool impact on design decision-making.

The second case study was as an as-built daylit museum space. The researcher collaborated with a group of experts during the visual comfort evaluation and decision-making process. The collected data was subdivided into quantitative and qualitative analysis. First, the selected asbuilt space served as a source of quantitative luminance and illuminance data that were compared with the tool output. This comparison helped to support the reliability. Second, through collaboration and immersion into a design project, the case study provided a qualitative assessment of the impact on design decision-making as shown in Figure 3-2.



Figure 3-2: Case study method overview

#### 3.4.2 Quantitative Evaluation of Case Study Data

To achieve qualitative analysis in both case studies, some quantitative evaluations took place first including: 1) space illuminance evaluation using the 3D model: the in-situ condition/base case illuminance was calculated and checked whether they met the useful daylight illuminance indexes thresholds. The condition with the maximum illuminance (i.e. date, time, and location peak case) was considered for further luminance evaluation (or the peak case). 2) Luminance evaluations were rendered from the visualization images for the selected peak case. 3) Multiple design alternatives were proposed to the in-situ condition/base case to minimize visual discomfort. 4) Alternatives were compared to detect the condition with the minimal glare (i.e. the modified case). 5) Finally the modified case's glare and visual discomfort were compared with the base case to examine visual comfort improvement as shown in Figure 3-3.



Figure 3-3: Case study visual comfort evaluation overview

### 3.4.3 Qualitative Evaluation of Case Study Data

Before being able to quantify the analyses, the researcher had to collect qualitative data during the case study feedback stage. The case study feedback can be divided into multiple phases: 1) during the first case study, the researcher's impression was recorded in a journal. The reflexive interpretation by the researcher helped make important while using the tool. 2) During the second case feedback from a purposeful sample of members was collected from interviews.

In this research the members' impressions and the researcher impression were analyzed using the following steps: 1) data reduction, 2) developing or choosing a coding scheme or formalism, 3) analyzing evidence in the coded protocols that constitutes a mapping to some chosen formalism, 4) seeking patterns in the mapped formalism, and 5) interpreting the patterns (Hasson et al., 2000).

# 3.5 Reliability and Validity Check of the Prototype Outputs

In order to compare the results in a reliability and validity check, quantitative data was collected from: 1) in-situ information (illuminance and camera images) obtained from the building and 2) computer simulations (i.e. simulated illuminance and images) collected from the 3D model, as shown in Figure 3-4.



Figure 3-4: Quantitative comparison overview

### 3.5.1 **Comparison of Illuminance and Luminance**

Measured and simulated illuminance values were compared using statistical analysis. Camera images and virtual images glare metrics were compared using statistical analysis.

Although the reliability and validity check presented a quantitative aspect of the research, the researcher maintained a qualitative reliability aspect using her notes, observations, and confirmability.

# 3.6 Delphi Feedback

The Delphi is a technique used by researchers to help improve the accuracy, credibility, and validity of a study or a prototype (Bellia et al., 2008); (L McCOLL and A VEITCH, 2001). In this research, the Delphi took place with a small group of purposefully selected members. Their impression of the tool was based on a thorough description of the second case study.

#### 3.6.1 Delphi Consensus Measurement

The goal of the Delphi study is to reach consensus, which means that there is general agreement about a given statement (Sumsion, 1998, CRISP et al., 1997). It can result in a quantitative indicator of consensus. The Delphi allows the members to be gradually swayed by the majority but without direct pressure. Many criteria have been used to measure consensus. In this research, the following steps were used to achieve consensus: 1) stipulated number of rounds, 2) cut-off rate, or the average percent of majority opinions (APMO), 3) statistics (using central tendency and Kendall's W coefficient), and 4) post-group consensus, as discussed in detail in Chapter-7.

### 3.6.2 Members' Feedback vs. Delphi Technique

As this research used both qualitative and quantitative methods, the researcher used both members' feedback and the Delphi technique to check and verify her data.

- **Delphi technique:** Based on the principle that decisions from an organized group of individuals are more accurate than those from unstructured groups or individuals. The experts answer questionnaires in rounds. In this research, after each round the researcher provided a summary of the experts' answers and the reasons they provided for their judgments.
- **Members' Feedback:** Examines the learned lessons from individual feedbacks, captures the process and summarizes it. In this research, the researcher presented the tool to a few participants individually to evaluate the usefulness of the tool as part of the immersive case study and the prototyping process, as shown in Figure 3-5.



Figure 3-5: Member feedback vs. Delphi techniques

Since stakeholders' opinions represent a significant factor in the qualitative research and prototyping process, feedback from purposefully selected members of the design community was collected and interpreted four times during these stages, based on: 1) the preliminary daylighting

tools questionnaire, 2) interviews member checking, 3) members' impressions from the case study, and 4) the final Delphi survey. After each stage, the researcher readjusted the tool based on the participants feedback during the process as shown in Figure 3-6.



Figure 3-6: Prototyping feedback different stages

# 3.7 Chapter Summary and Conclusion

The study of visual comfort is a significant matter when designing spaces. To this end, a design assistance tool is proposed to evaluate a given space from the visual comfort perspective by analyzing a range of simulated daylighting conditions. To achieve this goal, the research method essentially followed a qualitative approach with some quantitative aspects. In general, the qualitative approach consists of the logical argumentation prototyping and interpretivism using member checking, and an immersive case study strategy (discussed in Chapter 4). The quantitative approach involved the comparison of in-situ measurements with simulated outputs for reliability and validity check and the Delphi consensus analysis.

*"The experience is about how we get there, not the landing place."- Bill Buxton* (Buxton, 2010)

## 4.1 Introduction

As the primary objective of the research is to help improve design decision-making, a prototypical representation tool that considers visual comfort and glare was developed to achieve the research objective. The new prototypical tool considers time and space dynamics in daylit spaces to help designers make better-informed decisions. The research outcomes are expected to help researchers, designers, and decision makers with an approach to designing through re-imagining spaces and improving visual comfort and the quality of the place.

In this chapter, after briefly introducing prototyping as a research method, the four beginning stages of developing the prototype tool were described, including: 1) the preliminary daylighting survey, 2) logical argumentation that explored software configuration and visual comfort metrics, 3) the initial prototype (version one) developed from the literature review and the survey responses, and 4) the first round of member checking was used to test the initial prototype efficiency. The process of generating the second prototype version from the members checking feedback and the survey results will also be breifly discussed by way of a conclusion. The aim of this evaluation is to examine the tool effect on the design process and decision-making as shown in Figure 4-1.



Figure 4-1: Prototyping stages overview

# 4.2 **Prototyping as a Research Method**

A prototype was identified by Guha et al. (2004) as a model of a system with a particular purpose used by the designer to help solve design problems. In this case, prototyping could be utilized to reveal the strengths and the weaknesses in the context of how the tool would be used. Guha et al (2004) suggested a multi-staged prototyping process, with which the researcher applied the developing of the prototypical tool. As a framework, the researcher further adapted these stages of prototyping for use in this research into four essential steps: 1) identifying the user requirements, 2) developing the initial prototype, 3) matching the features of the prototype to the user needs, and 4) revising and enhancing the prototype. Stages three and four continually inform each other based on an analysis of member feedback as shown in Figure 4-2 and described in detail in the following sections.



Figure 4-2: Prototyping process essential characteristics

# 4.3 Stage One: Preliminary Daylighting Tool Survey

Survey questionnaires often seek to draw conclusions and to make recommendations using statistical analysis. Surveys depend on proper sampling of a population to draw inferences (Bargary et al., 2015). Although survey questionnaires are considered to be a quantitative research method, they can be informed by qualitative research (Jakubiec and Reinhart, 2010).

To understand the audience needs for this research and to verify findings from the literature review, a questionnaire was developed and executed with a purposeful sample of stakeholders.

The questionnaire was used to gather information about the design process; participants were asked to answer questions about their design experience and decision-making tactics. The questionnaire had four basic purposes: 1) collect the appropriate data—the collected data related to the research question on daylighting analysis software, difficulties facing the users and suggestions for enhancing existing software, 2) make data comparable and amenable to decision-making, 3) minimize bias in formulating and asking questions, and 4) make the questions engaging and varied (SareyKhanie et al., 2011).

#### 4.3.1 **The Objectives of the Survey**

The survey focused on design practitioners who integrate daylighting analysis in their design decision-making. It also aimed at: 1) understanding the barriers that prevent design professionals from using daylighting simulation software, 2) examining when daylighting simulations take place in the design process, 3) exploring the key reasons for not including daylighting simulation in the design process, and 4) providing feedback and guidance for the research.

#### 4.3.2 Survey Process

The average time to complete the survey ranged from two to ten minutes based on the participants' answers. The members of the study included architects, engineers, architecture researchers, and daylighting and building consultants. After receiving the IRB approval, the online responses to the survey were solicited from list-serve distribution to selected AIA chapters and VT Ph.D. students, in addition to through the professional connections of the researcher.

#### 4.3.3 Survey Questions and Responses

The survey questionnaire was structured into two parts. The first part investigated the participants' background. The second focused on the participants' use of daylighting simulation tools. For those that reported to not be considering daylighting during the design process, they were asked about the reasons for not including such consideration. For the participants that reported using daylight analysis in their designs, they were directed to Part Two of the survey as shown in Appendix B. Participants were encouraged to add comments and suggestions. A total of 218 responses were collected.
#### 4.3.3.1 Questionnaire part one

The objective of the questionnaire part one was to examine the participants background including profession and types of projects they had work on. It also invetgigated the percentage of the participants who integrate daylighting studies in their design process, as shown in Appendix B.

- **Participants' background:** The results showed that architects represented 53% of the sample, with engineers (11%), researchers (7%), consultants (6%), students (8%) and other professions including interior designers, builders, contractors, energy raters and lecturers (7% total). Participants were found to be working on a variety of projects including residential, commercial, educational, industrial, museums and art galleries.
- **Daylighting analysis integration:** It was found that 90% of the participants included daylighting analysis in their design process. However, the survey did not investigate how daylighting was considered and how that could affect the design process. Those not using daylight analysis were primarily involved in residential projects. Responses showed that 40% who answered that daylighting analysis was not considered in the design process stated that "daylighting analysis is not required by the client"; 22% of the participants indicated that "the tools are intended for daylighting experts." Other reasons included: "unfamiliarity with various tools and uncertainty for which one to use" (7%) and "tools are hard to learn" (11%). Some participants also indicated that "the tools results are not accurate" (5%).

#### 4.3.3.2 Questionnaire part two: simulation software

The objective of part two was to investigate the methods used by the participants for daylighting analysis (i.e. computer software, physical models, or sketches). It also examined when daylighting studies take place. Finally, it looked at the value of various indexes and metrics, and the most desirable forms of outputs, as shown in Appendix B.

- The Daylighting analysis in the design process: The majority of participants (91%) indicated that daylighting analysis is necessary for the conceptual and schematic design stages while the rest believed that it should occur in all phases of the design process.
- **Daylighting simulations output:** The survey findings showed that architects would prefer graphic outputs (38%). By contrast, engineers preferred quantitative outputs such as the

daylight factor and illuminance values (72%). The rest of the respondents were equally divided between daylight factor, daylight autonomy, and "I do not know" as shown in Appendix B.

#### 4.3.4 Survey Conclusion and Summary

The survey suggested that the following should be considered when designing the prototype: 1) daylighting analysis was considered important in 91% of the responses, 2) designers and decision-makers preferred daylighting analysis to take place early in the design process, and 3) architects preferred visual outputs over numeric, while engineers and researchers preferred numerical outputs. Although a large number of participants indicated that they introduce daylighting analysis in their designs, further responses showed that 4) a significant number of these members were not familiar with the most common daylighting analysis metrics. One useful conclusion that can be drawn from these responses is that some of the daylighting analyses may not be accurate or be based on valid daylighting metrics.

Participants proposed suggestions for future iterations of the tool including:

- Investigating the interactions of daylighting analysis and energy modeling on the decisionmaking processes ("Often daylighting is done as an afterthought and energy modeling inputs are not well understood by the modelers, who are usually mechanical or electrical engineers, not the building designer, and therefore, the inputs are limited to the modeler's field of discourse").
- When investigating heat and solar gain effects in daylit spaces ("Daylighting and solar gain have to be considered together").

# 4.4 Stage Two: Logical Argumentation

Arguments are chains of reasons leading to a conclusion with consideration of potential counterarguments at each step (Kleindienst and Andersen, 2009). In this way, logical argumentation was used in this research due to its ability to present knowledge and commonsense reasoning. The researcher used reasoning steps to generate conclusions from the proposed assumptions on software configuration and visual comfort evaluation metrics as discussed in the following sections.

#### 4.4.1 Software Configuration

Multiple software were used in the development of the prototype. Each component is examined using a series of statements to establish a proposition supported by a set of assumptions, as shown in the prototype components structure in Figure 4-3.



Figure 4-3: The Prototype Components Overall Structure

### 4.4.1.1 Rhinoceros (Rhino)

Rhinoceros (Rhino) is a 3D computer graphics and computer-aided design (CAD) application software. It is based on the NURBS mathematical model, which focuses on creating mathematically accurate representations of curves and surfaces (McNeel, 2014). This software was selected for the prototype tool because daylighting analysis needs a 3D model as the basis for architecture space re-imagination and because Rhino supports various 3D model and image file formats commonly used in architectural design without the need for third-party plug-ins. Moreover, the Rhino Evaluation version is free and does not require licensing. For these reasons, Rhino was used in the research for importing the 3D model.

### 4.4.1.2 Radiance

Radiance is a ray-tracing software developed with the primary support of the U.S. Department of Energy and the Swiss Federal Government. Because Radiance has no limitations for the space geometry or the materials simulated, it can evaluate daylighting systems and can be used by architects to predict visual quality and appearance of proposed spaces (Larson et al., 1998). Most importantly, Radiance has undergone many validation studies and has been proven to have high accuracy when compared with existing conditions (Grynberg, 1989, Reinhart and Andersen, 2006). For these reasons, Radiance was selected as the primary simulation software to allow for design flexibility and minimal restrictions

### 4.4.1.3 *Excel*

Excel is a spreadsheet application by Microsoft. Because Excel can easily and quickly display data as line graphs, histograms, and charts, it was used for data representation and to run basic statistical analysis on the data (Jacobson, 2007).

# 4.4.1.4 Parametric design (Grasshopper-GH)

Grasshopper is a visual programming language developed by David Rutten at Robert McNeel and Associates for parametric analysis of designs as shown in Figure 4-4.



Figure 4-4: Grasshopper interface

Since parametric design involves the analysis of alternatives based on a set of criterion (McNeel and Associates, 2007), then it was assumed that it can support design decision-making. Moreover, since Grasshopper runs within the Rhinoceros 3D-CAD application, it can also be used to build generative algorithms. Also, because scripting components can be added using VB DotNET and C# programming languages it can accept a broad range of plug-ins. For these reasons, Grasshopper was considered as an important component of the prototype.

#### a. DIVA-GH

DIVA is a daylighting and energy modeling plug-in for Rhinoceros software that interfaces with Radiance (Harvard, 2006). Since the DIVA for Grasshopper plug-in runs through Rhinoceros and allows users to carry out a series of environmental performance evaluations, which represents the main aspects of visual comfort, then it was used in the prototype to produce climate-based daylighting metrics and glare analysis.

#### b. Hoopsnake-GH

Ease of use and automated looping is a key factor in the prototype since it allows the designer to run multiple analyses and simulations faster and without continuous interactions with the software. Therefore, Hoopsnake (a GH-plug-in) was used to loop through the days and hours when simulations are performed (McNeel and Associates, 2007); (Chatzikonstantinou, 2015).

#### c. Ladybug and Honeybee-GH

Ladybug and Honeybee are two plug-ins for Grasshopper that help designers easily create and export rendered images to Evalglare, they were used for glare image evaluation (Roudsari and Pak, 2013).

#### d. Ghowl-GH

Ghowl is a plug-in for Grasshopper that consists of a set of components to help Grasshopper communicate and exchange data and information with other applications. For example, Excel can run through Grasshopper using Ghowl, which allows for the writing of a spreadsheet file (Fraguada, 2015). Since Ghowl can connect Grasshopper with Microsoft Excel, then it can export and import data for analysis and representation. For this reason, it was used in the prototype to facilitate data examination and illustration.

#### e. Horster-GH

Horster-GH is a plugin for Grasshopper was used in the prototype since it allows for camera control in Rhino viewport via Grasshopper.

# 4.4.1.5 Evalglare

Evalglare is a command line based tool to evaluate glare within a given image, primarily from daylit scenes (Suk and Schiler, 2012). Because Evalglare can provide accurate results for the luminance glare metrics (DGP and DGI) and because Evalglare can run through Grasshopper, then it can be used for image-based glare evaluation. For these reasons, it was employed in the research for glare image analysis.

A summary of the selected software employed in the prototype is shown in Figure 4-3 and Table 4-1:

Used Software	Purpose	Description	
Rhino	3D- Modelling input	It can read most known 3D-Model files including .3ds,	
		.3dm, .dwg, and .skp	
Radiance	Daylighting simulations	Validated simulation software to evaluate daylighting.	
Microsoft Excel	Data analysis and	A spreadsheet application by Microsoft used for data	
	presentation	analysis and presentation	
Grasshopper(GH)	Parametric design and	Parametric design allows for multiple design changes	
	software connection	and modifications.	
-GH-plug-in	-Daylighting	-Connect Grasshopper with other software to analyze the	
	simulations	data	
EvalGlare	DGI Calculation	Evalglare is Radiance based software. It can detect glare	
		sources	

Table 4-1: Selected simulation software configuration

# 4.4.1.6 **Operating system**

Since Rhino is not available for the Linux platform and is not supported by Mac, Windows was the only operating system that could be used for the prototype. Table 4-2 summarizes some of the considerations associated with each software product or sub-component:

Table 4-2: Softwar	e Configurations
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Software used	Windows			Mac
	Pros	cons	Pros	cons
Rhinoceros	-There is a	Not all designers		-Rhino for Mac is
	Rhinoceros version	use rhinoceros		an ongoing
	for Windows			development project.
Grasshopper-	-Grasshopper			-No version of
GH	originally runs on			Grasshopper runs
	Windows			on Mac

Software used	Windows			Mac
Radiance	-Radiance	-Radiance	-The program has	-Radiance
	Windows installer	runs primarily and	been compiled	runs mostly and
	is provided	faster on Linux	on Mac	faster on Linux
Evalglare	-There is a		-Evalglare	-Software must be
	Windows Version		installation is	compiled first
	from Evalglare		available on Mac	
Excel	-Excel is originally	-Files created in	-Microsoft Excel	-Microsoft is
	a Windows-based	GH need to be	is available for	originally windows
	software	exported to Excel,	Mac	software and runs
		which takes time		easier on it

Because the selected software can run easily on Windows and because the researcher has better knowledge when using Windows-based computers, Windows was selected as the tool operating system.

# 4.4.2 Visual Comfort Evaluation Metrics Argument

Several factors affect visual performance, including lighting level, uniformity of illuminance, color rendering, avoiding hard shadows, contrast rendition, physiological glare, balanced brightness distribution, luminance levels variation, discomfort glare, illuminance uniformity in the area around the visual task, and the balance between artificial lighting and daylight. The literature found that researcher cannot depend on a single metric to investigare all the aspects of a daylighting system. Moreover, most of the indices examined in previous research were devoted to predicting glare, the daylight distribution, the light quality, and distribution (Carlucci et al., 2015), consequently, metrics representing these different aspects were used as shown in Figure 4-5.



Figure 4-5: Visual discomfort examined aspects

Regarding glare evaluation, the tool used the Daylight Glare Probability (DGP) and the Daylight Glare Index (DGI). For light quality, the luminance ratio was used. Finally, the Useful Daylight Illuminance (with illuminance distribution) was used to evaluate the daylight distribution and light distribution in space as shown in Figure 4-6 and argued in the following sections.



4.4.2.1 Light distribution: Illuminance based evaluation

Because short execution times are necessary to provide feedback and decision-support promptly to the designer during the early stages of design, and because illuminance simulations consume less computing time when compared with luminance image simulations, illuminance metrics were applied as the first step for visual comfort evaluation.

# • Useful daylight illuminance (UDI)

Because the Useful Daylight Illuminance can quantify both over-lit and under-lit conditions, it can provide valuable information on the light distribution in the space. Consequently, UDI can be suitable for both short and long-term evaluation—especially when excessive sunlit penetration may cause intense glare. Because UDI is based on spatial renderings for every point on the calculation grid, it can be used to ensure that all of the simulation points meet the illuminance guidelines as suggested by Yin (2008). For the first version of the tool, UDI was tested on the solstices and equinox days only.

#### 4.4.2.2 Glare: Luminance based evaluation

The luminance evaluation took place for the peak illuminance areas and times. Future versions of the tool may utilize hourly luminance calculations as computer processing speeds increase. However, due to the limitations of current processor speeds available, results are based on the peak condition(s)-only simulations for the tool. The process of identifying glare conditions requires the implementation of one or more metrics with associated threshold levels. The following sections argue for the luminance metrics used in more detail.

# • Daylight Glare Probability (DGP)

Because comfort is defined according to user satisfaction and glare is a relative sensation and differs from one person to another, then probability distribution is a reasonable approach for predicting comfort. Because the literture review showed a strong correlation between the DGP and the occupants satisfaction, the DGP was used as a visual comfort indicator in the prototype.

### • Daylight Glare Index (DGI)

Daylight Glare Index (DGI) is a visual comfort metric that considers large glare sources (e.g. the sky viewed through a window). Because the DGI can be calculated using the Evalglare software based on the luminance of the image, date/time and sky conditions, and the materials properties of the interior finishes, and because the DGI can be normalized and compared with the overall DGP average as shown in Table 4-3 (Jakubiec and Reinhart, 2011), it was used in the prototype for an easier representation of the glare condition.

#### Table 4-3: DGI thresholds

DGI-effect	imperceptible	Perceptible	disturbing	intolerable
Value	< 18	18 – 24	24 – 31	> 31
Normalized value	<0.26136	0.26136-0.34848	0.34848-0.45012	>0.45012
(*0.01452)				

### 4.4.2.3 Light quality: Luminance based evaluation

Since light color and contrast are two main factors affecting the light quality, and since the light quality indexes that evaluate the color are typically used to only evaluate artificial lighting, their main reference light is daylight (i.e. Color rendering index, Color Rendering Capacity, Pointer's color, Color Preference Index, and Color Rendering Capacity) (Thornton, 1972); (Xu, 1984); (Pointer, 1986, Barbrow, 1964). Image contrast was used as a metric for daylight quality evaluation.

# • Luminance ratio

Previous research identified several luminance ratio guidelines applied to the three zones of the visual field (central, adjacent, and the non-adjacent). From this including luminance ratios of 1:3:10 identified by Osterhaus (2002), while Linney (2008) and Parpairi et al. (2002) argued that occupants can tolerate a ratio of 1:40 and up to 1:100 between the central zone and the surroundings, and a ratio of 1:3 for the visual task and immediate surroundings. Of these, this research used the ratio of 1:3:10 as a threshold value.

# 4.4.2.4 High Dynamic Range (HDR) imaging and Fisheye Lens

Previous research by Evans (1981) suggested using a modified human visual field with a fisheye lens. The modified visual field is cropped to match Guth total field of view as shown in Figure 4-7. The same research found that HDR photography was a more reliable method for luminance-based measurement. Consequently, the fisheye lens and the HDR images were used in this research for luminance-based image evaluation.



Figure 4-7: Modified fisheye lens glare analysis

### 4.4.3 **Placement of simulation points argument**

Simulation points were placed at the eye level of within the height range of a typical adult male along the circulation path. The placement of these points was intended to capture glare and discomfort that might occur along the path. Using these simulation points had two main functions: 1) to determine the illuminance values along the circulation path (for illuminance glare analysis) and 2) to simulate the visitors' visual field (for luminance glare analysis).

# 4.4.3.1 Vertical placement of simulation points

The average human height varies based on age and gender. A study by Openshaw and Taylor (2006) examined the standing eye-level height of women and men were found to be 4.7- 5.4 ft and 5.1-5.8 ft., respectively. As a result, the average standing male eye-level height used in this study was at 5.5 ft. For the sitting position the average eye height was 4.0 ft.

# 4.4.3.2 Horizontal placement of simulation points

Points were placed on the circulation path to capture the visitors' visual field every second based on the average speed of a walking adult (Knoblauch et al., 1996). A study by TranSafety (1997) showed that small differences ( $\pm 0.37$ seconds) occur depending on age and gender with an average of 4.5 feet per second. For this reason, the average pedestrian speed was used in the study and simulation points were placed horizontally at equal intervals equal to 4.5-foot intervals.

Based on the above information, simulation points were placed horizontally along the circulation path at 4.5-foot intervals and vertically at 5.5 ft (Travel, 2006).

# 4.5 Stage Three: Development of the Initial Prototype

The initial prototype aims to represent glare and visual discomfort conditions that may occur in a daylit space. The process of implementing the prototype was structured into four main steps: 1) Data input, 2) Analysis and simulations, 3) Evaluation of visual comfort condition, and 4) decision-making. The prototype was configured with multiple software that were used to evaluate visual comfort as illustrated in Figure 4-8. The design framework when using the tool is explained in detail in the following sections.



Figure 4-8: Analysis programs workflow

# 4.5.1 Data Input Module and Form Generation

The data input module is the module where the designer provided design information. The input module was intended to serve the tool objective regarding the dynamism of the sun and its relation to the building as a key factor when evaluating glare as summarized in Table 4-4. The main designer inputs are:

1) A 3D-Model with Materials Properties: The tool accepted as input 3D models for the space created in any 3D-modeling software and exported to Rhinoceros. The most common 3D-

modeling extensions are .3dm or .3ds formats because they can be created and/or exported from the majority of 3D modeling software. A generic material file included in the DIVA plug-in was used; it included generic materials with properties such as transparency, color, and reflectance. Custom RADIANCE materials can be added to the original file in future tool versions.

2) Building Site Geographical Location: Locally recorded weather data from preselected "typical" years is a significant input because each geographical location has a different sun orientation and sky conditions.

3) Sky Condition: The default "Clear sky no sun" was used in this tool version because glare problems are typically higher in clear sky conditions. Also, sun penetration is hard to predict, especially in the early stages of the design when no adjacent buildings, space furniture, or vegetation are present. However, in the following tool versions, the designer could select other sky conditions including overcast, uniform, and clear sky with the sun.

4) Simulation Hours and Days: Since annual simulation is time-consuming the initial tool prototype simulated only three full days (two solstices and one equinox) from 9 AM to 6 PM; The solstices selected include one full summer day (June 21<sup>st</sup>) and one full winter day (December 21<sup>st</sup>). Also, one equinox (March 21<sup>st</sup>) was simulated. However, the next versions of the tool would provide annual and customized days and hours for illuminance and luminance simulations.

5) Building Orientation: The building floor plan was oriented in Rhino with the default north as looking up, similar to the default architecture plan north direction.

6) The Examined Circulation Path and Points: As previously discussed in Chapter 3, the simulation path was determined with selected simulation points placed horizontally at eye level and vertically based on the average pedestrian walking speed. Simulations were performed along the path every one second (Araji et al., 2007). A summary of the data input module components with associated software is shown in Table 4-4.

#### Table 4-4: Framework data input

Variable	Description	Software used
Geographical location weather	The weather file was selected based on the geographical location. Weather files can be downloaded from <u>http://apps1.eere.energy.gov/</u> <u>buildings/energyplus/weatherdata_about.cfm</u>	
Sky condition	Clear sky without the sun was the default	]
Date and time (mm dd hr):	Equinox and Solstices simulations were the default.	DIVA Grasshopper
Materials properties	Generic DIVA plug-in materials	
Building orientation	Rhino software default north (pointing up) was used	Rhino
Building geometry (3D- model)	Building geometry and surroundings were exported to Rhino where Grasshopper (Rhino plug-in) could run a series of evaluation simulations. Geometry can be saved and exported to Rhino.	Rhino, accepting exported files from (3D-max, CAD or Sketch-up)
Simulation points/path	A circulation line or curve in the 3D-model. Simulation points were placed horizontally at the eye level and vertically based on the average pedestrian speed.	Grasshopper and Rhino

# 4.5.2 Generating Illuminance Data

Previous research by Plympton et al. (2000) simulated the average daylighting illuminance between the summer solstice and the months of May and July. The research results showed that the solstice can represent the most acute sun angels. Equinox and Solstices illuminance data were generated using DIVA-GH (Radiance interface in grasshopper). After that, Hoopsnake-GH-plug-in was used to loop through the default days and hours (McNeel and Associates, 2007).

# 4.5.3 Analyzing Illuminance Outputs

Illuminance data were exported to Microsoft Excel for analysis; peak conditions were identified and exported back to Grasshopper for further luminance analysis.

# 4.5.4 Generating Luminance Data

After Ghowl exported the peak condition(s), day(s), and time(s) to GH luminance data were generated through a DIVA-GH visualization simulation to produce an HDR image. An animated camera was placed on the circulation path at the peak point(s) using Horster-GH-plugin. The HDR image Glare evaluation was generated through the Ladybug/Honeybee GH-plug-in that interfaces with Evalglare.

# 4.5.5 Visual Comfort Evaluation Module

The examined space was considered comfortable when luminance based glare metrics (DGP DGI, and contrast ratio) thresholds were satisfied or not exceeded. Based on the evaluation results, visual comfort conditions (intolerable, perceptible or subtle) are presented as output.

# 4.5.6 **Designer Decision Module**

The proposed tool aims at decision support and it therefore is not intended to make design decisions. These design recommendations may be proposed to be applied to design changes in order to meet a prescribed visual comfort levels. The goal of these recommendations will be to introduce the designer to possible solutions, while final design decisions will still be left to the designer. However, because possible design alterations are endless, decisions concerning design modifications can be the focus of the future tool development.

# 4.5.7 **Prototype Framework Summary**

In this section, a summary of the selected visual comfort metrics and thresholds values are presented in Table 4-5. The prototype process flow is illustrated in Figure 4-9.

<b>Evaluation Index</b>	Applied Threshold	Description	
	Illumi	nance based	
Useful Daylight	50 <udi<2000 at<="" lux="" td=""><td>These can be considered as the visual system limits,</td></udi<2000>	These can be considered as the visual system limits,	
Illuminance (UDI)	least 50% of the time.	beyond these values the visual system cannot	
		comfortably function	
Luminance based			
Contrast luminance	95% of the points are	Previous research used different ratios depending on	
ratio	≤1:3:10	the required effect and function	
Daylight Glare	If $DGI > 31$ Intolerable,	DGI was originally based on an artificial light which	
Index (DGI)	< 18 Barely Perceptible	was considered a limitation when using DGI	
Daylight Glare	Imperceptible $\leq 0.33$	It uses total eye illuminance as a measurement of glare	
Probability (DGP)		caused by bright scenes; consequently, it produces	
		reasonable glare predictions for all view directions	

Table 4-5: Selected visu	al comfort indices and	thresholds values
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Figure 4-9: The prototype framework summary

# 4.6 Stage Four: Member Feedback

Following the development of the initial prototype, feedback concerning its usability was collected from a purposeful sample. The prototype was demonstrated to each participant through a one-on-one interactive session that lasted about forty-five minutes. During this process, the participants were interviewed through a series of open-ended questions as shown in Appendix C.

### 4.6.1 Interview Member Selection

Although interviews are widely accepted and are one of the most frequently used methods of data collection for qualitative research, there is little written on the appropriate sample size. Previous research by Islam et al. (2006) argued that the sample size depend on "theoretical saturation," which means that the researcher continues expanding the sample size until data

collection provides no new data. Research by Pesudovs et al. (2002) recommended a smaller number of interviews with more focused research questions.

Because this stage of the research focused on the usability of the tool, a purposeful sample of five stakeholders who share the benefits of the tool, and feedback was collected from those who were interested in the results. Such a small group allowed for more in-depth questions and one-on-one interaction. The focus group was represented by two daylighting expert, two architects, and one Ph.D. lighting research student. All five interviewees shared a good understanding of daylighting analysis.

# 4.6.2 **Interview Objective**

The main goal of the interviews was to collect members' feedback to improve the prototype. The interview data also allowed the researcher to develop a deeper understanding of the research question and role of the tool in the design process.

# 4.6.3 Interview Procedure Overview

Five independent interviews took place—three by phone and two in person. First, the researcher explained the interview process and objective to each participant. After that, she asked a set of open-ended questions to collect the participant's feedback based on his/her understanding. The questions focused on the participant's opinion and thoughts to permit spontaneous and unguided responses. When applying the member checking tactic, a set of questions was developed to structure the interviews as shown in Appendix C and summarized in Table 4-6:

<b>Research Question</b>	Definition	Interpretation
What is being	What is being "checked" is how	The initial claim was "the proposed tool
checked?	the researcher has "seen" the	framework may help designers make better-
	situation?	informed decisions."
With whom are	Who are the relevant	The members were: a daylighting expert, an
you checking?	"members" and what is their	architect and an interior designer with
	relation to your research topic?	daylighting analysis knowledge, all had a with a
		daylighting analysis expertise.
How would you	From the members' responses	The researcher repeated his understanding of the
interpret	the researcher starts to detect	responses of the member for interpretation.
agreement?	agreement "between the lines."	Also, the researcher categorized the answers to a
		set of themes.

 Table 4-6: Member feedback questions to inform the process

<b>Research Question</b>	Definition	Interpretation
What follows if	The researcher needs to be	If the members agreed on the ability of the
"they" agree?	prepared for the next step if the	proposed tool's framework to assist the designer
	members agreed.	in decision-making, the researcher may pursue
		the next step: the immersive case study to
		examine the tool application in the design
		process.
How does one	There are two situations to	As a final step in the interview process, the
interpret	consider: everyone disagrees	researcher re-stated the final participant opinion.
disagreement?	with the researcher, or there is	If a conflict occurs between members, it will
	disagreement among members	need to be examined separately.
	on the researcher interpretation.	

### 4.6.4 Interview Questions

The interview questions primarily focused on the graphic user interface, and the researcher gave a short presentation to each member to demonstrate the tool. The interview questions were categorized based on different phases of the tool (as shown in Appendix C) as 1) General graphical user interface, 2) Instructions and help menus, 3) Input data, 4) Evaluation process, and 5) Final feedback concerning efficacy for decision-making.

For each category, a set of questions evolved as shown in Figure 4-10. The questions investigated the members impression of the tool's different components, main areas of improvements, members ability to understand the inputs, the evaluation process and outputs, the final visual comfort condition evaluation and its effect on design decision-making, and the instructions and help menus. At the end of the interview, the interviewer (i.e. the researcher) gave the members a chance to add additional thoughts and suggestions for tool improvement.



Figure 4-10: initial prototype interview questions

### 4.6.5 Interview Data Collection

Data was collected during the interview using: 1) audio recordings transcribed into written texts and 2) the researcher's notes and observations used to supplement and clarify data derived from the interviews. The notes included the participants' facial expressions, comments, and questions during the meeting and body language reading when the tool interface tutorial was presented. Other notes focused on the participants' ability to understand the GUI. Additional notes regarding the interview environment and other nonverbal reading materials (e.g. interview location and time and overall participant comfort) served as indicators of a participant's experience. The data collected from the interviews was assembled into a single text for the analysis.

### 4.6.6 Interview Data Analysis

The data analysis followed six steps: 1) data familiarization, 2) records transcription, 3) data organization, 4) data coding, 5) themes identification, 6) report writing, and 7) researcher notes and journaling during the process.

### 4.6.6.1 Data familiarization

The aim of this stage was to become immersed in the data and more aware of the response process (Jacobson, 2007). The researcher listened to the interview recordings to familiarize

herself with the data and to start to identify general themes and take general notes—especially the ones she memorized that were not in the recordings including body language, interview environment, and facial expressions. Data familiarization conducted the following:

- Phone interview environments were comfortable for both the interviewer and the interviewees. Some took place in the interviewer's office (Interviewees 1, 3, and 5). While the in-person interviews took place in the interviewees' offices (Interviewee 2 and 4). The interviewer was comfortable to present the materials on her personal computer.
- Phone interviews body language and facial expressions were hard to record, but were concluded from the interviewees' ability to answer the interview questions and from their requests for clarification. The body language during in-person interviews was recorded, which gave a good overall impression that was recorded except for some moments where the interviewees seemed unable to understand some of the tool inputs and outputs and asked for clarifications as shown in Appendix C.

# 4.6.6.2 Data coding

Themes from the transcripts were developed using an open coding process (Richards and Morse, 2012). Labeling and categorizing helped the researcher to generate concepts while applying questions to break down the data: What are the main qualities of the tool? What are the major interface weaknesses? How can the tool's GUI be improved? How informative are the analysis outputs? Subsequently, data abstracted from the questions was compared. Similar ones were grouped together and given the same conceptual label: input /output comments, tool weaknesses, ideas for improvements, and general observations. The codes were expanded into words and phrases to inform the research question and objective. Similar transcripts were grouped and given the same conceptual label 4-7.

Table 4-7: Open coding examples

Interview transcript key quotes	Open coding
"interface is not very user-friendly."	Tool not user-friendly
"interface is not dynamic."	
"tool does not represent 3D animation."	
"does not attract me to use it."	
"more simplification of the tool is needed for it to be more user-friendly."	

"tool can alter the design process."	Tool may be beneficial
"this tool will be beneficial."	
"I guess with and future computing development it might be very beneficial."	
"the tool can expand to cover different topics."	Tool modification
"I guess a lot of improvement can be added."	
"future iterations and modifications."	
"it can be expanded."	
"Take the technical part away."	
"provide more guidelines for the architect."	GUI improvements
"Minimize the architect inputs."	
"instruction or guidelines to set up their models to take advantages of the tool."	
"a final report card with colors, graphics showing different areas."	

# 4.6.6.3 *Identification of the themes*

Previously identified categories were grouped into themes by collapsing similar responses and developing a list of categories. Questions lead to a series of themes: Two themes emerged from Question1 and Question2 on the graphical user interface:

- **Interface weaknesses:** Interviewee-1 mentioned the need for more interaction with the interface and that it needed to be more friendly and objective to dynamic light. Interviewee-3 stated that more simplification was needed with less technical information.
- **Improvement:** Interviewee-2 suggested including a tool name related to its objective. Interviewee-4 suggested incorporating some dynamic interaction, such as the ability to rotate and walk through the space and graphics during the simulation.

Two themes emerged from Question3 and Question4 concerning the Instructions and Help menus:

- **Interface weaknesses:** Interviewees-3 and 4 expressed their discomfort at the lack of "real" help menus and described the existing menus as "only definitions [that] do not help in the process and evaluation."
- **Improvement:** All interviewees expressed the need for more help menus explaining the definitions, especially simulation indexes, and evaluation outputs. To improve the instructions during the assessment process, Interviewee-5 suggested the use of video tutorials and especially basic examples for the download and installation process, and the potential applications of the tool. They also suggested a tutorial to help the user through the process and for understanding the outputs.

Three themes emerged from Question5 and Question6 on the input data:

- Qualities of the tool: Interviewees-1 and 5 expressed their ability to understand the required data inputs and parameters easily.
- **Improvement:** Interviewee-4 stated the need for more clarification of the inputs early in the tool introduction with a set of guidelines for the inputs (i.e. layers and materials organizations) to get all the benefits of the tool. Interviewees-2 and 3 described the need for the tool to read existing CAD layers and materials seamlessly with an option to modify or create new layers. They also indicated the importance of including a preset selection of days and times with the option to select custom times. They mentioned that a carefully selected set of days was a better option for the designer because the annual simulation is time-consuming and may have discouraged the user from using the tool.

Three themes emerged from Question7 on the evaluation process:

- **Improvement:** All interviewees described their need for additional help menus to understand the process better. Interviewees-3 and 4 expressed their concern for the metrics and thresholds and the reasons for using them and asked for a tab/explanation of why they represent the best options, which can help the designer better judge the tool's credibility.
- **Interface weaknesses and Improvement:** Interviewee-5 indicated that including multiple indexes in the evaluation may create differences between the thresholds; one may show subtle discomfort, and another can show imperceptible glare conditions. He suggested that the credibility and ability of the indexes to detect glare may have an effect on the final results, and this should be addressed in the working tool.

Two main themes emerged from Question8 and Question9 concerning the outputs and conclusions:

• **Improvement:** The interviewees expressed that graphical outputs are easier to understand when compared to numerical outputs. Interviewee-3 argued that numerical representation of the data needed to be an optional "external link" for the user wanting a further examination of the data. Also, Interviewee-1 suggested that an option for annual examination could be added if time allowed or if the detailed analysis was required.

• Qualities of the Tool and Improvement: Interviewee-5 mentioned the importance of the video representation of the glare condition with the option to add central vision "filters." He mentioned that the final representation of the visual discomfort condition could be better expressed as a chart. Also, Interviewee-5 suggested a "redesign" key on the tool evaluation page that allows the designer to go back to the original design to apply changes and redesign.

Two main themes emerged from Question10 and Question11 on improvements suggestions and general recommendations:

- Qualities of the Tool: All interviewees agreed that the tool could help designers in their decision-making process, especially in the early stages. Interviewees-3 and 4 indicated that the information for visual discomfort could assist the designer in evaluating alternatives and could help with decisions regarding furniture layout and space configurations.
- **Improvement:** Interviewee-4 mentioned that further improvements were needed to allow the designer to add furniture and vegetation. Also, Interviewee-3 indicated a necessity to simplify the interface and reduce technical information. All five interviewees indicated that the friendliness and ease of use the tool interface were key elements to encourage designers to use a tool.

A summary of the emerged themes and recommendations is shown in Table 4-8:

Feedback Category	Members feedback summary		
Graphical User	Tool not very user-friendly, more clarification needed, GUI needs to be more		
Interface	vibrant and attractive		
Instructions and help	More clarification is needed in the instructions, less technical details is		
menu	necessary, more help menus and tutorials are needed		
Input data	Less input is needed from the designer: auto insert for (layer names/geometry/		
	materials) according to folder path. Include visual representation of the input		
Evaluation	Minimize tool evaluation technical details, fewer evaluation indexes or indexes		
	summarizing may be required		
Output and conclusion	Suggesting of possible design solution may not be accepted by the designer		
Decision-making	The tool may be able to help design decision-making through the		
	representation of discomfort conditions		

#### Table 4-8: Members feedback summary

# 4.6.7 **Researcher Notes and Observations**

After each interview, the researcher transcribed her notes and observations and organized them into categories as summarized in Table 4-9 and presented in detail in Appendix C.

Category	Researcher notes/observations summary
Graphical user interface	Interviewees were somewhat puzzled about the interface, found it a new
	approach, need to be simpler
Instructions and help menu	Needed help understanding the process
Input data	Easy to understand
Evaluation and Output	Some interviewees needed explanation of the assessment process and
	outputs
Overall impressions/	Interviewees were overall satisfied with the tool new approach for dynamic
recommendation	light

Table 4-9: Researcher	notes and	observations
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### 4.6.8 Interview Limitations

Although the interview method has many advantages for collecting feedback from members, it also has some limitations:

- Open-ended answers were difficult to analyze. Interviewees can understand the questions differently, which may generate distinct responses.
- Some participants tend to ask questions during the interview process. It might be hard to compare their responses with those who did not ask questions.
- The interviews depended on the researcher's personal capabilities and her ability to perform reliable interviews.
- The interviews results depended on the participants' experiences. It may be unreasonable to compare participants' responses while each has a different level of expertise and knowledge related to the research topic.
- With qualitative interpretative research interviews, responses may be affected by the researcher's opinion—which might generate bias when interpreting the results.

### 4.6.9 Interview Conclusion and Recommendations for Prototype Version2

In summary, the participants agreed that the new tool was particularly effective to assist users. They believed that it achieved most of its goals to help designers and other users in evaluating the designed space's visual comfort and make informed decisions. The member check results and recommendations were used for the tool modification and adjustment to create the working version of the tool "Version2": The main recommendations taken into consideration for Version2 are shown in Appendix D and can be summarized as follows:

- A set of instructions and help menus and a series of tutorials on the installation process and the process of applying the tool were added to the interface.
- An auto-read of the existing CAD layers and materials was added with an option to modify or create new layers.
- Additional visual comfort assessment metrics were added to the tool evaluation (namely relative maximum luminance- RML) metric for light quality and annual illuminance for light distribution.
- A default annual illuminance simulation (typical occupied hours from 9am to 5pm) was added with options for faster simulations of the equinox and solstices, or specific days/hours.
- A help menu was added to include arguments for the metrics and thresholds.
- The researcher proposed a central vision area mask to help the designer recognize major sources of discomfort in the central visual field. The tool presented various visualization outputs based on the different discomfort indexes including DGI and DGP with highlighted discomfort zones. Finally, a video animation was generated for the discomfort condition(s) as shown in Figure 4-11.



Figure 4-11: Visual comfort evaluation from the tool interface

 Final representation of the visual discomfort condition was represented as a chart with colors associated with visual comfort conditions within a range of Subtle, Perceptible, and Intolerable with an explanation of each threshold (as shown in Appendix D and summarized in Table 4-10).

Index (DGI, DGP, or	Index1	Index2	Index3	Final Condition
Contrast ratio)				
	Subtle	Subtle	Subtle	Subtle
Glare condition (based on	Perceptible	Subtle	Subtle	Perceptible
threshold)	Perceptible	Perceptible	Subtle	Perceptible+*
	Perceptible	Perceptible	Perceptible	Perceptible++**
	Subtle	Subtle	Subtle	Subtle
	Subtle	Subtle	Intolerable	Intolerable
	Subtle	Intolerable	Intolerable	Intolerable+
	Intolerable	Intolerable	Intolerable	Intolerable++
	Perceptible	Perceptible	Intolerable	Intolerable
	Intolerable	Intolerable	Perceptible	Intolerable+
	Perceptible+: two o	of the indexes conc	luded a percep	tible glare condition
	Intolerable++ and	Perceptible++: t	hree of the	indexes concluded a
	perceptible glare co	ondition.		

Table 4-10: Visual comfort conditions - Tool version-2

- An option was added to place a building on Google Earth (using GHowl Grasshopper plug-in to export a kml. file path) to study the examined building effect on the adjacent buildings and also examine possible surroundings that could affect the visual comfort study.
- The new GUI became less technical and more graphical. Additional technical data was available in a tab when needed.
- A "Redesign" key was developed on the tool evaluation page to allow the designer to return to the original design to make changes and re-evaluate the design.

# 4.7 Chapter conclusion

The main objective of this chapter was to explore the prototyping stages that inform the design process and design decisions. First, the researcher initiated a daylighting software survey to examine the main issues and difficulties with the existing daylighting analysis tools and to verify the literature review findings. Afterward, she investigated the prototyping framework main modules. Then, she configured the logical argumentation of the software, hardware, and visual comfort metrics and inspected the guidelines set to evaluate the discomfort conditions. Next, the researcher collected members' feedback through a series of interviews. To do so, she analyzed the feedback, her notes, and her observations to help inform the prototyping process. The interview feedback and recommendations were used to improve the prototype. Some recommendations not used in Version2 may be implemented in future iterations, including various building functions and machine learning where the tool can learn from the designer preferences and previous decisions to propose design recommendations to meet a prescribed visual comfort levels. These recommendations will allow the designer to explore possible visual discomfort solutions while final design decisions will still be left to the designer. The second version of the prototype effect on design decision-making was tested in two immersive case studies as examined in Chapter 5.

# **5 CHAPTER 5: IMMERSIVE CASE STUDY**

"A profound design process eventually makes the patron, the architect, and every occasional visitor in the building a slightly better human being"- Juhani Pallasmaa

(Ingold, 2013)

# 5.1 Introduction

Design decision-related visual comfort studies are often key factors in the performance of daylit buildings—especially those with acute lighting conditions such as museums where adaptation is a key aspect of comfort. The main goal of this chapter was to collect and organize data demonstrating how the proposed tool (which combined features from several different softwares) supports decision-making and to describe the immersive case study, which demonstrated how design decision-making could be improved through the implementation of the evaluative framework via the prototype. To address two domains of design decision-making, two case studies were implemented: 1) a typical office was examined to address the design of a new building and 2) a museum gallery space was examined to address the alteration of an existing building. The case studies aimed to understand how the proposed prototype could support design decision-making by providing designers and decision makers with scenarios where representations generated by the tool might improve decision-making through re-imagining spaces.

# 5.2 Immersive Case Study Method Overview

When using the immersive case study as a descriptive tool, it is important first to understand its two constituent parts, namely the case study and immersion. On the one hand, the case study has been particularly successful in sociological and educational studies in revealing the different perspectives of stakeholders by using multiple sources of data as it can be an alternative to traditional methods of inquiry. Yin (1994) demonstrates that using various approaches to data collection can improve the reliability of the study (Swofford, 1998). However, a case study may be defined in several ways. Mitchell (1983) defines a case study as a "detailed examination of an event which the analyst's beliefs exhibits the operation of some identified general theoretical principles" (pp.190-191). Yin (1994) defines a case study as "an empirical inquiry that

investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (p.13). Feagin et al. (1991) define it as "in-depth, multi-faceted investigation, using mainly qualitative research methods, of a single social phenomenon" (p.20). In general, the case study can represent an appropriate methodology when an in-depth investigation into a phenomenon is needed.

On the other hand, the concept of immersion is generally defined as "forgetting the real world outside of the virtual environment and by a sense of being in a make-believe world generated by computational hardware and software" (Cavazza et al., 2007). Immersion is where mind, body and environment communicate inside an interactive computational environment. This means that immersion has multiple, flexible qualities that can be applied in different situations.

Thus, the immersive case study stage is important in the research process—following the prototyping of the tool. The aim of the immersive case study is to understand if and how the prototype supports design decision-making, which is defined as the process of identifying problems and opportunities and then resolving them (Biddle et al., 2001). A successful decision-making involves a series of steps that require the input of information at different stages of the process, as well as a process for feedback.

The immersive case studies will be a collaborative process. Collaborative activities are often important to the design process, especially when it comes to performance evaluation. Schrage (1995) defines collaboration in the context of value creation, as "the process of shared creation" where two or more individuals with complementary skills work together to create a shared understanding that was not possible to achieve with each individual alone. A study by Mattessich and Monsey (1992) examined the factors of successful collaboration, which included environment, membership, process, communication, purpose, and resources. Schrage (1995) suggests thirteen factors that influence collaboration including: competence; a shared, understood goal; mutual respect, tolerance, and trust; creation and manipulation of shared space; multiple forms of representation; the representation; communication; environments; clear lines of responsibility without boundaries; decisions do not have to be made by consensus; physical presence is not necessary; selective use of outsiders for complementary insights and information; and collaboration's end.

For the first case study, the researcher examined a typical side daylit office space. This case study was used to demonstrate the tool evaluative process in a typical office design. The study was later also used for a demonstration to panel members for a Delphi study, which helped them to understand the decision-support process when using the tool.

Moreover, the second case study was a collaborative design effort to evaluate the daylighting conditions in a museum located on the National Mall Washington DC. This case study was selected in an effort to allow for a thorough application of the tool, and since museums are often carefully lit because of the sensitivity of the exhibits to light. For this example, a purposefully selected group of experts were encouraged to apply the prototype to the selected case study as shown in Figure 5-1. These experts included a professional designer, a graduate student with daylighting analysis background, and a lighting expert.



Figure 5-1: Immersive case study method overview

Results from the case studies will then be triangulated in order to generate conclusions about the tool effect on the design decision-making process. Feedback from the first case study will be collected from a purposeful group of professionals and experts. This group will be questioned

using a Delphi to collect feedback on both tool effectiveness in informing design decisions and possible tool improvement. The second case study results are to be used to test the tool outputs reliability and validity (Chapter-6).

#### 5.2.1 Case Study Triangulation

Triangulation is a method of validation that was used in this study to cross-reference or check findings. According to O'Donoghue and Punch (2003), triangulation is a "method of crosschecking data from multiple sources to search for regularities in the research data" (p.20). A case study is a triangulated research strategy, as one of the strong aspects of case studies as compared with other methods is that evidence can be collected from multiple sources. Triangulation uses evidence from different sources to corroborate the same fact or finding. Bargary et al. (2015) claims that triangulation may occur with the data source, investigators, theories, and methodologies and represent the protocols used to ensure the research truthfulness and the validity of the process.

Literature review, case studies, and interviews and survey were used here for the purpose of comparing and checking results against each other and generating patterns. More specificcally, in this research, triangulation occurred between 1) the researcher as an interpretive instrument and her journal notes, 2) the experts' interpretation interviews, their thoughts and opinions on the decision support aspects of the tool, 3) the tool results comparison to test their reliability and validity, and 4) Delphi results when several expert investigators collaborated to examine the visual discomfort phenomenon in the case study space.

### 5.3 Case Study 1: Typical Office Space Design

Offices are long-term occupied spaces with typical activities and circulations of their occupants. Many attempts have been made to develop reliable evaluation models to investigate glare problem in offices, including previous research by (Osterhaus, 2005b), who concluded that available assessment and prediction methods have limited practical use, especially in the daylit spaces. In other words, these methods cannot evaluate integrated systems where daylighting and electric lighting are combined. Because daylight is dynamic and variable, additional challenges need to be considered to provide comfortable office environments. For this reason, the first case study was conducted in a typical office space. A new project design presented a purposeful

sample used in the case study to examine possible design changes in the conceptual and early design development stages. This case study will be used later to collect members' feedback via a Delphi tactic. This feedback will be focused on the tool benefits in evaluating visual comfort and to collect suggestions for improving the tool. The goal of the case study was to examine tool implementation on a new design in the course of the application of a range of design alternatives that are applicable to different stages of the design.

#### 5.3.1 **Overview of Design Process**

The researcher immersed herself into the process and use of the tool using the following steps. She carried out the main stages of the case study evaluation process, including: 1) selecting the design space, 2) generating the 3D model, 3) selecting a circulation path for the evaluation, 4) preliminary evaluation of visual comfort, 5) using the tool to collect information, 6) brainstorming, 7) identidying alternatives, 8) choosing among alternatives, and 9) drawing final conclusions and design decisions as shown in the case study process in Figure 5-2 and explained in the following sections.



Figure 5-2: Case study visual comfort evaluation process

#### 5.3.2 Selecting the Office Design

The researcher examined typical office designs to select the most suitable for the case study. She selected an average size office space with a single occupancy to examine possible glare and visual discomfort effect for one occupant. The modeled open office space was suitable for multi-source paperwork, reading, writing, analyzing was modeled, as shown in Figure 5-3.



Figure 5-3: Single-occupancy space examples - (100 ft.<sup>2</sup>) (Marmot and Eley, 2000)

### 5.3.3 Generating the 3D model

A 3D model was generated based on the typical office space standards and guidelines assigned for managerial, professional or technical staff. The selected design consisted of a single office space (15Ft. X 9Ft.) with one west-facing window (6Ft. X 3Ft.) and a 3-foot wide corridor as shown in Figure 5-4.



Figure 5-4: The selected office design

# 5.3.3.1 The 3D model inputs

To generate the examined space, input into the 3D model were the geographical location, sky conditions, simulation of days and times, material properties, building geometry and simulation points as shown in Table 5-1.

Table	5-1:	Case	study	data	input
Lante	• •	Cube	Study	unu	mput

Variable	Examined Case Properties
Geographical location	San Francisco weather file was used for this case.
Sky condition	Clear sky without sun+ Clear sky with sun
Date and time (mm dd):	Default-annual- (one-hour interval)
Material properties	Generic materials were used (as shown in Table 5-2)
Building orientation	The 3D model was rotated to match Rhino default orientation
Building geometry (3D-model)	A 3-D model was generated in Rhino
Surroundings	No surroundings were proposed
Simulation points	Points were positioned in the office 3D-model circulation corridor

# 5.3.3.2 *Material properties*

From the 3D model inputs, material properties were further specified by location. Generic material properties from Radiance were used in the 3D-model simulations as shown in Table 5-2.

Table 5	-2: Mate	erials pr	operties
			opereio

Item	Material
Ceiling	Generic ceiling-80% reflectance
Interior Floor	Generic floor-20% reflectance
Interior Wall	Generic interior wall-50% reflectance
Outside façade	Outside façade-35% reflectance
Outside ground	Outside ground-20% reflectance
Glass	Single pane clear-90% transmittance
Window Frame	Grey metal-50% reflectance

# 5.3.3.3 The occupants' circulation

Simulations were performed corresponding to two eye-levels: 1) the first set of points were placed horizontally along the circulation path at 4.5-foot intervals and vertically corresponding to standing/walking conditions at 5.5 feet, and 2) the second set of simulation points were set at a sitting/working position at the average eye-level at 3.3 feet and vertically at equal spacing (4.5 feet) as shown in Figure 5-5.



Figure 5-5: Simulation points and examined views in plan and section view

### 5.3.4 **Researcher as an Instrument**

Since the researcher was the primary data collection instrument, she used reflexivity when critically reflecting on her role in the data collection process, and how it has influenced the findings. The researcher used research journal notes to become aware of the process and collected data to maintain a careful consideration not only of the examined case study phenomena, but also her own assumptions and behavior. Moreover, the journals and short notes helped the research to get ideas down right when they occurred, which represented the beginning of the data analysis and were then subsequently organized based on the decision-making process as shown in the data analysis process overview in Figure 5-6.



Figure 5-6: Data analysis process

# 5.3.4.1 Preliminary visual comfort evaluation – defining the problem

The first domain of decisions was concerned with defining the visual discomfort and glare problem and whether enough of a problem merits a need for concern. To define the problem, the researcher examined the space's visual discomfort conditions that the occupants might experience during their daily work and circulation movements. The preliminary assessment of the space showed potential for visual discomfort from the unshaded window on the west façade. However, additional information was needed concerning the problem's locations, times, and percentage of occurrence.

### 5.3.4.2 Using the tool to collecting information on the solution requirements

In this phase, the researcher gathered information to help her to understand if glare and visual discomfort needed to be addressed. To answer this question, additional information was needed regarding 1) the glare evaluation metrics and whether they exceeded the acceptable thresholds, 2) the location of its occurrence and its relation to the occupants' visual field and working zones,
and 3) the time of glare occurrence and whether it exceeded the acceptable percentage of occurrence.

The tool was used during the visual comfort evaluation process to collect more useful information to support decision-making. The visual comfort evaluation metrics of the tool were categorized into 1) illuminance based, or "the light distribution" (i.e. Useful Daylight Illuminance, UDI and hourly illuminance distribution on the peak days) and 2) luminance-based glare problems (i.e. the Daylight Glare Index, DGI and the Daylight Glare Probability, DGP) in addition to the quality of light and contrast problems (i.e. the luminance ratio). Illuminance-based simulations were generated at each stationary point along the path, followed by image-based luminance simulations—as shown in Figure 5-7 and discussed in details in the following sections.



Figure 5-7: Problem identification process

# a. Light distribution evaluation – Useful Daylight Illuminance UDI (Illuminance based)

First, the annual UDI (The percentage of space with a  $UDI_{<100-2000lux}$  larger than 50%) was calculated along the circulation path for the circulation points and was found to be slightly below the acceptable thresholds. Afterwards, the hourly-annual-illuminance distribution was calculated. Illuminance distribution peak values were found to occur on June 21 at 3 PM. Consequently, both quality of light and glare analyses were performed for this day and hour for each design alternative.

#### b. Quality of Light and Contrast problems – Luminance Ratio (Luminance based)

High-dynamic range (HDR) images were generated for the key viewpoints along the circulation path. Simulations were generated for the times identified by the illuminance distribution simulation (in this case, June 21 at 3 PM). The contrast evaluation illustrated that images showed acceptable luminance ratio with no significant changes.

# c. Glare problems – Daylight Glare Probability and Daylight Glare Index (Luminance based)

Simulated DGP of the images showed imperceptible glare conditions. However, the DGI detected perceptible and disturbing glare conditions.

#### 5.3.4.3 Brainstorming to generate actions

From the base case evaluation, several problems were detected. These included direct glare zones in the occupants visual field, high contrast in the field of view, and overall poor light quality in the space, especially in the standing position. Moreover, illuminance distribution evaluation showed some light distribution problems. However, the luminance-based evaluation metric (DGP) showed imperceptible glare conditions. Based on the tool outputs, the researcher decided to propose a number of design alternatives to solve the visual discomfort and glare problems. Based on the evaluation outputs, only the standing position visual field was to be examined in the alternatives.

#### 5.3.4.4 Identifying alternatives

This phase aimed at testing possible design alternatives to improve visual comfort in the space. Five design alternatives were proposed and examined to solve the problems: 1) window size was inspected as a possible conceptual design stage modification, which aimed at avoiding the direct glare source in the visual field problem; 2) exterior shading and 3) altered glazing properties were evaluated in the development stage; 4) interior wall finish was evaluated in the construction stage; and finally 5) an interior removable device was tested in the post-occupancy stage as shown in alternatives identification in the design process stages in Table 5-3and the alternatives characteristics summary in Table 5-4. Each alternative was examined under clear sky conditions (with and without sun) and at the standing eye level.

Design process stage	Conceptual and Early Schematic	Design Development Stage	Construction	After construction/ Post Occupancy
Proposed Alternative	• Window size, location	<ul><li>Shading device</li><li>Glazing material</li></ul>	• Interior wall finish color	Interior removable shading device
Alternative purpose	Minimizing glare in the visual field	<ul> <li>Enhancing lighting distribution</li> <li>Minimizing contrast</li> </ul>	<ul> <li>Minimizing contrast</li> <li>Minimizing glare</li> </ul>	<ul> <li>Minimizing glare in the visual field</li> <li>A commonly used solution</li> </ul>

Tuble 5 51 Identified alter flatt to in the design process stages
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#### Table 5-4: Generic case design alternatives

Case name	Dimensions	Material Properties	Visualization
Baga Caga	9x15 ft. room	As shown in Table 5-2	15.01
Base Case	with a 6x3 ft. window (sill at 3ft.)		

Case name	Dimensions	Material Properties	Visualization
Alt-A window size	Window 4x2 ft. (sill at 3ft.)	Same as the base case (Single pane clear-90% transmittance)	
Alt-B exterior shading	6 ft. solid exterior shading, 6 in thick.	Generic -20% reflectance	
Alt-C glazing	Same as the base case 6x3 window (sill at 3ft.)	Tinted-40% transmittance	
Alt-D interior shading	Interior roller shades same as window size (6x3ft.)	Generic - 50% reflectance	

Case name	Dimensions	Material Properties	Visualization
Alt-E interior wall color	Interior wall finish color changed to dark brown RGB (0.01-0.003- 0.001)	Interior wall finish color RGB (0.01-0.003-0.001)	

# 5.3.4.5 *Choosing among alternatives using the tool*

The second domain of decisions was concerned with the comparison of design alternatives. The researcher applied the tool to evaluate and compare the proposed alternatives. The comfort metrics (including the daylight distribution, light quality and glare) were compared for the five design alternatives. Afterward, the most effective alternative regarding minimum visual discomfort and glare was compared with the base case condition. Changes in visual comfort were observed as shown in Figure 5-8 and are discussed in the following sections.



Figure 5-8: Choosing among alternatives

#### a. Illuminance-based comparisons between the alternatives

This stage aimed at evaluating illuminance-based glare and discomfort metrics for each alternative to select the most effective one(s).

#### • Light distribution (Illuminance based)

The UDI metric showed that Case-B (exterior shading) and Case-C (glazing) provided better annual UDI and illuminance distribution for the peak condition (in this case, June 21 at 3 PM).

#### b. Luminance-based comparisons between the alternatives

This stage aimed at evaluating image-based luminance for the design alternatives to examine differences in glare and light quality. The images along the circulation path were examined. The camera placement in the model along the path captured images every second (4.5 ft apart on the

path) as previously discussed in the logical argumentation section in Chapter 4. The DGI and the DGP were evaluated for each case then the luminance ratio was checked for contrast and light quality testing as shown in the images comparison in Figure 5-9.



Base case



Tinted glass



Window size





Exterior Shading



Interior wall color

Figure 5-9: Alternatives luminance evaluation

#### • Light distribution (Illuminance based)

The DGI was calculated for each image along the path. The average DGI of all the alternatives were then compared. It was found that Case-B exterior shading and Case-C glazing resulted in minimum DGI. The DGP was calculated for each image along the path for the alternating cases. The images DGP average in Case-B (exterior shading) detected imperceptible glare conditions in the occupant field of view.

# • Contrast and light quality

Two types of luminance ratios were calculated for the images captured along the path for each design alternatives. First, the ratio was calculated as central zone: adjacent zone: non-adjacent

zone—where the luminance ratio for all alternatives did not exceed the perceptible threshold value of 1:3:10. Second, Maximum: Average ratio; where ratio between the average and the maximum image luminance was examined, Case2-exterior shading concluded less contrast.

# c. Comparison summary

From the alternatives evaluation, improvement was found in the DGI and DGP based on the window size, exterior shading, interior finish color and tinted glazing cases, while the interior shading showed no improvement. No significant change in the luminance ratio was found between the design alternatives. Moreover, higher DGP and DGI values were detected in the clear-sky conditions with sun than clear skies without sun. However, DGP and DGI values showed less variation between alternatives in the clear sky with sun conditions. The researcher concluded that the exterior shading strategy and the tinted glazing cases generated better visual comfort under clear-sky with sun conditions. The window size and exterior shading produced less visual discomfort and glare under a clear sky without sun conditions.

# 5.3.4.6 Researcher Notes Coding and Analysis

During the process, the researcher modified codes, discarded old ones, while new ones emerged. She compared codes and clustered similar codes into categories, which is a higher level of abstraction than codes as shown in Figure 5-10.



Figure 5-10: Researcher journal keywords from Word Cloud

The researcher then examined the content of each category and determined if subcategories could be developed; then themes were generated from the categories as summarized in Figure 5-11 and shown in the following sections.



Figure 5-11: Journal and notes analysis process

# a. Examining notes

Data analysis involves organizing what has been seen, heard, and read so that sense can be made of what is learned (Glesne and Peshkin, 1992). To analyze the data collected during this study, the researcher reread her transcripts to identify codes and labels as shown in the coding and labeling process example in Figure 5-12.

<ol> <li>Preliminary assessment</li> <li>Possible glare and discomfort problem</li> </ol>	<ol> <li>From the preliminary assessment, I noticed that space has some glare. The window location and size may generate some glare and discomfort, especially with the west facing façade and the lack of shading device and/or curtains.</li> </ol>
<ul> <li>2. Enough of a problem to be concerned</li> <li>Discomfort problem detected</li> <li>Discomfort location</li> </ul>	2. I used to tool to judge if enough visual discomfort and glare problems existed in the space. The tool provided a set of outputs to help evaluate the space visual comfort conditions; there was a large percentage of days and times of the day and percentage of floor area where UDI (illuminance values) are above the acceptable limits. Also for the image-based simulations, the values of the DGP and the DGI are higher than the acceptable thresholds, especially in the sitting position looking at the computer screen.
<ul> <li>3. Problem solving actions</li> <li>The actions required for visual comfort solution</li> </ul>	3. Illuminance-based evaluation metric-UDI, also luminance-based metrics (DGI, DGP, and contrast ratio). All metrics detected glare and discomfort varying from perceptible to intolerable. To solve the problem

#### Figure 5-12: Coding example

# b. Preliminary analysis

A number of categories were generated from the researcher notes during the tool application and the decision-making process. After the preliminary coding, she labeled ten categories, rechecked the process, and then moved quotations between the categories as shown in the coding summary in Table 5-5.

#### Table 5-5: Categories coding summary

Category: Preliminary assessment
Code: Possible glare and discomfort problem
• Subcode: The window location and size may generate some glare and discomfort; west
facing façade; lack of shading device
Category: Enough of a problem to be concerned
Code: Discomfort problem detected; discomfort main location
• Subcode: Large percentage of days and times; above the acceptable limits; higher than the
acceptable thresholds; sitting position
<u>Category:</u> Problem solving actions
Code: The actions required for visual comfort solution
• Subcode: All metrics detected glare and discomfort varying from perceptible to intolerable
Category: Brainstorming to generate action strategies.
Code: Glare sources
• Subcode: Glare was caused by the window opening; glare was found in the center of the
visual field

- Code: Design alternatives proposition; Advantages and disadvantages of alternatives;
  - Subcode: A horizontal shading; can minimize sun penetration; can change the appearance of the building; change in the color of the walls; can produce less reflectivity; the wall is not very pleasant; tinted glass can prevent direct sun penetration; interior blinds are widely used for shading; window size and location can minimize glare in the central vision

Category: Evaluating alternatives

- Code: Strategy to evaluate alternatives
- Subcode: Day/times with the highest glare and visual discomfort will be examined for each alternative.
- Code: Design decision in different design stages
  - Subcode: Design decisions proposed in the early stages of the design process can be more beneficent.

<u>Category:</u> Develop strategy to implement the tool into the process

- Code: Comparing alternatives
- Subcode: Luminance evaluation metrics were tested for every alternative.
- Code: Selecting the best alternative
- Subcode: Based on its performance in all evaluation metrics; average sum of the DGI and DGP; annual UDI

Category: Comparing alternatives

- Code: DGI and DGP detected more discomfort than the contrast ratio
- Subcode: No significant differences were detected in the contrast ratio; DGP and the DGI significant differences existed between the alternatives

<u>Category:</u> Compare selected alternative with the base case

- Code: improvement in the visual comfort conditions
- Subcode: Less glare and contrast; evaluation metrics simulation curves became smoother and more uniform; better adaptation, light distribution, and less discomfort
- Code: Some design alternatives showed similar visual discomfort
- Subcode: Discomfort equal to the base case (interior shading)

Category: Process limitations

• Code: Worker facing the window may not be the most common in offices. Multi-occupants in an office may be more realistic

<u>Category:</u> Reflective thoughts on how the tool supported/improved decision-making

- Code: Help to detect glare location, days, and times of occurrence Help detecting the percentage of areas and times exceeding acceptable thresholds Help to generate the alternatives that corresponded to the intended objective (to minimize visual discomfort and glare)
  - Subcode: Detect the glare location and time of occurrence which I was not able to identify in the preliminary assessment; the time and space dynamics; percentage of days and times exceeding the acceptable comfort limits; percentage of days and times exceeding the acceptable comfort limits; to make a design decision on whether design changes were necessary or not; identify the alternatives that can help solving possible discomfort problems; identify the alternatives that can help solving possible discomfort problems; able to make better informed design decisions

### c. Generating themes

Coded data were organized as suggested by (Biddle et al., 2001), where the data units were grouped into common themes similar to codes and categories. The ten categories generated four themes: 1) base case examination and evaluation, 2) proposition and evaluation of alternatives, 3) comparisons and decision-making, and 4) tool application to improve decision-making. The theme generation process sample is shown in Figure 5-13 and explained in more detail in Appendix E.



Figure 5-13: Themes generation example

# 5.3.5 Typical Office Immersive Case Study Limitations

During the first immersive case study, some limitations were observed:

• Since the immersive case study was for an office space location, keeping the occupant and angle of view in mind (i.e. looking at the computer screen, doing paperwork at the desk or standing) can affect the results. Because of this, only two positions were studied here—standing and sitting, both looking straight forward. Other views directions were not considered.

- The luminance ratio did not indicate high contrast in the images, while the DGI and DGP did indicate glare. This indicated differenced in the glare metrics, which can be considered a limitation.
- The quality of light and glare luminance-based assessments were based on the peak condition (i.e. maximum illuminance distribution time and day), which was determined by the annual illuminance-based evaluation. The evaluation results may be more reliable with annual image luminance simulations. However, simulating visual image every hour for every simulation point for a full year for all the alternatives is time-consuming and unfeasible for the scope of this study.
- The researcher expected significant differences among the proposed alternatives, especially between those applied in the early stages of design and the others applied in the final design and post-occupancy stages. However, minimal change in the metrics was detected between the different alternatives. This could be due to the summer simulation hours where the sun is high and has no direct effect on the interior space.
- Design alternatives were assumed to demonstrate changes that could occur during different stages of the design process. However, it could be argued that the same design change could take place in multiple design stages.
- Another potential limitation is the investigator effect. This type of error emerges from the researcher being the data collection instrument and is produced when the researcher becomes tired or less productive over time.

Some improvement was found for the design alternatives, especially those applied in the early stages of the design process—while others actually showed an increase in glare and contrast. Although no significant changes were detected between the alternatives applicable in early and later stages of the design process, it was found that there are more design-alteration options applicable in the early stages than those applicable in later stages of the design process.

The alternatives comparison results are discussed in details in chapter-8.

#### 5.4 Case Study 2: As-Built Space

The Freer Gallery of Art was selected as the second study space and was also used in the validation and reliability check phases (Chapter 6). For this case, a selected circulation path was evaluated for visual comfort and a series of illuminance simulations and views experienced by occupants were tested along a circulation path through the space.

The researcher executed the study with a set of questions in mind. These questions included: "How do designers make design decisions related to glare and visual comfort? What are the factors affecting their decisions? What accounts for an effective design solution in terms of glare and visual comfort? How does the prototype tool affect design decision-making? How do designers describe their experience with the design decision-making process when using the tool?" The questions helped guide the design process, which is discussed further in the sections below.

In order to further guide the design, a collaborative interaction protocol was proposed with the main goal of creating a shared understanding. More importantly, collaborative interaction was considered the best for this research because: 1) of the small number of participants in the case study, 2) it was used for its ability to express the highest level of satisfaction—previous research showed that participants were more satisfied with their learning experience when compared with other interaction protocols for data triangulation (Jung et al., 2002), p.3), 4) it is typically used in medium to large scale projects where visual comfort analysis is more likely to be applied, and 5) one key factor to reduce risks in design decision-making is to involve stakeholders in the decision-making process (Yosie and Herbst, 1998).

Feedback from purposefully selected professionals during the case study process helped the researcher to understand and evaluate design procedures. In addition, it was thought that a more collaborative process would minimize bias. During the collaborative process, members provided their opinions concerning the in-situ visual conditions, the proposed design alternatives, evaluation, and comparison. Finally, they provided thoughts concerning their experience using the tool, its effect on the design process, and the potential for improvement. The researcher provided thoughts and analyzed the data collected from the experts and her observations as shown in Figure 5-14 and discussed in the following sections.

Immersive Process Stage	Researcher Participation	Professional members Participation
Building Selection	$\bigcirc$	
Space Initial Description and Examination	•	
In-situ Data Collection	<b></b>	
Visual Comfort Evaluation	<b></b>	
3D model Set-up	$\bigcirc$	
Alternatives Proposal		<b></b>
Alternatives Evaluation and Comparisons	•	•
Observations and final conclusions	•	

Figure 5-14: Immersive process overview

#### **Case Study Selection** 5.4.1

Museums are typically designed for visual comfort; it was thought that evaluative framework successfully applied to a museum space, may be applicable to other building types. Thus, the purposefully case study of a museum was selected to allow for both an in-depth study and because the researcher had an interest in generalizing the findings. In terms of generalized findings, extended data can be generated from this case through: 1) the examination of an asbuilt project to inspect possible design alterations on an existing project, 2) the verification and comparison of the existing visual conditions to simulated conditions validation and reliability check phases (Chapter 6), 3) experts participation, and 4) using the collaborative process to explore changes in the design process and applicable design alternatives limitations.

In terms of an in-depth study, the case study building was purposefully selected while considering the following: 1) sufficient access was needed for data collection, including people to be interviewed, in-situ lighting measurements, documents and records to be reviewed, or field observations; 2) the selected space needed to include a variety of lighting conditions and illumination levels; 3) the selected space included a variety of art materials (statues, paintings, sculptures); 4) no large exhibits were to be included to better examine the lighting quality (because a range of lighting conditions can occur for a single artifact); and 5) a medium-size building with a transitional space was needed where visual adaptation was an issue. With these considerations, the researcher explored a number of the Smithsonian museums in Washington, D.C. to find the best candidate. The candidate museums included: Smithsonian Castle, National Air and Space Museum, Smithsonian American Art Museum, Smithsonian National Museum of American History, National Museum of the American Indian, Freer Gallery of Art, Smithsonian National Museum of Natural History, Hirshhorn Museum and National Postal Museum as shown in Figure 5-15.



**Smithsonian Castle** 

National Air and Space Museum



**Smithsonian American Art Museum** 



National Museum of American

History



National Museum of the American

Indian



Freer Gallery of Art



**Smithsonian National Museum** of Natural History

**Hirshhorn Museum** 

**National Postal Museum** 

Figure 5-15: Examined Smithsonian museum spaces for the case study (Institution, 2015)

#### 5.4.2 Case Study Description – Freer Gallery of Art

The Freer Gallery of Art was selected for the case study. The Gallery is well-known for its collection of Asian art and The Peacock Room by American artist James McNeill Whistler. It was found to be the most suitable for this research because it satisfied the selection considerations: 1) the researcher had sufficient access to data collection including professionals to be interviewed, on-site visits for in-situ lighting measurements, and some building architectural drawings were available (while other measurements were measured or assumed based on in-situ conditions); 2) the gallery exhibits a variety of artwork and therefore lighting conditions vary significantly—including daylight (representing the main lighting source) and a corridor surrounding the main daylight source (i.e. the courtyard) serving as a transition space to minimize glare; 3) the selected space has a variety of art materials (i.e. statues, paintings, and sculptures); 4) the gallery contains no large exhibits; and 5) the building is a medium-scale museum (39,039 ft.<sup>2</sup> of public space) (Peck and Miranda Gale, 2014), as shown in Figure 5-16.



Figure 5-16: The Freer Gallery main exhibits

Construction of the Freer Gallery of Art was completed in 1921. The building is an Italian Renaissance-style building. The main construction material is granite, while the exterior of the gallery is pink granite. The courtyard has a carnelian granite fountain and walls of unpolished white marble. The gallery's interior walls are limestone, and the floors are polished marble; Figure 5-17.





In terms of lighting categorization, the building has six zones: Zone 1 – The Peacock Room which is the darkest room in the gallery (0.8-3FC), Zone 2 and 3 exhibit oil paintings (2-10 FC), Zone 4 includes the corridor transitional space separating the courtyard from the galleries (3-30

FC), Zone 5 holds old Chinese writings and books (1.2-4.5 FC), and Zone 6 – the courtyard (70-400 FC), as shown in Figure 5-18. Although visual comfort in Zone 4 (i.e. the corridor, or "transitional space" connecting gallery spaces) was selected for this case study, Zone 1 (i.e. The Peacock Room) and Zone 6 (i.e. the courtyard) will also be discussed.



Figure 5-18:Freer Gallery lighting zones

# 5.4.2.1 Transitional space examination

As previously mentioned, the researcher observed the circulation patterns for the visitors and selected one main circulation path for visual comfort evaluation: the corridor (Zone 4) connecting the Peacock Room (Zone 1) and the courtyard (Zone 6) (Figure 5-19).



Figure 5-19: Transitional space in the floor plan

# a. The Peacock Room (Zone 1)

The Peacock Room is one of the most visited spaces in the gallery. It houses works by James McNeill Whistler. The room was painted between 1876 and 1877 and is considered to be one of the greatest surviving aesthetic interiors representing the Anglo-Japanese style. The ceiling was constructed in a pendant paneled approach, and decorated with eight globed pendant gas light fixtures. Interestingly, the room was originally designed as a dining room in a townhouse in London, UK. In 1904, Charles Lang Freer purchased the entire room and installed it in his house in Detroit, USA. After Freer's death in 1919, "The Peacock Room" was permanently installed in the Freer Gallery and was opened to the public in 1923 (Merrill, 1998) as shown in Figure 5-20.





Figure 5-20: The Peacock Room original design

The room was initially installed in the Freer Gallery to allow daylight to enter, and thus the shutters were always open. However, the bright sunlight of Washington conflicted with the installed electric pendant lamps. Additionally, renovations at the time failed to match the original shade of blue and bright daylight made mismatch more noticeable (Merrill, 1998). To protect the room from potential damage from daylight and to add an air of romance to the room, the shutters were closed and the lamps were dimmed in 2011. It was argued that the room was intended to be a dining room, occupied at night, and artificially lit (as shown in Figure 5-21). However, dimming the light in the Peacock Room created a high contrast between the room and the rest of the Gallery, and thus created eye adaptation problems when entering and exiting the room.



The Peacock Room naturally and artificially lit

The Peacock Room naturally lit



The Peacock Room naturally and artificially lit



The Peacock Room naturally and artificially lit



The Peacock Room artificially lit only

The Peacock Room ceiling and light fixtures details

Figure 5-21: The Peacock Room before and after shutting the windows

# b. Transitional corridor passageway (Zone 4)

The corridor is the building's main and only circulation path that connects all the galleries. It separates the central courtyard from the galleries as shown in Figure 5-22.



Main hall from the corridor

Galleries and courtyard from the corridor



Courtyard from the corridor

Galleries from the corridor

Figure 5-22: Circulation corridor views

# c. Courtyard (Zone 6)

When the Peacock Room was first installed in the gallery, live peacocks were imported into the Freer Gallery courtyard. Otherwise, the courtyard was intended to be a place for quiet

introspection since the museum first opened. Layers of green vegetation surround the courtyard and the fountain centralizing the space. Large glass doors and windows were originally installed to allow air and natural light to enter the galleries, as the museum was constructed before climate control technologies were available. With technology developments and concerns for preserving the exhibits, the courtyard was closed off to prevent high humidity, direct sun, and temperature fluctuations than could damage the works of art (System, 2012) as shown in Figure 5-23.





Figure 5-23: Courtyard

# 5.4.2.2 Contacts and permissions

As a first step for implementing the case study, the researcher contacted the museum director and the Smithsonian museums lighting designer who gave permission to run the study. However, some restrictions were imposed including: prohibiting the use of camera flash, camera tripod, or monopod and the placement of any marks or tapes on the walls or floors; and circulation must be maintained in the building whenever visitors are present. In order to complete the study according to the parameters, the researcher had to get direct authorization from the museum director to use a tripod. The researcher was authorized to use a tripod, but had to maintain a distance of at least four feet away from all artwork and the researcher was required to remain with the tripod at all times.

# 5.4.2.3 As-built space examination

Upon obtaining permission to execute the study, the researcher examined the museum's visual conditions and developed several possible scenarios for the case study; namely, she examined the main visitors' circulation paths connecting various galleries, the entrance, and the courtyard as shown in Figure 5-24.



Figure 5-24: Visitors' circulation paths

#### 5.4.2.4 The 3D model generation

Based on the in-situ space examination, the researcher generated a 3D model for the case study space, and then verified it through a validation and reliability stage (Chapter 6). To simulate the as-built conditions, the researcher identified the building materials and surface properties to input into the 3D model. Through on-site observation, she was also able to make some assumptions for the sky conditions and measurements. For example, from the space examination, the researcher assumed that a clear sky with sun would produce higher glare conditions. A circulation line was then positioned in the 3D model to correspond to the selected circulation path where simulation points were positioned. Geographical location, sky conditions, simulation days and times, material properties, building geometry and simulation points were input into the 3D model as shown in Table 5-6.

Variable	Examined Case Properties		
Geographical location	Washington DC weather file was used for this case		
Sky condition	Clear sky with no sun		
Material properties	as shown in Table 5-7		
Building orientation	The 3D model was rotated to match Rhino default orientation		
Building geometry (3D-model)	A 3D model was generated in Rhino		
Surroundings	No surroundings were generated in Rhino		
Simulation points	Points were positioned in the museum 3D-model circulation path		

Table 5-6: Case study data in
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# a. Material properties

The properties of the materials used for simulating the interior finishes were measured from the in-situ conditions using a luminance meter (as discussed in Chapter 6). The material properties used in the 3D-model simulations are shown in Table 5-7.

Item	Material
Ceiling	Generic ceiling-80% reflectance
Interior Floor	Generic floor-20% reflectance
Interior Wall	Generic interior wall-50% reflectance
Outside façade	Outside façade-35% reflectance
Outside ground	Outside ground-20% reflectance
Glass	Single pane clear-90% transmittance
Window Frame	Grey metal-50% reflectance
Skylight	Single pane glass-60% transmittance

**Table 5-7 : Materials properties** 

# b. Openings characteristics

The main natural light sources in the space were: 1) courtyard windows and 2) gallery skylights. The dimensions of the window were taken from the as-built space. Some skylight and window measurements were approximated using a reference approach (Chapter 6).

# c. Sky conditions

A clear sky with sun was tested in the simulation as it presents higher potentials for glare and visual discomfort from contrast, illuminance distribution and direct sun penetration.

# 5.4.2.5 Placement of simulation points

Simulation points were placed at the eye level of within the height range of a typical adult male (or 5.5 ft.) along the circulation path, and horizontally at equal intervals equal to 4.5-foot intervals, as shown in Figure 5-25 and Figure 5-26.



Figure 5-26: Stationary illuminance points (section)

#### 5.4.3 Case Study Collaborative Design Process

As a first step in the collaborative effort, the researcher approached three experts with backgrounds in lighting and simulation. She shared with the experts a short description on the immersive case study process, their expected roles, and time commitment. Collaborative meetings were conducted in-person and by phone where screen-share was used via two-way communication patterns. The interviewer (i.e. the researcher) recorded the meetings, asked questions, and facilitated the follow-up. Two meetings took place during the process. First, upon the experts' acceptance to participate, the researcher shared an overview of the process, and walked through the building of the museum case study using a virtual tour and a 3D model. This meeting included a brainstorming session where the experts were asked whether the selected space had visual discomfort concerns, and whether additional information was needed to help assess the situation. The experts exchanged thoughts concerning problems and solutions during this meeting. The researcher encouraged the experts to use the prototype tool for design decision-support—as the tool highlighted the main glare and visual discomfort problems in the space, along with the percentage of occurrence and locations. Design alternatives were also discussed. The researcher recorded all of the opinions. Finally, she summarized and re-stated the opinions

of the experts that led to their agreement or disagreements, which were recorded and considered for evaluation.

After the initial space evaluation and identification of design alternatives, a second meeting was scheduled to discuss the proposed design alternatives and whether they were resulting in a better visual comfort in the space. The researcher then suggested re-using the prototype tool to evaluate and compare the proposed design alternatives. Based on this comparison, the researcher discussed the final design decisions with the experts. Finally, the researcher questioned the participants concerning the effectiveness of the tool in supporting design decision-making. The researcher recorded the process, added her notes and observations, analyzed the data and drew conclusions to conclude conclusions.

#### 5.4.3.1 Collaborative Design Participants

The immersive case study participants were selected based on their background and expertise, and their ability to effectively understand the goals of the research and willingness to interact with the tool.

**Members selection:** Participants with a background in daylighting analysis were preferred in this stage of the research as they had in-depth knowledge of both the process and expected outcomes. Therefore, a purposeful focus group of three professionals with daylighting analysis and computer simulation experience was selected.

**Members roles and tasks:** 1) engage in discussion, 2) interact with the tool, and 3) evaluate the visual comfort conditions in the case study space and the proposed design solutions.

Leader/researcher role and tasks: 1) contact the participants and provide them with a short summary containing information about the study, why they have been selected, and how the results were to be used, 2) be aware of all tool and engaged software capabilities, 3) foster a collaborative relationship among the participants, 4) answer questions and provide help for the participants, 5) help to initiate discussions, 6) engage in the process to ensure that the participants have an appropriate level of understanding with the case study investigation, and 7) take notes and record the data. Immersion of the participants into the design process was

categorized into: on-site immersion and remote immersion as explained in the following sections:

# a. On-site participants

One participant (the architect/researcher) with a background in daylighting analysis and museum lighting design was present during the walk-thru of the as-built space. This participant was involved in the in-situ data collection process and provided opinions concerning the appropriateness of the case study and provided the researcher with thoughts concerning lighting zoning and illuminance measurements.

# b. Remote participants

Two participants (one architecture professor/researcher and one professional architect) with a background in daylighting analysis and computer simulations did not walk through the building, but were provided a thorough description of the building. These participants were immersed in the design process through 3D modeling, images captured by the researcher, and a virtual tour that was available for the building through Google Cultural Institutions website (Institute, 2015) as shown in Table 5-8.

Participant background	Case study1: As built museum space Immersion method	As built museum space data source
Participant1: Architecture, daylighting research, experience with museum design and lighting.	On-site	<ul><li> Participants observations</li><li> In-situ measurements</li></ul>
Participant2: Architecture professor, daylighting research and daylighting computer simulations experience, previous research on visual comfort and daylighting analysis	Remote	<ul> <li>Images</li> <li>Virtual tours</li> <li>3D model</li> <li>Images</li> </ul>
<u>Participant3</u> : Professional architect with computer simulation knowledge, experience in museum design and lighting.	Remote	

Table 5-8: Immersive case study participant	e study participants
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# 5.4.3.2 First interactive meeting: An overview of the case study and in-situ evaluation

The first interactive meeting included a discussion that lasted for approximately one hour. The researcher developed a set of questions to guide the discussion, and then the group of participants

worked collaboratively to evaluate visual comfort. Questions in the first meeting were concerned with the visual comfort conditions in the space and whether visual discomfort problems occurred. The participants discussed possible design solutions as shown in Figure 5-27 and discussed in the following sections.



Figure 5-27: Immersive case study process-1

#### a. Introductory discussion

Once the members agreed to participate, the researcher shared with them an introduction to the study, namely discussing typical design problems concerning visual comfort and glare occurrence and solutions strategies. The researcher explained the objectives and goals of the case study including understanding if and how the prototype tool can support design decision-making. Afterwards, she introduced the prototype tool, evaluative process, and applied indexes. Participants were encouraged to ask questions to increase their understanding of the process and the tool.

#### b. Building examination

As previously discussed, the participants explored the case-study building through maps, a 3D model, and a virtual / on-site tour. This helped the participants to explore the nature of the

exhibits and the building in terms of architectural design and visual conditions as shown in Figure 5-28.



Figure 5-28: Freer Gallery virtual tour

From the preliminary examination of the space, the participants identified problems with visual discomfort but could not identify time or location of occurrence. They agreed that more information was needed to better judge the visual comfort condition.

#### c. Discussion and questions

The researcher and the participants discussed whether enough information was available to evaluate visual comfort for the case study and the types of information that would be needed for the evaluation. The participants indicated that visual discomfort and glare could possibly occur in the space, but more information was needed. Specifically, they requested information concerning the occurrence frequency and intensity, location, and time during the day for glare. The participants indicated that the design decisions related to visual comfort often consider visual adaptation, and glare (Participant1), light distribution and direction, (Participant1 and 3) room surface reflectances (Participant2), and user preference and task requirements (Participant1, 2,

and 3). Afterwards, the researcher highlighted the types of outputs provided by the prototype tool to evaluate three main factors affecting design decisions related to visual comfort including: contrast and quality of light, glare and the daylight distribution and discussed the use of the tool for evaluating visual comfort and glare.

### 5.4.3.3 **Prototype tool application: Visual comfort evaluation and analysis**

The visual comfort evaluation phase aimed at understanding how the decision-making process may be improved by representing glare and visual discomfort through the prototype tool.

The comparative metrics used in the analysis categorized into 1) illuminance based: which are based on the illuminance values at each test point along the circulation path and was intended to help in responding to the question concerning the time and location of discomfort and glare occurrence in the space, and 2) luminance based: which are based on brightness in the simulated images and was intended to help in answering the question concerning the severity and intensity of glare and its occurrence in the field of view. Luminance and illuminance metrics with associated thresholds were used in the evaluation process supported by the tool, as shown in Table 5-9 and discussed in details in the following sections.

Visual	Visual	Luminance/	Description	Threshold/Guidelines
Comfort	Comfort	Illuminance		
Aspect	metric	Based		
		Index		
Light	Useful		Insures that all the simulation	50% of the points
distribution	daylight	Illuminance	points illuminance are within	illuminance are
	illuminance		the useful limits (Yin, 2008).	100 <udi<2000 at<="" lux="" td=""></udi<2000>
	(UDI)			least 50% of the occupied
				time.
	Illuminance		Examines hourly illuminance	The evaluation aims at
	distribution		distribution and differences in	highlighting the time and
			the space based on the UDI,	location where the
			examined in the equinoxes and	highest illuminance
			solstice only.	difference occurs. This
				condition is inspected for
				further luminance
				evaluation.

 Table 5-9: Luminance and illuminance metrics

Visual	Visual	Luminance/	Description	Threshold/Guidelines			
Comfort	Comfort	Illuminance					
Aspect	metric	Based					
		Index					
Quality of Light and Contrast	Luminance Ratio	Luminance	The luminance ratio expresses the ratio between the luminance of three zones (the central zone, the adjacent zone delimited by a cone of 60deg, and the non-adjacent zone, delimited by a wider cone of 120deg)	Luminance ratios of the central zone, the adjacent zone, and the non-adjacent zone are $\leq$ 1:3:10.			
	Daylight Glare Probability (DGP)		DGP is based on the vertical eye illuminance as well as the glare source luminance (Harvard, 2006).	Points exceeding the average perceptible effect (0.33) threshold should not exceed 10% of the time.			
Glare Problems	Daylight Glare Index(DGI)		DGI considers the possibility of large glare sources, it was derived from human subject studies in daylit interiors where sky brightness was measured and given a size and position index.	(Imperceptible) < 18 (Perceptible) 18 – 24 (Disturbing) 24 – 31 (Intolerable) > 31			
Based on the luminance based indexes, a visual comfort condition (intolerable, perceptible or							
imperceptible) was concluded.							

The prototype tool used a series of existing software including Rhinoceros, Grasshopper, Evalglare, and DIVA-a Grasshopper and Rhinoceros sub-component that uses Radiance. The tool incorporated several features from each software to achieve spatiotemporal simulations-where space dynamics of and time were included in the analysis, as previously discussed in the logical argumentation in Chapter-4 and further examined in the following sections.

# a. Daylight distribution – Useful Daylight Illuminance UDI (Illuminance based)

This stage of the process and use of the tool helped provide information concerning the time and location of visual discomfort and glare in the space. The UDI is based on spatial rendering and was calculated for every point along the circulation path. The annual UDI was examined to conduct the total percentage of useful illuminance. Hourly simulations were conducted in order to examine illuminance distribution and differences along the path every hour. Using the UDI, the participants were able to determine the percentage floor area where illuminance values fell within the useful range in the space.

The evaluation of illuminance supported the conclusion that the annual UDI for the circulation path between the peacock room and the courtyard was equal to 18%. From the illuminance distribution calculated for the solstice and equinoxes the peak value (i.e. maximum illuminances) was found to occur on June 21 at 4 PM. Consequently, further evaluations (for example, quality of light and glare) were examined for this time and day.

#### b. Quality of light and contrast problems – Luminance Ratio (Luminance based)

This stage of the process and use of the tool helped provide information concerning the severity of glare conditions and their occurrence in the visual field. HDR pictures were generated for the key viewpoints along the circulation path. Simulations were generated for the day and times identified by the illuminance distribution simulations (in this case, June 21 at 4PM). The luminance ratio limits suggested by Osterhaus (2002) were used in the evaluation, namely a luminance ratio of 3:1 and 10:1 between the task and nearby surroundings, and the task and more distant surroundings for visual comfort. The evaluation showed that the luminance ratios for the generated views had little contrast between zones of the visual field (luminance ratios varied between 1:2:4 and 1:3:7). Maximum/average luminance ratio RML was equal to 1:0.71, which indicates a relatively high contrast in the field of view (low contrast  $\approx 1$ ).

#### c. Glare problems- Daylight Glare Probability (Luminance based)

For the case study, simulated DGP values ranged from 0.005 to 0.09, which are well within the permissible range (all perceptible conditions << 0.2).

#### d. Glare problems- Daylight Glare Index (Luminance based)

The simulated DGI values showed some perceptible glare ( $\geq 18$ ); it ranged from 1.9 to 18.8.

#### 5.4.3.4 Visual comfort evaluation findings

Through the evaluation of illuminance, the participants were informed whether daylight was beneficial in the space. UDI and illuminance distribution gave insight into the spatiotemporal dynamics of daylight illumination and also indicated the high and low levels of illumination that are associated with visual discomfort. This information helped the participants know how often visual discomfort occurred in the space.

To eliminate discomfort caused by high contrast, the luminance in the visual field must be reduced to be within acceptable ratios (central zone: adjacent zone: non-adjacent zone  $\geq$  1:3:10, and RML  $\approx$ 1) and glare sources must be eliminated. Through an examination of contrast and glare in the simulated scenes along the circulation path, the participants indicated that they were able to possible glare zones in the visual field, which helped in answering the second design question concerning the severity of the discomfort and glare in the field of view and was important for deciding on a solution.

#### 5.4.3.5 Visual comfort evaluation decision-making

The first challenge facing the participants was to assess the existing conditions as they related to visual comfort. Using the outputs from the tool, the participants were able to identify the locations and times when visual discomfort was likely to occur, in addition to the percentage of time when there was a problem. Although all the participants agreed that visual discomfort was a problem in the examined space, their responses concerning the need for design modifications varied: two agreed on the need to apply some design changes while one participant found design modification not necessary since visual discomfort was not severe. However, all were interested to use the tool to evaluate design modifications. Moreover, the participants proposed a set of alternatives that were intended to minimize glare and visual discomfort.

#### 5.4.3.6 Design alternatives

The main goal of this phase was to examine design alternatives. The selected design alternatives were evaluated based on the day and time (i.e. June 21 at 4 PM) where extreme illuminance distribution had been detected through the use of the tool. The participants and the researcher discussed possible design alternatives, and five design alternatives were proposed based on the tool outputs: 1) court coverage, 2) tinted glass on the southern windows, 3) a vertical wall on the southern court entrance, 4) horizontal louvers on the south entrance at 30 degrees and 5) horizontal louvers on the south entrance ( $30^{\circ}$  and  $60^{\circ}$ ). To reduce the time commitment for the

participants, it was agreed that the researcher would conduct the illuminance and luminance evaluations for each case, as explained in details in the following sub sections.

### • Alternative 1 – court coverage

Using outputs from the tool, the court was found to be a major source of glare. Covering the court was previously used in other Smithsonian museums to minimize glare and improve visual comfort in the court and adjacent spaces (Byrne, 2011). In this case, full court coverage was introduced and extended 80 x 80 ft. with laminated glass similar to the Gallery skylights, as shown in Figure 5-29.



Figure 5-29: Alternative A-Court coverage

# • Alternative 2- tinted glass on the southern windows

The existing Gallery glass was clear, which can contribute to high contrast—especially near the court entrance where no shading strategy was present. The participants agreed that light contrast can be controlled by using tinted, coated, or translucent glass. This can also reduce heat gain through the glass. The participants and the researcher agreed on tinted glass with 70% transmittance as a second alternative (Figure 5-30).



Figure 5-30: Tinted glass on southern windows

#### • Alternative 3– vertical shading on the southern court entrance

Based on the tool outputs, high illuminance values and contrast were detected at the courtyard entrance. Consequently, the participants and the researcher suggested shading strategies that included solid vertical shading at this point. Accordingly, the proposed shading was positioned vertically at ten-feet high to correspond to various viewing angles and to extend higher than the outdoor artifacts (8 ft. high). To determine an adequate shading-device, the horizontal dimension was determined based on the uniformity ratio *u*. Illuminance values were tested between the circulation path points where the average to minimum illuminance ratio ( $u = E_{min} / E_{average}$ ) needed to be 1:4 to maintain uniformity while the minimum illuminance was 9 Lux as shown in Figure 5-31. The uniformity ratio was achieved after the third point in the courtyard. Consequently, the vertical wall extended 15 feet to cover the three points at the court entrance where uniformity ratios thresholds were not met (Figure 5-31). The wall thickness was one-foot thick to match the museum wall thickness.



Figure 5-31: Illuminance ratio examination
The proposed material for the wall was a light grey with a 30% reflectivity, similar to the court and outdoor wall material properties as shown in Figure 5-32.



Figure 5-32: Alternative C-Vertical wall on the southern court entrance

# • Alternative 4 – horizontal louvers on the south entrance at 30 degrees

Horizontal louvers were proposed for the courtyard entrance. Louvers can come in a variety of materials including glass, metal, fabric, timber wood, terracotta clay and translucent acrylic. For a more diffused light, the proposed louvers were PVC-coated polyester that were also light weight. Twenty light louvers were proposed perpendicular to the courtyard entrance door. The louvers dimensions were based on research by Mestek (2012): they extended six feet horizontally from the court door, and eight feet vertically 0.5 feet apart and were one-inch thick (Figure 5-33).





Figure 5-33: Horizontal louvers on the south entrance at 30 degrees

# • Alternative 5- horizontal louvers on the south entrance 60 degrees

This Alternative is similar to Alternative-4, but with 60 degree angle louvers as shown in Figure 5-34.





Figure 5-34: Horizontal louvers on the south entrance 60 degrees

## 5.4.4 Participants feedback and information processing following first meeting

After the first meeting, the researcher coded and categorized all the recorded data. First, she listened to the recorded meeting several times to gain a better understanding of the examined data. She transformed the recorded audio data to textual data in order to prepare it for analysis. During this transformation, she took additional notes and removed irrelevant data such as participants comments unrelated to the research and personally identifying information. Afterwards, the researcher identified prominent themes then she further analyzed each theme as shown in the following sections.

# 5.4.4.1 Participants feedback Coding process

Coding was the first step in the data analysis and took place both during and after the meetings. In this stage, the researcher aimed at linking the data to generate themes by filtering and highlighting data from the participants' responses for interpretation. She used color coding to identify main categories as explained in Appendix E and in the coding process example in Figure 5-35.

Participants	Meeting Feedback Cod	ing - First Meeti	ng Categories Color Co	ding Process
Preliminary	Discomfort problem to	Problem	Brainstorming to	Tool
assessment	be concerned	solving actions	generate action	improvement
		using the tool	strategies	
<u>Cyan</u>	Light Grey	<u>Yellow</u>	Green	Grey

• Case 2-Museum: Participants Meeting Feedback Coding – First Meeting

Is there enough information to evaluate visual comfort for the case study?
 Participant1: It looks like the building has some visual discomfort issues. But it is hard to decide if it is a problem to be considered or not.

<u>Participant2</u>: Some <u>contrast is noticed in the courtyard entrance and may be the dark "Peacock"</u> room.

Participant3: I am not sure if relevant glare exists in the building, I cannot tell from simply looking at the space. I do see a possible problem, but I cannot identify its frequency and location of occurrence. I need to know when and where it represents a problem.

Figure 5-35: First meeting Color Coding Data Analysis

Five main categories immerged from the process: 1) Preliminary assessment, 2) Discomfort problem detected to be concerned, 3) Actions using the tool, 4) Brainstorming to generate action strategies, and 5) tool improvement (summarized in Table 5-10).

# Table 5-10: First interactive meeting immerging categories

Category: Preliminary assessment

- Code: Glare and discomfort problem in the space
  - Subcode: Space is successful regarding representing daylighting; participants reported little visual discomfort; the displayed artifacts and 3D model level of details; can affect the visual comfort evaluation; model need to be simulated with and without details; Peacock room entrance where high contrast is present; a possibility of visual discomfort conditions; but it was not detectable with the provided images of the space.

<u>Category:</u> Discomfort problem to be concerned

- Code: The information needed for evaluation
- Subcode: A wide range of information and parameters necessary annual simulation; type of the visitors; the analysis metrics, thresholds, and limitations.

Category: Actions using the tool

Code: Tool advantage in supporting design decision-making; Possible tool improvement

• Subcode: Participants seemed satisfied with the tool provided outputs; especially the process of going annually for the illuminance; worse case scenario condition to save time; future versions need to provide detailed.

<u>Category:</u> Brainstorming to generate action strategies

- Code: Generating alternatives
- Subcode: Design alteration options are endless; in this case study they are limited and restricted because of the building function.

## 5.4.4.2 Themes generating process

The researcher used the coding process and the proposed meeting questions to help in the categorization of themes. She interpreted each theme using an iterative process, drawing tentative conclusions and returning to the raw data to confirm particular lines of thinking. The categories were clustered under three main themes: 1) in-situ conditions visual comfort, 2) tool application and improvement, and 3) generating alternatives.

## 5.4.5 First Meeting Researcher Notes and Observations from the first meeting

This phase involved observing and recording the interactions between participants related to answers to the proposed questions and solutions to the design problems. In addition to the researcher's role as the leader of the collaboration, the researcher was the data collection instrument as she decided on the topics to record and developed the appropriate approach to the visual discomfort problem, established the evaluation questions, selected the analysis methods, and finally recorded her notes and observations. Primary researcher notes and observation examination is shown in Figure 5-36.



Figure 5-36: Researcher notes and observations primary examination

# 5.4.5.1 Researcher notes and observations coding

Observations were important to obtain comprehensive data when oral and visual data are vital to the research. For this case, the researcher participated as a member with the other participants while observing and keeping notes of the attributes of the subject that was being researched so that she could directly experience the study's phenomenon. Instructed observation was used where both challenging and supporting observations were recorded in the same stage of the design process then organized (as shown in detail in Appendix E). The researcher summarized and coded her thoughts concerning the responses of the participants and their actions including words of agreement and disagreement, and their understanding of the process. Observations were recorded at the time they occurred to prevent bias. Additional notes and reflective thoughts were added after the meeting. The data coding process example is shown in Figure 5-37 and summarized in Table 5-11.

<ul> <li>1. Preliminary assessment</li> <li>Glare and discomfort problem in the space</li> </ul>	1. From the preliminary assessment I noticed that the participants found the selected space is successful regarding representing daylighting; however, two of the participants reported little visual discomfort from the proposed virtual tour and images. They agreed that the displayed artefacts and 3D-model level of details can affect the visual comfort evaluation; they suggested that the model need to be simulated with and without details and visual comfort evaluation results need to be compared. They agreed on the importance of examining light transition in the space and that the transitional corridor space connecting the Peacock Room with the courtyard is ideal to test visual discomfort (especially in the courtyard entrance and the Peacock Room entrance where high contrast is present). I noticed that the participants did not have the same opinion on the space's visual comfort condition and whether a glare problem exists. However, there was a general agreement on a possibility of visual discomfort conditions, but it was not detectable with the provided images of the space.
<ul> <li>2. Discomfort problem detected to be concerned</li> <li>Problem solving actions using the tool</li> </ul>	2. The participants provided a wide range of information and parameters necessary to evaluate the space visual comfort condition. Participants had some questions regarding the evaluation process: they found annual simulation more realistic, especially for practical applications; they believed that light and dark adaptation simulated with maximum illuminance day/hour only showed the limits of the methodology and the tool. Participants wanted to understand the type of the visitors (age and gender) as this can affect their level of discomfort in the space. They questioned the analysis metrics, thresholds, and limitations.
3. Brainstorming to generate action strategies	3. The three participants agreed that thresholds for evaluation indexes cannot be general and need to be justified based on the user preferences or the building function. Participants seemed satisfied with the tool provided outputs; especially

Figure 5-37: Researcher notes and observation coding example

Table 5-11: Researcher notes categories

Category: Preliminary assessment

- Code: Glare and discomfort problem in the space
  - Subcode: Space is successful regarding representing daylighting; participants reported little visual discomfort; the displayed artifacts and 3D model level of details; can affect the visual comfort evaluation; model need to be simulated with and without details; Peacock Room entrance where high contrast is present; a possibility of visual discomfort conditions; but it was not detectable with the provided images of the space.

Category: The information needed for evaluation

• Code: A wide range of information and parameters necessary annual simulation; type of the visitors; the analysis metrics, thresholds, and limitations.

<u>Category:</u> Brainstorming to generate action (decision-making)

- Code: Tool advantage in supporting design decision-making; possible tool improvement
  - Subcode: Participants seemed satisfied with the tool provided outputs; especially the process of going annually for the illuminance; worse case scenario condition to save time; future versions need to provide detailed

<u>Category:</u> The characteristics of the design alternative

• Code: Design alteration options are endless; in this case study they are limited and restricted because of the building function.

From the four categories that emerged from the researcher notes and observations, two themes were most prevalent: 1) visual comfort evaluation and 2) alternatives generation. The researcher noted key quotes from the participants related to these themes, which are discussed in Appendix E and summarized in Table 5-12.

## Table 5-12: First interactive meeting researcher notes and observations themes summary

Pa	rticipants understanding
•	Participants had some questions regarding the evaluation process: they found annual simulation more realistic, especially for practical applications; they believed that light and dark adaptation simulated with maximum illuminance day/hour only showed the limits of the methodology and the tool. Participants seemed interested in understanding the type of the visitors (i.e. age and gender) as this can affect their level of discomfort in the space.
As	-Built Space examination
•	Participants found the selected space is successful in terms of representing daylighting; however, they reported little visual discomfort from the proposed virtual tour and images. The displayed artefacts and model level of details can affect the visual comfort evaluation, and it would be better to simulate the model with and without details and compare the visual comfort evaluation results. The transitional space connecting the Peacock Room with the courtyard is ideal to test visual discomfort (especially in the courtyard entrance and the Peacock Room entrance where high contrast is present).
An	alysis and Evaluation
• •	Thresholds for evaluation indexes cannot be general and need to be justified based on the user preferences or the building function. The tool can inform the designer when visual discomfort becomes unacceptable "it tells the designer when to stop."
Tool outputs and decision-making	
•	Participants seemed satisfied with the tool provided outputs; however, they pointed out some of the tool's limitations and output rendering qualities. Participants believed that future versions of the tool will have more potentials in providing detailed/ more realistic outputs.

#### 5.4.5.2 Second Interactive Meeting: Evaluation of Alternatives

After the initial space evaluation and development of design alternatives, a second meeting was initiated. The second meeting focused on evaluating the proposed design alternatives and answering questions concerning the visual comfort conditions for each alternative. To help support decision-making, the researcher worked with the participants to apply the tool to evaluate the design alternatives. To reduce the time commitment for the participants, the researcher re-applied the prototype tool to evaluate and compare the proposed design alternatives first, and then presented the results to the participants. The researcher recorded the participants' feedback on their design experience and the use of the tool for design decision-making. Subsequently, the researcher analyzed their feedback and comments along with her notes and observations in order to draw conclusions as shown in Figure 5-41 and discussed in the following sections.



Figure 5-38: Immersive case study process-2

## a. Initial Discussion during the Second Meeting

The second meeting began with the researcher reminding the participants of the discussions and conclusions from the first meeting. She then explained the goals for this second meeting, which were to examine the effect on design decision-making from the tool, determine whether the

design alternatives could produce better visual comfort conditions and minimized glare, and determine whether enough information was provided to make decisions. Then, the researcher suggested using the tool to evaluate the alternatives. Finally, she presented an overview of the proposed alternatives and demonstrated the evaluation framework and comparison between alternatives using the tool.

#### b. Prototype Application-2: Comparison of Design Alternatives

The key visual comfort metrics (including the daylight distribution, light quality and glare) were compared for the five design alternatives. Afterwards, the most effective alternative in terms of minimum visual discomfort and glare was compared with the conditions of the as-built space. Changes in visual comfort were observed and are discussed in the following sections.

#### c. Illuminance-based comparisons between the alternatives

This stage of the process aimed at evaluating glare and discomfort for each alternative. Afterwards the alternatives' illuminance distributions were compared and the most effective alternative(s) were selected.

# • The daylight distribution – Useful Daylight Illuminance UDI and illuminance distribution (Illuminance based)

The illuminance evaluation showed that Alternative-1 (court coverage) and Alternative-3 (vertical wall) produced better UDI and illuminance distribution.

#### d. Luminance-based comparisons between the alternatives

In this step, image-based luminance evaluations were conducted for the design alternatives to examine differences in glare and light quality. The images along the circulation path connecting the corridor and the courtyard looking both directions (towards and from the courtyard) were examined. The camera placement in the model along the path captured images every second (4.5 ft. apart on the path)—as previously discussed in the logical argumentation section in Chapter 4. The DGI and DGP were evaluated for each Alternative, and then the luminance ratio was checked for contrast and light quality testing.

## • Glare Evaluation – Daylight Glare Index (DGI)

The DGI was calculated for each image along the path. The average DGI of all the alternatives were compared. This showed that Alternative-3 (vertical wall on the southern court entrance) resulted in minimum DGI.

## • Glare Evaluation – Daylight Glare Probability (DGP)

The DGP was calculated for each image along the path for the alternating cases. The cases where average DGP did not exceed the perceptible threshold value of 0.33 were Alternative-1 (court coverage) and Alternative-3 (vertical wall on the southern court entrance).

## • Contrast and light quality – Luminance Ratio

The luminance ratio (RML and central zone: adjacent zone: non-adjacent zone) was calculated for each image along the path for each design alternatives. The luminance ratio for all alternatives did not exceed the perceptible threshold value of 1:3:10. The RML values varied from 1:0.57 (tinted glass) to 1:0.71(courtyard cover and louvers)

## a. Comparison between the as-built case and the alternatives

In this stage, the illuminance and luminance-based evaluation indexes were compared for each of the alternatives and with the as-built conditions. First, the illuminance-based indexes were compared with the existing conditions to ensure that the selected alternative(s) improved the illuminance distribution. Afterwards, luminance evaluation indexes were compared to minimize visual discomfort and glare in the visual field as shown in the following section.

## • Illuminance-based comparison

The annual illuminance evaluation index (UDI) of the as-built conditions was compared with alternatives that were shown to have the best UDI, which were Alternative-1 (courtyard coverage) and Alternative-3 (vertical wall at the courtyard entrance). More uniform illuminance distribution and less contrast were observed for both alternative cases when compared with the existing conditions.

#### • Luminance-based comparison

The luminance evaluation indexes (DGP, DGI, and luminance ratio) were compared for the most effective design alternatives—Alternative-1 (courtyard translucent cover) and Alternative-3 (vertical wall at the courtyard entrance)—and with the existing conditions. The comparison indicated that visual comfort was improved for both alternatives.

## 5.4.5.3 Decision-making

The second challenge facing the designers was determining if the design alternatives improved visual comfort and glare. The analysis results and comparisons using the tool showed some improvements, while two alternatives showed improved illuminance distribution and minimal glare (Alternative-1 and Alternative-3). However, some design alternatives actually showed more glare or contrast (Alternative-4 and Alternative-5).

Based on the outputs from the tool, the participants were able to evaluate and compare the design alternatives and draw conclusions concerning the effectiveness of these alternatives.

## 5.4.5.4 Participants Feedback and Information Processing Following Second Meeting

After the meeting, the researcher collected the participants' feedback and comments during the process. She searched for contrasts/comparisons and commonalities, which lead to categories; during and after coding, she looked for further connections between codes to generate themes as shown in the following sections.

## 5.4.5.5 Coding process

Similar to the first meeting, the analysis process included coding and interpretation. The researcher recorded the participants' responses and comments, and then the collected data was reduced and organized. Afterwards, the researcher looked for distinct concepts and categories in the data using color coding, which formed the basic units of the analysis. Examples of the coding process are shown in Figure 5-39.

Evaluation and Using the tool to support Tool in the daylighting Future Comparison of decision making dynamism recommendations alternatives using the tool Cyan Light Grey Yellow Green 1. How did the tool support the alternatives evaluation and comparison? Participant1: I like that the tool provided a visual representation-graphical images of each alternative. This allows the designer to explore each alternative and make wiser decisions based on the glare condition and the visual appearance of the space. Participant2: Proof of positive effect of thes s need to be examined, negative e ctionality of the space can take place: for example, it can lead to less occupancy and less favorable spaces by the visitors. It would be beneficial to und rstand what happened when one of the applied indexes thresh

Case 2-Museum: Participants Meeting Feedback Coding – Second Meeting

Figure 5-39: Coding process example

Four main categories immerged from the process as shown in the concepts and categories data in

Table 5-13.

Table 5-13: Second	l meeting feedback	concepts and	category
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Category: Evaluation and Comparison of alternatives using the tool

- Code: Alternatives comparison
- Subcode: Provided a visual representation-graphical image; allows the designer to explore each alternative and make wiser decisions; alternatives are good example of how designers can react differently to the visual comfort problem.

<u>Category:</u> Using the tool to support decision-making

 Code: Tool either confirmed these expectations; informing my future experience and expectations; the tool will not change my design concepts, but it will help enhance my thinking; typically 3D modelling is for representation. I used to do 3D modelling for simulation; design decision aid soft.ware to visualize anticipated lighting conditions that mimic real visual conditions; a simulation tool for decision support, not for representation.

<u>Category:</u> Tool in the daylighting dynamism

• Code: The tool provides a unique insight on the dynamism of the occurrence journey in the space building; the tool provides a simulation combination of the change of time and space.

Category: Future recommendations

• Code: Proof of positive effect of these alternatives need to be examined; effect on the usage and functionality of the space; understand when one index threshold meets the requirements guidelines in one case while the others do not.

# 5.4.5.6 *Theme generating process*

The researcher grouped the data according to their corresponding stage in the design process. Summaries were created and irrelevant data were disregarded. Four themes emerged from the data categories: 1) alternatives evaluation, 2) the tool effect on the decision-making process, 3) dynamism of the tool daylighting, and 4) future recommendations. Key quotes and comments are shown in Table 5-14:

#### Table 5-14: Second meeting feedback main quotes

Alternatives evaluation
Proof of positive effect of these alternatives needs to be examined; negative effect on the usage and
functionality of the space can take place: for example, it can lead to less occupancy and less favourable
spaces by the visitors.
It would be beneficial to understand what happened when one of the applied indexes' thresholds meet
the requirement guidelines in one case while the others do not.
Tool effect on the decision-making process
The tool gave the options and the designer can make his/her own decision whether to make these
changes or not.
Further design stages will be to monetize the benefit, will the new design create a better space, more
visitors and better space functionality or not.
The designer need to run a feasibility study where the view of the visitors and the flow of the visitors
needs to be examined in each alternative.
• These alternatives are good example of how designers can react differently to the visual comfort
problem based on the design requirements budget or occupants' preferences

## 5.4.6 Second Meeting Researcher Notes and Observation

After the second meeting, the researcher reviewed her notes and added details in order to give a full and clear account of the collaborative process. Themes were generated from the feedback from the participants during the decision-making process while using the tool. The researcher avoided making personal judgments or assumptions concerning the participant feedback; judgments and interpretation were only included in the notes based on the researcher's observations where key categories and themes emerged—as shown in Appendix E and summarized in the researcher's notes and observations key quotes in Figure 5-40 and in Table 5-15:

#### 1. Researcher notes on the second meeting

1. Alternatives analysis advantages and disadvantages	I noticed that the participants found the illuminance simulation somewhat time consuming, however that thought that the equinox and solstices simulations are not enough to make a design decision.
	The participants were overall satisfied with the tool, and how it positively effects design decision-making
2. Process limitations	The participants questioned the evaluation indexes weight and if one was more reliable than the rest. They found annual simulation more reliable to make design decisions.
3. Reflective thoughts on how the tool supported/improved decision-making	From the participants use of the tool, I noticed that the most preferred tool features were the tool abilities to inform the designers with the glare days, times, location, and percentage of occurrence in the space. The second important feature was the tool visual-dynamic representation of the visual discomfort.

#### Figure 5-40: researcher notes and observation from the second meeting

 Table 5-15: Researcher notes categories and themes

Category: Alternatives analysis disadvantages
• Code: Annual illuminance simulations were time consuming; equinox and solstice simulations are
a limitation for the process; some indexes are more sensitive
Category: Alternatives analysis advantages
Code: The evaluation indexes weight; annual simulation more reliable
Category: Reflective thoughts on how the tool supported/improved decision-making
• Code: Most preferred tool features were the tool's abilities to inform the designers with the glare
days, times, location, and percentage of occurrence in the space the tool visual-dynamic
representation.

## 5.4.7 As-Built Immersive Case Study Limitations

The researcher observed the participants during the design process, and the following summarizes the observations in regards to noted limitations.

**Immersion process limitation:** the experience of the participant that visited the case study was different from the participants that did not. This was because the visiting participant was able to closely examine the space conditions, exhibits, and lighting layout. Moreover, even for those participants that were only introduced to the case study virtually, the degree of immersion varied between individuals. However, the data generated from all participant experiences were analysed and coded together, which can unduly influence the process.

<u>Collaborative process limitations</u>: Conference calls and phone meetings did not allow for realtime sharing for some information and materials. In-person meetings typically generate more interactive communication. **Evaluative process limitation:** The evaluation of alternatives was based on a single sky condition (clear sky with sun penetration); and a single weather file. In addition, luminance-based evaluations were based on single day/time simulations. Results could vary considerably under different sky conditions or for different days/times. For example, the Typical Meteorological Year (TMY) weather file contains daily sky conditions ranging from completely clear to completely overcast skies. Such variation needs to be considered in future tool iterations where different sky conditions are evaluated.

**Using Feedback to Improve the Prototype:** The participants indicated several factors affecting design decisions related to visual comfort, including contrast and quality of light, glare, daylight distribution, direction, user preference, outside views, radiation and task requirements. The prototype tool examined only three of these factors (quality of light, glare and the daylight distribution). Other factors like user preferences and task performance may have an effect on visual comfort and need to be considered in future iterations of the tool and thus, can be considered a limitation in the existing version.

# 5.5 Chapter Summary and Conclusion

This chapter aimed at examining the application of the tool in the design process and its potential to positively inform design decision-making to enhance visual comfort conditions in an existing building. Two immersive case studies were used for this examination. The first case study explored a typical daylit office space. A circulation path of a worker walking through the corridor then arriving to the office was examined. Two eye levels were examined along this path—first, standing eye level was examined in the corridor, and then sitting eye level was used to simulate when the worker arrives to his/her desk. The researcher used the tool during the process to evaluate the base case, and then design alternatives were proposed and evaluated. The most effective alternative in terms of minimal glare and improving visual comfort was compared with the base case.

The second case study used an as-built space, namely the Freer Gallery of Art, a Washington DC museum, as a test case for visual comfort evaluation. A key circulation path connecting two of the museum main zones was selected for visual comfort evaluation. The tool was used to support two aspects of decision-making: first to evaluate visual comfort for the existing conditions and

second, to evaluate alternative design modifications and whether design adjustments could improve better visual comfort. This case employed a collaboration process: a group of designers with backgrounds in daylighting and computer simulations were selected to use the tool and provide feedback on the impact on the decision-making process. Feedback from the participating professionals and notes from the researcher were analyzed. Through the immersive collaborative process, the participants indicated that the tool can positively affect design decision-making considering glare and visual discomfort.

From the immersive design process of the designers and the researcher in both case studies, it was concluded that the tool helped inform the design decision-making. In other words, designers obtained more information using the tool, which helped answering design/visual comfort-related questions and they were able to understand their design-decision consequences. Accordingly, the decision-making could be altered and/or improved from the use of the tool in new and existing buildings. It was also concluded that better understanding for visual discomfort problems in the early stages of design can help in solving visual discomfort issues, as shown in the decision-making process in Figure 5-41.



# 6 CHAPTER 6: RELIABILITY

"The validity of the case study depends not on the typicality or representativeness of the case but upon the cogency of the theoretical reasoning"- J. Clyde Mitchell (Mitchell, 2006)

## 6.1 Introduction

Reliability is defined as "the degree to which an assessment tool produces stable and consistent results" (Carmines and Zeller, 1979). There are several forms of reliability studies including test-rated, parallel, inter-rate and internal consistency. In this research, the parallel form of reliability—a measure of reliability obtained by overseeing different versions of an assessment tool—is used to judge different performance metrics for the proposed prototype tool simulation outputs (Moskal and Leydens, 2000). While reliability requires stable and consistent results, these alone are not sufficient; for a test to be reliable, it also needs to be valid. One way to determine if a test is valid is through convergent validity, which is defined as "the degree to which two measures of constructs that theoretically should be related, are in fact related" (Sullivan, 2009). For convergent validity, high correlations between the simulated and measured values would be evidence of convergent validity is used in this research to validate the outputs from the proposed tool. This approach examines the degree to which the tool simulation outputs are similar to existing in-situ measurements taken for existing in-situ conditions.

This chapter aims at testing the prototypical tool outputs using reliability and validity as two quantitative and qualitative assessment tactics. To conduct the reliability and validity study, a direct measurement data collection strategy was applied. Quantitative data was collected over a five week period in the field, including: 1) illuminance in-situ measurements and 2) luminance data using a photographic approach—where camera images were collected and examined for glare and visual discomfort phenomena. While direct measurements were not technically complex, they required precision and practice from the researcher (as errors can occur if data collectors are not well trained to use them). Qualitative data including the researcher

observations, field notes, and journal were used to clarify the collected data and direct the analysis process.

# 6.2 Reliability and Validity Method Overview

The study was carried out using the data collected from the Freer Gallery of Art, a Washington DC Smithsonian Museum. The data was collected from a circulation path through the building that was selected for the study. Quantitative and qualitative comparisons were then applied. The goal of the quantitative comparison was to analyze the differences in illumination between the simulated and measured conditions statistically. The qualitative assessment aimed at finding qualities in the research when assessing the detail and similarity of the tool simulation outputs with the as-built space.

For the quantitative comparison, in-situ vertical illuminance values were measured every hour from 10:30 AM to 4:30 PM (museum working hours) over a five week period from June 21<sup>st</sup> to July 28<sup>th</sup>, 2014. Afterward, a 3D computer model was generated for the space using Rhinoceros 3D modeling software. The 3D model was used as input for the prototype and illuminance values were generated for the same examined in-situ period. In-situ illuminance values were compared with their simulated corresponding values. For the qualitative comparison, the researcher used qualitative assessment to maintain quality in the research.

## 6.2.1 Reliability

Parallel-Form reliability was used to test the quality of the tool simulations and outputs when compared with their corresponding in-situ measurements. The correlation between the two parallel forms is the estimate of reliability. The aim of the reliability conclusions was to prove that the in-situ simulation data are reliable enough to alternate the in-situ data.

The two sets of data (simulated and in-situ) were constructed independently. Quantitative indicators were conducted for the quantitative illuminance assessment including the average illuminance, basic statistics, and t-test.

#### 6.2.2 Validity

The validity study examined how accurate the proposed prototypical tool simulations were. More importantly, it also ensured that the proposed arguments and findings were not only based on the researcher's impressions. The validity study showed that the tool simulations outputs are valid by comparing them with some already valid tools, including: Radiance, and luminance and illuminance meters. It was demonstrated from the calculations that the data generated from the 3D model (i.e. simulated measurements and photographic analysis) were related to their corresponding in-situ measurements in reality. Luminance indicators included the relative error and correlation coefficient. Finally, the researcher used confirmability as an appropriate indicator for illuminance and luminance qualitative assessments as shown in Figure 6-1.



Figure 6-1: Case study phase1: Calibration

#### 6.2.3 Space Selection

Some criteria were needed when selecting a space that would be suitable for the reliability and validity study. These criteria included: 1) daylight should be present since the proposed tool aims at evaluating daylit spaces, 2) access to data such as drawings for the as-built space, and 3) access to the space over time for collecting in-situ measurements and images. Using these criteria guidelines, the researcher considered some the Smithsonian museums in Washington DC as possible spaces.

The Freer Gallery of Art primarily houses Asian art and was selected as the best option for the study (Figure 6-2). A daylit transitional space in the gallery was most appropriate for the study because: 1) daylight was the main lighting source in a series of full height windows along the space, 2) the researcher had access to architectural drawings (floor plan) and the rest was generated from in-field measurements (e.g. windows and doors dimensions), and 3) the selected gallery was located in Washington DC, which was accessible for daily visits.



Figure 6-2: Museum courtyard

## 6.2.4 Circulation Path Selection

The selected "transitional space" connected multiple gallery spaces and separated the outdoor central court from the galleries. The main circulation paths taken by the visitor were also observed and documented and subsequently used to inform the analysis. Two main circulation paths were observed: 1) the first (Path1) connected the dark Peacock Room with the outdoor court, and 2) the second (path2) connected the entrance lobby with The Peacock Room. The second path (Path2) was used for the reliability and validity tests as shown in Figure 6-3.



Figure 6-3: Reliability and validation study selected path

# 6.3 3D Model Generation

To determine the reliability and validity of the simulations, a 3D model was generated for the existing museum daylit space using Rhinoceros 3D modeling software and Grasshopper visual programming and its sub-components (as previously discussed in Chapter-4). Excel was used for analysis and statistics. Key inputs needed to establish the study included space geometry, windows and skylights dimensions and characteristics, and the relevant properties of the building materials. Other inputs such as vegetation and nearby obstructions were also necessary as shown in Figure 6-4.



Freer Gallery entrance lobby



**Gallery court** 



Transitional space



The Peacock Room

Figure 6-4: The Freer Gallery circulation views

## 6.3.1 Geometry Data

The researcher generated the 3D model based on the floor plan drawing shown in Figure 6-5. A basic section drawing was available on one of the museum's brochures (Institute, 2015) as illustrated in Figure 6-5. The researcher verified some drawings measurements using Google Earth. A 3D mass was also available on the Google Earth Library for Sketch-up (warehouse, 2014). The researcher exported the 3D mass to Rhinoceros software and justified it using field measurements and approximations from the in-situ conditions.



Figure 6-5: Geometry data sources

## 6.3.1.1 Material properties data

The researcher used a Minolta LS 110 luminance meter (Minolta, 2015) to collect the properties of the materials used for simulating the interior finishes (Appendix H). Since in-situ luminance values were collected in Cd/m2 and CIE-L\*ab and the Radiance material properties used RGB color formatting, a converter engine (available online) was used to convert CIE-L\*ab to RGB color format (Calculations, 2015). Some material properties such as reflectance and transmittance were taken from the Radiance software materials library (Mistrick, 2000). The applied materials summary is shown in Table 6-1.

Item	Material
Ceiling	Generic ceiling-80% reflectance
Interior Floor	Generic floor-20% reflectance
Interior Wall	Generic interior wall-50% reflectance
Outside façade	Outside façade-35% reflectance
Outside ground	Outside ground-20% reflectance
Glass	Single pane clear-90% transmittance
Window Frame	Grey metal-50% reflectance
Skylight	Single pane glass-60% transmittance

## 6.3.1.2 **Openings characteristics**

The main natural light sources in the space were: 1) courtyard windows and 2) gallery skylights. The dimensions of the window were taken from the as-built space. Some height measurements were approximated from the camera images using one vanishing point perspective measuring technique. The researcher used a known measurement as a reference to calculate other new measurements (D'amelio, 2013) as shown in Figure 6-6.



Figure 6-6: Dimension referencing from images

Some skylight measurements were also approximated using a reference approach (in proportion with their adjacent measured geometries) and were compared with the Aperture to Floor Area Ratio (APR) corresponding to 2%, 3.5%, 5.5%, 7.5% or 10% of the roof area (Ghobad, 2013). Skylight1 and Skylight2 were found to be 7.5% of the roof area and Skylight3 was 10% of the roof area. Skylight glass properties and outside geometry were assumed by the researcher based on similar museum skylights glass transmittance of 60% properties as shown in Figure 6-7



Figure 6-7: Skylights-roof proportions

## 6.3.1.3 Other inputs

**Building orientation:** The 3D model was oriented to correspond to the direction of the as-built building. The model orientation was adjusted using observations from Google Earth.

**Vegetation:** Vegetation that could affect the simulations outputs were the shrubs and trees located in the outdoor court. These plants were not modeled in the 3D model because vegetation rendering is time-consuming. Also, some of the trees were not implanted (meaning they were potted), and others were seasonal deciduous trees, as shown in the courtyard pictures taken in different seasons as illustrated in Figure 6-8. This inferred that the effect of this vegetation was variable, depending on location of the pots and time of the year.



Figure 6-8: Court vegetation in different seasons (winter, left and summer, right)

**Nearby obstructions and surroundings:** Beyond the court and external to the test building, the surrounding buildings or large vegetation were low in elevation and at a distance so as to have little impact on the hemispherical sky-vault view from the test site. Consequently, no adjacent buildings or trees were modeled.

**Sky condition:** the study took place during the summer months of 2014. Therefore, the sun azimuth angle was calculated for the building during the test period (which varied from 112 to 255 degrees). As shown in Figure 6-9, the courtyard protected the test space from direct sun penetration in the early morning and early afternoon (10:30 AM to 3:30 PM). Consequently, a clear sky with no sun was assumed to be the prevalent sky condition. However, as previously mentioned, the simulations did not consider the court vegetation that also blocked direct sun penetration. This can be considered a limitation of the study.



Figure 6-9: Sun angle (July 18h)

**Simulation times:** Once a geometrically described 3D model of the test space was created, multiple simulations were generated at one hour intervals corresponding to the in-situ measurements taken at 10:30 AM to 4:30 PM from June 21<sup>st</sup> to July 28<sup>th</sup>, 2014. A summary of the 3D model approach is shown in Table 6-2.

Collected data	Resources and Details
Geometry	Researcher generated 3D model in Rhino
	Google Earth 3D mass, floor plan drawing
	• One-point perspective measuring technique applied on the camera images
	In-situ measurements
Material properties	Colors collected from the building using a luminance meter
	• Reflectance and transmittance were created from the Radiance software
	manual instructions, approximation with similar library materials.
Openings	• Field measurements
characteristics	One-point perspective measuring technique
	• Skylight measurements were eyeballed and compared with the Aperture to
	Floor Area Ratio.
Building orientation	• 3D model was oriented to correspond with the as-built building
	• 3D model orientation was adjusted using Google Earth
Vegetation	• Vegetation were not rendered in the 3D model
Nearby obstructions	• No adjacent buildings or trees were simulated
and surroundings	
Sky condition	• Clear sky, no-sun

#### Table 6-2: Illuminance simulation data summary

# 6.4 Illuminance Data Collection

Illuminance data was collected from both the 3D model and the in-situ measurements. Afterward, statistical analysis was applied to determine the average difference between the simulated and measured values. According to Radiance calibration studies conducted by Hasson et al. (2000), a simulation is considered valid when the average difference between the measured and simulated values is within the  $\pm$ -20% (Hasson et al., 2000).

## 6.4.1 In-Situ Illuminance Measurements

Vertical illuminance readings were collected using a set of five photometers. The photometers were placed at the eye level height (5.5ft.) and along the circulation path at 7.7ft. intervals. A total of twenty segments and twenty-one points were included on the path. The photometers were placed on tripods where vertical height had been determined and remained constant during the entire measuring process. After the measurements had been taken, the photometers were repositioned to the locations of the next five points as shown in Figure 6-11.





Figure 6-10 Photometer setting on a tripod

Figure 6-11: Photometers positioning in the space section drawing

#### 6.4.2 3D Model Illuminance Simulations

Vertical illuminance values from the 3D model simulations were generated using Grasshopper and DIVA-for-Rhino interfaced with Radiance and Daysim. Simulation points were positioned in the 3D model on a circulation line (total length 154 ft.) connecting the Peacock Room with the main entrance corresponding to the in-situ measurements. The line was placed at the eye level and divided into twenty equal segments of 7.7 ft. each, resulting twenty-one points in the 3D model and the in-situ conditions as shown in Figure 6-12, Figure 6-13, and Figure 6-12.

A total of 5,145 readings (21 measuring points  $\times$  7 hours per day  $\times$  7 days a week  $\times$  5weeks) were collected over the examination period.



Figure 6-12: Simulation points on the circulation path





Figure 6-13: Stationary illuminance points (floor plan)



# 6.5 Quantitative Illuminance Comparison

The quantitative reliability test was a comparison of the in-situ illuminance measurements and corresponding simulated values. The selected as-built space served as a source of quantitative illuminance measurements that were compared with the corresponding simulated values from the tool output.

# 6.5.1 In-Situ/Simulation Illuminance Validity Correlation

To establish convergent validity, the researcher needed to show that a relationship between the measured and simulated outputs existed. Convergent validity was estimated using correlation coefficient for the illuminance values—a measure of the strength and direction of the linear

relationship between two tested variables datasets and varies between -1.0 and 1.0 (Nikolić et al., 2012). The correlation coefficient was calculated from the following equation (Equation 6-1).

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$
Equation 6-1

Where: X is the simulated values, Y is the measured values,  $\overline{x}$  and  $\overline{y}$  are the sample means average (simulated) and average (measured) (Udovičić et al., 2007).

The coefficient was positive and close to 1, indicating a strong correlation between the simulated and measured illuminance values as summarized in and discussed in details in Chapter 8-Results.

#### 6.5.2 Statistical Analysis – T-Test

A t-test statistical significance indicated whether or not the difference between the two groups averages most likely reflected a "real" difference in the population from which the groups were sampled. The researcher assumed that distribution of the sample's means was normally distributed in order to run a t-test analysis (Bland, 2000). The t-test statistics were calculated for the measured and simulated hourly average illuminance values and summarized. The t-test results concluded that the difference between the two sets was not significant.

Because the means were different, the researcher calculated the Coefficient of Variation (the ratio of the standard deviation to the mean) (Everitt, 1998p.299)) to help her compare the data it was calculated using the following equation (Equation 6-2).

CV= (standard deviation SD/Mean)\*100

Equation 6-2

#### 6.5.3 **The Illuminance Average Difference**

The average difference between the measured and simulated illuminance values was calculated for each point. Then, the difference was divided by the simulated value. The absolute value was transformed into a percentage as in Equation 6-3.

The average difference was calculated to be +/-24%, which was somewhat higher than the acceptable calibration threshold (+/-20%) as proposed by Reinhart and Andersen (2006). The results indicated that the maximum difference between in-situ and simulated illuminance occurred on July 29<sup>th</sup> at 3:30 PM. Simulations from this time were selected for image simulations comparisons.

# 6.6 Luminance Data Collection

In this stage, the luminance glare index values (as represented by the Daylight Glare Probability) were collected from the camera images along the selected path. These values were taken on July 29<sup>th</sup> at 3:30 PM. Two view directions were examined along the main circulation path. The first started from the dark Peacock Room to the main entrance (View1), the second started from the entry of the Peacock Room (View2) as shown in Figure 6-15.



Figure 6-15: Luminance comparison plan/section views

## 6.6.1 Camera Images Data

In general, human field of view in the horizontal is close to 180 degrees. Therefore, to obtain similar photographic image, a fisheye lens was needed (Chapter 4.4.2.4). The DGP values were collected from fisheye photographic images using a High Dynamic Range (HDR) camera with a (Canon EOS Rebel T5i 18.0 MP SLR with an EF-S 18-135mm IS STM Lens) and an 8 mm lens Sigma 8 mm f/3.5 EX DG fisheye lens. The camera locations were the same as the illuminance measuring points previously described. The camera was installed on a tripod where the height

was set to eye-level at 5.5 ft., which remained constant during the photographic process as shown in Appendix G.

## 6.6.2 **3D Model Images Data**

Simulation images were collected in an HDR format from the 3D model using a virtual fisheye camera. The camera was positioned to correspond with the in-situ camera points. Evalglare software was used to generate the DGP for both the in-situ and computer images. The images were uploaded to the software using the Grasshopper plug-in to interface with Evalglare. An example of the simulated and camera images are shown in Figure 6-16.





Figure 6-16: Illuminance measurement points simulated and in-situ images (View2)

# 6.7 Quantitative Luminance Comparison

For the quantitative luminance comparison, photographic images from the selected as-built space were compared with the simulation outputs. Luminance glare metric (DGP) was calculated from the in-situ camera pictures and was compared with the corresponding 3D model using relative error and in-situ/simulation validity correlation.

# 6.7.1 **DGP Relative Error**

Relative error is an indicator of how good a measurement is regarding the size of the object being measured. Typically, the human eye can distinguish relative luminance error higher than 5% (Reinhard et al., 2010). However, the simulated DGP tends to underestimate the actual glare with an error of 10% (Kleindienst and Andersen, 2009). Consequently, a relative error threshold of 10% was used for the image glare luminance comparison.

DGP values from the camera and simulation images were saved and exported to Excel, where the average relative error between the DGP from the in-situ camera images and the computer simulations was calculated from Equation 6-4 as follows.

$$DGP \ Relative \ error \ = \ Average \left[ \frac{Camera \ image DGP - Simulated \ image DGP}{Simulated \ image DGP} \right] \% \qquad Equation \ 6-4$$

The average relative error was examined for the two views directions (i.e. towards and from the Peacock Room) and was found to be 18% for View1 and 16% for View2. Both percentages were higher than the acceptable DGP relative error ( $\leq 10\%$ ).

#### 6.7.2 In-Situ/Simulation Validity Correlation

Similar to the illuminance correlation, the luminance convergent validity was estimated using correlation coefficient for the DGP.

The coefficient was positive and close to 1, indicating a strong correlation between the simulated and measured luminance values. The validity evaluation was considered successful since the testing proved a high correlation between the simulated and real outputs (Trochim and Donnelly, 2001).

# 6.8 Qualitative Assessment: Reliability

Reliability qualitative assessment aimed at finding qualities in the research. Methodological triangulation was the criterion used to distinguish the research qualities. However, the criterion used for judging the qualitative assessment was confirmability, which referred to the degree to which the results could be confirmed. To enhance confirmability, the researcher followed a documentation strategy where she documented the procedure for checking and rechecking the data through the study.

## 6.8.1 Illuminance Qualitative Assessment

Illuminance photometers measurements were collected at each stationary point twice. When different readings occurred, a third reading was established and compared with the previous readings. If the third reading was equal to a previous reading, then that reading was used. If the three readings were different, an average was calculated from the three readings as shown in Figure 6-17. Photometer readings were considered equal if values varied within a range of +/- 5% in the first reading when the maximum reading is  $\leq 10,000$  Lux, and +/-3% of repeated readings as specified in the photometer tool specifications (Co, 2010).



Figure 6-17: Illuminance readings qualitative assessment

Similar to the in-situ conditions, illuminance values were collected from the 3D model at each point twice to ensure the accuracy of the simulations outputs. Minimal acceptable differences were detected based on the DIVA stochastic process guidelines (Rushmeier et al., 1995).

#### 6.8.1.1 Luminance qualitative assessment

Material luminance properties collected from the in-situ conditions varied depending on the lighting conditions and their effect on the color and appearance of the materials. To ensure reliability of the luminance data, confirmability assessment was applied, luminance materials properties were collected from the same material under different lighting conditions, and the average values for the color and brightness were used for the generated material properties file.

## 6.9 Sources of Errors

The reliability and validity study results showed multiple sources of errors that were identified including:

## 6.9.1 In-Situ Errors

- The measurement device: Some Luxmeter readings were suspect in The Peacock Room center; very low illuminance readings were detected (0.6 to 0.8 Foot Candle)—which represents a twilight condition. However, the room lighting was enough to see the artifacts clearly in the room. For this, 2 to 5 FC would be needed in this situation (Mills and Borg, 1999).
- The researcher (i.e. human factor): Errors in using the instrument included: while taking the readings (hand shaking, tripods frequent adjustments and repositioning along the process), measuring distance (possible inaccuracy using measuring tape and taking measurements from unmarked points in the space), and height (researcher used her eye-level, which is different from the average eye level to take measurements)
- The weather conditions: Some days experienced variable sky conditions which likely affected the illuminance measurements.
- The museum rules: The museum restricted the use of tripods in the galleries, requested that the researcher leave no floor marks, and that she not obstruct circulation of the visitors—all of which meant make precise measurements difficult.
- Space geometry and skylight properties: The fact that actual measurements may be more exact than the construction drawings that were available, as the drawings did not have detailed dimensions.

# 6.9.2 Model Errors

- The used software could be a source of errors as modeling algorithms are only an approximation of reality.
- Inaccuracy with translating the as-built conditions to a digital model, including: ceiling height, window dimensions, electrical lighting characteristics and interior details were all approximated.
- Uncertainties in specifying materials properties from the as-built building to the 3D model, as color and reflectance properties were approximated.
- Some details of the as-built condition were not accurately modeled such as: the courtyard vegetation (trees and vegetation consumes a lot of time to model and render; the
existence of variable species including deciduas seasonal trees and other unidentified trees species), exhibits (artifact geometry modeling was difficult and time-consuming, simplified masses, and space holders were generated for major exhibits only), spotlights (no data was available for the researcher, the researcher assumed that small spotlights would have minimal effect on the simulation).

• Previous research argued that using the fisheye lens still does not give the correct perception as it generates straight lines of perspective (Kingslake, 1989).

## 6.9.3 General Comparison Limitations and Researcher Observations

- In general, the image comparisons were not consistent because of the difficulties in positioning the in-situ camera at the same location for each measurement period and the location of the simulated camera view with the same rotation was almost impossible. Because only one camera was available, there were also differences in the sun position and images capturing time (±10 minutes between all the pictures).
- Multi-image capturing was not possible because of the strict rules from the museum administrators and the limited resources and tools available for the data collection. The researcher believes that the results would have been more reliable if multiple cameras were carefully positioned and synchronized.

## 6.9.4 Reliability and Validity Summary

The tests for reliability for the 3D model simulations incorporated a set of parameters such as data sources, measurement methods, materials properties and circulation path points as summarized in Table 6-3.

Parameter	In-situ data	Simulated data
Luminance/illuminan	<ul> <li>Existing building</li> </ul>	• 3-D model
ce data source		
Illuminance	• Illuminance	• DIVA Radiance interfaces with Rhinoceros
measurement method	meter(Photo/Lux meter)	and Grasshopper
Luminance	• HDR camera with fisheye	• DIVA Grasshopper generated HDR fisheye
measurement method	lens	view images
and analysis	• Evalglare evaluated the	• Evalglare evaluates the simulated HDR images
	HDR camera images	

Parameter	In-situ data	Simulated data
Materials properties	• N/A	<ul> <li>A Luminance meter (Minolta luminance meter L-S-100) records material colors and reflectance from the building</li> <li>Materials data were saved in the material folder in Radiance</li> </ul>
Circulation path/points	• Marked in building	• A line in the 3D model

# 6.10 Chapter Summary and Conclusion

This chapter presented the tests for reliability and validity of the simulation output. The chapter started with an introduction to reliability and validity as a research method. In order to test the reliability and validity of the phenomenon that the proposed tool is designed to measure, a museum transitional daylit space was selected for the study where a 3D model was generated, and building materials and geometry were described and input as closely as possible to the insitu conditions. Some geometry inputs such as skylight details, wall and ceiling heights and curvatures were assumed or approximated. Building surroundings, interior and exterior vegetation were not considered in the 3D model.

Using the museum space, a comparison between illuminance in-situ measured data and simulation data took place. In-situ illuminance-based indexes were compared with their corresponding 3D model simulated indexes. The time with the maximum difference between measured and simulated data was examined for the further image-based qualitative study. In-situ HDR images were captured from the space with a virtual camera that was placed in the 3D model at the same points of location within the existing building. In-situ images were compared with their corresponding simulated 3D model images using the average Daylight Glare Probability (DGP).

A strong correlation was found between the in-situ and simulated data outputs. This correlation was determined based on five factors. 1) A correlation coefficient was calculated to be 0.973 between in-situ measured and 3D model images glare evaluation index (DGP). 2) The correlation coefficient index between the in-situ and measured illuminance values was equal to 0.971, which showed a strong correlation between measured and simulated illuminance values. 3) The average illuminance difference between the measured and simulated illuminance values was found to be +/-23%, which was somewhat higher than the Radiance proposed thresholds. 4) T-test results

analysis indicated small differences between the simulated and measured illuminance values. 5) The average relative error was examined for the two tested view directions (i.e. towards and from the Peacock Room) and was found to be 18% and 16%, respectively. The average relative error for both views was somewhat higher than the acceptable DGP relative error ( $\leq 10\%$ ). This showed that to some extent, high accuracy was found in the glare evaluation simulation.

From the findings, it could be argued that the researcher's validity and reliability findings truly represent the phenomenon that the proposed prototype claimed to measure (via quantitative and qualitative assessment). Although there were multiple sources of possible errors, the validation results met or were close to the recommended guidelines and acceptability criteria. Based on the findings, the researcher felt that the prototype was reasonably reliable and valid for visual comfort evaluation.

# 7 CHAPTER 7: DELPHI

"It takes two of us to create a truth, one to utter it and one to understand it." -Kahlil Gibran (Mitroff and Turoff, 2002)

# 7.1 Introduction

Professional feedback is an essential factor for researchers who seek to know what experts think about their research strengths and weaknesses or to test the effectiveness of the proposed research. The Delphi method can help uncover data in a variety of research directions and can also be used to gather current and historical data, or elucidate unclear information (Franklin and Hart, 2007).

The Delphi method is a structured communication technique, based on interactive estimation based on a panel of experts (Rowe and Wright, 1999). It is flexible regarding the research type and purpose; it can be used to examine the significance of historical events, explore urban and regional planning options, structure a model, and define the advantages and disadvantages of software—the later being most applicable to this work. In addition to helping develop and explicating fundamental relationships in complex phenomena, the Delphi method can identify real and perceived human motivations and personal values, which is also applicable to this research (Information Resources Management, 2015).

Previous research by Skulmoski et al. (2007) preferred the Delphi method over interviews for its ability to achieve consensus among a panel of experts. Typically, one, two, or three rounds of questionnaires can be used in a Delphi study to obtain consensus (subsequently obtained using statistical analysis). The Delphi method can be used when the sample size has a significant variance and expertise of the participants is diverse. The number of members required to generate consensus can vary.

This chapter aims at collecting feedback from professionals concerning various characteristics and attributes of the tool with three primary goals: 1) gaining consensus on the usefulness of the tool to support design decision-making, 2) ranking and rating the attributes of the tool based on importance and effect on design decision-making, and 3) collecting feedback and recommendations for enhancements.

# 7.2 Characteristics of the Delphi

There are three key features of the Delphi study used in this research. 1) Iteration: where the researcher summarized the respondents' judgments, which served as feedback or necessary information for the consecutive round. This process was repeated until stability in the responses was achieved (Dushkes, 2012). 2) Controlled feedback: where after each round, the researcher analyzed and summarized the survey data, she decided on the type of feedback analysis. 3) Statistical group response: where the researcher presented the analytical results both numerically and graphically. After reviewing the group statistics, each participant was able to decide whether to change his/her previous answers. Members usually tended to either change their responses, if different from the majority or provide explanations for their unique opinion.

# 7.3 Selection of the Delphi Methodology

Although the researcher could have conducted a traditional survey to gather input from members of the stakeholders concerning glare analysis and visual comfort evaluation, she considered the Delphi method as being more appropriate for generating more precise and accurate feedback from experts and stakeholders for the following reasons:

- 1. This study was an investigation of the efficiency of the proposed visual comfort evaluation tool, which is a complex issue that requires knowledge from experts who have experience with glare, daylighting, computer simulation and architectural issues. The Delphi panel size requirements were based on Reid (1988), who noted that panel sizes can range from 10 to 1,685. Also, the success of the Delphi study depends not only on the panel size but also on the qualifications of the panelists. The researcher selected a small number of experts with knowledge of the research objectives.
- The Delphi study design is flexible regarding the nature of the questions. The researcher integrated a set of open-ended questions, which led to a deeper understanding of the research questions.
- 3. The procedure outlined by Schmidt (1997) for conducting Delphi studies was applied where open-ended, rating and ranking questions were involved. This would serve the dual

purpose to solicit feedback from experts and to have them rank and rate the proposed tool attributes according to their importance.

4. The Delphi method allowed the group of individuals, as a whole, to deal with the problem, as it can generate better results when compared to research conducted in the lab (Creswell, 1999). The Delphi was used for its ability to structure group communication, and to facilitate group consensus building.

# 7.4 The Delphi Method Overview

The researcher needed to collect the judgments of experts in a decision-making group setting. The Delphi method was used to gather the expert feedback using a series of questionnaires. Although the Delphi is typically used as a quantitative technique that relies on measurements, it can also be used as a qualitative method when considering judgment (Rowe and Wright, 1999). In this study, the researcher used qualitative methods by integrating the Delphi method in the conversation with a group of experts in a natural setting. Also, the quantitative statistical analysis was applied to the collected data to achieve harmony.

In the general form, two conditions are used as the stopping criterion in the Delphi method: 1) stability, or the consistency of answers between the rounds of the study (Dajani et al., 1979) and (SareyKhanie et al.) 2) consensus, or the agreement between judgments (Cantrill et al., 1998). Research by Linstone and Turoff (1975) suggest that a Delphi of two or three iterations is sufficient to reach stability or consensus for most quantitative research. More importantly, they suggest that fewer than three rounds might be enough to reach consensus in qualitative research. Although the number of rounds is variable and dependent upon the purpose of the research, factors such as time constraints can affect the number of rounds. However, limiting the number of rounds may prevent some Delphi statements from reaching stability and consensus standards (Murphy et al., 1998).

In this study, a multi-round Delphi was hard to achieve because experts in the field were busy and unable to participate in all rounds. Consequently, a two-round Delphi was generated to ensure consensus measurement.

# 7.5 The Delphi Process

The Delphi used in this study has eight distinct phases: 1) develop the research questions; 2) design the research; 3) define the research participants sample; 4) develop round one questionnaire; 5) analyze round one questionnaire; 6) develop round two questionnaire; 7) analyze round two questionnaire; and 8) generalize and document research themes. The eight Delphi process phases are explained in the following sections.

#### 7.5.1 **Develop the Research Questions**

The research questions were generated from previous research stages including: 1) the literature review findings, 2) the member checking interviews, 3) the reliability and validity check, and 4) the pilot study represented in the immersive case study. The developed research questions focused on the tool efficiency to evaluate visual comfort. The questions also tested if informing the designer about discomfort problems early in the design process could positively affect his/her decisions. Specifically, the research study investigated the following questions:

RQ1. Can the proposed research tool positively affect the designer decision-making? If so, how?

RQ2. What forms of daylighting and glare analysis outputs have the most potential effect on the designers' decisions?

RQ3. What are the most and least important features of the proposed tool?

RQ4. Can the tool affect architects in designing their project spaces?

RQ5: Can the tool be improved to better enlighten the designer decisions? If so, how?

#### 7.5.2 **Design the Research**

This stage followed the research question development phase. The researcher created the Delphi scenario to help answer the research questions. Some design guidelines were conducted to guide the method including the following:

• Two-round Delphi questions were needed: 1) Round one questions were based on the research findings from previous stages (immersive case study, validity and reliability check, and participants' impressions) and the literature review on drawbacks of existing tools. This

round included a set of open-ended questions, which was analyzed using a coding process to identify the participants understanding of the subject and their main concerns. Round one findings presented the foundation for round two. 2) Round two consisted of well-focused questions where members rated, and ranked different tool attributes and essential features.

- Quantitative and qualitative analyses were needed: the qualitative analysis from the first round of questions could help identify themes between participants' responses. The analysis from the second round would be a quantitative statistical analysis to measure consensus.
- The Delphi process needed to take place in the participants' offices in order to ensure the participants' comfort and eliminate any influences of stress that could affect their responses.
- An in-person meeting (i.e. interview) was needed. Face-to-face interaction has been found to be a more reliable method, allowing for more engaged interaction among the participants. It would also enable the researcher to record her observations when participants show signs of agreement, disagreement, and confusion.
- The initial researcher interpretation of the process was designed in two steps: 1) Research Presentation: where the researcher presented the main research objectives, Delphi process and goal, and 2) Tutorial Presentation: where the researcher immersed the members in the tool via a typical office space design (i.e. a tool application on a proposed design project). The tutorial also examined the designer decision-making process when using the tool.

#### 7.5.3 **Define the Research Participants Sample**

The Delphi participants needed to meet some requirements to provide more valuable feedback: 1) be knowledgeable and experienced with the issues under investigation (examined in Section 7.5.3.2), 2) be willing to participate, 3) have time to participate, and 4) possess effective communication skills (Adler and Ziglio, 1996).

Although there are no rules to regulate the sample size, some factors needed to be considered to increase the participants feedback value:

• Heterogeneous vs. homogeneous sample: in a heterogeneous group, a broad cross-section is likely required to reach consensus while in a homogeneous group, a small sample may yield satisfactory results.

• Decision quality: decision quality can increase as sample size increases. In other words, a very small group may not return effective decisions, and outcomes may not be realistic (Lam et al., 2000).

The participants in this research were considered homogeneous; all the participants were designers, with an interest in the research topic. Consequently, a purposeful sample (a group of professionals selected specifically to serve the Delphi purpose) of ten participants from the design community was selected to yield satisfactory results.

#### 7.5.3.1 Members selection

Based on the identified purposeful sample requirements, the researcher examined a variety of candidates' professional profiles through professional connections. When selecting the participants from the candidates, she considered the following: 1) inviting members with a level of knowledge on the subject to be examined and 2) inviting members from a variety of architecture firm sizes to collect feedback from designers working on different project sizes. Two sets of participants from two different architecture firms were questioned. Firm 1, located in New York City, is one of the 15<sup>th</sup> largest firms in the U.S. and has many practice areas worldwide including urban and city planning and interior and graphical design. It has also designed a wide variety of architecture projects including residential, hospitality, senior living, healthcare, science and technology, K12 and higher education, retail, large scale mixed used, public buildings, courthouses and cultural facilities. Firm 2, located in Winchester, Virginia, is a small scale architectural office that does not specialize in one building type or style. It works on a wide variety of projects including museums, large and small houses, schools, offices and historic buildings. Most of the firm's projects took place in the Shenandoah Valley of Virginia, with some in Northern Virginia, West Virginia, and Maryland.

#### 7.5.3.2 Maximum variance strategy

To satisfy these requirements, the researcher followed the maximum variance strategy to select Delphi participants. Maximum variance is a purposeful sampling strategy that aims to sample for heterogeneity (Patton, 1990). In this case, the researcher wanted to understand how the visual comfort phenomenon is understood among different people. Consequently, she classified the participants into four groups based on their background: 1) Group one: designers with daylighting knowledge and computer application experience, 2) Group two: designers who do not typically introduce daylighting analysis in their designs, but have computer application experience, 3) Group three: designers with some daylighting analysis knowledge, but who have no computer application background, and 4) Group four: designers with no daylighting analysis knowledge and no computer application experience (Table 7-1).

Table 7-1: Participants	s maximum	variance
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	Daylighting analysis knowledge	Computer application experience	Number of participants
Group one	Yes	Yes	3
Group two	No	Yes	3
Group three	Yes	No	2
Group four	No	No	2

## 7.5.4 Develop Round One Questionnaire

The round one questionnaire aimed at collecting the participants' opinions regarding the visual comfort problem and on the tool efficiency in evaluating that problem. The first set of questions included seven open-ended questions. This questionnaire was the survey instrument for the second round of data collection; it yielded useful information that helped the researcher explore a number of research issues that had no predetermined responses such as: 1) the experts' feedback on visual comfort and daylighting analysis importance, 2) the stage of the design process which the participants apply these studies, and 3) how the proposed new tool can be improved to better inform designer decision-making.

## 7.5.5 Analyze Round One Questionnaire

After the completion of the round one questionnaire discussion, the researcher transcribed the recorded data into textual data. Subsequently, she qualitatively analyzed the data, first by coding to generate themes from the responses. Such thematic categorization helped the researcher to describe, compare, and explain the participants' responses as explained in the following sections.

# 7.5.5.1 Text analysis approach

The text analysis involved four stages: 1) discovering themes, 2) deciding which themes were the most important, 3) building a hierarchy of themes, and 4) linking themes to build a model.

Because of the data size and the small number of participants, the researcher used constant comparison techniques to approach the data by comparing each participant's coded response on specific questions with the other participants. This process ensured that the coding was consistent; it also allowed the researcher to examine codes that did not fit into the same pattern or theme. Figure 7-1 is an example of a constant comparison of the questions responses.



Figure 7-1: Constant comparison approach

In addition to the constant comparison approach, the repetition technique was used to identify themes in the data by looking for commonly used words. These words were detected from both the participants responses—including "useful tool," "will use the tool," "somewhat beneficial," and "desirable for architects"—and from the researcher's notes on participants reactions—such as "the participant seemed satisfied with the tool," "was interested in using the tool," and "was encouraged by the tool capabilities and found it useful and beneficial."

Afterward, the researcher shared the round-one result summary with the participants to improve their understanding and justify the findings. Table 7-2 summarizes the resulting themes of the round-one analysis:

Question	Themes (thoughts and concerns)		
Overall, how satisfied were you	Requires some modifications (as mentioned in the following		
with the new tool?	thoughts and concerns)		
How interested would you be in	Would use the tool to evaluate glare and visual comfort, but		
using the new tool?	sometimes visual comfort and glare are associated with solar		
	radiation and thermal discomfort.		

Table 7-2: Delphi round one themes summary

Question	Themes (thoughts and concerns)		
Are there additional attributes that	Integrate artificial lighting with daylighting		
you would incorporate into the tool	Present a summary of visual comfort condition.		
to better serve its purpose?	Introduce a set of building types to select from.		
	Introduce practical help menus.		
Who do you expect will benefit	Daylighting experts are the first to take advantage of the tool.		
from the tool?	Architects with daylighting consultancy/analysis expertise.		
	Architects with no daylighting background can still benefit from the		
	tool.		
	Architect students can examine their design decisions taking into		
	consideration glare conditions.		
	Every design team member can use the tool.		
Can this tool positively change the	ol positively change the Yes, if the designer is provided with the glare and visual discor		
architectural design? How?	problems (i.e. times and locations), he/she can avoid these issues.		
	Design solutions included in the early design process, and budget		
	planning, are better than solutions at the final design stages or post		
	occupancy where changes are harder.		
How can the tool be improved to	Have a more simplistic interface with less quantitative technical		
better inform the design process?	information.		
	Include more numerical details and explanation of the outputs.		
Please provide any additional	Needs to provide an explanation of the glare problem.		
comments about our proposed tool.	Includes guidelines on the final outputs.		
	Includes a drop down menu for building functions and artificial		
	lighting.		

## 7.5.6 Develop Round-Two Questionnaire

The second set of questions included a satisfaction and agreement rating set of questions: the researcher asked the participants to rate different tool features from 1 to 5; where 5 indicated "most satisfied" and 1 "least satisfied." Also, she asked the participating members to rate or "rank order" some of the main attributes of the tool to establish preliminary priorities among items. Rating ranged from 1 to 5, where 1 referred to the "most important attribute(s)" and 5 referred to the "least important one(s)". Participants were allowed to give the same rating to multiple items that they felt had the same importance. Because of the participants' limited time for meetings, the researcher shared the questions with the participants on a large screen. The participants responded individually to the questions, and then also shared their thoughts on the responses while the researcher recorded the individual answers and kept notes during the process. As a result of Round-two, areas of agreement and disagreement were identified. Since round two represented the final round, minority opinions and items achieving consensus were presented to the panelists. Subsequently, the researcher provided the participants with the opportunity to review their judgments.

#### 7.5.7 Analyze Round Two Questionnaire

The consensus measurement is an important component of the Delphi analysis for the purpose of demonstrating that there is general agreement about a statement. In the study, the consensus achievement was the main stopping criterion; the study was terminated when the consensus was achieved. Many criteria have been previously used to measure consensus and stability. However, there is no general agreement on the consensus proportion for the Delphi because agreement levels depend on several factors, including sample size, the Delphi goal, and resources. Research by Hasson et al. (2000) suggests that consensus should be associated with 51% agreement amongst respondents. Other research by Sumsion (1998) recommends 70%, while Green et al. (1999) suggests 80%. CRISP et al. (1997) argues that the constancy of the consensus percentage through a series of rounds is a more reliable indicator of consensus.

In this research, a 70% consensus percentage was used for the Delphi Round-two. Three evaluation techniques were used to measure consensus of the study: 1) cut-off rate (the average percent of majority opinions, or APMO), 2) statistics including central tendency analysis and Kendall's W coefficient, and 3) judgment-based bias and minimizing the effect of the bias, as explained in details in Appendix I.

#### 7.5.7.1 APMO Cut-off Rate (average percent of majority opinions)

To reach consensus, a statement must achieve a percentage for 'agree' or 'disagree' that is higher than the APMO cut-off rate. As examined by Cottam et al. (2004), an APMO cut-off rate of 69.7% was used for consensus measurement.

$$APMO = \frac{\text{majority agreements + majority disagreements}}{\text{total opinions expressed}} \times 100\%$$
(Equation 7-1)

In this case, an agreement was achieved if ratings of the items fell within the range of the mean +/- 1.64 standard deviation (Heiko, 2008).

The APMO cut-off rate for the Delphi second round was seventy-two majority agreements plus seven majority disagreements divided by the ten opinions, which equated to an APMO rate of 79%. The percentage of agreement was higher than the cut-off rate; thus consensus was reached.

## 7.5.7.2 Statistics

The measures of central tendency and level of dispersion are the major statistics used in previous Delphi studies and were applied in this research (Hasson et al., 2000). Also, Kendall's W coefficient was used to measure consensus, as well as to evaluate agreement among raters when the ranking was used for evaluation.

#### a. Central tendency

Central tendency (i.e. means, median and mode) and level of dispersion (i.e. standard deviation and interquartile range) were used to present information concerning the collective judgments of respondents in questions 1 through 8. Detailed statistical analysis is examined in Appendix I, Section 1. Rather, a statistics summary is shown below:

1- IQR: Consensus was reached when the IQR is no larger than 2 units on a 10-unit scale (Linstone and Turoff, 1975).

In this case IQR=2, thus consensus was reached.

2- Median: Consensus was reached when 50% or more of the group rating is above the median (Heiko, 2012).

In this case Median=2 and average rating=3, therefore, consensus was reached.

3- Mode: Consensus is reached when the mode was larger than the average (Chakravarti et al., 1998)

In this case Mode=3, since mode=mean, thus, consensus was suspected.

4- Standard deviation: Consensus was achieved if ratings for the items were higher than 1.64 standard deviation (West and Cannon, 1988).

In this case, Standard deviation = 0.922, SD\*1.64=1.51, 90% of the total rating was higher than 1.64 SD. Therefore, consensus was suspected since not all participants' responses met the guideline.

Research by Murphy et al. (1998) recommended using the median and interquartile range rather than the mean and standard deviation in the Delphi research because they are an indication of strong consensus.

### b. Kendall's W coefficient

Kendall's W coefficient is a consensus measure used to evaluate agreement among raters. It ranges from 0 to 1. A coefficient of 0.1 indicates very weak agreement and 0.7 and higher indicates strong agreement (Dushkes, 2012).

Kendall's W coefficient was calculated for one question (Question 9-from A to H) as shown in Appendix I. Participants were asked to order some tool attributes importance to a scale factor from 1 to 8, where 1 was the most important and 8 was the least important. Participants were allowed to order multiple attributes with the same rank. Kendall's W coefficient was obtained in the Delphi from the following equation:

$$W = \frac{12R}{m^2(k^3 - k)}$$
 (Equation 7-2)

Where, **m** is the number of participants' (i.e. judges') rating k is the subjects in rank order from 1 to k, and **R** is the squared deviation.

Kendall's W coefficient of 0.78 was found for the responses to the questions that indicated a strong agreement among the participants' answers. Also, the total rating was examined to observe the participants' responses to the tool attributes' importance. It was concluded that the participants believed that the most important tool factor was the graphical user interface. Artificial lighting, integration of different building types to select from, and visual representation were a close second in importance, followed by the numeric outputs and the multi-directions and definitions. The least significant feature was the design recommendations; all participants agreed that the tool is solely an evaluative decision support tool and that the tool should not offer design decisions or recommendations to the designer. Moreover, they confirmed that every project is different and requires different design solutions, and that many factors were affecting the designers' decisions. The rating calculation details are shown in Appendix I.

## 7.5.7.3 Judgment-based bias and minimizing its effect

There are many forms of bias. However, the previous research examined major forms of bias for their ability to impact the quality of the results of a Delphi study negatively. Since the Delphi research questions were controversial in nature, judgment was used in the decision-making. In this study, a general assumption was made that the participating experts were capable of providing expert judgment using reasoning. Because the participants reviewed and critiqued the tool features, interface, and contents, their reasoning was assumed to be used to recognize patterns, correlation, and relationships.

The researcher examined the effect of three key types of bias that may have affected participants' judgment: collective unconscious, dominance, and myside effects.

#### a. Collective unconscious effect

Collective unconscious bias can take place when decision makers agree to popular belief without examining the qualities of the position (Jung, 2014). As participants tend to feel pressure to agree with the general belief; consequently, it is of concern in this study. The effect was minimized in this research using reasoning and controlled feedback through three steps: 1) the researcher presented an organized summary of the prior iteration to allow the participants to make additional comments and to clarify the information developed by the previous round; 2) the researcher asked participants to provide brief justifications for their ratings during the second round (this justification was summarized and reported as part of the controlled feedback) (cf. Hallowell and Gambatee, 2009), and 3) statistical analysis techniques allowed for an objective and unbiased analysis. Moreover, they reduced the potential of group pressure for agreement (Hsu and Sandford, 2007).

## b. Dominance effect

Dominance bias effect can take place if one participant shows control over the other participants (Rozin and Royzman, 2001). The researcher noted that some participants were more vocal than others, which could have affected the other members' responses. This bias was minimized in the study through 1) equal weight of the answers—the researcher tried to give each participant equal times for answers and justifications—and 2) running multiple rounds of Delphi.

## c. The Myside effect

The Myside bias effect can take place when individuals generate arguments only on one side of an issue, or when they do not seek objective viewpoints (Toplak and Stanovich, 2003). This biasing effect was important to consider since the main goal of the Delphi study is to achieve consensus among the experts, and such bias can impede the study from achieving its goal.

The Myside effect was minimized through 1) considering the participants' multiple viewpoints through reasoning, 2) analyzing answers statistically, especially central tendency and 3) describing the participants responses briefly in round two of the Delphi. The controllers used to minimize the biases effects are summarized in Table 7-3. The Delphi analysis of round one and round two questionnaires is summarized in Figure 7-2. All analysis results are included in the following chapter, Chapter 8.

Bias effect	Controller used to minimize the bias effect		
Collective unconscious	Include reasons for the controlled feedback to the Delphi panel for each round		
Dominance	Ensure anonymity of expert panellists when generating reports		
	Equal weighting of responses		
	Running multiple rounds of Delphi		
Myside	Include reasons for the controlled feedback and report final ratings		
	Analyze statistically, especially central tendency		
	Describe the participants' responses in round two of the Delphi		

Table 7-3: Controllers used to minimize bias effect



Figure 7-2: Delphi round one and two questionnaires process

# 7.5.8 Generalizations and Document Research Themes

During the coding and theme identification stage, the researcher acted as a theme filter by sorting the data and recording her observations during the process. Afterward, the researcher put the final feedback into a set of themed conclusions that can help with tool refinement and future recommendations. Several conclusions were generated based on the feedback of the experts, including:

- The tool can help the designers make better design decisions through the representation of maximum glare conditions: "I like that the tool can help me know when to stop."
- Different group members can benefit from the tool including students, designers, researchers and daylighting experts: "Anyone with architecture or lighting knowledge can take advantage of the tool."

- Future tool iterations could be more beneficial if proposed modifications are achieved: "I will use the next version of this tool."
- No design recommendations should be presented to the designer: "Designers know best how to solve their design problems."
- Some designers believe that numerical outputs and detailed process explanations are necessary, while others believe that graphical outputs are more informative and less confusing: "I would like to know better about the numeric outputs," "Why do you care to know?"
- A user-friendly tool interface, the graphical representation, and compatibility with other tools and software are key factors for the tool success: "Some daylighting simulation tools are still used even after many studies proved their results' inefficiency simply because they are more user-friendly and provide high-quality graphical results."
- Visual representation is a major factor for architects when considering visual comfort and glare conditions. "A red flag means a lot more to an architect than a large DANGER sign".
- The tool represents one element of a "comfort checklist"; acoustical, mood and thermal comfort need to be considered when designing for the occupants' comfort.

## 7.5.9 Advantages of the Delphi

The Delphi method was used in this research as a supporting study to extend a careful investigation of the proposed tool. The main Delphi advantages for this research were: 1) the ability to achieve consensus from participating members at the end of the process, 2) the flexibility of the Delphi technique, in terms of sample size, 3) being a good tool for qualitative research through open-ended questions and the interaction among participants and with the researcher, 4) the statistical treatment of data where responses were examined using statistical analysis to investigate consensus, 5) the iterative approach, which allowed the experts to reconsider their judgments in the light of feedback from peers, and 6) the tendency for the members to be gradually swayed by the majority opinions to gain consensus without direct pressure, or the ability to see what others have said then rethink if their own position had an influence on the final conclusions; and 7) the bias control, which was used in the process to help eliminate researcher and participants bias and personality influence (Skulmoski et al., 2007, CRISP et al., 1997).

## 7.5.10 Disadvantages of the Delphi

Although the Delphi process presented an important element to support the research and reliability, some disadvantages were found in the process: 1) the participants represented diverse backgrounds with a range of experience, and their responses varied based on their knowledge, 2) the limited sample size made it less efficient to interact in a face-to-face exchange, and 3) time commitments and participants' busy schedules made frequent group meetings infeasible; consequently only two rounds took place. More valuable feedback could have been achieved by increasing the number of rounds.

The Delphi method applied in this study to evaluate research tool effectiveness can be summarized as shown in Figure 7-3.



Figure 7-3: The Delphi summary

# 7.6 Chapter Summary and Conclusion

This chapter presented the Delphi method as one method for gaining a better knowledge of and to evaluate the explored visual comfort phenomenon of the proposed tool. The Delphi study was used as a part of the triangulation with the other previous research approaches (i.e. the immersive case study, the reliability and validity check, and the participants' impressions interviews) to help the researcher justify the research findings (Figure 7-4). A group of designers and decision makers was asked to share their impressions of the tool usability, its efficiency, and its effect on the design process. Their feedback was used for the tool assessment and improvement.



Figure 7-4: Delphi and research triangulation

After briefly introducing and identifying the Delphi method and previous studies, the main objectives, components, and characteristics were examined. Next, the Delphi design considerations were presented, followed by the members' characteristics, the inspected number of rounds, and the main Delphi process phases. Different bias effects were examined, and control methods were used to minimize these effects. Finally, the researcher's impression and notes during the Delphi process were summarized, and the main advantages and disadvantages were illustrated.

The Delphi is a flexible and adaptable tool that facilitated the researcher's data gathering and analysis. Moreover, it provided the researcher with real feedback from stakeholders and provided the participants interested in the research topic with possibilities to integrate visual comfort evaluation in their designs. It was concluded from the Delphi process and the two rounds of analysis that the participating members agreed that the tool can positively affect design decision-making; however, it was also concluded from the Delphi that the proposed research tool needs enhancement and modifications. The questionnaire suggested various recommendations for improving the tool as shown in more detail in Appendix I. The Delphi results and findings are discussed further in Chapter 8.

# 8 CHAPTER 8: RESULTS

"Progress, of the best kind, is comparatively slow. Great results cannot be achieved at once; and we must be satisfied to advance in life as we walk, step by step."- Samuel Smiles (Einstein, 2007)

# 8.1 Introduction

To ensure trustworthiness of the research findings, the researcher needed to demonstrate that these conclusions presented an actual picture of the examined phenomenon. Therefore, she needed to provide sufficient details on the methodological framework in order to 1) allow readers to make informed decisions on the established environment, and compare it with similar situations which they are familiar with, 2) verify that the findings can justifiably be applied to other settings, 3) demonstrate that the findings emerged from the data and were not the researcher's opinion, and 4) present outlying deviant cases that do not fit with the central interpretation.

The research findings were collected from the responses to five key questions that related to the design process in the two case studies: 1) Does a visual discomfort problem exist? 2) Is there enough discomfort to be of concern and in need of corrective action? 3) What are the actions required to solve the problem? Moreover, what are the design alternatives? 4) What strategy should be chosen from among the alternatives? 5) What are the decisions of the designer that were supported through the use of the tool? The researcher sought to collect results through triangulation from the researcher's notes and observations, the feedback from the participants during the case study, and the Delphi. Finally, to ensure the trustworthiness of the research findings she sought to satisfy four criteria: credibility, dependability, transferability, and confirmability.

# 8.2 Tool Results in the Design Process of the Two Case Studies

In general, the aim of the tool is to improve design decision-making through the evaluation of visual comfort conditions in the design process. The tool's innovative evaluation process lies in its dynamic daylight simulations of time (annual evaluations) and place (movement through space). In both case studies presented in this research, questions of the design process and

decision-support were addressed. For the first case study (Office Space: Case A), results and findings were based on notes and observations from the researcher when using the tool. As for the second case (Museum: Case B), the results and findings were based on feedback from the participants in addition to observations and notes from the researcher. The questions associated with the design process and use of the tool are shown in Figure 8-1 and discussed in the following sections.



Figure 8-1: Results and findings during the design process from the two case studies

### 8.2.1 Does a Visual Discomfort Problem Exist?

According to the observations of the researcher (Case A), and the feedback from the participants (Case B), the potential for glare and visual discomfort was present in the office near an unshaded window (Case A) and the museum courtyard (Case B). This suggested the need for additional analysis to determine the illuminance distribution along the workers'/visitors' path. The researcher recorded her observations and the responses from the participants in each case to check if the outputs from the tool could be used to determine visual discomfort problems and if additional features and information would be needed from the tool.

## 8.2.2 Is There Enough Discomfort to be of Concern?

As shown in the evaluative tool with outputs from both cases, the occurrence of discomfort and glare in addition to illuminance and luminance results were found to be a concern. Two illuminance-based metrics (i.e. the Useful Daylight Illuminance-UDI and the Illuminance distribution) and three luminance-based glare metrics (i.e. Daylight Glare Index-DGI, Luminance Ratio, and Visual Comfort Probability-DGP) were analyzed. The evaluation results are presented in the following sections.

## 8.2.2.1 Illuminance evaluation results

In both cases, the low values of Useful Daylight Illuminance (UDI) indicated possible illuminance distribution problems (Case A: 43% - Case B: 36.1%) as previously discussed in Chapter-2. For Case A, times that needed further evaluations (maximum illuminance values) were found to be on June 21 at 3 PM. As for Case B, hourly illuminance distributions were analyzed for the peak values (maximum illuminance days). The results showed times and locations that needed further luminance evaluations (quality of light, contrast, and glare) point 18 – at the museum courtyard entrance, with the maximum difference occurring on June 21 at 4 PM (Figure 8-2).



Figure 8-2: Peak times illuminance distribution in the museum (Case B)

## 8.2.2.2 Luminance evaluation results

In both cases at the problematic times, the Daylight Glare Index, the Daylight Glare Probability, and Luminance Ratio were calculated to assess glare, light quality, and contrast. The Daylight Glare Index (DGI) showed significant glare conditions while the Daylight Glare Probability (DGP) and the Luminance Ratio (RML and Central: Adjacent: non-Adjacent) did not show that glare was present.

Having had enough information concerning the visual comfort conditions, including the locations, times, severity, and percentage of time when glare was a condition, the researcher/participants was/were able to continue the design process while addressing the following questions. The calculated indexes (highlighted ones indicated possible discomfort) for both cases are summarized in Table 8-1.

	Evaluation metric	Case A: Typical office	Case B; Museum
	UDI-annual	43%	36.1%
Illuminance	Peak condition Hourly	June 21 at 3 PM	June 21 at 4 PM
evaluation results	illuminance distribution		
	DGI(comfort zone)<16	22 (0.32 normalized)	13.5 (0.196 normalized)
Luminance	DGP(comfort zone)<0.38	0.25	0.15
evaluation results	Luminance Ratio (Central:	Cen: adj: non-	Cen: adj: non-adj= 1:1:1
	adjacent: non-adjacent) and	adj=1:1:1 and RML=	and RML= 1: 1.72
	RML comfort zone $\approx 1$	1:0.557	

## Table 8-1: Illuminance and Luminance metrics results

# 8.2.3 What are the Actions Needed to Solve the Problem? Moreover, What are the Design Alternatives?

• <u>Case A</u>: Since the investigated office space was a new design, the researcher sought to examine design adjustments at different stages of the design process. While trying to generate the design options, she noticed that a variety of design alternatives can be applied at the early stages, while others are applicable at later stages. She selected one design option that represented each stage (Alt.1-window size, Alt.2-exterior shading, Alt.3-windows tinted glass, Alt.4-interior wall finish color change, and Alt.5-interior removable shading). She aimed at examining the alternatives' ability to solve the visual discomfort and glare problems to determine how effective changes might be at the different design stages.

<u>Case B:</u> Based on the tool evaluation outputs, the participants agreed that some design alternatives can be tested to improve visual comfort in the museum. They proposed the alternatives based on the tool outputs and the collaboration during the interactive meetings. To improve visual comfort and minimize glare in space, the participants collaborated with the researcher and proposed five design alternatives (Alt.1-courtyard cover, Alt.2-windows w/ tinted glass, Alt.3-vertical shading strategy, Alt.4 and Alt.5-horizontal louver systems at 30° and 60°, respectively). The two case studies alternatives are shown in Table 8-2

Case/Alternative	$C_{acc} \wedge (Office)$	Case <b>D</b> ( <b>M</b> useum)
Case/Alternative	Case A (Office)	Case D (Museum)
Alt.1	window size	Courtyard cover
Alt.2	Exterior shading	Windows w/ tinted glass
Alt.3	Windows tinted glass	Vertical shading strategy
Alt.4	Interior wall finish color change	Horizontal louver systems at 30°
Alt.5	Interior removable shading	Horizontal louver systems at 60°

**Table 8-2: Case studies alternatives** 

#### 8.2.4 What Strategy Should be Considered to Choose Among the Alternatives?

The researcher/participants used the tool to compare the alternatives and select the one(s) with better visual comfort and minimal glare; illuminance and luminance based evaluation metrics were also compared among the alternatives. Then, changes in the visual comfort conditions for each base case (Case A and Case B) were compared when applying the selected alternative with minimal visual discomfort.

#### 8.2.4.1 Tool illuminance outputs for comparison among the alternatives

A comparison between the Useful Daylight Illuminance (UDI) of each base case and its proposed alternatives is shown in Figure 8-2 and Figure 8-3. It was concluded that all alternatives applied in Case A showed better performance when compared to the base case, except when changing the wall surfaces' reflectivity. The best performance took place when an external shading (Alt.2) was added to the office window (UDI= 64%). As for Case B, the results showed differences in the effect of each tested alternative in the base case. The highest value of UDI was achieved when covering the museum courtyard (32%), however, the lowest performance occurred when adding the horizontal louvers (Alt.4 and 5, UDI = 9%).



## 8.2.4.2 Tool luminance outputs for comparison among the alternatives results

The path images of the office (Case A) and at the courtyard entrance facing both directions (Case: B) for every alternative were compared. The comparative results intended to help the designer in the selection among the design alternatives.

• <u>Case A</u>: the results indicated that Alt.1-window size, Alt.2-exterior shading, and Alt3-glazing showed lower DGI and DGP when compared with the base case. However, a better luminance ratio (closer to 1) was collected from Alt1 and Alt2, which indicates better contrast as shown in the comparison results in Table 8-3 and Figure 8-4.

	DGI			
<b>Base case/ Alternatives</b>	(Normalized)	DGP	Luminance ratio	Design stages
			Central/adjacent/ non-	
			adjacent=0.3/0.3/0.3	
Base case	0.32	0.25	RML=1:0.557	N/A
			0.29/0.29/0.29	Conceptual/early
Alt. 1- window size	0.274	0.04	RML=1: 0.29	Schematic
			0.29/0.29/0.30	
Alt. 2-exterior shading	0.27588	0.04	RML=1:0.35	Development
			0.29/0.29/0.31	Construction-late
Alt. 3-glazing	0.27588	0.09	RML=1:0.08	Development
			0.29/0.29/0.32	
Alt. 4-interior shading	0.316536	0.18	RML= 1:0.08	Post occupancy
			0.07:0.07:0.07	Construction-late
Alt. 5-interior wall color	0.35	0.25	RML= 1:0.135	Development

Table 8-3: Glare and light quality comparison Case A



Figure 8-4: Glare metrics comparison between alternatives- Case A

• <u>Case B</u>: Using the tool's results from comparing the alternatives, the participants preferred Alt.1-courtyard cover and Alt.3-vertical shading system since they generated less glare and contrast without affecting the interior space appearance (as these alternative presented lower DGI and DGP, in addition to better RML closer to 1). Also, they indicated that less contrast between the glare source and the background was noticed in the image. However, the Central: Adjacent: Non-adjacent luminance ratio values of the alternatives were all very close. Moreover, they all showed insignificant glare and were not included in the results as shown in Figure 8-5 and Table 8-4.



Figure 8-5: Luminance evaluation comparison between the alternatives

Luminance Evaluation Comparison -in- Direction					
Base case/ Alternatives	DGI-norm	DGP	(DGI+DGP)/2	Maximum/average	
				luminance ratio RML	
Base case	0.25	0.32	0.285	1: 0.70	
Alt.1- courtyard cover	0.245	0.21	0.23	1: 0.71	
Alt.2- tinted glass	0.24	0.35	0.29	1:0.70	
Alt.3- vertical wall	0.19	0.22	0.2	1:0.70	
Alt.4- 10 louvers at 30 degrees	0.23	0.30	0.265	1:0.70	
Alt.5-10 louvers at 60 degrees	0.24	0.32	0.28	1:0.70	
Lumina	nce Evaluatio	n Comp	oarison -out- Dire	ction	
Base Case/ Alternatives	DGI-norm	DGP	(DGI+DGP)/2	Maximum/average	
				luminance ratio RML	
Base case	0.06	0.1	0.08	1:0.71	
Alt.1- courtyard cover	0.10	0.20	0.15	1:1.71	
Alt.2- tinted glass	0.12	0.19	0.155	1:0.57	
Alt.3- vertical wall	0.11	0.20	0.155	1:0.68	
Alt.4- 10 louvers at 30 degrees	0.10	0.20	0.15	1:0.7	
Alt.5- 10 louvers at 60 degrees	0.10	0.20	0.15	1:0.7	

 Table 8-4: Luminance evaluation comparison summary

Based on the comparison results and findings in this case (Case B), the participants sought to compare the selected alternative (Alt.3-vertical wall) with the in-situ conditions to record any change in the visual conditions as shown in the next section.

- Case B Comparison between the in-situ and the selected alternative (Luminance-based metrics)
  - <u>DGI</u>: The path image's average DGI comparison was 13.5 for the base case images with 40% of the points exceeding the perceptible threshold value. The average DGI of the modified case images was 1.9 with no points exceeding the perceptible threshold value. This indicated less presence of glare areas in the visual field of the modified case when compared to the base case as shown in Figure 8-6.



Figure 8-6: The DGI comparison between the base case and the modified case

**DGP**: The average DGP of the in-situ conditions images showed that 20% of the pictures exceeded the perceptible threshold value, while 0% of the modified case images exceeded the perceptible threshold value. It is important to mention that the standard deviation for the in-situ condition was 0.1; while in the modified case was 0.08—which indicated constancy in the DGP values and less contrast and variation among the luminance values on the path as shown in

Figure 8-7.



### Figure 8-7: The DGP comparison between the base case and the modified case

**Luminance ratio RML**: The standard deviation of the in-situ condition images RML was 0.97 and for the modified case images was 0.6, which indicated better luminance uniformity and less contrast as shown in Figure 8-8.



Figure 8-8: Luminance ratio comparison between the base case and the modified case

### 8.2.5 What are the Designer's Final Decisions According to the Confirmed Findings?

The last stage of the design process was to confirm the case study research findings. This was completed using two phases: 1) the interactive process of the Delphi method was a part of the data triangulation used to confirm the research findings on the tool usefulness (Case A) and 2) a reliability and validity check phase tested the quantitative and qualitative assessment tactics (Case B). The reliability check examined whether the results were the same from both the in-situ measurements and the tool simulations while the validity check questioned whether the measurements were accurate.

## 8.2.5.1 Confirming the findings using Delphi: Participants' feedback results

A set of themes emerged from the Delphi question responses as discussed in Chapter 7 and summarized in Table 8-5. The resulting responses presented evidence of the tool's ability to provide useful outputs and positively inform the design process decision-making. The participants clarified that the incorporation of these recommendations in future iterations of the tool could help the designers to better understand their design problems regarding glare and visual comfort and evaluate their solutions.

#### Table 8-5: Round one Delphi results summary

Subject	Themes (thoughts and concerns)		
Satisfaction with the tool	Satisfied, with the implementation of some modifications.		
Interest in using the tool	Would use the tool to evaluate glare and visual comfort.		
Additional attributes needed to	Introduce user-friendly help menus; present a summary of the results;		
incorporate into the tool	include solar radiation and thermal discomfort evaluation; integrate		
	artificial lighting; add a set of building types.		
Community that can benefit from	Daylighting experts; architects with daylighting consultancy/analysis		
the tool	expertise; architects with no daylighting background; architecture		
	students; design team members.		
Ways the tool can positively	Providing the designer with the glare and visual discomfort problems		
change the architectural design	(times and locations); designers can avoid glare problems by		
process	recognizing them early in the design process; design solutions are		
	easier to implement at the early stages than applying their		
	corresponding solutions at the final design stages.		
Tool improvement to better	A more simplistic interface; include more numerical details and		
inform the design process	explanation of the outputs; include fewer details.		

Round two of the Delphi consisted of twelve questions (shown in Appendix I) whose results were evaluated both quantitatively and qualitatively. The results of questions 1 through 8 were analyzed using statistics, whereas the results of question 9 were analyzed using Kendall's W coefficient. As for questions 10 through 12, the researcher used coding and themes. The question analysis results are discussed in the following sections.

- Questions 1- 8 analysis results: The descriptive statistics are as following:
  - <u>APMO Cut-off Rate (average percent of majority opinions)</u>: 9 out of 10 participants' scores showed agreement producing a APMO rate of 79% (above the acceptance threshold of 70%).
  - <u>Central tendency</u>: IQR= 2, Mode=3, median=2, and standard deviation=0.922

The results showed that consensus was reached among the participants on 1) the tool's ability to help the designer improve his/her designs, 2) the tool's success at performing its intended task (to evaluate visual comfort in spaces), and 3) their willingness to use the tool in future projects as summarized in Figure 8-9.



Figure 8-9: Statistics analysis results

## - Question 9 analysis results

Kendall's W coefficient was used for assessing agreement among raters, ranging from 0 (no agreement) to 1 (complete agreement). In this case, W was found to be 0.781875, which was higher than 0.7 (agreement threshold). This indicated high correlation among the participants' answers regarding the importance of the tool's various factors as shown in Figure 8-10.



Figure 8-10: Tool attributes ratings

The results of the ratings showed that the participants somewhat agreed on the order of the importance of the tool's attributes: the highest rating was given to the graphical user interface (GUI), followed by visual representation. Some ratings were relatively close (e.g. artificial lighting integration and including various building types with various thresholds). Some results put a high value on the numerical outputs while others found it invaluable. It was noticed from the results that all participants agreed that the least important attribute of the tool was providing design recommendations, and they commented that: "no designer likes to be told what to do."

Although the participants were satisfied with the tool outputs, and its evaluative capability of visual comfort conditions, as well as selecting among alternatives, they questioned the truthfulness of the tool outputs and whether they can trust its results to represent the real conditions.

## 8.2.5.2 Confirming the findings using Reliability and Validity Check

As previously discussed in Chapter 6, the study examined a Washington DC Smithsonian Museum circulation path for quantitative and qualitative data comparison that was collected over five weeks. In the quantitative comparison, statistical analysis was used to compare the simulated and measured illumination conditions. The qualitative assessment aimed at finding qualities in the research findings. The researcher used the confirmability criteria during the process to confirm the results (as discussed in Chapter 6).

# • Illuminance data comparison results: Statistical analysis results

The statistical analyses applied were the t-test, average difference, and standard deviation as shown in Table 8-6 and examined the following sections.

### Table 8-6: Illuminance statistical analysis

Number of variables				Measure	Tests
1	(2	matched	populations-	Mean, median, propositions	Paired t-test, correlation
simulated/measured)					

- <u>The t-test:</u> Statistics from a t-test were calculated for the measured and simulated hourly average illuminance values, as shown in the t-test analysis in Appendix I. The researcher performed the two-tail test for determining inequality between the two sets. The noted difference between the means was not convincing enough to say that the average value between the measured and simulated illuminance values was significant (t-value1.48< critical t-value 1.64).
- The Illuminance Average Difference Percentage: The total average difference between the in-situ illuminance measurements and the computer simulated ones (from the five weeks of illuminance data) was used to check for differences. The difference varied from +/-19% to +/-27%, concluding with a mean of +/-23% that was somewhat higher than the Radiance allowed calibration threshold (+/-20%)—which was a sign of relatively close values as shown in Figure 8-11.



Figure 8-11: Average illuminance difference percentage

- <u>Standard Deviation/Coefficient of Variation:</u> A standard deviation of 6.7 for the measured illuminance and 6.3 for the simulated illuminance were found. Since the t-test results produced different means, the researcher calculated the Coefficient of Variation to help her compare the data results as follows:
  - The simulated illuminance values; CV=6.7/8.9\*100=75.3%
  - The measured illuminance values; CV=6.3/7.8\*100= 80.7%

A relatively close Coefficient of Variation was found between the two sets of data indicating a high similarity between them.

<u>The illuminance correlation coefficient:</u> This was calculated to test the relationship between the measured and simulated illuminance values, and was equal to 0.971—indicating a strong positive correlation between the simulated and measured illuminance values.

## • Luminance Data Comparison Results

The luminance comparison checked the Daylight Glare Probability (DGP) generated from both the in-situ camera images and the computer simulated ones.

The DGP relative error: The average relative error between the DGP of the in-situ camera images and the computer simulations was examined from the directions of the two views (towards and from the Peacock Room), and was found to be 18% for view1 and 16% for view2; both percentages were higher than the glare threshold distinguished by the human eye, (acceptable DGP relative error ≤ 10%) as shown in Figure 8-12.



Figure 8-12: Relative error percentage
- <u>The correlation coefficient:</u> The luminance correlation coefficient was calculated to be 0.974 between simulated images and in-situ camera images. DGP indicated a strong correlation between the reproduced and captured images glare.

# 8.3 Research Results Criteria for Acceptability

How can one guarantee the acceptability of results? Positivists often question the trustworthiness of qualitative research findings, since their concepts of validity and reliability are addressed differently when compared with quantitative studies. Several investigators attempted to respond to the issues of validity and reliability in their qualitative studies. For instance, Guba and Lincoln (1994) proposed four criteria that they believed should be considered when evaluating the qualitative research findings: credibility, dependability, transferability, and confirmability. These four criteria were subsequently used to examine the acceptability of the results from this study.

## 8.3.1.1 Credibility

To ensure credibility of the research results, the researcher followed Lincoln and Guba (1985) highlighted requirements to promote accuracy of the recorded phenomena including:

## a. Adoption of recognized research methods

- The researcher selected immersive and collaborative case studies, reliability and validity checks and Delphi research methods since they are recognized and previously applied in similar research.
- The study of previous research was important to frame the findings.
- The data analysis method presented in the statistics comparison between the two sets of data using relative error and average difference percentage were successfully utilized demonstrate reasonable accuracy (Cormode et al., 2005, Van Giang Tran and Polit, 2008).

## b. Sampling of individuals

• The researcher selected participants with different backgrounds based on maximum variance sampling, which helped to generate various feedbacks.

## c. Triangulation

- Results and conclusions were based on multiple resources (members' feedbacks, and the researcher's notes and observations).
- In the case study, different data resources were incorporated to collect the examined data. The 3D model input data were obtained using 1) a model generated by the researcher, 2) an existing and verified 3D mass available online, 3) in-situ measurements, and 4) Google Earth.

## d. Ensuring results' honesty

• During the case study, the participants freely expressed their opinions on open-ended iterative questions during the course of two meetings, where feedback was collected from several data collection dialogues.

## 8.3.1.2 Dependability

• Dependability was obtained in this research through in-depth methodological description: the researcher recorded all the steps to allow the study to be repeated.

### 8.3.1.3 Transferability

The researcher was responsible for ensuring that enough appropriate information was provided for the validity and reliability check, which allowed practitioners to relate to their work including 1) data collection period and simulation hours, 2) in-situ data collection tools and process, 3) 3D model development details and materials properties, and 4) previously-used software. During the process, a detailed description of the phenomena being examined was provided from the collected data plus the researcher's notes and observations, which allowed for the thorough examination of the process.

## 8.3.1.4 *Confirmability*

Confirmability was obtained at this stage of the research through:

• Triangulation using: 1) a detailed methodological description, 2) a documented procedure for checking and rechecking the data through the study process, and 3) registered notes and observations during the process.

- Assumptions: The researcher did not tell the participants her beliefs, but only stated them in this document to reduce the effect of her bias.
- Limitations: The researcher explained the study's limitations and their potential effects.
- Methodology: The researcher provided a detailed description of the method to allow for transparency of the research results.
- Audit trail: The researcher incorporated some diagrams that interpreted the applied process.

The criteria for acceptability are summarized in Table 8-7:

Quality	Possible provision made by researcher
Credibility	<ul> <li>Adopting recognized research methods</li> <li>Sampling of individuals</li> <li>Triangulation (use of different methods)</li> <li>Ensuring honesty of results</li> </ul>
Dependability	In-depth methodological description to allow study to be repeated
Transferability	• Provision of background data to establish context of study and detailed description of phenomenon in question to allow comparisons to be made
Confirmability	<ul> <li>Triangulation to reduce effect of the researcher bias</li> <li>Highlighting the researcher beliefs, observations, notes and assumptions separately</li> <li>Showing the study limitations and their possible effects</li> <li>Providing detailed description of the methodology to allow for transparent research results</li> <li>Use of diagrams to demonstrate "audit trail."</li> </ul>

Table 8-7: The	e criteria for	acceptability
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# 8.4 Chapter Summary and Conclusion

Decision support tool features and characteristics plus key observations during the design process stages are summarized in Table 8-8.

Stage	e Decision-making key observations		Features built into the tool current/future iteration
Immersive study	case	<ul> <li>Providing information on the problem times and locations</li> <li>Importance of glare locations and times and frequency of occurrence</li> </ul>	• Daylighting dynamism representation; highlighting visual discomfort points and images in the field of view.

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I anie X-X. Ke	v onservations in i	rne design nrocese	s and their ettect	i on teatures nuut	1010 The 1001
Lubic 0 0. He	y observations m	me design process	j unu unen eneet	on reactines built	meo the tool

Stage	Decision-making key observations	Features built into the tool current/future iteration
Delphi	<ul> <li>Importance of evaluation summary</li> <li>Importance of the Graphical user interface (GUI)</li> <li>Importance of the graphical representation of the outputs</li> <li>Allowing the designer to control indexes if needed</li> <li>Building type can vary regarding glare threshold based on the space activities and occupants</li> </ul>	<ul> <li>Add a simulation summary</li> <li>Enhance the GUI</li> <li>Enhance the graphical representation of the outputs</li> <li>Adding a feature to set own guidelines/thresholds (if different from default)</li> <li>Adding a list of building types with corresponding luminance/illuminance metrics thresholds</li> </ul>
Reliability check	Maintain data truthfulness	Multiple evaluation indexes

From the research findings during the design process of the two examined case studies, it was confirmed that the tool succeeded in its intended goal as an informative decision support method, which positively affects design decision-making. The research findings presented a change in the normative design decision theory; the research approach attempted to improve upon existing design practices, towards a new method for how design should be done. The existing and the proposed shifted design process with the tool as related to the case studies are shown in Figure 8-13.



Figure 8-13: Existing and shifted design process with the tool

## 9 CHAPTER 9: CONCLUSIONS AND FUTURE WORK

"It is paradoxical, yet true, to say, that the more we know, the more ignorant we become in the absolute sense, for it is only through enlightenment that we become conscious of our limitations. Precisely one of the most gratifying results of intellectual evolution is the continuous opening up of new and greater prospects. "- Nikola Tesla (Rubin, 2010)

## 9.1 Research Motivation

Although several studies have examined visual comfort, several issues still exist when implementing daylight into contemporary designs. This is because most existing tools do not consider two important dynamic issues – time and space. Also, a large number of lighting analysis tools are not applicable during the early stages of the design process and are only accessible to professionals with specialized computing and programming skills. Therefore, the researcher was motivated to improve designers' decision-making by informing the process from a much early stage in a way that was more approachable. To achieve this goal, a shift in the design process was proposed to evaluate visual comfort through the development and implementation of a prototype tool.

## 9.2 Research Journey

The researcher attempted to make sense of the examined phenomena of visual comfort and glare through a research journey to develop an evaluative tool. This journey consisted of data collection triangulation from resources including case studies, personal experience, reflective and in-depth interviews, Delphi feedback, observations, and visual text.

In the beginning, the researcher conducted a literature review on daylighting, glare and visual comfort. She found previous research gaps in multiple daylighting aspects including the dynamism of time and movement in space. Also, the researcher noticed that most of the previous research results were based on either luminance or illuminance for daylight evaluation and none considered the interaction between them. In addition, she found that daylighting analysis required specialized knowledge in daylighting techniques, evaluation metrics, and some programming knowledge with no simple tools that could be used directly by architects. For these

reasons, she concluded that there was a need for a shift in the design process to allow daylighting aspects and visual comfort to be considered early in the design process. She worked on developing a first-of-its-kind tool that considers daylight's dynamic aspects, is applicable in the initial stages of the design process, is accessible to architects, and interfaces with 3D modeling software used by architects.

As a first step towards prototyping, the researcher conducted an initial survey to justify the literature review findings, to inform the prototyping process, and to explain/confirm the researcher's theory about the nature of the problem. The study targeted a large, diverse group of stakeholders that are interested in the topic. The investigation confirmed the researcher's assumptions and showed further unexpected findings—including that architects do not apply daylighting software because they are unaware of which metrics are being used and that clients sometimes do not require daylighting analysis to take place in their designs. However, it was found that there is a strong belief among all the survey participants that daylighting analysis is an important aspect and should be considered early in the design process.

Based on the survey findings and the literature review, the researcher established the initial version of the prototype while considering the following: no single glare metric can adequately evaluate glare since one category of these metrics considers the brightness of the light/glare source (luminance-based) while the other category considers the daylight distribution illuminating the surfaces (illuminance-based).

To evaluate the first prototype version, member checking was applied (i.e. a purposeful group of experts in daylighting simulation assessed the tool). The members showed interest in using the tool and provided the researcher with necessary modifications. Also, some members suggested applying the tool to an existing building that holds special lighting conditions, while others recommended testing it in an office space—similar to previous research case study analysis. Based on the member check results and her recorded notes, the researcher revisited the tool to apply the suggested modifications and generated the second version of the tool.

To test the second version of the prototype, the researcher used it in two immersive case studies. In the first case study, the researcher examined a typical unbuilt office space and used a series of design modifications that can be applied in different design process stages. The researcher expected that the design changes applicable to the early phases of the design process would yield better visual comfort and minimal glare when compared to those that apply in later stages. The results were not significantly different, but during the decision-making process, she learned that the number of design modifications appropriate in the early stages considerably exceeds those that are applicable in later stages. The researcher recorded her notes and observations during her immersion in the design process. She concluded that the tool significantly informed her design decisions during the problem identification stage (i.e. the evaluation of the visual comfort) and the selection between alternatives.

In the second case study, the researcher collaborated with a group of professionals; she followed a focus-group strategy to integrate members with daylighting and simulation backgrounds and experience to maximize the collaboration benefits. During the process, she was able to monitor carefully the design decisions being made during the design process. One important observation she learned was how designers perceive daylighting analysis-related decisions differently. Some developers indicated that light contrast is a significant issue when designing for daylighting, while others insisted on the importance of lighting uniformity within the space. However, they all agreed that whether the designer's intention was to incorporate some contrast or ensure uniformity, the proposed tool would be beneficial for informing the designer about the contrast condition in space, while still leaving it to the designer to make the final design decision.

To ensure the truthfulness of the research findings, the researcher applied a Delphi method and reliability and validity checks. During the reliability and validity checks, the researcher compared the illuminance and luminance values from the tool with their corresponding in-situ measured ones. She expected that the illuminance values would dramatically vary since she made some assumptions (weather conditions, in-situ measurements approximations, and accuracy of the used instruments) during the data collection process. However, the illuminance and luminance simulated values did not change significantly from the measured ones.

During the Delphi interview, she collected feedback from a purposeful group of members regarding the tool findings from the office case study. She followed a maximum variance strategy to integrate members with a variety of backgrounds and experience to maximize the benefits of the feedback. The members indicated that the proposed tool would be beneficial, especially to bring daylighting simulations and analysis in-house since they are normally sent to daylighting experts/consultant offices, commenting: "I like that the tool can tell me when to stop." Moreover, in the second round of the Delphi the members ranked and ordered various features of the tool. The researcher expected that the members would highly recommend design recommendations to easily modify the proposed plans. However, the results showed that all participants agreed that these design suggestions are not useful, and justified this with the statement that "no architect likes to be told what to do." The members also explained that design solutions differ drastically depending on many factors that are also variables from one project to another. Therefore, they agreed that the tool should be a decision support tool only, to help designers during their design process. Their final comments included: "It is the first time to use 3D modeling for decision support, not for representation only"; "I never knew I was facing this problem every day until I saw the tool presentation"; and "The tool provides a unique insight on the dynamism of the occupants journey in the space."

### 9.3 Key Moments of Discovery and Learning

One primary goal of this qualitative research was to discover patterns that emerge from close researcher observation, documentation, and thoughtful analysis of the research topic. This process of discovery is the philosophic underpinning of the qualitative approach.

During the research journey, the researcher was an active learner, where key moments of discovery were recognized. To support the learning process, the researcher relied on her journal during the office case study, her notes and observations from the collaborative case study, and Delphi feedback collection process. With these steps, she began to identify concepts, categories, and themes from the collected data by looking for relevant meanings in the participants' comments and her recorded notes and observations. Then, she analyzed the data using multiple levels of abstraction—or preliminary categorizations of themes that can be combined with larger themes—from the particular to more general subject matters. Finally, she constantly compared her data where new themes and concepts emerged.

### 9.4 Contribution to the Body of Knowledge

The research was an in-depth understanding of glare and visual discomfort phenomena; it provided an approach describing in explicit detail the dynamics of space-making. The research concluded arguments regarding glare and visual comfort phenomena that are supported with examples, and interpretation of patterns and themes from the experienced data. The reliability, validity, and efficiency of field research were proved using statistical analyses that defined quantitative research products. The research made a contribution to prospective theory by developing and demonstrating an improvement in the design decision-making process. The researcher moved between quantitative (Delphi and reliability checks) and qualitative (interviews and observations) types of data and drew on each to inform the design process and answer its central questions, which provided a deeper understanding of the research problem.

### 9.5 Future Research

The emotional and romantic experience of architectural spaces emphasizes the quality of the visual environment. This quality creates a complete phenomenological experience, which can improve our understanding of the relationship among daylighting, the quality of the place, and occupants' satisfaction, health and well-being. Thus, the proposed tool can be used to enhance the connection between architectural forms, light, and shadow to create poetic spatiality in a building. Using the results of this study as a starting point, the research suggests several avenues of future research in the following sections.

**Multidisciplinary application.** This research is multidisciplinary by nature. The developed tool can be used to improve wayfinding; especially for elderly and visual impaired pedestrians. As one example, in a recent journal paper, the researcher demonstrated the developed tool's capabilities by evaluating and enhancing metro commuters' visual adaptation in their passageway of entering and exiting metro stations. The tool framework addressed both types of adaptation: dark adaptation and light adaptation and how they can affect the pedestrians/metro commuters' experience. The proposed framework can be expanded to support many U.S. Department of Transportation's Livability Initiatives and Accessible Transportation Technologies Research Initiative (ATTRI) program (Hafiz, 2016, p.229).

**Incentivizing walkability in cities.** Investigations into spatial and temporal glare analysis of visual comfort effect can help connect the city by ensuring comfortable visual adaptation between the inside and outside environment, subsequently enhancing the connection between the buildings and the city. The museum case study presented a starting point of incentivizing walkability within a confined space, which could then be applied to incentivizing walkability in an open space.

Additional features of the tool. The tool succeeded in assisting designers in the decisionmaking process. However, there is still room for improvement: from the researcher's observations during the process, she c oncluded that other features can be added to the current version of the tool including multiple lighting directions, eye directions, and visual discomfort in occupants with visual impairments. Other features emerged from the participants' feedback including a database of electrical lighting to be considered in the simulations, and the study of the effect of thermal, acoustic and mood comfort on visual comfort. Also, the tool future versions need to provide an independent/dependent variables relationship between parameters of influence for visual comfort in space. This is specifically relevant for the envelope conditions (size, material, fenestration systems, etc.) and the interior environment (surfaces colors, reflectances, room geometry, etc.). A correlation study of such parameters would be beneficial to examine the accuracy and dependency of the thresholds in the tool. The tool future iterations need to investigate the communication between the architect and the lighting consultancy. This can take place by providing multiple editions of the tool with levels of interaction with the tool and outputs details. The research investigated the integration of BIM (Revit) using Grasshopper; this can be implemented in the next version of the tool and could become a valuable part of the typical process of implementing BIM in offices.

**Future contribution to the body of knowledge.** The research tool could contribute to the body of knowledge through different approaches: the tool can be part of a course on lighting /daylighting, comfort, occupants as a source of energy and the examining visual comfort effect on the behavior of the occupants. The profession of architecture can be improved through educating students in the studio about the importance of considering visual comfort in the decision-making process and its effect on design decision-making.

# 9.6 Final Thoughts

"Architecture is the learned game, correct and magnificent, of forms assembled in the light." - Le Corbusier

Architects always try hard to create beautiful shapes and spaces that inspire humans within. Although the perception of beauty is subjective ("beauty is in the eye of the beholder"), the pleasure found in surrounding architectural spaces and forms is universal. Architecture has the power to influence who we are and how we feel. In fact, comfort has a lot to do with how spaces engage occupants through each of their senses, especially when considering the harmonization of all aspects of comfort including visual, thermal, acoustics, and mood.

The proposed research succeeded in assisting designers in making informed design decisions concerning glare and visual comfort in daylit spaces. The true success of daylit buildings will be measured in beautiful architecture that creates comfortable, exhilarating places in which to be. The research will continue to assist designers and decision makers to create beautiful spaces.

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# Appendix A. List of Definitions

This section presents the definitions of the key parameters presented in the research.

*Illuminance:* is defined as the total density of the luminous flux incident on a surface, per unit area. It gives the information on how much the incident light illuminates the surface. Figure A-1 provides an example of typical sunny day illuminance distribution. It can be measured in footcandle or Lux, 1 Lux= (1Lumen/m2) (REA, 2010, Linstone and Turoff, 1975, Guha et al., 2004).



Figure A-1: Illuminance typical values at noon on a clear day in temperate climates

- Solid angle (ω): measures the portion of space about a point bounded by a conical surface whose vertex is at the point. It is also defined as the ratio of the surface area of a sphere centered on that point to the square of the sphere's radius. It is measured in steradians (REA, 2010).
- *Luminance:* is defined as the amount of light passing through a particular area and falling within a given solid angle. Luminance is measured in Candella/ meter<sup>2</sup> or (nits) (Cottam et al., 2004, REA, 2010).
- *Brightness:* can be defined as the subjective sense of luminance. It characterizes an area of the color of a known size is supposed to produce, transmit, or reflect a larger or smaller amount of light without judging the light source (REA, 2010). The term luminance is sometimes misused to mean brightness. The term "brightness" cannot be used for a quantitative explanation; it can only refer to subjective non-quantitative sensations of

light. They can be distinguished by calling them (subjective brightness) and (measured brightness) (Kapoor, 1987).

- *Perceived Brightness:* The possible received effects by varying surface reflectance and illuminance is called *perceived brightness*. As the background luminance of a scene increases the background luminance of a scene decrease the perceived brightness of the light source (Islam et al., 2006). A good example that explains this incident is the appearance of cars headlights; they are brighter during the night more than the day. This is caused by the high morning luminance but low subjective brightness. Because of the subjective nature of brightness, one person may feel a particular luminaire is brighter than another person.
- *Adapted brightness:* An ambient light sensor used for adapting to the environment surrounding results is an automatic brightness adjustment or (*Adapted brightness*). This technique can be applied to the computer screen to adjust its brightness automatically according to the surrounding ambient light (Carlucci et al., 2015).
- *Luminance/contrast ratio:* is defined as the ratio of the luminance of the brightest color (White) and the darkest color (Murphy et al.); it is different from the luminance ratio which expresses the ratio between the luminances of any two areas in the visual field (Rea, 2000, REA, 2010).
- Adaptation Luminance: represents the luminance the observer can adapt to. It is proposed that the observer can adapt to the luminance of our fixation point which approximately covers 1 to1.5 visual degree. Adaptation luminance value is the sum of the average scene luminance and the veiling luminance due to disability glare (Roudsari and Pak, 2013). Adaptation luminance can also be called (adaptation brightness; adaptation level, brightness level, field brightness, field luminance) (Pesudovs et al., 2002).
- *Artificial sky:* An *artificial sky* is an enclosure that aims for testing physical daylighting models by imitating the luminance distribution of a real sky. The most common shapes of artificial skies are a hemispherical dome and a mirror box artificial sky as shown in Figure A-2. A scaled model is used under an artificial sky to predict daylight penetration inside the building, especially under unusual situations or for complex geometries (Chatzikonstantinou, 2015).





- *Guth index:* represents a position indicator of each glaring luminaire about the direction of observation. It depends on the distance from the line of sight of the viewer and varies from 1, on the line of sight, to 15 on the boundary of the visual field. It is used to calculate the Unified Glare Rating (Cavazza et al.) and Visual Comfort Probability (VCP) to evaluate discomfort glare from lights located above the line of sight (Plympton et al.).
- *Position Index:* is a factor that represents the average relative luminance for a sensation at the borderline between comfort and discomfort (BCD) for a source located anywhere within the visual field (REA, 2010). Position index (P) is different from Guth position index (Plympton et al.) is that (P) is an indicator for any specific reference point which represents the eye position of a person performing visual tasks in the chosen direction of observation. P can be calculated from Figure A-3 and Equation A-1:

 $P = \exp[(35.2 - 0.31889\alpha - 1.22e^{-2\alpha/9})10^{-3}\beta + (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5}\beta^2]$ Where, Equation A-2  $\alpha$  = angle from vertical of the plane containing the source and the line of sight, in degrees,

 $\beta$  = angle between the line of sight and the line from the observer to the source.



Figure A-3: Position index geometry calculation

• **Daylight glare probability:** It is an empirical approach based on the vertical eye illuminance as well as the glare source luminance, its solid angle and its position index (Harvard, 2006). DGP calculation considers the overall brightness of the view, the position of glare sources and visual contrast. This method provides a strong connection to the user response concerning glare sensitivity when compared to other existing glare models. DGP can be calculated from the following equation:

DGP = 5.87 X10<sup>-2</sup> 
$$E_{v} + \frac{9.18 X 10^{-2} \log(1 + \sum L_{Si}^{2} \cdot \omega_{Si})}{\left[(E_{v}^{C4} \cdot P_{vi}^{2}) + 0.16\right]}$$
 Equation A-3

While  $E_{v=}$  Vertical illuminance at eye level (Lux) Ls is the luminance of the source (cd/m<sup>2</sup>),  $\omega$  is the solid angle of the source (Cormode et al.), and P is the Guth position index.

Term 1: measurable visual comfort aspects that depend on the vertical eye illuminance (may be calculated using DAYSIM software) and Term 2: immeasurable visual comfort aspects that depend on the detected glare sources: size, luminance and position (needs an image evaluation).

A simplified method to calculate the DPG was presented by Wienold (2009). This method shows a reasonable glare perception judgment when considering only vertical

space illuminance at eye level. Therefore, a simplified DPG (DGPs) was found (Weinold and Christoffersen, 2005).

 $DGPs = 6.22 X 10^{-5} E_{\nu} + 0.184$ 

Equation A-4

- *Horizontal diffused illuminance:* can be defined as the illuminance produced by the visible part of the diffuse solar radiation (on a primarily not incident work plane or surface). It is measured in Lux (Pesudovs et al., 2002, Rea, 2000).
- *Vertical space illuminance: Vertical space illuminance* is the illuminance measured on vertical surfaces (walls). It aims to make spatial proportions and spatial limits visible, in addition to the presentation of vertical surfaces. It is measured in Lux (Pesudovs et al., 2002).
- *Vertical eye illuminance:* is the illuminance value extracted from a sensor pointing in the same direction as a human eye. It is used to calculate the simplified Daylight Glare which neglects the influence of individual glare sources (Wienold, 2009).
- *True Vs used error:* the data measured or used is normally different from the true value. The error comes from the measurement inaccuracy or the approximation used instead of the real data. Absolute error, relative error, and percent error can be used to represent such discrepancy:

absolute error =  $|V_{true} - V_{used}|$ relative error =  $|(V_{true} - V_{used})/V_{true}|$  (if  $V_{true}$  is not zero) percent error =  $|(V_{true} - V_{used})/V_{true}| \times 100$  (if  $V_{true}$  is not zero), Where Vtrue is the true value, and Vused is the value used (Guha et al., 2004).

- *Purposive sampling:* This means that the researcher selects those members of the community whom he/she thinks will provide the most useful information to serve the research objective.
- *Maximum variance:* is a purposeful sampling strategy that aims to sample for heterogeneity (Patton, 1990 #297).
- *Proscriptive environment:* refers to an environment that operates by prohibiting inappropriate actions, while not limiting the means or order in which tasks are performed. Consequently, the environment is more flexible and unexpected problems are easier to handle.

- *Prescriptive environment:* indicates that the process environment strictly controls the means by which a task is to be completed, and the order in which tasks are to be performed (Keil et al., 2002). The primary disadvantage of a prescriptive system is that it can take away control and minimize creativity.
- *Diagnostic:* diagnostic judgment involves using intuition, visualization, organization and structuring of evidence, and the understanding of relationships to reach a conclusion.
- *Inductive:* inductive reasoning requires the synthesis of evidence and information from a variety of sources. Induction requires the use of an individual's awareness of signs and evidence to draw conclusions. The ability to draw correct conclusions using inductive reasoning is directly related to an individual's experience, observations and ability to recognize evidence.
- *Interpretive:* interpretive reasoning involves the recognition of patterns, spatial relationships, correlations and causal relationships.

	Purpose of case study			
Type of Structure	Explanatory	Descriptive	Exploratory	
Linear Analytic Typical article format Problem statement Literature review Methods Results	X	x	x	
Chronological (Narrative sequence)	Х	X	Х	
Theory-BuildingSequence depends on logic oftheory development	X		X	
Unsequenced Sequence is interchangeable		X		

• *Yin case study typology:* (Groat and Wang, 2002; Yin, 2009)

**Descriptive:** Aims to present a description of a situation within its context (deals with *how* and *why* questions).

**Explanatory:** Seeks to explain cause-effect relationships to discover theory, it focuses on covering background information and accurate description (Larson et al., 1998).

Exploratory: Aims to define the questions and hypotheses (deals with what question).

- *Kendall's: W coefficient* is a non-parametric statistic used for assessing agreement among raters. It ranges from 0 (no agreement) to 1 (complete agreement) (Kendall and Smith, 1939).
- *Confirmability of research results:* Confirmability ensures that the research findings present the outcome of the experience, and not the characteristics and preferences of the researcher (Shenton, 2004)
- Open coding: where words and phrases are labeled in the transcript,
- Axial coding: where a theme is created by grouping and sorting codes and labels
- *Selective coding:* where the researcher selects the core category, relate it to other categories and explain the relationship between them (CRISP et al., 1997)
- *The hermeneutic method:* is a qualitative research strategy that is well-grounded in philosophy. It enables a deep understanding of the investigated phenomenon. According to Martin and McIntyre (1994), "The interpretation aims to bring to light an underlying coherence or sense" ((Martin and McIntyre, 1994). Hermeneutic method focuses primarily on the meaning of qualitative data, to make sense of the object of study.
- *Credibility of research findings:* The credibility of quantitative research depends on instrument construction; in qualitative research, "the researcher is the instrument". Thus, the credibility of the research results depended on the effort and ability of the researcher to answer the question "How congruent are the findings with reality?"
- **Dependability of research findings:** Dependability ensures that similar results would be obtained if the work were repeated, in the same context, and with the same methods, (Hoepfl, 1997).
- *Transferability of research results:* Transferability is often concerned with demonstrating that the outcome of the proposed research can be applied to a wider population. However this cannot apply to qualitative research since the findings of a qualitative project are unique to a small number of environments. Stake (1995) suggested that practitioners might relate the findings to their positions if they found that the situation described in the study was similar to their situations.
- APMO Cut-off Rate (Average Percent of Majority Opinions): APMO is a measure of consensus using qualitative analysis and descriptive statistics. The consensus is assumed to be achieved when a certain percentage of the votes fall within a prescribed range (Linstone

and Turoff, 1975). The prescribed range was determined by the Average Percent of Majority Opinions (APMO), which produced a cut-off rate that determines whether consensus has been achieved (Kapoor, 1987). To reach consensus, a statement must achieve a percentage for 'agree' or 'disagree' that is higher than the APMO cut-off rate (Kapoor, 1987). APMO was calculated from the following equation:



Equation A-5

Multiple studies attempted to calculate an APMO Cut-off Rate (Islam et al., 2006). APMO Cut-off Rates of 70% (first round) and 83% (second round) are used for consensus measurement.

# Appendix B. Daylighting Simulation Tools Questionnaire

# • Introduction

Before building the prototype tool a preliminary daylighting tool survey on daylighting software was conducted to collect opinion from a variety of members about the difficulties facing users of the existing daylighting analysis tools, preferred forms of outputs and suggestions towards daylighting analysis tool improvements as shown in the questionnaire framework in Figure B-8. Subsequently, the initial prototype was created based on the questionnaire and the literature review. The questionnaire was available online for six weeks through the following link:

https://docs.google.com/forms/d/12Wg88d9mQGy5AOtwpQA5dnobH5h9ipr9iY81KrHUaHQ/v iewform

# • The introduction letter of the survey

"The Virginia Tech school of Architecture and Design student Dalia Hafiz and Professor Jim Jones initiated a study to collect opinion on daylighting simulations software in the design process. It will be very appreciated if you could take a few minutes to fill this short survey. The survey should take about 2 minutes to complete. If you have any questions or comments about the survey, please contact us via email at (<u>dalia1@vt.edu</u>). "All survey participants must be at least 18 years old."

This research may be used for dissertations and/or publication, and the data is collected anonymously. There are no more than minimal risks associated with participation, and that participation is voluntary. For any concerns, the IRB Chair's contact information: Dr. David Moore, IRB Chair, moored@vt.edu or (540) 231-4991.

Thank you for your time,

Dalia Hafiz."

# Questionnaire part one: Participants background

This phase examined the participants background including profession and types of projects they work on. It also documented how different professional groups and buildings types.

## Profession

The sample was grouped as follows: architects 53%, engineers 11%, researchers 7%, consultants 6%, students 8% and 7% of other professions including interior designers, builders, contractors, energy raters and lecturers as shown in Figure B-1: Profession distribution



# **Types of Projects**

The common projects types as indicated by the participants were categorized as residential at 43%; offices represented 19%, all buildings types represented 6%, commercial and museums at 3%, hospitals, and industrials at 2% and other at 8% which included landscaping, urban design and institutional buildings as shown in Figure B-2.



Figure B-2: Projects worked on responses

## **Daylighting analysis integration**

It was found that 91% of the participants included daylighting analysis in their design process as shown in Figure B-3. Those not using daylight analysis were primary involved in residential projects.





### Reasons for not including daylighting analysis

From the responses, it was shown that 40% who answered that daylighting analysis is not considered in the design process stated that "daylighting analysis is not required by the client." A total of 22% of the participants indicated that another reason for not including daylight analysis was "the tools are intended for daylighting experts". Other reasons included: "unfamiliarity with

various tools and uncertainty for which one to use (7%)", "tools are hard to learn (11%)" and some participants indicated that "the tools results are not accurate," Figure B-4.



Main reason for not including daylighting analysisl



## Questionnaire part two: simulations software

The objective of part two was to investigate how participants considered the relationship between computer simulation software and daylighting analysis. Part two also examined the preferred daylighting indexes and visual comfort metrics, and the most desirable forms of outputs, as shown in Figure B-5



3D modeling software vs. preferred daylight evaluation indexes



#### Daylighting analysis in the design process

75% of the participants stated that daylighting analysis occurs in the schematic and conceptual design stage, and 25% stated that it takes place in the final design phase. Finally, 93% of the participants believe that daylighting analysis should occur in the conceptual and schematic design stages while 4% believe it should happen in all phases as shown in Figure B-6



Figure B-6: Daylighting analysis stage in the design process Vs believed daylighting analysis stages

### **Daylighting simulations outputs**

Survey findings showed that 36% of the architects preferred graphic simulations outputs. Engineers seem to prefer quantitative outputs such as; the daylight factor was found to be the engineers preferred output at 36%, followed by illuminance values and visual simulations at 29%. In total, the preferred simulation outputs were: visual simulations at 40%, and then illuminance value and daylight factor at 25%, 9% of the participants believe that all types of simulations outputs are equally important. The rest of the respondents were equally divided between daylight factor and daylight autonomy and "I don't know". Architect, engineer, and researcher responses are shown in Figure B-7.



Figure B-7: Preferred simulations output

## Participants comments and suggestions

At the end of the survey participants could give comments and suggestions. Some of the main comments were:

- Address the current need to use different models for the several areas of the same project.
- Investigate daylighting analyses effect on mechanical systems especially for LEED modeling and decision-making processes. "Often daylighting is done as an afterthought and energy modeling inputs are not well understood by the modelers, who are usually mechanical
or electrical engineers, not the building designer, and therefore, the inputs are limited to the modeler's field of discourse."

- Energy modeling is a major factor in a good daylighting tool. Daylighting and solar gain have to be considered together.
- Questionnaire flow chart



Figure B-8: Daylighting tool questionnaire framework

## Appendix C. Member Check Interview

#### • Introduction

The researcher gets the participants verbal consent:

"My name is Dalia Hafiz; I am a graduate student at Virginia Tech, working with my faculty advisor, Professor James Jones in the School/Department of Architecture and Design. I would like to invite you to take part in my research study, which concerns to knowing the members feedback on the effect of using the research proposed visual comfort evaluation tool and get their feedback on the understanding of the different tool modules".

"If you agree to participate in my research, I will conduct an interview with you personally/on the phone at a time of your choice. After a small presentation, the interview will involve questions about daylighting analysis, the proposed tool interface ease of use and users understanding of the tool different stages. Each participant represented a user group; three groups were examined: architects, daylighting experts and architecture researchers

"The interview should last about 45-60 minutes. With your permission, I will audiotape and take notes during the interview. The recording is to record accurately the information you provide, and will be used for transcription purposes only. If you choose not to be audiotaped, I will take notes instead. If you agree to be audiotaped but feel uncomfortable at any time during the interview, I can turn off the recorder at your request. Alternatively, if you do not wish to continue, you can stop the interview at any time".

"The study data will be handled as confidentially as possible. If results of this study are published or presented, individual names and other personally identifiable information will not be used. When the research is completed, I may save the recordings and notes for use in future research done by myself or others and data will remain confidential".

# • Interview Questions

The interview questions as summarized in Table C-1.

Questions category	Questions	
General graphical user	Tel me about your experience with the tool.	
interfaces questions	How do you feel about the interface organization?	
Instructions and help	How do you think about the help menus, download instructions, and	
menus questions	additional tutorials?	
Input data questions	Tell me about the clarity and your understanding of the inputs	
Evaluation process	Could you please describe your impression on the assessment process?	
questions	How does the tool compare to other types of tools you have experienced in	
	the past?	
	What do you like the most about the tool?	
Final feedback from all	How do you feel about the tool effect on the design decision making?	
previous stages on . Do you have anything to add?		
decision making.	Is there anything I should have asked?	
	How could the program be improved?	

Table C-1: Interview questions

# Interview Results Analysis and Interpretation

The interview results key quotes are shown in Table C-2

Questions	Member ID	Response main quotes
category		
General	Member1	"I think the interface is not very user-friendly especially in the
graphical		introduction stages: I did not understand if it through another program
user		or a standalone tool, a little explanation is needed here."
questions	Member2	"The interface is not dynamic. The tool aims at dynamic daylight and the interface is very static".
	Member3	more simplification of the tool is needed for it to be more user-friendly
	Member4	I think I need to see a set of guidelines that help me to see at the
		indexes thresholds to pay attention for.
	Member5	"The tool does not represent 3D animation. It does not attract me to
		use it especially at the very first impression".
Instructions	Member1	"Help menus need to include more explanation."
and help	Member2	"There are too many details on the download which seems very
menus		complicated and discourage me from downloading the tool through this
questions		long process."
	Member3	"A final report card with colors and graphics showing different areas."
	Member4	The tool needs to provide an explanation of the glare problem before
		the designer start using the tool
	Member5	"I guess the instructions, tutorials and glare indexes explanations
		should all be in the help menu, only when the user needs them."
Input data	Member1	"I find the input page quite understandable; I have no problem inserting
questions		the data."

Table C-2. Thiely lew results quotes	Table	C-2:	Interview	results	quotes
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	Member2	"I think there is some missing explanation in this section, especially if the user has a small background on daylighting simulation. An additional help menu is needed in this section".
	Member3	"I would like to get some information about how the model can be set up so the evaluation tool can be most effective, may be the way we set up the layers too"
	Member4	"Main building surroundings and topography need to be modeled to generate more trusted results."
	Member5	"Since the tool is a plug-in for software, I believe the input should mostly be automated from the initial 3D modeling software-Rhino. Unless the user needs to change the geometry or simulation days, all input should be automatically loaded into the new tool".
Evaluation process questions	Member1	"I do not think the architect needs to see a table with illuminance values." "I am not aware of a previous tool that can do visual comfort evaluation."
	Member2	"I like the illuminance heat map; I don't quite understand the graphs. Daylighting systems are endless, by representing a set of recommendations you may end up with a misleading recommendation to the designer. I think it is better to let the designer decide what he needs to change in the design because you will do a lot of effort trying to help him solve the visual discomfort problem and your solutions may still not work because of different reasons including budget, design concept, architectural context, rules and other restrictions".
	Member3	"Provide the designer with a list of different building types to select from and recommendations to start with."
	Member4	"I would like to see the building on the map."
	Member5	"It is important to see the annual distribution of the illuminance values, may be through a link to an excel sheet if you don't want to display all this information in the results summary. Also, there is no way you will be able to represent all possible design recommendations, so I am not sure if it is necessary to introduce them at this stage. The idea of evaluation is what makes the tool different from other daylighting analysis software".
Final feedback	Member1	"I do think that the tool can alter the design process but with some modifications for light experts and non-experts."
from all previous stages on decision making.	Member2	"I think future iterations of this tool will be beneficial especially when introducing annual numeric and visual analysis. The idea of being able to evaluate visual comfort in space is a relatively new idea that still has not been fully covered in the previous research. I do also believe that the tool can expand to cover different topics and different building types since transitional spaces are present in all buildings." I guess much improvement can be added to the tool regarding interface, it needs to be compatible with other software. A manual guide needs to be developed or may be a "cheat sheet" quick start.
	Member3	"The tool can help provide feedback on glare and visual comfort condition that can be incorporated into the design."
	Member4	I also need to see the sun path and the examined space floor plan with the glare days and times next to the pictures (like a final summary or as an explanation of the whole process)

Member5	"At this stage I am not sure if the tool can make changes in the design process, but I guess with future iterations and modifications and future computing development it might, especially if it can be expanded as
	software that can do all the work and not a plug-in."

#### Interview Analysis Main Themes

The interview themes are shown in Table C-3

Themes	Codes	Corresponding text from interview		
Interface friendliness	Hard, easy, friendly, complex,	"not very user-friendly," "need more		
		explanation,"" very static," "does not attract me to		
		use it."		
Tool benefit	Helpful, benefit, useful,			
Evaluation process	understand	"don't quite understand"		
comprehension				
Tool improvement	Future, improvement, next iterations, suggest, expand, modifications, need to see, I would like to see more, you can add	"At this stage, I am not sure, with future computing development it might," "future iterations of this tool will be beneficial," "with some modifications."		

Table C-3: interview themes summary

### **Researcher notes and analysis**

**General observations:** Three of the five interviews were done throw the phone (only Interviwee2 and 3 were in person); it was somewhat hard to predict their facial expressions and body language. In general, the interviewees seemed interested in the topic and encouraged by the tool usefulness. Some participants seemed somewhat confused about the process; they asked several questions during the presentation which indicated some lack of explanation. This issue needs to be considered especially in future member checking. Some of the comments need to be considered in future tool iterations "ex. Need to be more simplistic, not very user-friendly". All the participants agreed on the tool usefulness in making better design decisions through the understanding of the visual discomfort conditions in the space either in the current or future tool iterations.

**Interviewee1-by phone:** the interviewee seemed encouraged by the research process; he did not have questions during the presentation which indicated that he was knowledgeable about the research topic.

**Interviewee2-in-person:** the interviewee seemed positive about the research and found it to be "new" regarding the idea of the dynamism of space. She had little questions during the process

which indicated that she was very knowledgeable about the research topic. She seemed a bit confused about the interface configuration and was looking everywhere on the screen.

**Interviewee3-in-person:** the interviewee seemed interested in the research, but seemed a bit puzzled about the interface, the thresholds and outputs representation and kept asking questions regarding threshold values and different numbers explanations which showed some short explanation in the outputs representation and guidelines

**Interviewee4-by phone:** the interviewee found the tool inputs, evaluation, and outputs somewhat hard to understand for an architect with no daylighting experience. He was emphasizing the idea of simplicity during the interview process.

**Interviewee5-by phone:** The interviewee seemed not satisfied with interface graphics and animation. He believes that the interface is a key factor in the tool success. Many of his comments discussed the rendering images quality.

Members feedback summary is represented in Table C-4

Feedback Category	Members feedback summary			
Graphical User Interface	Tool not user-friendly, more clarification needed, the interface needs to be			
	more dynamic and simpler with less technical details.			
Instructions and help	More clarification is needed in the instruction, fewer details on the engine is			
menu	necessary.			
Input data	Less input is needed from the designer: auto insert for (layer			
	names/geometry/ materials) according to folder path.			
Evaluation	Minimize tool evaluation functionality details. Fewer evaluation indexes are			
	required.			
Output and conclusion	Suggesting possible design solution may not be accepted by the designer.			
Decision making	The tool may be able to help design decision making through the			
	representation of discomfort conditions.			

Table C-4: Members feedback summary

#### • Interviews text

#### **Interviewee number 1: Background**

Associate Professor of Architecture has consulted on several hundred building projects with architects and engineers regarding daylight, integrated design, and low-energy strategies has presented at many conferences and workshops. He has authored several papers related to integrated design, daylighting, visual comfort, and low-energy design strategies.

#### **Interview process: Pre-interview question**

What are the information and data needed to run a daylighting analysis study and what are the tools needed?

First visual comfort and daylighting study are rarely done and mostly not done by architects. There are some case studies where daylighting analysis was done, and it was a simple representation of interior renderings where the movement in the space was not examined. It was a point in time study.

#### **Questions set No1 on GUI**

I think the interface is not very user-friendly especially in the introduction stages: I did not understand if it through another program or a standalone tool, a little explanation is needed here.

#### **Questions set No2 on Instructions and help menus**

Help menus need to include more explanation. Very little designs look at daylighting analysis, and if we dig deeper that's even a smaller percentage or designer and examining visual comfort and looking at transitional spaces that's even less, we are looking at a 0.01% from the population of designers.

#### Question set No 3 on the input data

I find the input page quite understandable. I think we need to look at different lighting directions and head direction. If we are looking at a task or a target is the working plane or this objective represent an input or not, where does the viewer look can affect visual comfort and glare.

#### **Questions set No5 on outputs and conclusions**

I think it would be nice if we can see the annual analysis. Also looking at annual sun exposure can be a good metric to look at.

#### Questions set No6 on design decision making and conclusion

The tooling process is different: first because visual comfort because in the general daylighting study is rarely done and also because the tool embedded such study in the design process. I believe that the glare and visual comfort problem are significant and to build an instrument that does it all is probably not possible. However, I think the entry sequence and flag areas where problems of adaptation happen. I understand that the tool has a broader scope, but if the tool can do only this well, that's an excellent contribution.

#### Interviewee number 2: Background

Professor of Architecture with expertise in daylighting analysis and designing for daylit spaces. Consulted on many large scale building projects including healthcare facilities, museums and educational buildings to maximize daylight and minimize glare. Has authored several papers on daylighting, visual comfort, and low-energy design strategies.

#### **Interview process: Pre-interview question:**

What are the information and data needed to run a daylighting analysis study and what are the tools needed?

A long time ago we used Radiance, which required special expertise and coding experience but recently more simplistic software that can interface with Radiance started to kick in, and these require less experience with Linux and coding and an architect can begin to learn them and obtain some valuable, informative, easy to understand results. However, still these new tools require some time to learn and get familiar with.

#### **Questions set No1: GUI**

The interface is not dynamic. The tool aims at dynamic daylight, and the interface is very static.

#### **Questions set No2: Instructions and help menus**

There are too many details on the download which seems very complicated and discourage me from downloading the tool through this long process.

#### Question set No 3: the input data

I think there is some short explanation in this section, especially if the user has a small background on daylighting simulation. An additional help menu is needed in this section. The tool needs to read CAD files with layers and materials automatically.

#### **Questions set No 4: the evaluation process**

I like the illuminance heat map; I don't quite understand the graphs. Daylighting systems are endless, by representing a set of recommendations you may end up with a misleading recommendation to the designer. I think it is better to let the designer decide what he needs to change in the design because you will do a lot of effort trying to help him solve the visual discomfort problem, and your solutions may still not work because of different reasons including budget, design concept, architectural context, rules and other restrictions.

#### **Questions set No5: outputs and conclusions**

I think future iterations of this tool will be beneficial especially when introducing annual numeric and graphical analysis. The idea of being able to evaluate visual comfort in the space is a relatively new idea that still has not been fully covered in the previous research. I do also believe that the tool can expand to cover different topics and different building types since transitional spaces are present in all buildings.

#### Questions set No6: design decision making and conclusion

I guess much improvement can be added to the tool regarding interface, it needs to be compatible with other software. A manual guide needs to be developed or may be a cheat sheet quick start.

#### Interviewee number 3: Background

Visiting Scholar, LEED AP. AIA, AICP, Architect with extensive experience in the design of international large-scale projects, many in the fields of sports architecture and event. In addition to a variety of civic, health care, educational, mixed-use, hotels and urban planning projects.

#### **Interview process: Pre-interview question**

What are the information and data needed to run a daylighting analysis study and what are the tools needed?

The software depends on the case project itself, much time our daylighting consultant help us with daylighting analysis for the technical part. We don't do too much of the quantitative technical part, but in the house, we use our rendering software- Ecotect. For example, in a military/ educational project, we were studying the effect of the light shelf on the classrooms and how the light was reflected and also heat gain from this light reflection the lighting consultant did all the calculation.

#### **Questions set No1: GUI**

I think more simplification of the tool is needed for it to be more user-friendly. Take the technical part away from the designer where he can use it; like the days and times, it gets confusing when we provide all the outputs. The designer needs to know did I do it good or I did it badly. Is it a good lighting a bad one, is there enough light or no, is there glare or no, is this the right kind of lighting for this type of building or no. They don't need to know the luminance ratio, the DGI or the DGP. For example, if I am designing a senior living space and I need natural lighting with no glare and good distribution so the tool needs to find the guidelines needed and simplify it based on the project type or occupancy type or may be both. Maybe identifying what this evaluation is for.

#### **Questions set No2: Instructions and help menus**

Maybe if we have a final report card with colors, graphics showing different areas. Like a summary for the designer to look at and if he wants to see more details he can.

#### Question set No 3: the input data

Because everyone is trying to create their model I would like to get some information about how the model can be set up so the evaluation tool can be most effective, may be the way we set up the layers and materials as sometimes people can analysis their models very quickly without giving too much attention to the layers and materials. It would be helpful to have some guidelines to set up their models to take advantages of the tool. We may design the same model but in many different ways and this can affect the outputs. We may expect different outputs depending on the way we set up our models.

#### **Questions set No 4: the evaluation process**

I think it is a fascinating because the lighting is a critical element to obtain a good design. The architect is very rarely getting into the nuances of lighting, and the tool can very quickly go off the deep end, very technical to this particular kind of lighting condition. I would think if you provide more guidelines for the architect that help him on what we need to achieve to evaluate his design without the need to understand the world of lighting. The architect needs to have a design with less glare and better lighting distribution. So I think the tool deals with some technical elements, so if you provide the designer with a list of different building types to select from and recommendations to start with. In all building types, we need daylight but the levels and spaces where we need them differ from one building type to another (ex. Operation room in a health care facility). May summarize the three categories of lighting aspects, and the designer can play with them based on his different kinds of building. Simply the designer can find if his design is right or bad and tweak these guidelines. Have a list of presents based on the building type (senior living, healthcare).

#### **Questions set No5: outputs and conclusions**

I think designers, lighting experts, and people interested in lighting, professional architects or academics can benefit from the tool.

#### Questions set No6: design decision making and conclusion

The tool can help provide feedback on glare and visual comfort condition that can be incorporated into the design. Designers are very creative, and they can come up with different solutions for their designs, may be general rules of thumbs could be helpful on the condition itself (if the design has too much glare or if it is acceptable in terms of percentage of the occupancy times and percentage of days exceeding the acceptable conditions).

It's an interesting research and you are an architect that is way more aware of the problem so if you can set that up with two kinds of outputs where a simplified one is for a typical designer with information on how I did in my design and how to do better and another detailed one for a more knowledgeable one. I would love to see more about it when you are done and happy to help with my opinion. I believe a real case study would be vital to see what an actual evaluation looks like.

#### Interviewee number 4: Background

Architect with experience in the design of large-scale international projects, especially in the field of educational and healthcare buildings. In addition to experience in a variety of projects including healthcare, transportation warehouses and building renovations.

#### **Interview process: Pre-interview question**

## <u>What are the information and data needed to run a daylighting analysis study and what</u> <u>are the tools needed?</u>

As a big firm, we are not very involved in the daylighting analysis, normally a daylighting consultant is the one who does that. I do believe that have their tools and software to either meet the LEED or the client requirements. We have a couple of projects where we run typically building shadow studies in Ecotect. We know that Ecotect has been disqualified in many lighting committees, but it is still used as it provides a good representations and renderings for the client.

#### **Questions set No1: GUI**

I think I need to see a set of guidelines that help me to see at the beginning what do I need to achieve regarding illuminance values or indexes thresholds to pay attention for.

#### **Questions set No2: Instructions and help menus**

Maybe the tool needs to provide an explanation of the glare problem before the designer start using the tool; For example ( The visual comfort is considered accepted if it is within a certain percentage and not accepted if it is more, Or a number of days in the year that we shouldn't exceed. Also, the architect can set his guidelines too based on the building type, or the glare project restrictions).Target values I need to achieve so if I noticed that from the first stage I have problems I can stop and make design modifications and restart the evaluation so that could save time. It is better to have such information early in the tool better than having the outputs and final results then start looking at guidelines and thresholds which may cause confusion to the designer.

#### Question set No 3: the input data

I love to see more details on the geographical location; I would like to be able to insert the building on the map, as we generally know the exact building location, I do not feel comfortable

running the analysis on the building as it is in the middle of the desert, main building surroundings and topography need to be modeled to generate more trusted results.

#### **Questions set No 4: the evaluation process**

I would like to see the building on the map. Sometimes we do designs on Sketch-up, and we need to study the building shadow on the map for specific days and times. Although we cannot see the other buildings heights, we can see the shadows on the map which can help in further studies on the adjacent affected buildings. It can also show buildings sun reflections.

#### **Questions set No5: outputs and conclusions**

I need to see the maximum and minimum threshold values on the screen.

I also need to see the percentage of the glare points of the condition so when I redesign I can compare the percentages of each condition. It would also be nice if I can compare the results of different design alternatives. I think if I can save different designs and can load and compare each parameter (for example the light distribution was improved by x % in this case, X % reduced glare) that will be easier for the designer.

#### Questions set No6: design decision making and conclusion

I need to see the guidelines on the final outputs. I also need to see the sun path and the examined space floor plan with the glare days and times next to the pictures (like a final summary or as an explanation of the whole process). I would think about what are the questions that may come to the designer's mind (north, vegetation, and surrounding buildings). I don't think giving the solution is a good idea as the solution depends on many factors. I think the tool can help in furniture layout and space configurations.

#### Interviewee number 5: Background

Ph.D. student in Architecture. Previous experience in sustainable building designs. Masters research examines artificial lighting control strategies. Experience in different daylighting software tools

#### Interview process: Pre-interview question:

What are the information and data needed to run a daylighting analysis study and what are the tools needed?

As an architect, I used the more simplistic provided software similar to DIVA and Ecotect. We used the 3D model, weather file, and material properties. We ran different alternative designs for the proposed design iterations-shading device- using the Grasshopper parametric design and look at the different results.

#### **Questions set No1: GUI**

The tool interface does not represent 3D animation. In my opinion, the interface is a critical aspect of the tool. Even if other tools can represent more accurate results, we tend to use the one with the friendlier interface.

#### **Questions set No2: Instructions and help menus**

I guess the instructions, tutorials and glare indexes explanations should all be in the help menu, only when the user needs them. I suppose you can include a video tutorial especially with analyzed examples to explain the analysis procedures, others for the download and installation process.

#### Question set No 3: the input data

Since the tool is a plug-in for software, I believe the input should mostly be automated from the initial 3D modeling software-Rhino. Unless the user needs to change the geometry or simulation days, all input should be automatically loaded into the new tool.

#### Questions set No 4: the evaluation process

It is important to see the annual distribution of the illuminance values, may be through a link to an excel sheet if you don't want to display all this information in the results summary. Also, there is no way you will be able to represent all possible design recommendations, so I am not sure if it is necessary to introduce them at this stage. The idea of evaluation is what makes the tool different from other daylighting analysis software. Using multiple metrics may be confusing, especially if each detects different glare areas and rate, I would either select one index or find a way to recap his or her analysis into one new metric.

#### **Questions set No5: outputs and conclusions**

I would like to see a better rendering of the video. I also would like to a "redesign" key for the designer to go back and revise his design.

#### Questions set No6: design decision making and conclusion

At this stage, I am not sure if the tool can make changes in the design process, but I guess with future iterations and modifications and future computing development it might, especially if it can be expanded as software that can do all the work and not a plug-in.

# Appendix D. Tool interface

## Version-1

Introduction	Introduction _ + ×
Get started Definitions Instructions	Get started Definitions Instructions
1-The proposed tool represents a dynamic visual comfort evaluation tool that allows the designer to investigate and evaluate the spaces from the visual comfort perspective in the early stages of design. Next Skip to Evaluation	Double click to show a definition         Illuminance         Luminance         Brightness         Contrast ratio         Daylight glare probability (DGP)         Useful daylight illuminance(UDI)         Illuminance ratio         Vertical eye illuminance         Maximum glare points         Field of view         Daylight glare index (DGI)         Previous         Next         Skip to Evaluation
DVCE Tool	DVCE Tool
Introduction       - * ×         Get started       Definitions       Instructions         1- First in order to have this tool on you computer you need to have: 1-Rhino       (Evaluation version is free for download) at http://www.rhino3d.com/download/rhino         /5/latest?PageSpeed=noscript.       2- Grasshopper (Free at http://www.grasshopper3d.com /page/download-1.	Introduction       + ×         Get started       Definitions       Instructions         1. Open Rhino, open the DVCE tool and load your geometry (sketchup,rhino, 3Dmax or CAD files). load each layer to its assigned material.       2. Select simulation path (curve/line) at eye level.         4. If different than the default day/time/sky condition values make changes to suit your design.       3. Run the simulation (a set of simulations
Previous Next Skip to Evaluation	Previous Next Skip to Evaluation
DVCE Tool	DVCE Tool

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Figure D-1: Tool interface Version1

#### Version-2

Get started Definitions Instructions	Get started Definitions Instructions
ntroduction	Double click to show a definition
The proposed tool represents a dynamic visual comfort evaluation tool that allows the designer to investigate and evaluate the spaces from the visual comfort perspective in the early stages of design. The tool examines three aspects of visual comfort: Glare, Light Quality and the Amout of Light:	Illuminance         Luminance         Brightness         Contrast ratio         Daylight glare probability (DGP)         Useful daylight illuminance(UDI)         Illuminance ratio         Vertical eye illuminance         Maximum glare points         Field of view         Daylight glare index (DGI)
Next Skin to Evaluation	Previous Next
troduction + ×	Introduction + ×
troduction	Introduction DVCE Tool - + X Get started Definitions Instructions Evaluation Overview
Instruction       DVCE Tool       Image: Tool         Get started       Definitions       Instructions         Download and Installation       In order to have this tool on you computer you need to have:         1-Rhino (Evaluation version is free for download) at http://www.rhino3d com/download/rhino         /5/latest?PageSpeed=noscript.         2. Grasshopper (Free at http://www.grasshopper3d.com/page/download-1.         3. The tool full desciption and tutorials are available at: www. DVCEtool.download.com	Introduction       DVCE_Tool         Get started       Definitions       Instructions         Evaluation Overview       Instructions       Instructions         Evaluation Overview       Instruction       Instructions         Image: Started Definitions       Instructions       Image: Started Definitions         Image: Started Definitions       Instructions       Image: Started Definitions       Image: Started Definitions         Image: Started Definitions       Instructions       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions         Image: Started Definitions       Instructions       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions         Image: Started Definition Overview       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions         Image: Started Definition Overview       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions         Image: Started Definition Overview       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions         Image: Started Definition Overview       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions       Image: Started Definitions       Im

inpat-	DVCE Tool - + >	Input + ×
Geometry MM/DD/T/Pa	th Help?	Geometry MM/DD/T/Path Help?
Load Rh	nino layers and materials	Please select evaluation month, days and hours if different than default
Layer1 (rename)	Select Material	Month Default (3, 6 and 12)
Layer2 (rename)	Select Material	Day Default (21)
Layer2 (rename)	Select Material V	Time Default (9, 12 and 15)
Layer3 (rename)	Select Material	Select simulation nath Select Building Location(weather file)
Layer4 (rename)	Select Material	
Add new layer Proceed to simulation til	mes	Run Simulation
Description UDI DGP/	/DGI Iuminance ratio Help? /aluation: Amount of Light	Description         UDI         DGP/DGI         Luminance ratio         Help?           2.Visual Comfort Evaluation: Glare
	Load UDI distribution Jun21/ 9 AM	a. DGP(avg) condition:0.20=Subtle Subtle perceptible Disturbing Intolerable 0.33 0.38 0.42 0.53
	Jun21/ 12 PM Jun21/ 3 PM Jan21/ 8 AM	b. DGI(avg) condition:18.4-=Perceptible Subtle perceptible Disturbing Intolerable
	Jan21/ 12 PM	
	Mar21/ 9 AM Mar21/ 12PM	Flay Fassage Glate Evaluation
	Mar21/ 3PM	
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	Luminance Ratio	Play walkthrough video June21- (9AM) June21- (12 Noon) June21- (3PM) Apply Effects DGP DGI Central vision	Play video
Luminance ratio avg:1:2:6		Save Results Place Building on G	Evaluate Another Design
Light Quality ef	ffect: Subtle	*Perceptible Daylight Glare Index (DGI): sensation	there is percptible glare

# Appendix E. Immersive Case Study Text Analysis

# • Case 1-Typical Office: Researcher Notes Coding Process

<ol> <li>Preliminary assessment</li> <li>Possible glare and discomfort problem</li> </ol>	1. From the preliminary assessment, I noticed that the space has some glare. The window location and size may generate some glare and discomfort, especially with the west facing façade and the lack of shading device and/or curtains.
<ul> <li>2. Enough of a problem to be concerned</li> <li>Discomfort problem detected</li> <li>Discomfort location</li> </ul>	2. I used to tool to judge if enough visual discomfort and glare problems existed in the space. The tool provided a set of outputs to help evaluate the space visual comfort conditions; there was a large percentage of days and times of the day and percentage of floor area where UDI (illuminance values) are above the acceptable limits. Also for the image-based simulations, the values of the DGP and the DGI are higher than the acceptable thresholds, especially in the sitting position looking at the computer screen.
<ul> <li><b>3. Problem solving actions</b></li> <li>The actions required for visual comfort solution</li> </ul>	<b>3.</b> Illuminance-based evaluation metric-UDI, also luminance-based metrics (DGI, DGP, and contrast ratio). All metrics detected glare and discomfort varying from perceptible to intolerable. To solve the problem, a design adjustment is needed; contrast need to be minimized, glare source (the window) needs to be covered, or avoided from the visual field, and direct sun penetration needs to be avoided.

4. Brainstorming to generate	4. From the evaluation I noticed that glare was caused by the
<ul> <li>Glare sources</li> <li>Design alternatives proposition</li> </ul>	window opening; I noticed that high glare was found in the center of
	the visual field (the window, the window wall, and floor adjacent to
	the window). A set of design alternatives were proposed to minimize
of alternatives	discomfort: 1) a horizontal shading device can minimize sun
	penetration and can shade the window, which can minimize glare.
	However horizontal shade can change the appearance of the
	building, which may not be preferred by the designers. 2) A change
	in the color of the walls can produce less reflectivity, which can
	generate less glare and contrast from the white original wall color.
	However, a darker wall is not very pleasant when compared with
	brighter colors and may not be preferred by the occupants. 3) Tinted
	glass can prevent direct sun penetration without darkening the
	interior space. 4) Interior blinds are widely used for interior shading;
	it would be nice to examine its effect on visual comfort. 5) Window
	size and location; since glare was found in the central vision, moving
	and or changing the window size can minimize glare in the central
	vision of the occupant.
5. Evaluating alternatives	<b>5.</b> It is decided that the day/times with the highest glare and visual
Strategy to evaluate     alternatives	discomfort—detected in the preliminary assessment—will be
Design decision in different	examined for each alternative. The proposed alternatives represent
design stages	design solutions for a new design that can take place in different
	design stages, to examine if design decisions proposed in the early
	stages of the design process can be more beneficial when compared
	with the ones applied in latter stages.
6. Develop strategy to	6. The tool is intended to evaluate visual comfort in the early stages
implement the tool into the process	of the design process. The tool was used to evaluate each alternative
Comparing alternatives     Selecting the best	visual comfort: first, the luminance evaluation metrics were tested
bereeting the best	

alternative

	for every alternative on the selected day and time with the minimum
	UDI (worse case) – June 21 at 4 PM. The DGP and DGI were
	calculated for each case. Aft.erward, I applied annual illuminance
	evaluation to examine. The best alternative was selected based on its
	performance in all evaluation metrics; first the average sum of the
	DGI and DGP was calculated, then annual UDI was calculated and
	examined.
7. Comparing alternatives	7. During the alternatives comparison, I noticed that no significant
• DGI and DGP detected	differences were detected in the contrast ratio. However, for the
contrast ratio	DGP and the DGI significant differences existed between the
	alternatives. This could mean that the contrast ratio has lower
	sensitivity in detecting glare, high contrast, and discomfort when
	compared with the other metrics.
8. Compare selected	<b>8.</b> I noticed from the comparison of the selected alternative with the
• The selected design	base case that not only the metrics showed less glare and contrast;
alternative showed	also, the evaluation metrics simulation curves became smoother and
comfort conditions	more uniform, which indicated better adaptation, light distribution,
Some design alternatives     showed increase of visual	and less discomfort. I also noticed that DGI and DGP in two cases
discomfort	were detecting discomfort equal to the base case (interior shading)
	some alternatives showed an increase in glare and contrast.
9. Process limitations	<b>9.</b> Worker facing the window may not be the most common in
	offices Multi-occupants in an office may be more realistic the
	office task can affect the occupants' movement in the space and
	visual comfort effect

#### 10. Reflective thoughts on how the tool supported/improved decision-making

- Help detecting glare location, days, and times of occurrence
- Help detecting the percentage of areas and times exceeding acceptable thresholds
- Help generating the alternatives that corresponded to the intended objective (to minimize visual discomfort and glare)

**10.** During the preliminary assessment of the base case, I expected that potential glare will take place from the window. I noticed that while applying the tool, I was able to detect the glare location and time of occurrence, which I was not able to identify in the preliminary assessment. The tool provided outputs concerning the time and space dynamics, which included the points exceeding the applied metrics thresholds and the percentage of days and times exceeding the acceptable comfort limits and helped me evaluate the visual comfort conditions in the space. This helped me to make a design decision on whether design changes were necessary or not.

Design modifications are endless; using the tool outputs, I was able to identify the alternatives that can help solving possible discomfort problems (the glare souce in the central vision, the direct sunlight, and high contrast between outside and inside). While making design decision during the braistorming phase, I insured when developing the design alternatives to select the ones that maintained outside views (provided by the outside shading and tinted glass cases). However, I needed to identify the alternatives that could help solving possible discomfort problems. With the tool provided outputs, I was able to make better informed design decisions.

## • Case 1-Typical Office: Researcher Themes Development Process

Data	Categories	Themes
The space has some glare; the window location	Preliminary	
and size may generate some glare and	assessment	
discomfort; west facing façade and the lack of		
shading		
A large percentage of days and times UDI	A problem to be	
(illuminance values) are above the acceptable	concerned with	<b>Base Case</b>
limits; DGP and the DGI are higher than the		<b>Examination and</b>
acceptable thresholds; all metrics detected		Evaluation
glare and discomfort varying from perceptible		
to intolerable		

Data	Categories	Themes
A design adjustment is needed; contrast need	Problem solving	
to be minimized, glare source (the window)	actions	
needs to be covered, or avoided from the visual		
field; direct sun penetration needs to be		
avoided		
Glare was found in the center of the visual	Brainstorming to	
field (the window, the window wall, and floor	generate action	
adjacent to the window); a horizontal shading;	strategies.	
can minimize sun penetration; the color of the	-	
walls; can produce less reflectivity; tinted glass		Alternative
can prevent direct sun penetration; interior		<b>Proposition and</b>
blinds are widely used for interior shading;		Evaluation
window size and location can minimize glare		
in the central vision.		
Day/times with the highest glare and visual	Evaluating alternatives	
discomfort will be examined for each	-	
alternative		
The tool is intended to evaluate visual comfort	Develop strategy to	
in the early stages of the design process;	implement the tool	
luminance evaluation metrics were tested for	into the process	
every alternative; DGP and DGI were	-	
calculated for each case; aft.erward, I applied		
annual illuminance evaluation; the best		
alternative was selected based on its		<b>Comparisons and</b>
performance in all evaluation metrics; first the		<b>Decision-Making</b>
average sum of the DGI and DGP was		
calculated, then annual UDI was calculated and		
examined		
No significant differences were detected in the	Comparing	
contrast ratio; DGP and the DGI significant	alternatives	
differences existed between the alternatives		
The metrics showed less glare and contrast; the	Compare selected	
evaluation metrics' simulation curves became	alternative with the	
smoother and more uniform; better adaptation,	base case	
light distribution, and less discomfort;		
discomfort equal to the base case (interior		
shading)		
Worker facing the window may not be the	Process limitations	
most common in offices; multi-occupants in an		
office may be more realistic		
Detect the glare location and time of	Reflective thoughts on	
occurrence which I was not able to identify in	how the tool	
the preliminary assessment; outputs concerning	supported/improved	
the time and space dynamics; points exceeding	decision-making	

Data	Categories	Themes
percentage of days and times exceeding the		
acceptable comfort limits; percentage of days		Tool Application to
and times exceeding the acceptable comfort		Improve Decision-
limits; helped me to make a design decision on		Making
whether design changes were necessary or not;		
identify the alternatives that can help solving		
possible discomfort problems; identify the		
alternatives that can help solving possible		
discomfort problems; make better informed		
design decisions.		

Participants Meeting Feedback Coding - First Meeting Categories Color Coding Process				
Preliminary assessment	Discomfort problem to be concerned	Problem solving actions using the tool	Brainstorming to generate action strategies	Tool improvement
<u>Cyan</u>	Light Grey	<u>Yellow</u>	Green	Grey

# • Case 2-Museum: Participants Meeting Feedback Coding – First Meeting

#### 1. Is there enough information to evaluate visual comfort for the case study?

**Participant1:** It looks like <u>the building has some visual discomfort issues</u>. But <u>it is hard to</u> <u>decide if it is a problem to be considered or not.</u>

**Participant2:** Some contrast is noticed in the courtyard entrance and may be the dark "Peacock" room.

**Participant3:** <u>I am not sure if relevant glare exists in the building</u>, <u>I cannot tell from simply</u> <u>looking at the space</u>. <u>I do see a possible problem</u>, but I <u>cannot identify its frequency and location</u> <u>of occurrence</u>. I need to know when and where it represents a problem.

2. What are the types of information that would be needed for the evaluation? How do designers make design decisions related to glare and visual comfort?

**Participant1:** different parameters are needed such as the source of light, the position of the person, and his/her location in the space, how gradually the lighting is, the distance between dark and bright zones and if enough space is there for visual adaptation.

**Participant2:** as previously said we don't know the location and time of these conditions. There is a set of parameters needed to judge the space including light source, distance between the dark and bright and whether it is enough for visual adaptation, materials properties, eye direction and/or visual field, illuminance values, and other sources of light.

**Participant3:** also the <u>illuminance values and the ratio between them</u>. Also I believe <u>the field of</u> <u>view, the viewing angle and direction</u>. It might be worth it to examine <u>the type of space visitors</u> (<u>particular age group or gender</u>) and see if that would change the design considerations and design decisions. However If there is a tool that considers all needed aspects it can be used to easily evaluate visual comfort.

#### 3. How does the prototype tool affect design decision-making?

**Participant1:** Based on the tool provided outputs some visual discomfort can be generated in the space. However **I am not sure if there is enough evidence to redesign the space.** I like to see variable or controllable thresholds, occupants age/ gender and eye level, false color renderings of the plan.

Participant2: I like that the tool provides various evaluation metrics; also the process of evaluation from annually to hourly saves time. However, I don't believe the space needs redesigning, I would have not made design changes based on the tool provided visual comfort evaluation in real-life application. I believe detailed numeric outputs are important in the tool. Participant3: In order to judge the tool outputs, the building needs to be examined in all the museum occupied days and hours and also all sky conditions since the weather file only predicts the dominant sky condition for this time, which sometimes cannot be the real one. The outputs can widely differ depending on the level of details in the model. More accurate model can graphical outputs, annual analysis, I believe that the tool did a good job finding the problem day and time, evaluate the problem, gave ideas to solve the problem without giving solutions. I also like that the tool considers the dynamic daylight of the sky and movement in the space.

4. What accounts for an effective design solution in terms of glare and visual comfort? And what are the characteristics of the design modification/alternative?

**Participant1:** Design solutions are endless based on many factors. However, an example from possible design solution category can be applied and results could be examined.

**Participant2:** Since this is <u>an existing place</u>, so design general <u>solutions are limited in this case</u>, we can <u>add a screen</u>, change the glazing properties, perforation, daylighting and solar techniques and play with the number of the louvers or the angle or transmittance properties.

**Participant3:** We <u>cannot change the window size or dimensions</u> so maybe <u>add a partial or full</u> <u>court cover or shading strategy</u> can help solving the problem, however its <u>effect needs to be</u> tested, to make sure the place is not dark or underlit and this can affect the legibility of the

artifacts.

# • Case 2-Museum: Participants First Meeting Feedback Themes Generation

Data	Themes
<ul> <li>It looks like the building has some visual discomfort issues.</li> <li>Some contrast is noticed in the courtyard entrance and may be the dark "Peacock" Room.</li> <li>I am not sure if relevant glare exists in the building.</li> </ul>	In-situ conditions visual Preliminary assessment
<ul> <li>We don't know the location and time of these conditions. There is a set of parameters needed to judge the space including light source, distance between the dark and bright and whether it is enough for visual adaptation, materials properties, eye direction and/or visual field, illuminance values, and other sources of light.</li> <li>However, if there is a tool that considers all needed aspects it can be used to easily evaluate visual comfort.</li> <li>The building needs to be examined in all days and museum hours of the year and also all sky conditions since the weather file only predicts the dominant sky condition for this time, which sometimes cannot be the real one.</li> <li>The outputs can widely differ depending on the level of details in the model. More accurate model can generate more realistic outputs.</li> </ul>	Tool modifications
<ul> <li>Based on the tool provided outputs some visual discomfort can be generated in the space. However, I am not sure if there is enough evidence to redesign the space.</li> <li>I don't believe the space needs re-designing, I would have not made design changes based on the tool provided visual comfort evaluation in real-life application</li> <li>Design solutions are endless based on many factors. However, an example from possible design solution category can be applied and results could be examined.</li> </ul>	Redesigning

# • Case 2-Museum: Researcher Notes and Observation Coding – First

meeting

<ul> <li>1. Preliminary assessment</li> <li>Glare and discomfort problem in the space</li> </ul>	1. From the preliminary assessment I noticed that the participants found the selected space is successful regarding representing daylighting; however, two of the participants reported little visual discomfort from the proposed virtual tour and images. They agreed that the displayed artefacts and 3D-model level of details can affect the visual comfort evaluation; they suggested that the model need to be simulated with and without details and visual comfort evaluation results need to be compared. They agreed on the importance of examining light transition in the space and that the transitional corridor space connecting the Peacock Room with the courtyard is ideal to test visual discomfort (especially in the courtyard entrance and the Peacock Room entrance where high contrast is present). I noticed that the participants did not have the same opinion on the space's visual comfort condition and whether a glare problem exists. However, there was a general agreement on a possibility of visual discomfort conditions, but it was not detectable with the provided images of the space.
<ul> <li>2. Discomfort problem detected to be concerned</li> <li>Problem solving actions using the tool</li> </ul>	2. The participants provided a wide range of information and parameters necessary to evaluate the space visual comfort condition. Participants had some questions regarding the evaluation process: they found annual simulation more realistic, especially for practical applications; they believed that light and dark adaptation simulated with maximum illuminance day/hour only showed the limits of the methodology and the tool. Participants wanted to understand the type of the visitors (age and gender) as this can affect their level of discomfort in the space. They questioned the analysis metrics, thresholds, and limitations.
<ul> <li>3. Brainstorming to generate action strategies</li> <li>The prototype tool effect on the design decision-making</li> <li>Tool advantage in supporting design decision-making</li> <li>Possible tool improvement</li> </ul>	3. The three participants agreed that thresholds for evaluation indexes cannot be general and need to be justified based on the user preferences or the building function. Participants seemed satisfied with the tool provided outputs; especially the process of going annually for the illuminance evaluation and not time-consuming, and being more focused on a single worse case scenario condition to save time and do not end up with a large data set impossible to analyze. However, they pointed some of the tool limitations and outputs rendering qualities. The participants believed that the tool future versions need to provide detailed/more realistic outputs.
4. The characteristics of the design alternative	4. The participants agreed that there was no single design alternative that can satisfy all the design considerations. Also, they agreed that design alteration options are endless. However, they agreed that in this case study, they are limited and restricted because of the building function as a museum space and that it is an existing building. They discussed some possible design alternatives.

# Case 2-Museum: Participants Meeting Feedback Coding – Second Meeting

Evaluation and Comparison of alternatives using the tool	Using the tool to support decision making	Tool in the daylighting dynamism	Future recommendations
<u>Cyan</u>	Light Grey	<u>Yellow</u>	Green

1. How did the tool support the alternatives evaluation and comparison?

**Participant1:** I like that the tool **provided a visual representation-graphical images** of each alternative. This **allows the designer to explore each alternative and make wiser decisions** based on the glare condition and the visual appearance of the space.

**Participant2:** Proof of positive effect of these alternatives need to be examined, negative effect on the usage and functionality of the space can take place: for example, it can lead to less occupancy and less favorable spaces by the visitors. It would be beneficial to understand what happened when one of the applied indexes thresholds meet the requirements' guidelines in one case while the others do not.

**Participant3:** When I used the tool, I had my own expectations and assumptions of the evaluation results. The <u>tool either confirmed these expectations</u>, which help <u>informing my future</u> <u>experience and expectations</u>.

2. How did the prototype tool affect design decision-making?
Participant1: <u>The tool will not change my design concepts</u>, but it will help enhance my thinking.

**Participant2:** <u>Typically, 3D modeling is for representation. I used to do 3D modeling for</u> <u>simulation.</u> These <u>alternatives are good example of how designers can react differently to the</u> <u>visual comfort problem</u>, based on the design requirements, budget, or occupants' preferences.

**Participant3:** This is a design <u>decision aid soft.ware to visualize anticipated lighting conditions</u> <u>that mimic real visual conditions.</u>

**3.** How do designers describe their experience with the design decision making process when considering daylighting dynamism?

**Participant1:** The first time to use <u>a simulation tool for decision support, not for representation</u> only, not like other tools. <u>The tool provides a unique insight on the dynamism of the occurrence</u> journey in the space building.

**Participant3:** In any other tool I had to select either change in time or location, but here <u>the tool</u> <u>provides a simulation combination of the change of time and space.</u>

# Appendix F. Case Studies Images Analysis

• Case Study1: Base case





Figure F-1: Case Study1- Base case

• Selected modified case: Outside shading





Figure F-2: Selected modified case- Outside shading

• Case Study2: Base case – East Circulation





• Case Study2: Base case – West Circulation




Figure F-4:Base case – West Circulation

• Case Study2: Base case – Alternatives comparison







**Glare Points in the Visual Field – Base Case** •





Figure F-6: Glare Points in the Visual Field – Base Case

• Glare Points in the Visual Field – Modified Case





Figure F-7: Glare Points in the Visual Field – Modified Case

## • Base Case Luminance Evaluation Summary (Glare and Contrast)

	DGI, DGP and luminance ratio Base case									
lmage No	DGI-base case	DGP-base case	Luminance ratio-base case	Max glare points % base case						
1	1.97	0.037	1.612496851	0						
2	5.19	0.014	0.014615385	8.80%						
3	12	0.036	1.416361416	6.70%						
4	16	0.088	1.744393022	11.90%						

	5	16.83	0.166	0.0200491	8.25%
I	6	18.59	0.18	2.133580705	9.40%
I	7	18.49	0.187	2.43902439	10.60%
I	8	18.81	0.21	2.913279133	17.80%
I	9	13.47	0.2	1.610070258	14.00%
I	10	14.8	0.26	2.482269504	5.30%
l	0	12.4	0.34	2.61627907	7.60%
	AVG	13.50454545	0.156181818 Standard dev	1.727492621	0.091227

0.10223

### • Modified Case Luminance Evaluation Summary (Glare and Contrast)

<b></b>				
Image	DGI-mod	DGP-mod		Max glare points %-mod
No	case	case	luminance ratio-mod	case
1	2.82	0.02	1.311605723	23%
2	3.94	0.007	1.537298387	0%
3	-5.1	0.22	2.141582391	17%
4	-4.65	0.22	2.356202356	17%
5	-5.5	0.22	2.711323764	17%
6	-7.1	0.22	2.714932127	18%
7	-9.7	0.22	2.803030303	18%
8	-12.3	0.22	2.77777778	18%
9	8.9	0.21	2.704678363	17%
10	11.9	0.24	3.463541667	23%
0	-5.12	0.22	2.141582391	17%
1.9	0.18	2.42	0.060302	17%
AVG		Standard dev 0.084324		

• Evaluation summary from the tool



#### Appendix G. Reliability and Validity Check Analysis

Table G-1: t-test summary									
	Measured illuminance (Variable 1)	Simulated illuminance (Variable 2)							
Mean	8.948058	7.835974							
Variance	46.06184	40.11242							
Observations	154	154							
Hypothesized Mean Difference	0								
df	305								
t Stat	1.486651								
P(T<=t) one-tail	0.06907								
t Critical one-tail	1.649865								
P(T<=t) two-tail	0.13814								
t Critical two-tail	1.967772								

Two tailed t-test analysis results are summarized in Table G-1

The P-value is significant when P < 0.05, it means that there is less than 5% chance that the two xamined sets are close, and then it is considered a significant difference. On the other hand the larger the t-value is the larger the difference. A "critical t-value" is the minimum t-value needed in order to have P < 0.05. If the t-value is greater than or equal to the critical t-value, then a significant difference occurred. In our case critical t-value was 1.649865, and t-value was 1.486651, therefore the difference between the two sets was small. The two-tailed P-value was 0.138, which was greater than 0.05; we can call the difference between the two sets as not significant.

#### • Reliability Check Comparison

Point	10:30 Sim	10:30 meas	DIFF	11:30 Sim	11:30 meas	DIFF	12:30 Sim	12:30 meas	DIFF	13:30 Sim	13:30 meas	DIFF
1	2.0	0.6	69%	2.0	0.7	64%	2.0	0.77	61%	2.0	0.75	62%
2	2.2	2.7	24%	2.3	3	31%	2.2	3	38%	2.1	3.1	46%
3	2.8	3.57	28%	2.8	3.7	33%	2.8	3.8	36%	2.8	3.2	15%
4	3.4	3.58	4%	3.4	4.5	31%	3.4	4	16%	3.4	3.4	1%
5	3.6	4.1	14%	3.6	5.5	53%	3.4	4	16%	3.5	3.6	3%
6	4.3	4.3	1%	3.9	5.5	40%	3.9	4.8	22%	3.9	3.9	1%
7	5.0	5.5	11%	5.1	6.3	24%	4.9	4.8	2%	4.9	5.6	14%

 Table G-2: The average difference between measured and simulated illuminance values on the circulation path

8	5.7	5.5	4%	5.7	4.8	16%	5.7	4.2	27%	5.7	5.4	6%
9	5.6	5.3	5%	5.4	5.4	0%	5.4	4.7	13%	5.6	4.8	14%
10	5.1	4.7	7%	4.8	5	4%	4.9	4.7	4%	5.1	4.8	5%
11	4.8	4.2	12%	4.7	4.7	1%	4.7	4.4	7%	4.8	4	16%
12	6.0	4.37	28%	5.7	5.4	6%	5.6	4.7	16%	5.4	4.6	15%
13	6.2	8.3	33%	6.1	7.5	24%	5.9	7.4	25%	6.1	9.4	55%
14	5.4	6.5	20%	6.1	7.8	29%	5.6	6.5	17%	5.6	5.5	1%
15	5.1	5.1	0%	5.1	6	18%	5.4	5.2	5%	6.1	4.8	21%
16	7.4	6.8	8%	8.0	7	13%	8.7	7.2	17%	8.5	6.7	21%
17	15.1	9.5	37%	15.9	10.3	35%	16.9	10.3	39%	15.2	7.6	50%
18	17.4	12.1	30%	19.5	13.5	31%	18.1	11.5	36%	16.9	10	41%
19	17.9	13.8	23%	18.7	15.3	18%	17.5	15.5	12%	17.9	10.2	43%
20	20.6	17.7	14%	19.6	18.8	4%	18.8	19.8	5%	19.9	15.5	22%
21	19.3	26	35%	17.4	32	84%	20.0	31.1	55%	17.7	27.7	57%
22	19.8	29.1	47%	19.8	30	51%	20.0	16.5	17%	20.8	16	23%

Point	14:30 Sim	14:30 meas	DIFF	15:30 Sim	3:30 meas	DIFF	4:30 sim	4:30 meas	DIFF	
1	2.0	0.8	59%	2.0	0.8	59%	2.0	0.7	64%	
2	2.1	2.8	31%	2.1	3.0	41%	2.2	3	38%	
3	2.8	3.3	19%	2.8	3.4	22%	2.8	3.3	19%	
4	3.4	3.7	8%	3.4	3.8	10%	3.6	3.6	1%	
5	3.5	4.3	23%	3.9	4.3	9%	3.9	4.3	9%	
6	4.0	4.5	13%	3.9	4.6	17%	4.1	4.6	12%	
7	5.1	5.5	9%	5.1	5.1	1%	4.9	5	2%	
8	5.7	4.5	22%	5.7	5.1	11%	5.7	5.5	4%	
9	5.4	4.7	13%	5.6	4.7	16%	5.7	4.7	18%	
10	4.8	4.5	5%	4.8	4.5	5%	5.1	4.2	17%	
11	4.8	3.6	24%	4.8	5.0	5%	4.8	4.1	14%	
12	5.4	3.8	30%	5.9	5.6	6%	5.4	5.3	2%	
13	6.2	6.5	4%	6.2	14.6	135%	6.2	14.4	131%	
14	5.6	6	8%	5.6	10.9	96%	7.0	8.6	22%	
15	6.2	3.5	44%	6.6	6.6	1%	5.6	5.8	4%	
16	9.7	4.4	54%	11.3	7.7	32%	13.6	8.1	40%	
17	17.7	5.7	68%	17.9	10.1	43%	18.8	10	47%	
18	18.2	6.2	66%	19.8	9.6	52%	20.5	9.6	53%	
19	21.0	8.2	61%	22.4	12.6	44%	21.7	13	40%	
20	18.7	9.3	50%	23.6	15.5	34%	24.6	15.5	37%	

21	19.5	12.6	36%	21.2	19.1	10%	22.8	24.5	8%		
22	19.0	18.5	3%	21.5	18.0	16%	20.0	22	10%	Total Diff=23%	Avg

## Appendix H. Illuminance and Luminance in-Situ Measuring Tools

a-Digital Illumina	ance Meter (DT-1309)	0	<i>•</i>
(a guing anta 201	5 #150)	b-Minolta lum	inance meter ls 110(Minolta, 2015
(equipments, 201	5 #150)		
		Specifications	
		Model	Luminance Meter LS-110
Specifications		Туре	SLR spot luminance meter for measuring
		A ( 1	light-source and surface brightness
Display	3-3/4 digit LCD with high speed 40 s	Acceptance angle	1/3° 85mm f/2 8 lens: SLP viewing system: flare
		Optical system	factor less than 1.5%
Measuring Range	Lux,400.0 Lux,4000 Lux,40.00 KLux	Angle of view	9°
	1FC=10.76Lux 1KLux=1000Lux 1KL	Focusing distance	1014mm (40 in.) to infinity
		Minimum	Φ4.8mm
Over range Display	LCD will show "OL" symbol	measuring area	
Spectral Response	CIE Photonic (CIE human eve respo	Receptor	Silicon photocell
opeena response	ener i notopie. (ene naman eye respo	Relative Spectral	Within 8% (f1) of the CIE spectral luminous $f(x) = V(x)$
Spectral Accuracy	CIE V $\lambda$ function f1'less than6%	Response time	EAST: Sampling time: 0.1s. time to display:
Cosine Response	f2' less than2%	Response time	0.8 to 1.0s.
Cosine response	12 1055 dian270		SLOW: Sampling time: 0.4s, time to display:
Accuracy	±5% rdg±10d.(<10,000Lux)±10% rdg		1.4 to 1.6s
Repeatability	+3%	Luminance units	cd/m <sup>2</sup> or fL (switchable)
Sampling Rate	1.5 times/sec of analog bar-graph indi	Measuring range	FAST: 0.01 to 999,900cd/m <sup>2</sup> (0.01 to
1 0	display		291,800fL)
Photo Detector	One silicon photo diode and spectral i		145 900fL)
Operating tomporature	$0^{\circ} a = 10^{\circ} a (32^{\circ} E = 104^{\circ} E) g = 00/42^{\circ}$	Accuracy	$0.01 \text{ to } 9.99 \text{ cd/m}^2 \text{ (or fL}): \pm 2\% \pm 2 \text{ digits of}$
& Humidity	0 C 10 40 C(32 F10 104 F) & 0% 10 8		displayed value
Storage Temperature	-10°c to 50°c(14°F to 140°F) & 0% to		$10.00$ cd/m <sup>2</sup> (or fL) or greater: $\pm 2\% \pm 1$ digit
& Humidity			of displayed value
Power Source	1 piece 9V battery		Illuminant A measured at ambient
		Domostal 111	temperature of 20 to 30 °C/68 to 86 °F)
Photo detector Lead	150cm (approx.)	Repeatability	$0.01 \text{ to } 9.990 \text{ cd/m}^2 \text{ (or 1L)} \pm 0.2\% \pm 2 \text{ digits of}$
Length			greater: $\pm 0.2\% \pm 1$ digit of displayed value
			(Measurement subject: Illuminant A)
		Temperature /	Within $\pm 3\% \pm 1$ digit (of value displayed at
		humidity drift	20°C/68°F) within operating temperature /
			humidity range
		Calibration mode	Minolta standard/user-selected standard
		Color correction	Set by numerical input: range: 0.001 to 9.999
		factor	Set e, numericar input, range. 0.001 to 7.777
		Reference	1: set by measurement or numerical input

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luminance		
Measurement	Luminance; luminance ratio; peak luminance	
modes	or luminance ratio	
Display	External: 4-digit LCD with additional	
1 2	indications	
	Viewfinder: 4-digit LCD with LED backlight	
Data	RS-232C: baud rate: 4800bps	
communication	······	
External control	Measurement process can be started by external device connected to data output terminal	
Power source	While measuring button is pressed and viewfinder display is lit: 16mA average While power is on and viewfinder display is not lit: 6mA average	
Operating	0 to 40°C, relative humidity 85% or less (at	
temperature /	35°C) with no condensation	
humidity range		
Storage	20 to 55°C, relative humidity 85% or less (at	
temperature /	35°C) with no condensation	
humidity range		
Dimensions	79 x;208 x;150mm (3-1/8 x;8-3/16 x;5-7/8	
	in.)	
Weight	850g (30 oz.) without battery	
Standard	Lens cap; Eyepiece cap; ND eyepiece filter;	
accessories	9V battery; Case	

Figure H-1: Illuminance and Luminance in-situ measuring tools

### Appendix I. Delphi questionnaire

#### • Round two questionnaire

Hello! You are invited to participate in our second round of the Delphi survey on the dynamic visual comfort evaluation tool. In this investigation, approximately ten people will be asked to complete a questionnaire. At this stage, the questions are more focused on the tool efficiency and effectiveness. It will take approximately 10 minutes to complete the questionnaire. Your participation in this study is completely voluntary. There are no foreseeable risks associated with this project. However, if you feel uncomfortable answering any of the questions, you can withdraw from the survey at any point. It is very important for us to learn your opinions. Your survey responses will be strictly confidential, and data from this research will be reported only in the aggregate. Your information will be coded and will remain confidential. If you have questions at any time about the survey or the procedures, you may contact Dalia Hafiz at 862-579-7858 or by email at the email address specified below. Thank you very much for your time and support.

1. Overall, l	how satisfied were you with your new too	1?						
A. Not	at all satisfied	0						
B. Son	newhat Satisfied	1						
C. Neu	ıtral	2						
D. Sati	sfied	3						
E. Del	ighted	4						
2. How interested would you be in using the new Tool?								
A. Ver	y interested	4						
B. Inte	prested	3						
C. Neu	ıtral	2						
D. Uni	nterested	1						
E. Ver	y uninterested	0						
3. Who do	you expect will benefit from the tool?							
A. Stud	dents only	2						
B. Day	lighting researchers only	2						
C. Arc	hitects and designers only	2						
D. Eng	gineers only	2						
E. All	the above	4						
4. Do you a	agree that this tool could improve the desig	n process?						
A. Stro	ongly disagree	0						
B. Son	newhat disagree	1						
C. Nei	ther agree nor disagree	2						
D. Son	newhat agree	3						
E. Stro	ongly agree	4						

5. How	v likely are you to use the tool if it has all	l the at	ttribute	s described a	lbove?			
A.	Very likely		4					
B.	Somewhat likely		3					
С.	Neutral		2					
D.	Somewhat unlikely		1					
E.	Very unlikely		0					
6. Over	rall, I am very satisfied with the performa	ance o	f the wa	ay the new (I	Dyna-Com	fort)-tool in th	nis project.	
А.	Strongly Disagree		0					
В.	Somewhat Disagree		1					
C.	Neither Agree nor Disagree		2					
D.	Somewhat Agree		3					
E.	Strongly Agree		4					
7. Pleas	e indicate the degree to which you agree/	'disagr	ee with	the following	ng statemer	nts	-	
		Stron	gly	Somewhat	Neutral	Somewhat	Strongly	
		Disag	ree	Disagree		Agree	Agree	
A.	The new tool can help designers	0		1	2	3	4	
	improve their designs							
В.	The tool succeeds at performing its	0		1	2	3	4	
	intended task (evaluating visual							
	comfort)							
C.	Based on my experience with the tool I	0		1	2	3	4	
	will use it in future designs to evaluate							
	the visual comfort in my space							
8 Do 1	VOLL agree that this tool can positively cha	ange th	ne archi	tectural desi	on?			
A.	Strongly Disagree	**** <b>9</b> 0 tr	0	tooturur uoor	5			
B.	Somewhat Disagree		1					
C.	Neither Agree nor Disagree		2					
D.	Somewhat Agree		3					
E.	Strongly Agree		4					
9. Order	r these eight factors based on your belief	of the	ir impo	rtance from	1to8 where	e the most imp	oortant is 1	
to the le	east important is 8 ( you can give 2 or mo	re fact	ors the	same rating	if you hav	e they have th	e same	
value)								
Factor				Impor	rtance Rai	nk(from 1 to 8	8)	
A.	User-friendly interface							
B.	Detailed definitions of the terms used							
C.	Detailed numeric outputs							
D.	Visual representation (image/video) of th	e glar	e times					
E.	Recommendations for possible design so	olution	IS					
 F.	Multiple building types menu							
G	Multiple visual field directions (looking	un do	wn or s	sides)				
H	Integrate artificial lighting	p,o						
10 4 -	there additional attailates that are 1	J	40 1		into 11 1	.19		
10. Ale	there additional attributes that you would	i wani	. to be 1	ncorporated		01?		
11 How	y can the tool be improved to better infor	m the	design	process?				
				F-00000				
12. Plea	se provide any additional comments abo	ut our	propos	ed product.				

# • Round two responses and analysis

Questions 1through 8 were analyzed using statistics

Question no/Respondents	Question1	2	3	4	5	6	<b>7</b> A	7B	7C	8
Respondent 1	2	1	2	2	2	1	1	1	1	1
2	3	3	4	3	3	3	3	3	3	3
3	2	3	4	4	4	3	3	4	4	3
4	1	4	4	4	4	4	4	3	4	3
5	3	3	3	4	3	4	4	4	3	3
6	2	4	4	4	4	4	4	3	4	3
7	2	2	4	2	2	2	3	2	3	2
8	3	3	2	4	3	4	4	4	3	3
9	2	3	4	4	4	3	3	3	3	3
10	2	2	4	4	4	3	2	2	2	2

Mode= 3

Mean= 3

median= 3

St Dev= 0.921132

Question no 9: analysis using Kendall's W coefficient

Question no /Respondents	Α	В	С	D	Ε	F	G	Н
1	1	7	7	2	8	2	3	4
2	1	5	5	3	7	3	4	2
3	2	6	7	4	8	3	2	1
4	1	5	6	3	8	2	5	3
5	1	5	8	1	8	4	5	3
6	1	2	6	3	8	4	5	3
7	1	5	6	3	7	3	4	3
8	1	5	5	2	8	3	5	3
9	1	5	6	3	8	2	5	3
10	1	5	5	3	8	2	4	3
sum(Ri)	11	50	61	27	78	28	42	28
	877.6406	87.891	415.1	185.6	1397	159.4	1.891	159.4

Sum total= 325

$$W=\frac{12S}{m^2(n^3-n)}$$

From Equation,

W= 0.781875> 0.7, thus, high agreement was detected.