INVESTIGATING OCCUPANT'S VISUAL COMFORT AND VISUAL INTEREST TOWARDS SUNLIGHT PATTERNS IN DAYLIT OFFICES

by

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DISSERTATION ABSTRACT

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Title: Investigating Occupant's Visual Comfort and Visual Interest towards Sunlight Patterns in Daylit Offices

Sunlight is a multidimensional phenomenon that influences occupant's comfort and well-being through its dynamic visual and thermal attributes. Previous studies suggested that the presence of sunlight patterns in space was cheering and visually interesting, which could improve visual comfort and space quality. However, it remains unclear what the attributes of visually interesting sunlight patterns are, and whether their visual interest influences visual comfort. This dissertation aims to answer three main questions: (1) is there a difference in visual interest and mood response among different projected light patterns? (2) How do sunlight patterns of different geometries influence visual interest and visual comfort in offices? And (3) what are the geometrical attributes of sunlight patterns that should be implemented in office spaces?

To address these questions, a series of four studies were conducted. The first two studies extended empirical findings on visual interest and mood responses elicited by varying complexities of fractal and non-fractal light patterns projected on walls and floors of an interior space. These two studies determined which patterns to be further examined in Studies 3 and 4, which investigated the visual comfort, visual interest of sunlight patterns, and view quality under three different window conditions in office spaces.

The results of studies 1 and 2 suggested that fractal light patterns of medium to medium-high complexity, quantified by the fractal dimension in the range (D=1.5-1.7), were significantly more visually interesting than other patterns. Both studies found that fractal compared to non-fractal light patterns provided a better balance between relaxation and excitement. Study 3 found that the fractal pattern was associated with a significant increase in visual comfort, compared to the striped pattern, though the difference in visual interest between the two patterns was not statistically significant. Study 4 found that the effect of the fractal pattern on visual comfort, visual interest of sunlight patterns, and view quality was dependent on occupant’s view direction and façade orientation. These findings can have implications for the design and control of facade systems to improve occupant’s visual comfort, interest, and view quality in work environments.

This dissertation includes both previously published/unpublished and co-authored material.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

Sunlight has been one of the most influential form drivers in architecture for millennia. In addition to its importance for illumination and passive heating, sunlight can help create stimulating interior spaces that enhance occupants' connection to the outside environment through its dynamic luminous and thermal variations. These variations influence occupant's visual and thermal comfort as well as their well-being. Previous studies found that sunlight can regulate melatonin suppression and phase shifts (Duffy & Czeisler, 2009), expedite recovery for depression patients (Beauchemin & Hays, 1996; Benedetti, Colombo, Barbini, Campori, & Smeraldi, 2001), boost the body's vitamin D supply, regulate melatonin production (Mead, 2008), and increase brain serotonin levels (Lambert, Reid, Kaye, Jennings, & Esler, 2002). Excessive exposure to sunlight, however, can cause negative effects on the skin (Mead, 2008), eye, and immune system (WHO, 2016). Given that people spend about 87% of their time in enclosed buildings (Klepeis et al., 2001), it is essential to effectively manage sunlight exposure in buildings to enhance occupant's comfort, satisfaction with indoor environments, and well-being.

1.1. Research Problem

Unlike diffuse daylight, direct sunlight creates sharp-edged shadows with higher contrast levels, exhibits directionality over the course of the day, and conveys a sense of time. Hence, direct sunlight and diffuse daylight can create and promote different perceptual and behavioral experiences in space (Khanie et al., 2013; S. Rockcastle, Amundadottir, & Andersen, 2017; Na Wang & Boubekri, 2010). Focusing on the visual experiences, there have been several studies suggesting that the presence of sunlight in space (hereafter sunlight patterns) can contribute to improving occupant's visual comfort and visual interest through cheering effects (Boubekri & Boyer, 1992; Ne'Eman, 1974; Van den Wymelenberg, Inanici, & Johnson, 2010).

However, the attributes that distinguish visually interesting and cheering sunlight patterns are not well understood, e.g. luminance, geometry, size, location, and duration. Further, it remains unclear how combinations of these attributes influence visual interest and visual comfort. This gap has contributed to the common practice of blocking or greatly limiting sunlight exposure in buildings to eliminate potential visual discomfort. While this practice might reduce visual discomfort, space quality is likely to be dull (Reinhart 2015) with reduced sunlight benefits. To address this issue, a more comprehensive approach for managing sunlight exposure should address the visual interest of sunlight patterns and potential effects on visual comfort.

One of the main sunlight pattern attributes that might influence visual interest is geometry. The geometry of sunlight patterns is typically shaped by external and/or internal obstructions such as shading systems, aperture, furniture, and trees. Expectedly, there is a wide range of possible sunlight pattern geometries that might exhibit different levels of visual interest. Currently, there are not enough studies to determine whether different sunlight pattern geometries elicit different levels of visual interest and visual comfort. Addressing this gap is particularly beneficial to office workers who typically spend prolonged times in fixed view directions.

1.2. Research Questions

This dissertation aims to answer three main questions: (1) is there a difference in visual interest and mood response among different projected light patterns? (2) Do sunlight pattern geometries influence visual interest and visual comfort in offices? And (3) what are the geometrical attributes of sunlight patterns that enhance visual comfort and visual interest in office spaces?

Previous studies in Psychology concluded that fractal patterns were more visually preferred over non-fractal patterns (Spehar, Clifford, Newell, & Taylor, 2003; Taylor & Spehar, 2016). However, in these studies, patterns were typically viewed on a computer screen with no relationship to spatial and environmental variables like distance, lighting, room surfaces, outdoor views, and glare. This restricts the applicability of their findings to sunlight patterns in an architectural setting. This dissertation utilizes an interdisciplinary approach by building upon studies and methods in both Psychology and Architecture to examine the visual interest of sunlight pattern geometry, and to investigate whether visual interest influences occupant's visual comfort ratings. Further, it examines outdoor view quality to determine the extent to which patterns applied to window influence view quality ratings. Implications of this research can inform the design of future shading and daylight systems to improve occupant's visual comfort and interest in work environments.

This dissertation conceptualizes interactions among the visual interest of sunlight patterns, view quality, and visual comfort to influence and shape occupant's visual preferences towards sunlight patterns. The proposed conceptual model illustrates this idea and aims to incorporate qualitative aspects of sunlight patterns to assess occupant's visual comfort and interest in daylit office spaces (Boubekri, Hull, & Boyer, 1991; Ne'Eman, 1974; Van Den Wymelenberg et al., 2010).

1.3. Research Goals and Objectives

Overall, this dissertation intends to advance the understanding of the effects of sunlight pattern geometry on occupant's visual interest and visual comfort in daylit office spaces. Therefore, there are two objectives for this dissertation: first, to assess the visual interest and mood response to projected light patterns with the focus on identifying light patterns of high and low visual interests; second; to examine differences in visual comfort, visual interest, and view quality under different sunlight pattern geometries and window conditions. The following sections describe each objective and outline specific research questions.

1.3.1. Assessing the visual interest and mood response to projected light patterns

There are currently not enough studies to delineate the influence of projected light pattern geometry on visual interest and mood response. Therefore, the first goal was to assess the visual interest and mood response to projected light patterns of different geometries. This assessment is essential to inform the selection of patterns that can be used to examine differences in visual comfort in following phases of the dissertation.

Regarding patterns of high visual interest, previous psychological studies suggested that viewing mid-complexity fractal patterns on a computer screen resulted in positive perceptual and physiological responses (Taylor et al., 2005; Hagerhall et al., 2015; Spehar et al., 2003). It is unclear, however, if similar responses would be elicited if the fractal patterns were projected as light patterns on room surfaces, e.g. walls and floor. In contrast to fractal patterns, striped patterns were considered more likely to cause visual discomfort because they have Fourier amplitude spectra that depart maximally from those of natural scenes (Wilkins, 2016).

Given the potential difference in visual interest between fractal patterns and striped or Euclidean patterns, these two pattern types were included to examine their visual interest when spatially projected in space. The main questions to be answered are: would mid-complexity fractal patterns be considered more visually interesting than non-fractal patterns even when spatially projected in space? And how do different projected light patterns influence reported mood response in terms of relaxation and excitement?

1.3.2. Investigating differences in visual comfort, visual interest, and view quality under different sunlight patterns and window conditions.

Currently, there is a gap in addressing and identifying the geometrical attributes for visually interesting sunlight patterns. Further, it remains unclear whether visually interesting sunlight patterns influence occupant's subjective visual comfort ratings. Thus, the goal is to examine differences in visual comfort, visual interest of sunlight patterns, and outdoor view quality under different sunlight patterns and window conditions.

The main questions to be answered are: is there a difference in subjective visual comfort, view quality, and visual interest of sunlight patterns under different sunlight and window conditions? and what are the positive geometrical attributes of sunlight patterns that are preferred by occupants, and should be implemented in daylit office spaces?

1.4. Dissertation Overview

This dissertation is structured as a series of chapters that explored different topics related to the research goals. Committee members have contributed to these papers; hence, listed as co-authors. The following outlines the main topics and research questions addressed in each chapter.

Chapter 1 and 2 provide an introduction and summarize existing literature related to visual comfort, positive attributes of sunlight patterns, and view quality with a focus on light pattern geometry. A conceptual model is proposed to describe occupant's visual preferences towards sunlight patterns in daylit offices, and to highlight the relationships between various study variables. Lastly, an overview of the different studies is discussed.

Chapter 3 reports on the results of Studies 1,2, and 3, which extend empirical findings of fractal visual preference and human impacts by examining the visual interest and mood response elicited by Euclidean patterns and various complexities of fractal light patterns. This was the first step to transition from displaying patterns on a computer screen to being projected on a wall as light patterns. The two papers included in this Chapter were co-authored with Professors Ihab Elzeyadi, Richard Taylor, and Margaret Sereno; and will be published.

Chapter 4 reports on the results of a quasi-experiment (Study 4) conducted in an office building in Portland, OR where three experimental settings were created at the office with different window treatments to create three sunlight geometries. These three window treatments are: fractal Pattern, striped Pattern, and clear, which were tested and compared for their impact on the visual interest of sunlight patterns, visual comfort, and view quality. The paper titled "The Relationship between Sunlight Pattern Geometry and Visual Comfort in Daylit Offices" was co-authored with Professor Ihab Elzeyadi and was published at the ARCC–EAAE 2018 Conference, 2018. The other paper titled "A Study of Visual Comfort, Visual Interest of Sunlight Patterns, and View Quality under Different Window Conditions in Offices" was co-authored with Professors Ihab Elzeyadi, Richard Taylor, and Margaret Sereno; and will be published.

Chapter 5 reports on the results of a five-week field study (Study 5) where 33 office workers were subjected to three sunlight patterns and window conditions: fractal pattern, striped pattern, and clear at an office building in San Francisco, CA. Differences in visual comfort, visual interest of sunlight patterns, and view quality are examined across the three conditions. The paper titled "Do Visually Interesting Sunlight Patterns Impact Occupants' Perceived Glare in Daylit Offices?" has been published at the IES Research Symposium 2018: Light + Human Health. The other paper titled "Investigating Visual Comfort, Views, and Visual Interest of Sunlight Patterns under Fractal and Striped Window Conditions" was co-authored with Professors Ihab Elzeyadi, Kevin Van Den Wymelenberg, Grant Jacobsen, Richard Taylor, and Margaret Sereno; and will be published.

Lastly, Chapter 6 summarizes main conclusions and outlines future warranted studies.

CHAPTER II

LITERATURE REVIEW AND CONCEPTUAL MODEL

Chapter I highlighted the significance of effectively controlling sunlight exposure in buildings, and identified the need to address the visual interest of sunlight patterns. While previous studies suggested that sunlight patterns were associated with visual interest or cheering effects, it remains unclear what geometrical attributes elicit these effects. This chapter discusses in further detail the variables influencing visual comfort, visual interest of sunlight patterns, view quality, and light pattern geometry.

In Section 2.1 of this chapter, previous studies that investigated visual comfort towards sunlight are summarized, and the limitations of current approaches are discussed. In Section 2.2, positive sunlight attributes are discussed in relation to their effects on various perceptual and behavioral outcomes. Studies related to view quality and its effect on visual comfort are reviewed in Section 2.3, focusing on two main variables: view type, e.g. views of nature and urban views, and view direction in relation to views and glare sources. Section 2.4 summarizes the results of previous studies that examined fractal and striped patterns, and highlights variables that might influence visual interest if these patterns are projected as light patterns on room surfaces. Section 2.5 shows a conceptual model on occupant's preferences towards sunlight patterns and highlights main relationships and variables. Lastly, Section 2.6 provides an overview of the studies and Chapters in this dissertation.

2.1. Visual Comfort

Sunlight admission and control in buildings has been examined to delineate occupant's ranges of acceptance and comfort under different sunlight conditions. For instance, Elzeyadi & Lockyear [2010] surveyed occupants in a LEED Platinum building and found that those in East and West facades reported extreme glare discomfort, compared to occupants in North and South facades that received less sunlight exposure and less variation in luminance patterns. Therefore, it is essential to effectively manage occupant's sunlight exposure in buildings to improve their visual and thermal comfort, well-being, and the quality of indoor spaces.

Previous studies focusing on evaluating discomfort glare have not been able to reliably predict occupants' visual comfort when direct sunlight is present in space. Metrics like Daylight

Glare Index (DGI), CIE Glare Index, and CIE Unified Glare Rating System (UGR) are only valid for conditions when direct sunlight does not enter the space (Jakubiec and Reinhart 2012; Nazzal 1998; Iwata, Tokura, and Shukuya 1992). Daylight Glare Probability (DGP) was found to be a better predictor of visual comfort than DGI despite some limitations (Konstantzos & Tzempelikos, 2017b; Mcneil & Burrell, 2016; Van Den Wymelenberg & Inanici, 2014).

Other approaches include using ‘the presence of sunlight on work plane’ which could identify 34.8% of visual discomfort; ‘direct visibility of the sun’ which predicted 20.4%; and the combined use of vertical illuminance and direct vertical illuminance when the sun can be seen through roller shades (Konstantzos & Tzempelikos, 2017b). The inconsistency in used metrics and their predictability suggests that there might be aspects of sunlight exposure not currently addressed in these metrics such as the visual interest of sunlight patterns, interactional effects between glare and view quality, and related psychological effects. This paper defines ‘sunlight patterns’ as direct sunlight projected onto different surfaces of an interior space. This term will help distinguish between the solar disc and sunlight projections in space.

In a previous study that utilized questionnaires and daylight simulations to investigate the relationship between solar penetration levels and visual comfort (HMG, 2012), It was found that less than 300-350 hours of sunlight exposure per year resulted in positive visual comfort assessments. The resulting annual solar exposure metric ($ASE_{1000,250h}$) recommended that sunlit areas (>1000 lux) should not exceed 10% of floor area for 250 hours per year (IES, 2013). Some researchers may argue that the generalizability of the ASE metric is questionable, particularly because it does not consider shading system type, orientation, view direction of occupants, and shape of sunlight patterns. Indeed, this metric has been critiqued as a strict metric that limits solar exposure and promotes dull spaces (Reinhart 2015). A recent study found no correlation between annual daylight glare probability (DGP) and ASE (Dutra de Vasconcellos, 2017). Recently, the area requirement of the ASE metrics has been recently extended for up to 20% of floor area (USGBC, 2017). Various discussions and commentary in scientific conferences and meetings suggest that the ASE metric, though useful in some cases, warrants further studies and explorations to critique its limitations (Heschong, 2017). From the above, it is suggested that the current ASE metric warrants further investigation and refinement.

Previous studies examined the relationship between sunlight and visual comfort in various settings. When occupants reported their long term evaluations of visual comfort, they tended to be most sensitive to direct sunlight (Jakubiec and Reinhart 2013). Particularly, sunlight is likely to cause visual discomfort if it falls directly on the work plane or the eye, (Jakubiec, Reinhart, and Wymelenberg 2014). Yet, in several studies, participants preferred to allow sunlight on their desks when asked to adjust blinds to a preferred setting (Kent, Altomonte, Wilson, & Tregenza, 2017; Van Den Wymelenberg & Inanici, 2014). Overall, sunlight can influence visual discomfort by increasing the luminance of work surfaces and/or by increasing the contrast between task and surroundings within occupant's field of vision (Suk, Schiler, & Kensek, 2016).

Despite an increased interest in evaluating daylight glare metrics, most existing studies did not use specific sunlight pattern characteristics such as size, location, and luminance to test visual discomfort, instead, sunlight patterns were assessed using glare calculations such as DGP that do not provide information regarding specific preferred characteristics. While few studies have included planar measurements of the sunlit area by means of its size, illuminance, and distance from occupants (HMG, 2012; N. Wang & Boubekri, 2010), more studies are warranted to identify the patterns and geometries of visually comfortable sunlight patterns.

2.2. Sunlight Patterns

In a study conducted on office buildings in and around London, 73% of participants considered sunlight a pleasure while 61% preferred a good view over indoor sunlight (Longmore & Ne'Eman, 1974). Interestingly, this study reported that one of the liked effects of sunlight is the 'improved appearance of interiors'. Ne'Eman (1974) created a qualitative scale for occupant's reactions to sunlight, and stated that sparkle, brightness, and mental stimulus are characteristics that make sunlight patterns pleasant. These results are in line with results of another study where Boubekri, Hull, & Boyer (1991) found that optimal sunlight penetration levels that create maximum degrees of relaxation are from 15%-25% of floor area. They concluded that sunlight "sparkles" are preferred over large areas of sunlight patches. It was also found that sunlight as manipulated by size, season, time of the day has significant impacts on the affective state of occupants, which influences their indoor satisfaction. Boubekri et. al. stated that horizontal Illuminance under sunlight is higher than recommended light levels for any task; so visual perception of sunlight is mainly associated with the quality not the quantity of sunlight. In another study, the presence of sunlight was thought to have caused cheering and pleasant effects that could have increased glare tolerance (Boubekri & Boyer, 1992). Table 2.1

shows positive sunlight pattern attributes that were found to influence different perceptual and behavioral responses.

Study	Dependent Variable	Sunlight Pattern Attributes
(Van den Wymelenberg & Inanici, 2009)	Preference ratings	Adequate luminance variations
(Van den Wymelenberg et al., 2010)	Satisfaction	Carefully located sunlight patterns
(Ne'Eman, 1974)	Pleasantness	Brightness and sparkle
(Boubekri et al., 1991)	Mood	Size of sunlit area= 20-25% of total floor area. View direction. Small sun patterns (sparkles) are preferred over large floods.
(Boubekri & Boyer, 1992)	Glare tolerance	Possible cheering and pleasant effects
(Phil Leather, Pyrgas, Beale, & Lawrence, 1998)	Job satisfaction	Area of sunlight patterns
(Siobhan Rockcastle, Ámundadóttir, Andersen, Res, & Smarchs, 2016)	Perceptual response	Modified spatial contrast.
(Na Wang & Boubekri, 2010)	Seating preference	Location of sunlight patterns
(Reinhart, 2015)	Space quality	Presence of sunlight patterns

Table 2.1: Studies that highlighted factors influencing preferences towards sunlight patterns.

Wang and Boubekri (2011) examined subjects' seating preferences while doing a paper-based task in an experimental sunlit space and found that most subjects chose to sit close to or within the sunlight pattern even though average horizontal illuminance for chosen locations ranged from (527-14052) lux. In a controlled experiment, Wymelenberg, Inanici, and Johnson (2010) found that 11 out of 12 participants preferred to allow sunlight patterns into space when it was available. It was argued that adequate luminance variations create a stimulating and interesting environment that improved occupants' preference ratings. These results are in line with results of another study (Kim 1997) which found that sunlight improved positive emotions more than daylight, in both winter and summer seasons in classrooms.

2.3. View Quality

2.3.1. View type

In addition to the importance of windows for illumination, windows were found to provide many psychological benefits such as providing access to environmental information and sensory change, connection to the outside world, and restoration (Wener & Heerwagen, 1990). It is well established that access to outdoor views, specifically scenes of nature, can contribute to a higher satisfaction and positive physiological benefits. For instance, one study found that an unobstructed view of natural surroundings was associated with improvements in self-reported physical and mental health during a residential rehabilitation program (Raanaas, Patil, & Hartig, 2011). Ulrich (1981) concluded that scenes of nature had a more positive influence on the psychophysiological states than urban scenes. In a subsequent study, Ulrich (1984) found that patients in rooms with windows looking out on a natural scene had shorter postoperative hospital stays and took fewer potent analgesics than those in similar rooms with windows facing a brick wall. Another study (Leather, Pyrgas, Beale, & Lawrence, 1998) found that a view of natural elements buffered the negative impact of job stress on intention to quit. Chang & Chen (2005) found that participants were less nervous when watching a view of nature and/or indoor plants were present.

Scenes of nature were also found to improve performance (Tennessen & Cimprich, 1995), less sick leave rates in an office building (Elzeyadi, 2012), and a more consistent responding to the task and less omission errors, compared to viewing a concrete roof (Lee, Williams, Sargent, Williams, & Johnson, 2015). The question to be asked is why viewing nature is more restorative and more preferred than viewing urban scenes? A recent study (Van den Berg, Joye, & Koole, 2016) investigated this question and concluded that differences in restorative quality were mediated by the complexity of natural scenes. This study suggested that fractal-like patterns are an important cue underlying the restorative potential of natural and built environments.

Regarding visual comfort, significant differences in subjective evaluations of visual discomfort were found for different views at the same luminance (Shin, Yun, & Kim, 2012). This study found that distant views received lower visual discomfort ratings than close views, which could be due to the sense of extent provided by distant views compared to close views (Kaplan, 1995). In another study, visual interest of view was found to have a marginally significant relationship with visual comfort (Aries, Veitch, & Newsham, 2010; Hirning, Isoardi, & Cowling, 2014). These results are in line with results of another study (Tuaycharoen & Tregenza, 2007) which found that glare discomfort decreased as interest in view increased at the same mean luminance value. Tuaycharoen and Tregenza concluded that the four factors typically used in glare formulae – source luminance, source size, surround luminance and a position index – are not enough to predict visual comfort.

In addition to view type and interest, two important concepts related to views are the effective outside view and view clarity. The effective outside view is the portion of the occupant’s visual field that is covered by a window (Konstantzos & Tzempelikos, 2017a) whereas view clarity refers to the ability of occupants to see and distinguish outdoor environmental details. A recent study (Konstantzos et al., 2015) proposed and developed the view clarity index, which addresses view clarity through roller shades. This index was calculated as the mean of responses related to clarity of outside view and sky condition, the vividness of colors, distinguishing outside objects and colors, and visual acuity. These various aspects were equally weighted but further research might suggest different weights for different aspects or show the need to add additional aspects. The developed view clarity index was based on shade openness factor and normal visible transmittance. Other variables that significantly influenced view clarity are sky condition, viewing distance, and fabric type. This study highlights the need to examine view clarity through shades and window patterns.

2.3.2. View direction

An important concept related to visual comfort towards sunlight patterns is whether these patterns can typically be seen by occupants. Most studies that examined sunlight size, did so using planar measurements in relation to floorplan area, which might not represent the actual pattern size seen by occupants. For instance, in the New York Times building, automated shades were controlled to limit sunlight penetration to a few feet from the façade (E. Lee, Fernandes, Coffey, Mcneil, & Clear, 2013). Yet, questionnaire results showed that 42% of users, who manually overrode shade position, chose to reduce the amount of sunlight in the space. View direction is particularly important in offices with fixed desk layouts with limited ability to alter the location of computer screens.

In offices that utilize flexible workstations, occupants can more easily adjust their view direction to avoid or mitigate glare. This concept is referred to as the adaptive zone (Jakubiec & Reinhart, 2012), which showed that when sunlight patterns are present in space, a relatively small change in view angle could considerably influence the probability of visual discomfort (Figure 2.1). Even under overcast sky conditions, a study found differences of up to 36% in glare source luminance values when measured at different view angles (Fan, Painter, & Mardaljevic, 2009). Another study showed that occupant's view direction, e.g. perpendicular or parallel to the window, influenced perceived glare from sunlight patterns and window size (Boubekri & Boyer, 1992). Lastly, Day & Creed (1996) examined occupants' assessments of the sunlight received in dwellings by relating them to objectively calculated number of hours during which a direct unobstructed view of the sun can be expected to be seen from a defined reference point.

The use of reference points from which sunlight can be seen is an essential component to effectively quantify and control sunlight patterns in space.

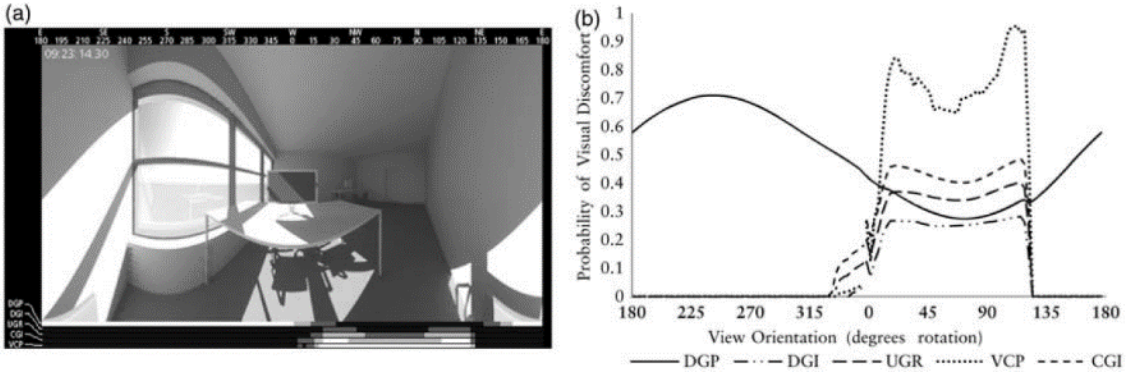


Figure 2.1: Discomfort glare predictions as a function of view direction. Following (Jakubiec & Reinhart, 2012).

2.4. Light Pattern Geometry

Previous studies that examined visual preference and psychological response to pattern geometry are mainly within the domain of environmental psychology, however, there have been attempts to extend the applicability of these studies to architectural settings. For example, a recent study that examined visual comfort in schools suggested that venetian blinds can cause pattern glare because of the spatial frequency of the striped sunlight patterns (Winterbottom & Wilkins, 2009). Such striped patterns are more likely to cause visual discomfort because they have Fourier amplitude spectra that depart maximally from those of natural scenes (Wilkins, 2016). Even checkerboard patterns (which have contrast energy in several orientations) are less uncomfortable than stripes in which the energy varies only in one orientation (Wilkins et al. 1984).

On the other hand, existing literature shows that natural scenes are more preferred than urban scenes, (Purcell, Peron, & Berto, 2001) and are believed to elicit many physiological and psychological responses such as higher alpha activity (higher relaxation effects), and positive emotional states (R. S. Ulrich, 1981). Several theories and hypotheses were proposed to explain people’s fascination with nature. For instance, Kellert (2005) stated that people attach meaning or derive benefit from nature through its naturalistic and aesthetic values. The naturalistic value reflects the perception of nature as a source of stimulation, diversity, and detail; whereas the aesthetic value reveals the natural world as a source of beauty and attraction. Kaplan (1995) proposed the attention restoration theory which implies that natural environments are particularly rich in characteristics necessary for restorative experiences. The question, therefore, is what are these characteristics? And what are the mechanisms that link these characteristics to positive psychophysiological responses?

One theory suggested that these effects can be explained by fractal patterns, which are prevalent in nature (Purcell, Peron, and Berto, 2001; Joye and van den Berg, 2011; Hagerhall et al., 2015) such as trees and clouds. Fractal patterns can be defined as shapes that display a cascade of never-ending, self-similar, meandering detail as observed at various levels of scales (Bovill 1996; Harris 2012). While fractal patterns vary in complexity, the prevalence of mid-complexity fractals has caused the human visual system to adapt to easily process and comprehend them. This adaptation is known as the fractal fluency theory (Taylor & Spehar, 2016). Studies suggested that adaptations exist at multiple stages of the visual system (Taylor and Spehar 2016), such as aesthetic appreciation (Aks & Sprott, 1996; Taylor, 1998; Spehar, Clifford, Newell, & Taylor, 2003), pupillary oscillations (Moon et al., 2014), restorative effects (Hagerhall et al. 2008), as well as stress recovery benefits (Taylor, 2006). Additionally, adaptations are also evident in heart beat rates (Goldberger et al., 2002), motor hand activity (Aybek et al., 2012), and retinal circulation (Masters, 2004). These studies suggest a deep resonance and interaction between fractal patterns and observers (Taylor and Spehar 2016). The mechanism that relates fractal patterns to visual preference is shown in Figure 2.2.

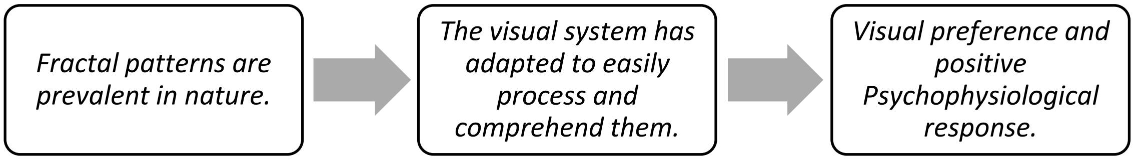


Figure 2.2: The mechanism underlying the fractal fluency theory.

Fractal patterns are typically characterized by a variable called the fractal dimension (D). This parameter quantifies the fractal scaling relationship between the patterns at different magnifications. Behavioral studies have confirmed that the rise in D is accompanied by an increase in perceived visual complexity (Taylor & Spehar, 2016). Based on the D value, fractals can be categorized into low (D=1.1-1.3), medium (D=1.3-1.5), and high complexity (D=1.5-1.9). Fractal patterns are classified into two categories based on the manner in which the patterns repeat at different scales (Hagerhall et al. 2015); these two categories are statistical, and exact fractals. Statistical fractals are found in nature and exhibit randomness and variety in sizes at different scales such that only the pattern's statistical qualities repeat (Taylor and Spehar 2016). In contrast to exact fractals, the natural form of statistical fractals was found to be an important factor for inducing alpha responses, an indicator for a wakefully relaxed state (C M Hagerhall et al., 2015). Figure 2.3 shows an example of fractal patterns with different levels of complexity.

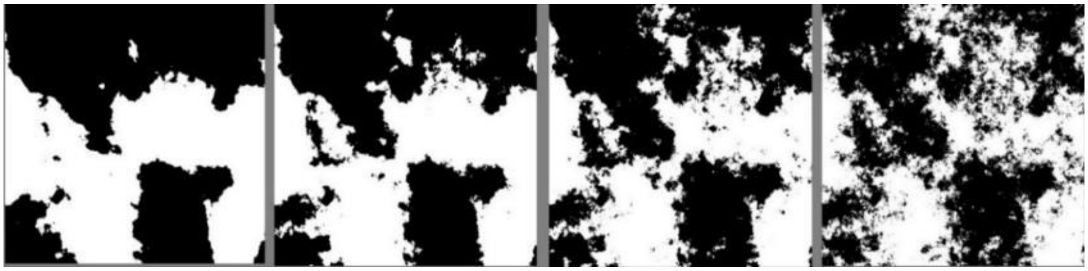


Figure 2.3: Fractal patterns with increasing D value and complexity (left to right). Courtesy of Cooper Boydston, Richard Taylor, and Margaret Sereno.

2.4.1. Perceptual and physiological response to fractals

Previous studies showed that fractal patterns are more preferred than non-fractals. For instance, Taylor (1998) found that 95% of participants preferred fractals to non-fractal patterns. Because fractal patterns vary in complexity, researchers investigated the relationship between visual preference and D (Hagerhall, Purcell, and Taylor 2004). Aks and Sprott (1996) found that all participants preferred patterns with a fractal dimension between 1.17-1.38. Aks and Sprott found slight differences in preferences based on personality traits, e.g. creative people prefer less detailed patterns. Another study (Spehar et al., 2003) concluded that preferences congregate within the range D=1.3-1.5. Spehar and Taylor (2013) found that the visual preference peaked at D=1.25-1.5. Generally, these studies suggest that fractals with a D=1.3-1.5 are more preferred than other fractal patterns.

Taylor (2006) investigated effects of viewing fractals on human physiological response to stress. In this study, each participant was seated in a room facing one of three images: a fractal image of savannah landscape with D value of 1.4, a fractal image of a forest with D value of 1.6, a non-fractal pattern; and a white panel as a control. The results showed that only fractal patterns, the savannah landscape and the forest, were associated with 44% and 13% stress reduction compared to the white control panel, respectively. On the other hand, the non-fractal pattern increased stress response by 13% compared to the control panel. The researcher stated that the image of the savannah (D=1.4) falls into the 'aesthetically pleasing' range" and concluded that the magnitude of the change in the mean conductance between work and rest periods was dependent on which pattern participants viewed.

It is well-documented in existing literature that people prefer fractal patterns over non-fractals (Taylor 2006; Spehar et al. 2003). To explore whether there are any underlying physiological mechanisms to these preferences, researchers have examined brain activity while viewing fractals. For example, Hagerhall et al. (2008) examined effects of fractal patterns on brain activity while participants viewed four computer-generated fractal horizons with different fractal dimensions ranging from D=1.14-1.7. While viewing, electroencephalography (EEG) was continuously measured to assess the brain’s cerebral cortical activity. The results show that fractal dimension of D=1.3 elicited the highest alpha in the frontal region which suggests that these fractals elicited restorative and relaxing effects (a wakefully relaxed state). Further, these fractals generated the highest beta in parietal area, which means that they generated most activation in the processing of the pattern’s spatial properties (an alert state). It should be mentioned that delta is an indication of a state of sleepiness and drowsiness, which was lowest for fractals of 1.3 fractal dimension.

2.4.2. Projected fractal patterns in space

Most previous studies that examined the visual preference of fractal patterns were conducted using a computer screen to display the patterns (Spehar et al., 2003; Spehar & Taylor, 2013; Taylor, Spehar, Hagerhall, & Van Donkelaar, 2011). Since building occupant’s reaction to brightness patterns and stimuli might be influenced by spatial and environmental variables, these preferences might differ based on the viewing method and experimental setting. Particularly, because of the interest in examining sunlight patterns in architectural spaces, it is important to investigate visual preference to spatially projected fractal light patterns.

When a fractal pattern is projected on room surfaces, there are many variables that come into play that might influence visual preference and interest. These variables can be categorized into spatial, complexity, illumination, and interaction variables. Spatial variables include projection surfaces, the distance between observer and patterns, view direction, material properties, viewing angle, and size of the pattern. Complexity refers to that of fractal patterns in terms of the D value. Illumination variables include luminance variability, contrast, glare, as well as psychological effects of light. Third, interaction variables are related to the presence of other environmental stimuli, such as outdoor views, and the overall combined effect on the visual preference of a certain pattern. These variables might influence perceptual and/or psychological responses, hence influencing the applicability of utilizing the fractal fluency theory in architecture (Spehar et al., 2003; Taylor et al., 2005; Taylor and Sprott, 2008; Taylor & Spehar, 2016).

2.5. The Conceptual Model

This dissertation conceptualizes the relationship among visual interest, visual comfort, and view quality from a systemic epistemological perspective (Elzeyadi, 2002). The proposed model (Figure 2.4) hypothesizes that occupant's visual preference towards sunlight patterns is a result of interactions between three main constructs: visual interest of sunlight patterns, visual comfort, and view quality. This means that when sunlight enters a space, occupant's visual reaction is a response to various aspects including its visual, cheering, and psychological attributes as well as view quality. Particularly, because sunlight patterns are likely to be shaped by window shading or exterior obstructions, which also influence view quality.

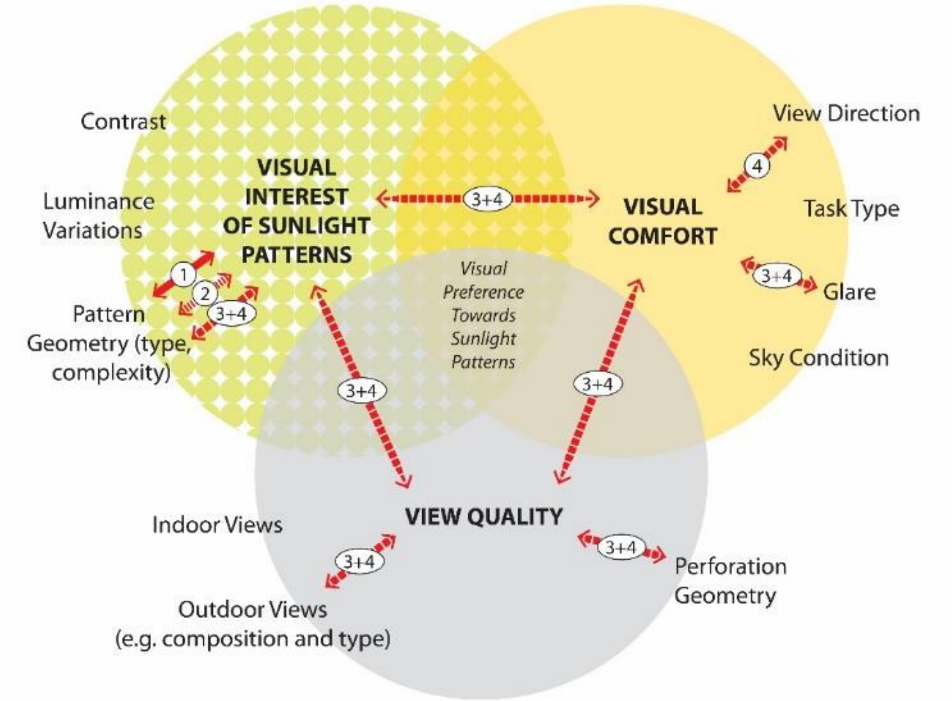


Figure 2.4: Occupant's preferences towards sunlight patterns in office spaces. These preferences are a result of visual comfort mediated by the visual interest of sunlight patterns and view quality. The arrows highlight some of the main variables examined by each study in this dissertation. The number placed on the arrows refers to study number.

It should be mentioned that the visual preference and visual interest are related yet different constructs. In this model, it is hypothesized that visual preference is a result of multiple factors including visual interest. Generally, visual interest in space can be influenced by several factors such as scene contrast (S. Rockcastle et al., 2017) and luminance variations (Van den Wymelenberg et al., 2010). Based on previous studies reviewed in Sections 2.1 through 2.4, it is hypothesized that sunlight pattern geometry can influence visual interest for these patterns. Further, it is hypothesized that the visual interest of sunlight patterns, visual comfort, and view quality interact and influence each other. The interaction among these three variables influences and defines overall scene visual satisfaction.

2.6. Overview of Studies and Methods

To investigate the visual interest of sunlight patterns, view quality, and visual comfort under different window conditions and sunlight pattern geometries, four sequential studies were conducted. These four studies were structured to build upon existing literature in Psychology and Architecture. The overall process can be summarized using the following points, which are shown in Figure 2.5.

- Assessed the visual interest of two-dimensional light patterns projected on a room surface, such as walls. This step examined spatial variables and their potential effect on visual interest, compared to previous studies outlined in Section 2.4.
- Assessed the visual interest of renderings of an interior space that included simulations of light patterns projected on multiple room surfaces. This step introduced distortion in light projections and potential association with daylight in an office setting.
- Investigated whether visual interest is influenced by the distance between an observer and pattern. And examined differences between visual preference and visual interest.
- Results of the previous steps informed the selection of patterns that were applied to windows in an office space to Investigate occupant’s visual comfort, visual interest of sunlight patterns, and view quality under three different window conditions. This study focused on short exposure durations under relatively low glare levels.
- Investigated visual comfort, visual interest of sunlight patterns, and view quality under three window conditions with a focus on longer exposure durations, a wider range of daylight conditions, and while conducting typical office tasks.

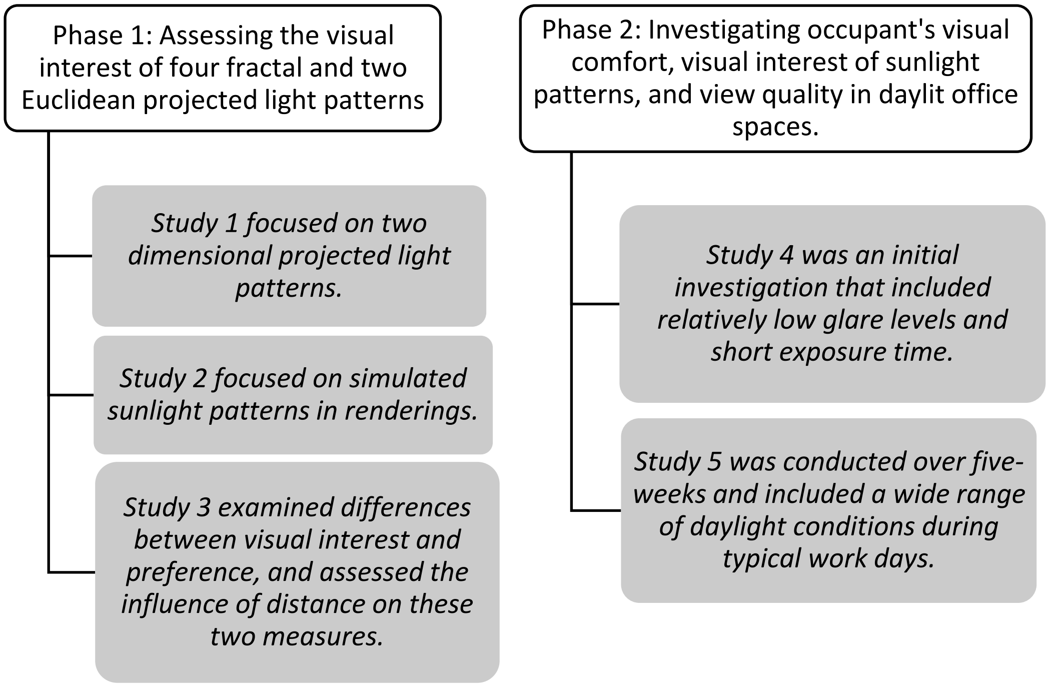


Figure 2.5: A diagram of the process and relationships between the five studies included in this dissertation. The first Phase guided the selection of two patterns that were further investigated in the second Phase.

2.6.1. Summary of methods

The methods used in this dissertation were based on previous studies in two disciplines: Architecture and Psychology. The following sections discuss the selection of research settings and the use of research instruments.

2.6.1.1. Research settings

The research setting for the first three studies is a lecture room where a remote polling system was leveraged to collect responses from all participants at the same time. Compared to viewing patterns on a computer screen, projecting light patterns on a wall allowed for incorporating spatial and environmental variables as discussed in Section 1.1.1. The selected room was equipped with lighting control which was used to adjust lighting such that light pattern projections and room surfaces can be clearly seen by participants. Such lighting conditions, however, did not cause glare levels comparable to those in daylit office spaces. Therefore, for studies 3 and 4, there was a need to transition from light projections in a windowless room to sunlight patterns in office spaces. The research settings selected ensured that sunlight can access the spaces, and that occupants were in perimeter building zones within 10 feet from windows. Figure 2.6 shows differences in luminance distribution in the studies.

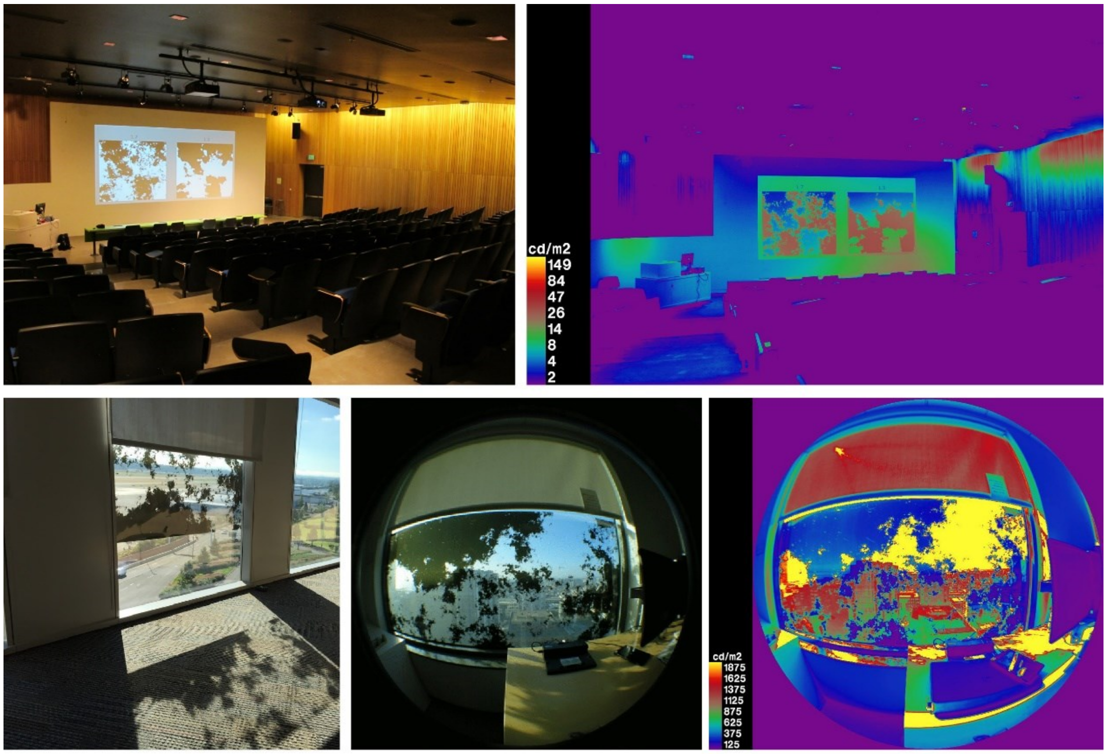


Figure 2.6: The lecture room used for studies 1, 2, and 3; and a false color of luminance distribution in the room (top). Images of sunlight patterns and luminance distribution in studies 4 and 5 (bottom).

2.6.1.2. Assessment procedures

Previous studies that assessed visual preference of patterns utilized a forced-choice paired comparisons, which is often regarded as the most adequate procedure for estimating value judgements (Spehar et al., 2003). This required each pattern to be paired with each other patterns to create all possible combinations. This procedure was used in Studies 1, 2, and 3. For the field studies 4 and 5, there was a need to pair subjective occupant's responses with objective physical measurements of illumination and thermal environment. Previous studies utilized brief questionnaires and data collection stations to collect longitudinal data over periods ranging from days to months (Kelly, Painter, Mardaljevic, & Irvine, 2012; Konis, 2013; Painter, Mardaljevic, & Fan, 2010; Van Den Wymelenberg & Inanici, 2014). Hence, data collection stations were assembled and utilized for capturing a wide range of daylight conditions without the presence of the experimenter, particularly in Study 5.

CHAPTER III

FRACTALS IN ARCHITECTURE: THE VISUAL INTEREST, PREFERENCE, AND MOOD RESPONSE TO PROJECTED FRACTAL LIGHT PATTERNS IN INTERIOR SPACES

Professors Ihab Elzeyadi, Richard Taylor, and Margaret Sereno contributed to this paper by guiding study design, analyses, and interpretations. The fractal patterns were developed by Professors Taylor and Sereno. I was the primary contributor to the studies, conducted data collection and analyses, and wrote the manuscript.

The visual patterns of fractal objects and the brightness patterns of light projected onto surfaces have independently been shown to influence human perceptual response. For instance, previous studies suggested that viewing mid-complexity statistical fractal patterns on a computer screen was associated with a higher visual preference and a wakefully-relaxed state. It is not clear, however, if similar responses would be elicited if the same fractal patterns were projected as light patterns on room surfaces, like walls. Since building occupant's visual perception and reaction to stimuli might be influenced by brightness patterns and spatial dimensions, it is important to investigate human responses to spatially projected fractal light patterns.

This chapter reports on the results of three studies that extend empirical findings on visual interest, visual preference, and mood responses elicited by varying complexities of fractal light patterns projected on walls and floors of an interior space. The patterns examined include four fractal light patterns of varying complexities and two non-fractal light patterns. The visual interest and mood response to light patterns that were directly projected on a wall, or simulated in renderings of an interior space were assessed in Studies 1 and 2, respectively. Study 3 examined the effect of distance, between observer and projection wall, on visual interest and visual preference.

3.1. Introduction

People's appreciation for nature has been investigated by many researchers who proposed several hypotheses and theories to explain this phenomenon. For instance, Kellert (2005) stated that people attach meaning or derive benefit from nature through its variability and aesthetic values. This notion was based on Edward Wilson's hypothesis of Biophilia (Wilson, 1984). Another theory proposed by Kaplan is the attention restoration theory which he outlined in his seminal article "The restorative benefits of nature: Toward an integrative framework" (Kaplan, 1995). Kaplan implied that natural environments are particularly rich in characteristics necessary for restorative experiences. Ulrich's (1981) work on the influence of scene type, e.g. urban vs. nature, revealed a positive psychophysiological influence associated with scenes of vegetation, as compared to urban scenes. His consequent study showed that people with access to views of nature were able to reduce their hospitalization recovery time and requested fewer pain medications (Ulrich, 1984). For all these hypotheses and theories, a logical question to ask is 'What are the characteristics in natural scenes that elicit such positive responses?'.

In an attempt to identify these characteristics, one approach suggested that effects of natural scenes on attention restoration can be explained by fractal patterns, which are prevalent in natural scenes (Purcell, Peron, and Berto, 2001; Joye and van den Berg, 2011; Hagerhall et al., 2015). Examples include trees, mountains, rivers, clouds and lightning. Fractal objects display a cascade of self-similar patterns over a range of magnification scales (Mandelbrot, 1983), building visual stimuli that are inherently complex. The degree of complexity varies between the different fractal objects based on the relative contributions of the coarse and fine scale patterns. The prevalence of mid-complexity fractals in nature has caused the human visual system to adapt to efficiently process them. This adaptation is known as the fractal fluency theory (Taylor & Spehar, 2016). This theory was selected as a basis for the two studies presented in this paper because of its relation to the attention restoration theory and the Biophilia hypothesis. Further, the ability to accurately generate fractal patterns of specific complexities and densities was advantageous to control for certain study variables, such as light. The term 'density' hereafter refers to the ratio between black-colored regions and white-colored regions of the fractal pattern.

Previous studies suggested that fractal patterns induce relaxing and restorative effects (Hagerhall et al. 2008), aesthetic appreciation (Aks & Sprott, 1996; Taylor, 1998; Spehar, Clifford, Newell, & Taylor, 2003), as well as stress recovery benefits (Taylor, 2006). These effects might be mediated by the positive visual preference, which Taylor (2002) refers to as the aesthetic pull of fractals. For example, in one of his experiments, Taylor (1998) found that 95% of participants preferred fractal over non-fractal patterns. Thus, it is important to examine the applicability of utilizing fractal patterns where people spend most of their time, in interior spaces (Klepeis et al., 2001).

Most previous studies, however, examined perceptual responses to fractals using two-dimensional visualizations on a computer screen (Taylor et al., 2005; Hagerhall et al., 2015; Spehar et al., 2003). Thus, the applicability of findings to actual environmental stimuli and indoor brightness patterns remains limited. This is mainly because the impacts of spatial projection, lighting, projection surfaces, material properties, light reflectance value, viewing angle, size of pattern, contrast, brightness variability, and distance between pattern and subjects were not considered. Understanding the effects of these variables is essential to maintain perceptual and physiological benefits that were found when fractals were viewed on a computer screen. To address this gap. The studies presented in this paper investigate the visual interest to projected light patterns in space.

3.1.1. Perceptual and physiological response to fractal patterns

Fractals are typically characterized by a variable called the fractal dimension (D). This parameter quantifies the fractal scaling relationship between the patterns at different magnifications. As the contribution of the fine scale patterns grows, the D value rises from 1 to 2. Behavioral studies have confirmed that this rise in D is accompanied by an increase in perceived visual complexity (Taylor & Spehar, 2016). Based on the D value, fractals can be categorized into low (D=1.1-1.3), medium (D=1.3-1.5), and high complexity (D=1.5-1.9). Fractal patterns can also be categorized into statistical and exact fractals. This paper focuses on statistical fractals, which are found in nature and exhibit randomness such that the statistical qualities of the pattern repeat at different scales, unlike exact fractals which appear exactly the same at different magnifications (Hagerhall et al., 2015). Exact fractals also exhibit a different aesthetic dependence on D (Bies, Blanc-Goldhammer, Boydston, Taylor, & Sereno, 2016) that is not discussed in this paper.

Regarding visual preference, it is important to note that not all fractal patterns are equal. For statistical fractals, previous studies have consistently found that people's preferences congregate within fractal dimension ranges of 1.3-1.5 (Spehar et al., 2003; Spehar and Taylor, 2013; Taylor et al., 2005). Aks and Sprott (1996) found that participants preferred patterns with a D value between 1.17-1.38, and suggested that aesthetic preference may reflect stable individual differences and traits, such as creativity. In another study, Spehar et al. (2003) examined visual preferences for three types of fractals that were generated with different methods: natural, computer-generated, and human-produced fractals. The results show that preferences congregate within the range D=1.3-1.5, regardless of the generation method. Figure 3.1 shows examples of fractals generated with different methods. It is important to mention that in these studies; fractal patterns were viewed on a computer screen located directly in front of each participant, and that the two alternative forced-choice procedure was successfully used in previous studies of visual preference (Spehar et al., 2015).

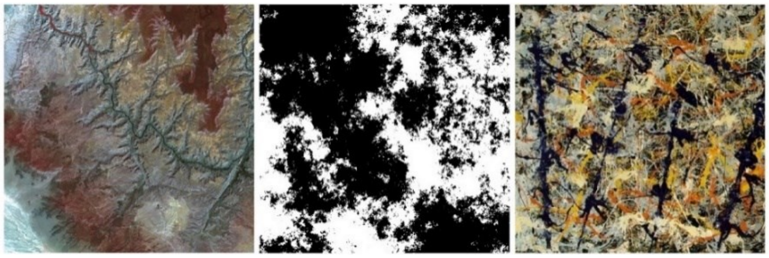


Figure 3.1: (left to right) Natural, computer-generated, and human-produced fractals. Sources: GeoEye/Space Imaging (left); Boydston, Taylor, and Sereno (middle); and the Pollock Krasner Foundation (right).

In addition to visual appeal, the D=1.3-1.5 range was also found to significantly reduce stress by 40% (Taylor, 2006). This was a unique study because fractal patterns were mounted, each measuring 3.2 x 6.5 feet (1 x 2 m), on a wall in front of participants. In a subsequent study that examined brain activity using electroencephalogram, the natural form of fractal patterns was found to induce an alpha response (Hagerhall et al., 2008), which is an indicator of a wakefully-relaxed state. Further, these fractals generated the highest beta response in parietal cortex, which means that they generated most activation in the processing of the pattern's spatial properties and contribute to a state of alertness. Delta activity, which is an indication of a state of sleepiness and drowsiness, was lowest for fractals of D=1.32. Because these studies indicated a difference in stress recovery and brain response, Studies 1 and 2 in this paper examine mood response to determine whether similar differences are reflected in mood response.

Participants' profiles and sampling criteria varied across previous studies. Some studies included undergraduate students at the University of New South Wales as volunteers or in exchange for a credit (Spehar et al., 2003; Spehar & Taylor, 2013), whereas others included members of a University community with age range between 17-31 (Aks & Sprott, 1996). Large-scale studies such as (Draves & Al, 2008) included 20,000 people who voted while a computer screen saver was active.

3.1.2. Environmental perception

A previous study showed that natural environments were more likely to be considered restorative, and received positive evaluations of recovery, which appeared to explain the higher preference for forest slides over the city slides (Staats, Kieviet, & Hartig, 2003). Another study (Hartig, Evans, Jamner, Davis, & Gärling, 2003) found that positive affect increased after walking at a nature reserve and decreased after walking in an urban environment. This later study also found that sitting in a room with tree views promoted a more rapid decline in diastolic blood pressure than sitting in a viewless room. These results are in line with another study (Brooks, Ottley, Arbuthnott, & Sevigny, 2017), which concluded that both actual and pictorial nature contact benefits mood, though actual nature is more effective.

In addition to views of nature, light is one of the main environmental factors that can influence people's perception and mood in interior spaces. A previous study found that light correlated color temperature significantly affected spatial brightness perception, visual comfort, satisfaction, and self-reported productivity (Wei et al., 2014). Another study found that the perceiver's emotions can affect the perception of brightness (Zhang, Zuo, Erskine, & Hu, 2016). A pioneer lighting designer, Richard Kelly, utilized lighting to influence sensation, and categorized lighting as an element of spatial design into three types: ambient luminescence, e.g. twilight haze; focal glow, e.g. a pool of light; and play of brilliants, e.g. sunlight on a fountain (Cialdella & D. Powerll, 1993). He associated each type with certain behaviors and sensations. For example, he argued that play of brilliants had potential to excite the optic nerves and stimulate the body (Figure 3.2).

Research studies by John Flynn examined effects of lighting conditions on impressions and behavior, and suggested that light can be used as a vehicle that alters the information content of the visual field, which has some effect on impressions and behavior (Flynn, Spencer, Martyniuk, & Hendrick, 1973). For instance, Flynn examined impressions of visual clarity, spatial complexity, contrast, spaciousness, and relaxing vs. tense space. A recent study found a link between contrast and visual interest in architectural renderings (Siobhan Rockcastle et al., 2016). While such studies are helpful, the field of lighting and perceptual response is rich and complex and requires further studies to separate effects of architectural composition from those of light and brightness patterns.

Figure 3.2: Dappled sunlight patterns through trees is an example of play of brilliants. Source: Steven Holl Architects /courtesy of Susan Wides.

While arguably related, visual interest and visual preference are different concepts. Generally, visual preference is more commonly assessed in psychological studies that examined fractal patterns (Section 1.1), while visual interest appears more prominently in architectural studies perhaps for the desire to create visually interesting spaces and avoid dull spaces. Hence, the current study examines visual interest to establish a reference for future studies in architecture, and investigates differences in visual preference between patterns projected on a wall compared to those viewed on a computer screen.

3.2. Hypotheses

The projection of light patterns on room surfaces and other spatial variables might impact perceived pattern detail and, hence, visual interest and preference. Therefore, we propose the following hypotheses: first, we expect mid-complexity fractal patterns to be more visually interesting than other fractal and non-fractal patterns; second, it is expected that fractal compared to non-fractal patterns would provide a better enhancement for both relaxation and excitement; third, it is expected that the distance, between observers and pattern, influences visual interest and preference, hence, the relationship between these two measures and fractal dimension for projected light patterns is expected to be different from those viewed on a computer screen.

3.3. Study 1: Visual Interest and Mood Response to Projected Light Patterns

3.3.1. Methods

3.3.1.1. Participants

Participants were recruited from a pool of students enrolled in a human-factors course in the department of architecture at the University of Oregon. Recruitment was conducted using two methods: first, the course instructor posted a recruitment script on the course learning management system one week before the experiment; second, in-person recruitment was conducted at the beginning of the experiment. The experiment took place after a brief lecture by the instructor on a topic unrelated to the experiment. After this, students uninterested in partaking in the experiment were given five minutes to leave the lecture room. A total of 92 participants of varied gender (51 females, 35 males, and 6 declined to answer) and age (18-29 years of age) who studied architecture or interior architecture participated in this experiment. Responses from participants who required vision correction but did not wear spectacles during the experiment were excluded. The total number of participant responses was 89. This study was carried out in accordance with an Institutional Review Board (IRB) protocol, which was approved by the Research Compliance Services office of the University of Oregon. All participants signed a consent form and, upon completion, received an extra participation credit in that course.

3.3.1.2. Study setting

The experiment was conducted in a lecture hall at the University of Oregon, Eugene, OR at noon during winter term of 2017 (Figure 3.3). The dimensions of the room were 49.66 x 52.83 x 18 feet (15.1 x 16 x 5.4 m). An overhead projector was used to project different patterns on a white wall located in front of participants. The projection area of each light pattern was 8 x 8 feet (2.4x2.4m). Participants were seated in front of the projection wall such that each participant had a clear unobstructed view. The nearest person to the projection wall was 17 feet (5.1m) away, and the farthest person was 46 feet (14m) away. The projector (Panasonic PT-DZ6700U) had a resolution of 1920 x 1200 pixels, and a brightness of 6,000 lumens. Lighting in the room was set to allow for a clear view of both the light pattern projections and room surfaces, and remained constant for the duration of the experiment. The luminance of the white and black regions of the pattern were 45 cd/m^2 and 9 cd/m^2, respectively. Horizontal illuminance varied across the room from 4 lux in the back of the room to 225 lux in the front. Mean horizontal illuminance was 49 lux, and vertical illuminance at the projection wall, excluding the lighting contribution from the projector, was 23 lux.

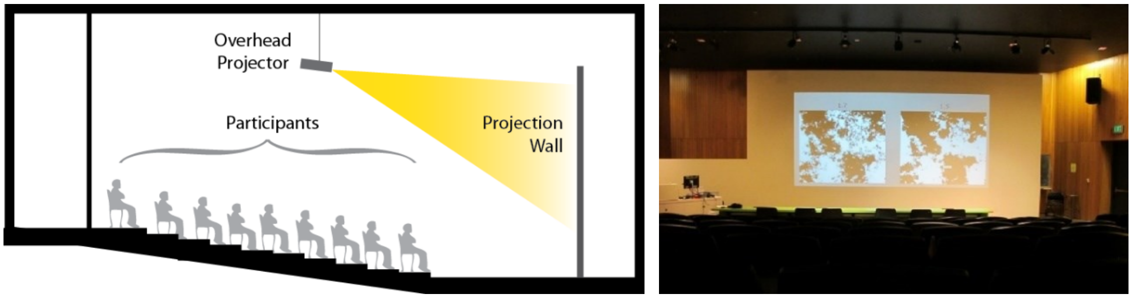


Figure 3.3: A section drawing (left) and a picture (right) of the lecture room used in this study.

3.3.1.3. Visual stimuli

Black and white fractal and non-fractal patterns were used in this experiment. The selected fractal patterns included 4 statistical fractal patterns (D = 1.1, 1.3, 1.5, and 1.7) and two non-fractal patterns, a rectangular and a striped pattern (Figure 3.4). All the patterns were generated with an identical black-to-white ratio of 50% to control for lighting distribution across different projected light patterns. This set of patterns was used to create 30 combinations such that each pattern is paired with every other pattern in the set, and presented twice, once on each side of the projection wall (for visual interest assessment). Stimulus order was randomized. To evaluate the impact of the projected light patterns on mood, projected light patterns were presented one at a time and rated using a Likert-type scale of four identified mood categories. Participants completed their selections using wireless polling remotes (iClicker) and each participant was identified with a unique identifier.

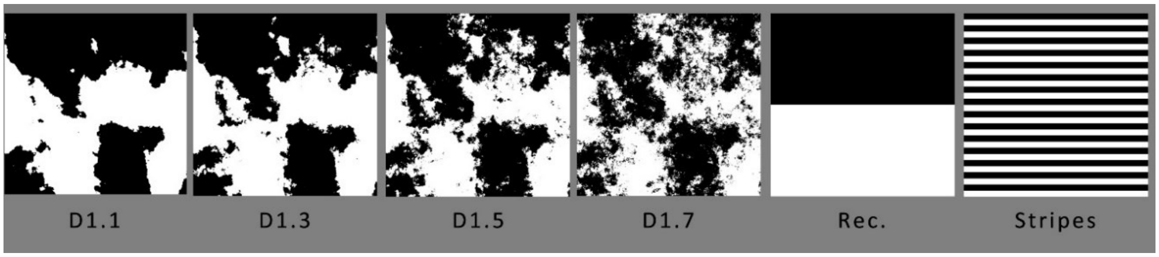


Figure 3.4: The four fractal patterns were selected to convey various levels of fractal complexity, whereas non-fractals were selected to mimic light patterns of a venetian blind (Stripes) and a roller shade (Rectangular). Fractal patterns are courtesy of Cooper Boydston, Richard Taylor, and Margaret Sereno.

3.3.1.4. Assessment procedure

For assessing the visual interest of light patterns, a two-alternative forced-choice (2AFC) procedure was used in which pairs of images were presented simultaneously. The 2AFC procedure has been successfully used in previous studies of visual interest and preference (Spehar et al., 2015). For assessing mood, a rating procedure was used on individual items. This procedure involved 24 item presentations (six patterns x four mood parameters). The six patterns were presented in random order and rated for one mood at a time using a 5-point Likert-type scale (see Figure 3.5 for an example stimulus). Feelings provoked by light patterns were assessed using two main indices: relaxation and excitement. Relaxation was based on two feelings: calm and peaceful; whereas excitement was based on feelings of stimulation and excitement. These four parameters were selected based on previous studies (Russell & Pratt, 1980; Boubekri, Hull, & Boyer, 1991). Only four parameters were selected to reduce participant fatigue. The two indices were utilized following Russel and Pratt's conceptualization of affective meaning as a two-dimensional bipolar space.

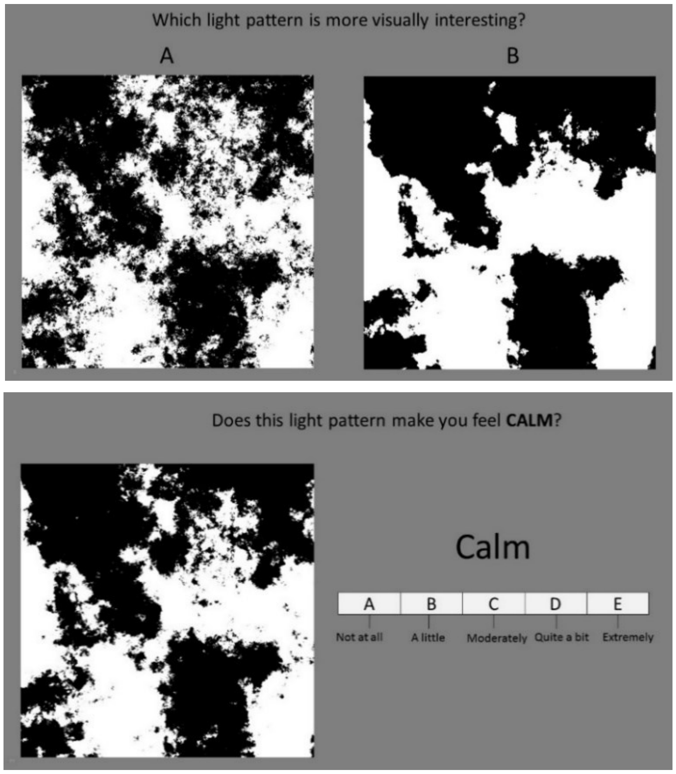


Figure 3.5: Example stimuli as presented: visual interest assessment (top), and mood assessment (bottom).

Participants were given 17 seconds to make their assessment and were instructed to follow an impulsive first-impression selection. This duration was based on pilot testing conducted by the experimenter which suggested that a response period from 10-20 seconds would ensure that responses are received from all participants and recorded by the polling station receiver. After each assessment, a neutral gray color was shown for five seconds. Responses were collected from all participants at the same time. The time required to complete viewing and assessments was 40 minutes. Prior to the start of the experiment, practice questions were presented to ensure the clarity of question and experimental procedure. Each participant selected a letter A/B of the pattern that is more visually interesting (“Which light pattern is more visually interesting?”), and the level to which a pattern makes him/her feel. For example, “Does this light pattern make you feel PEACEFUL?”, and the scale used was “Not at all”, “a little”, “moderately”, “quite a bit”, and “extremely”.

3.3.2. Results

Data were analyzed to determine visual interest ratings of the various light patterns. The total number of times a certain pattern was selected was divided by the total possible times to calculate the percentage of times a certain pattern was selected (Figure 3.6). To examine differences in visual interest among the different patterns, the Wilcoxon Signed-rank test was used, as a Shapiro-Wilk test confirmed a violation of the T-test normality assumption. Wilcoxon signed rank test is a nonparametric alternative to the paired T-test (Berman & Wang, 2012), which does not require variables to be normally distributed.

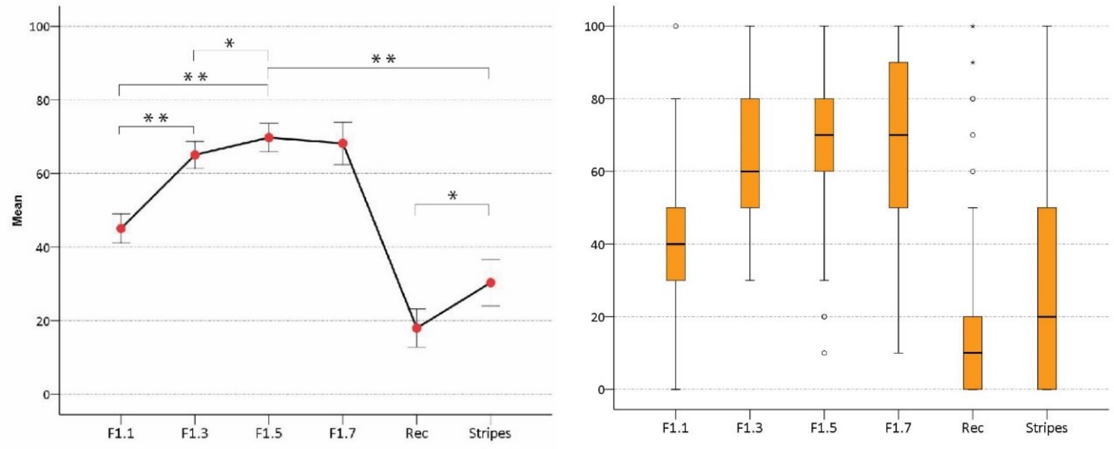


Figure 3.6: Mean percentage chosen for each light pattern (left), error bars represent standard error; and boxplot shows corresponding distribution. * represents p<0.05, ** represents p<0.01.

Results showed that visual interest ratings peaked for mid-complexity fractals of D=1.5, (Mean=69.7%, SD=18.27). Further, the visual interest for the projected fractal light pattern of D=1.7 (Mean=68.2%, SD=27.3) and D=1.3 (Mean=65%, SD=17.5) was not significantly different. Generally, the two non-fractal patterns, rectangular and the stripes, were significantly less visually interesting than all fractal patterns. In addition, there was a significant difference (Z=3.056, *p*<0.01) between visual interest ratings for the rectangular and striped light patterns.

The four mood indices (calm, peaceful, excited, and stimulated) were measured on a linear 5-point Likert-type scale that ranged from “Not at all”, “a little”, “moderately”, “quite a bit”, and “extremely”. These 5 levels were converted to a numerical scale 0-4, respectively, for statistical analyses. Ratings for excited and stimulated feelings were highest at 2.25 and 2.96 for fractal patterns D=1.5 and D=1.7, respectively. The only pattern at which the four mood responses are relatively similar is D=1.3. The lowest excited and stimulated ratings were for the rectangular pattern; while the lowest calm and peaceful ratings were for the striped pattern. Calm and peaceful ratings gradually dropped as fractal dimension increased. Interestingly, the ‘Excited’ line resembled the visual interest curve that previous studies found.

The four mood variables for each light pattern were factor-analyzed to confirm the two main indices proposed by Russell & Pratt (1980). The data indicated the existence of two underlying factors with eigenvalues generally higher than 1 as recommended by Berman & Wang (2012). These values confirmed the use of two reliable scales to measure each factor, relaxation (1) and excitement (2). Table 3.1 shows load bearings of the mood variables on each index. These load bearings were used to calculate each index as a weighted average. Overall, Calm and Peaceful had high load bearings on the Relaxation index ranging from 0.79-0.93, while the Excited and Stimulated variables had high load bearings on the Excitement index ranging from 0.77-0.93. Mean mood ratings are shown in Figure 3.7.

Pattern:	D=1.1		D=1.3		D=1.5		D=1.7		Rec.		Stripes	
Factor:	1	2	1	2	1	2	1	2	1	2	1	2
Calm	0.82		0.88		0.91		0.92		0.93		0.92	
Peaceful	0.88		0.79		0.90		0.93		0.92		0.91	
Excited		0.85		0.84		0.92		0.82		0.93		0.92
Stimulated		0.77		0.85		0.91		0.84		0.93		0.91

Table 3.1: Factor loadings after Varimax with Kaiser Normalization for Relaxation (1) and Excitement (2).

Generally, it was found that as D increased, excitement increased and feelings of relaxation slightly decreased. Fractal light patterns with D=1.5 and D=1.7 were rated highest in excitement (Mean=2.5, SD=0.9). Unlike the striped pattern, which ranked lowest in relaxation (Mean=0.6, SD=0.9), and the rectangular pattern which ranked lowest in excitement (Mean=0.49, SD=0.81), fractal patterns have maintained more balance between relaxation and excitement. *Table 3.2* summarizes Wilcoxon signed-rank test results in terms of the Z statistic and significance level (2-tailed).

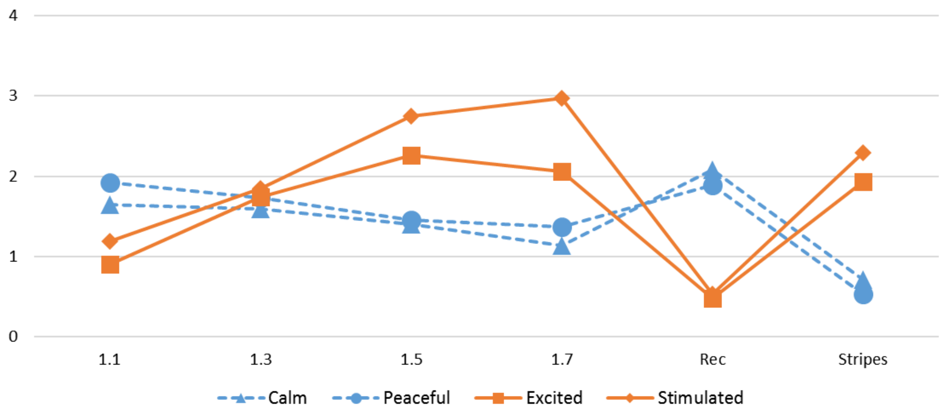


Figure 3.7: Means of the four mood responses. The Y axis shows level to which participants felt that a certain pattern made him/her feel such that 0=Not at all,1= A little, 2= Moderately, 3= Quite a bit, 4=Extremely.

		Visual Interest (Z)	Relaxation (Z)	Excitement (Z)
1.1	1.3	-6.73**	-1.87	-7.11**
	1.5	-6.04**	-2.63**	-7.71**
	1.7	-4.66**	-3.19**	-7.69**
	Rec	-6.40**	-1.16	-4.79**
	Stripes	-3.33**	-6.79**	-6.04**
1.3	1.5	-2.15*	-1.69	-6.11**
	1.7	-0.69	-2.47*	-6.07**
	Rec	-7.54**	-2.07*	-6.96**
	Stripes	-6.12**	-6.11**	-2.08*
1.5	1.7	-0.73	-1.22	-1.32
	Rec	-7.37**	-2.40*	-7.57**
	Stripes	-6.37**	-4.66**	-1.85
1.7	Rec	-6.98**	-2.97**	-7.73**
	Stripes	-6.13**	-3.67**	-2.65**
Stripes	Rec	-3.06**	-6.65**	-7.11**

*Table 3.2: Wilcoxon signed-rank test results for Visual Interest, Relaxation, and Excitement. * represents p<0.05, ** represents p<0.01.*

3.3.3. Discussion

Study 1 found that as D value increases from D=1.1 to D=1.5, visual interest increases, after that visual interest slightly decreases for D=1.7. The two Euclidean patterns were significantly less visually interesting than all fractal patterns. These results are in line with results of previous studies which suggested that fractals, particularly mid-complexity fractal patterns, are more preferred than non-fractals. Further, it seems that there is a range of fractal complexity that is ideal for enhancing visual interest.

Regarding mood response, the results showed that fractal light patterns of D=1.3,1.5, and 1.7 not only received the highest visual interest ratings but also maintained a better balance between relaxation and excitement, as compared to D=1.1 and non-fractal patterns. The finding that relaxation was highest for the rectangular pattern and for D=1.1 aligns with results of a recent study (Hagerhall et al., 2015) that found highest alpha for D=1.1 in the parietal and temporal electrode positions. In frontal brain regions, however, the highest alpha responses were for fractal patterns of 1.3-1.32 (Hagerhall et al., 2008; Hagerhall et al., 2015).

While the use of a linear scale to assess mood limited the comparison to circumplex models of affect, like the one presented by Boubekri, Hull, and Boyer (1991), it can be inferred that fractal light patterns of D=1.5 and D=1.7 were particularly more arousing. It can also be inferred that the striped light pattern was less relaxing because it was rated low in relaxation and moderate in excitement. The rectangular light pattern was rather dull because it was rated low in excitement and moderate in relaxation. The use of a differential scale would help examine these inferences.

One of the limitations of this study is not including a fractal pattern with D=1.9 due to concerns about participant fatigue and duration of the experiment. In retrospect, one possible approach would have been to increase the D increment between fractal patterns to 0.3, e.g. D=1.1, D=1.4, etc. However, to compare results to previous studies, the 0.2 increment between D values was utilized. Another difference is that the mean of the light pattern luminance was 27 cd/m^2 which is less than 58 cd/m^2 when displayed on a computer screen (Spehar, Walker, & Taylor, 2016). While this study suggests that certain fractal light patterns are more visually interesting than others, the results cannot yet be extended to daylight patterns through windows. Hence, Study 2 looked specifically at simulated sunlight patterns in renderings of an interior space.

3.3.4. Conclusion

We summarize the results of Study 1 using the following conclusions:

- The mid-complexity fractal light pattern with D=1.5 was significantly more visually interesting than those of D=1.1, D=1.3, and the two non-fractal light patterns.
- The fractal light pattern of D=1.7 was slightly less visually interesting than that of D=1.5, though not significantly different. This more complex pattern (D= 1.7) received higher visual interest ratings than it did in previous studies when patterns were viewed on a computer screen.
- Results suggest that spatial variables may have influenced visual interest ratings and warrant further investigation.
- The rectangular light pattern was rated lowest in excitement, whereas the striped pattern was rated lowest in relaxation. Fractal light patterns, on the other hand, receive more moderate assessments in both categories.
- Further studies are needed to determine levels of excitement and relaxation desired for different tasks, and to examine variability in mood response.

3.4. Study 2: Visual Interest and Mood Response to Simulated Light Patterns

Figure 3.8: An example of the rendered space showing fractal pattern D=1.7 projected on room surfaces.

Study 2 examined the visual interest of light patterns when projected on multiple surfaces (e.g. floor and wall) and depict sunlight coming through a side window. Introducing these two variables, spatial projection on multiple surfaces and depiction of sunlight through a window, aims to expand empirical evidence toward actual architectural spaces with sunlight patterns penetrating through façade systems. With that said, Study 2 focused on assessing visual interest and mood response to renderings of an office space that included sunlight patterns coming through a side window (Figure 3.8). One might argue that viewing a rendering of a space containing a fractal pattern is not as experiential as being in the space itself. While this is true, the use of rendered images allowed for the control of several variables that may influence participants' perceptual responses such as lighting, visual comfort, task, and view direction.

3.4.1. Methods

This study followed the same participant recruitment and seating, presentation procedure, assessment, and timing as in Study 1. The main difference between this study and Study 1 is the stimuli. The stimuli were rendered images of an interior space with sunlight patterns cast on room surfaces. Although the window itself is not shown in the renderings, its presence is depicted. For mood assessment, the 6 images were presented one at a time while participants assessed four mood parameters for each. Study 2 was conducted in the spring term of 2017 in the afternoon. These renderings were generated by placing the 6 black and white patterns, used in study 1, over a squared window such that black regions were opaque and white regions were clear. The renderings were generated, using Autodesk Revit modelling software (version 2016), of an office space with a side window through which sunlight patterns penetrated and were cast on the room's floor and opposite wall. Figure 3.9 shows the six renderings of which four are fractal light patterns and two are non-fractals.

Study 2 involved 68 participants, of which 94.1% were architecture or interior architecture students. From the 68 participants (27 male and 41 female), 77.9% were 18-29 and 17.6% were 30-39 years of age. All participants filled out a consent form and received an extra participation point. Out of the 68 participants, 24 also participated in Study 1.

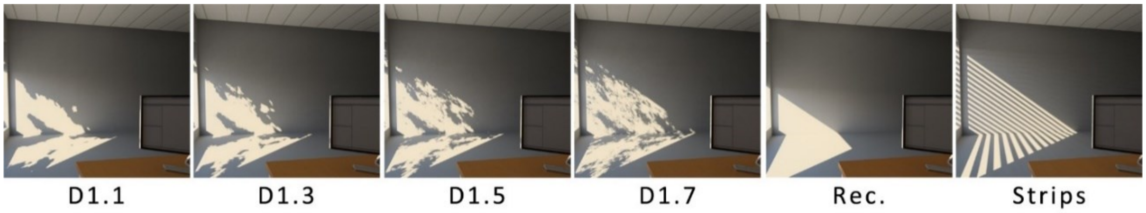


Figure 3.9: The view is selected so that only sunlight pattern projections are visible and not the pattern on the window. The same patterns from study 1 were used to create these renderings. Fractal patterns are courtesy of Cooper Boydston, Richard Taylor, and Margaret Sereno.

3.4.2. Results

Like the results of Study 1, Study 2 found that visual interest increases as fractal dimension increases (Figure 3.10). The fractal light pattern with D=1.7 was the most preferred (Mean=70.2%, SD=29.4), and was significantly more preferred than all other patterns. The fractal with D=1.5 received the second highest ratings for visual interest (Mean=64.2%, SD=19.3). The rectangular pattern was significantly the least preferred light pattern (Mean=15.8%, SD=18.6), which is in line with results of Study 1. However, a contrasting finding was that the striped light pattern (Mean=54.1, SD=33.4) was found to be significantly more visually interesting than the low-complexity fractal with D=1.1 (Mean=38.3, SD=21.6).

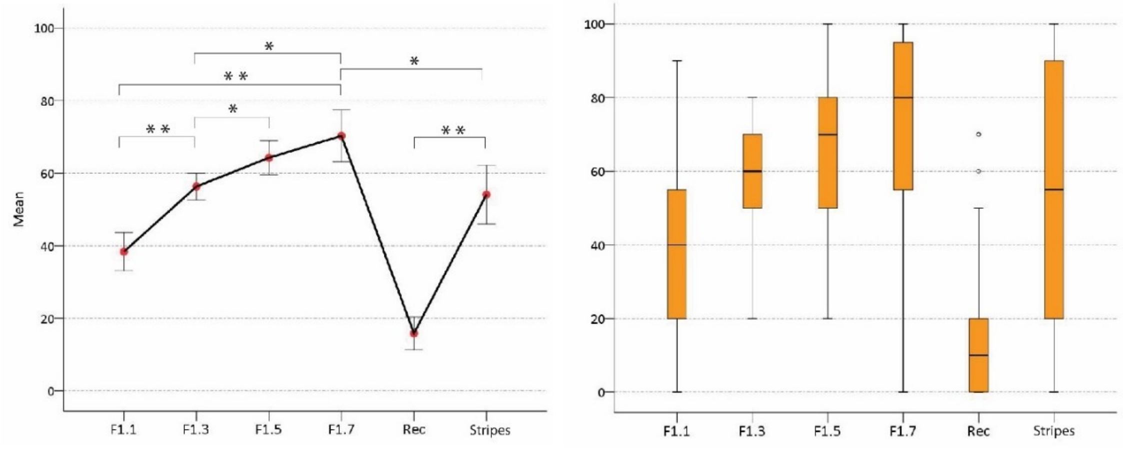


Figure 3.10: Visual interest ratings: mean percentage chosen as a function of pattern type (left); whiskers represent standard error. Box plots of visual interest ratings (right). * represents p<0.05, ** represents p<0.01.

The four mood responses were assessed on a scale ranging from ‘Not at all’, ‘A little’, ‘Moderately’, ‘Quite a bit’, and ‘Extremely’. These five levels were converted to a numerical scale 0-4 for statistical purposes (Figure 3.11). Regarding mood response, the lowest mean for stimulation and excitement was for the rectangular pattern at 0.65 and 0.36, respectively. Generally, ‘Excited’ and ‘Stimulated’ ratings increased as D increased. Furthermore, none of the means of the mood responses exceeded moderate levels. This suggests that the renderings were less likely to elicit a mood response, as compared to a fractal pattern directly projected as in Study 1. By conducting a factor reduction (Table 3.3), ‘Calm’ and ‘Peaceful’ were used to calculate a ‘Relaxation’ index, whereas ‘Excited’ and ‘Stimulated’ were used to calculate an ‘Excitement’ index.

Pattern:	D=1.1		D=1.3		D=1.5		D=1.7		Rec.		Stripes	
Factor:	1	2	1	2	1	2	1	2	1	2	1	2
Calm	0.83		0.94		0.96		0.94		0.93		0.89	
Peaceful	0.88		0.88		0.92		0.93		0.93		0.94	
Excited		0.93		0.87		0.88		0.77		0.73		0.80
Stimulated		0.84		0.87		0.83		0.92		0.95		0.87

Table 3.3: Factor loadings after Varimax with Kaiser Normalization for each mood variable on the two indices Relaxation (1) and Excitement (2).

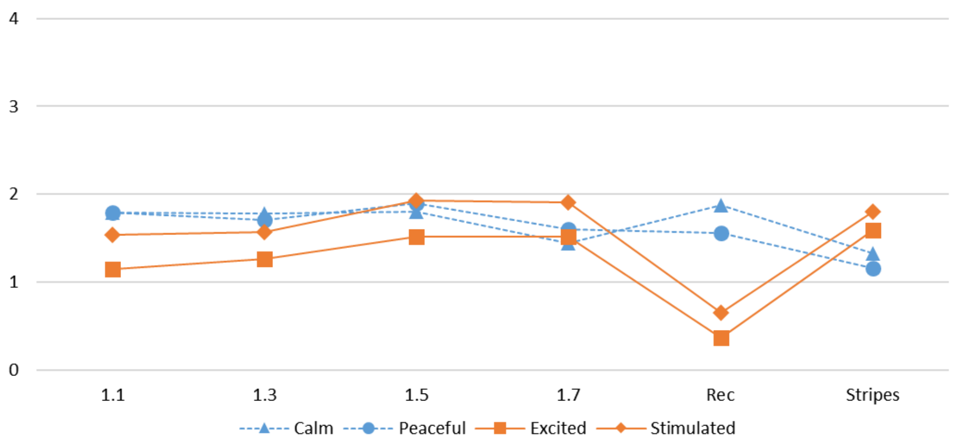


Figure 3.11: Means of the four mood responses. The Y axis shows the level to which a certain pattern made him/her feel, such that 0=Not at all,1= A little, 2= Moderately, 3= Quite a bit, 4= Extremely.

In comparison to the results of Study 1, mean excitement levels for all light patterns were notably lower. The fractal light pattern with D=1.5 provided the highest levels of relaxation and excitement (Mean =1.86 and 1.72, respectively). Similar to the results of Study 1, the rectangular light pattern resulted in an excitement level (Mean=0.51) significantly lower than all of the other patterns. In contrast, the striped light patterns resulted in a relaxation Mean of 1.24, which is significantly lower than all the other patterns ($p<0.05$) except for D=1.7. A dimension reduction analysis showed that load bearings ranged from 0.73 to 0.96 with a Mean of 0.89. Table 3.4 summarizes Wilcoxon signed-rank test results in terms of the Z statistic and significance value (2-tailed).

		Visual Interest (Z)	Relaxation (Z)	Excitement (Z)
1.1	1.3	5.924**	0.013	1.595
	1.5	5.087**	0.369	3.464**
	1.7	4.525**	-1.821	3.284**
	Rec	-5.154**	-0.239	-4.526**
	Stripes	2.729**	-3.199**	2.547*
1.3	1.5	2.623**	0.709	3.135**
	1.7	2.861**	-1.298	2.776**
	Rec	-6.639**	-0.586	-4.65**
	Stripes	-0.472	-2.638**	1.52
1.5	1.7	1.977*	-1.704	.000
	Rec	-6.723**	-0.5	-5.498**
	Stripes	-1.807	-2.687**	-0.24
1.7	Rec	-6.524**	0.818	-5.134**
	Stripes	-2.469*	-1.245	-0.506
Rec	Stripes	6.016**	-2.325*	6.401**

Table 3.4 shows results of Wilcoxon signed rank test for visual interest, relaxation, and excitement. * represents $p<0.05$, ** represents $p<0.01$.

3.4.3. Discussion

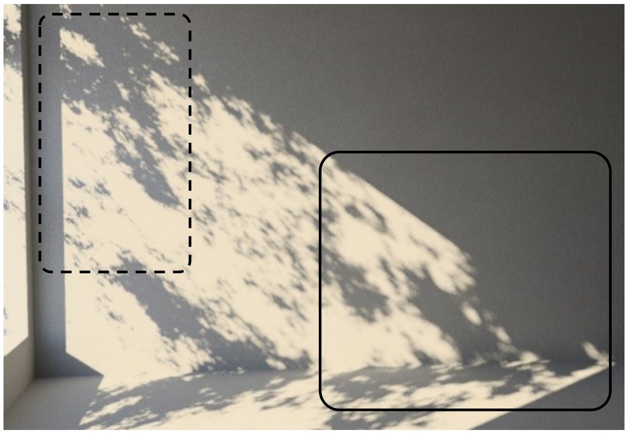


Figure 3.12: The two highlighted regions are different in terms of blurriness for the fractal shadow of D=1.7. The region marked with the continuous line looks blurrier than the region marked with dashed lines.

Results showed that visual interest increased gradually as D increased and peaking at D=1.7. One of the key differences between the stimuli in Study 2 and those in Study 1 is the size and projection of the fractal patterns. The rendered sunlight patterns in Study 2 were distorted because of the orientation of projection surfaces in the rendered room, e.g. the wall and floor. Additionally, the farther the projection surface from the window the greater the edge blurriness (Figure 3.12). This suggests that the resulting shadows feature a reduced amount of fine structure compared to the fractal pattern used to cast the shadows. Therefore, Study 2 adds another source of complexity reduction to that hypothesized for the patterns used in Study 1 (Section 2.3). The blurriness caused by the shadow effect and the reduction in resolution caused by viewing distance (between subjects and screen) both contributed to lowering the perceived complexity. Thus, a higher D value might be needed to generate the same level of complexity as observed in Study 1. This increased the D value at which visual interest peaked to a value of 1.7.

As compared to the results of Study 1, mood responses for Study 2 congregated in low excitement. We hypothesize that this muting effect is due to the change in medium, renderings vs. direct projection. Therefore, the relative difference not the absolute value is what should be examined. This experiment expands empirical evidence regarding projected fractal light patterns and their applicability in architecture. Future studies should examine spatial variables, light intensity, glare and views, and their effects on visual interest and mood response. Implications of such studies would inform the design of future façade systems and glare control mechanisms, such as internal and external shades not only to enhance occupant’s mood but also to improve the quality of interior spaces.

The two studies presented have highlighted an important research pathway, which focuses on the effects and application of fractal patterns in interior spaces. Further studies are warranted to examine occupants’ perceptual response and visual comfort towards spatially projected fractal light patterns in real settings such as office spaces. A forthcoming paper examines the relationship between visual comfort and visual interest in daylit spaces. The implications of such studies can inform the design of future daylighting and shading systems to enhance occupants’ visual comfort and satisfaction with their indoor environment.

3.4.4. Conclusion

The results of Study 2 are summarized in the following points:

- This study shows that the fractal pattern with D=1.7 is significantly more visually interesting than all other patterns.
- The striped pattern was significantly more visually interesting than the fractal with D=1.1. The rectangular pattern was significantly less visually interesting than all other patterns.
- The fractal pattern with D=1.5 provided more balance between relaxation and excitement, as compared to the other light patterns.
- The use of wireless polling to collect responses from all participants at the same time—in both experiments--helped ensure that all participants were subject to the same experimental settings and procedures and would help future studies testing similar hypotheses.

3.5. Study 3: Visual Preference of Projected Light Patterns

While the previous two studies focused on visual interest and mood responses, this study examined visual interest and visual preference assessments, and the effect of distance between observers and pattern on these assessments. The same stimuli and 2AFC assessment procedure from Study 1 were used. Visual interest assessments for all patterns were collected, followed by visual preference. Patterns were randomized in order. At the beginning of this study, participants (n=39) were randomly divided into two groups, a group whose participants sat in the first two rows of the room (n=14), and another whose participants sat in the last two rows (n=18). Responses from participants who required vision correction but did not wear spectacles during the experiment were excluded. Responses from 32 participants were included in the analyses (19 females, 12 males, and one no answer). The age group of 26 participants was 18-29 years.

A three-way analysis of variance (ANOVA) revealed that the fractal dimension affected visual interest and visual preference differently ($p<0.05$). While visual preference peaked at D=1.5 (mean=59.3, SD=21.1), visual interest peaked at D=1.5 (mean=64.5, SD=22.3) to D=1.7 (mean=65.1, SD=34.2), as can be seen in Figure 3.13. Consistently, means of visual interest and preference were lower for those in the back of the room for fractals of D=1.7 and D=1.3. On the other hand, both means were higher for those at the back of the room for fractals of D=1.1 and D=1.5. Although there were variations in mean percentage chosen for visual interest and visual preference between the two groups, there was no significant interaction effect of the group on these assessments (Table 3.5).

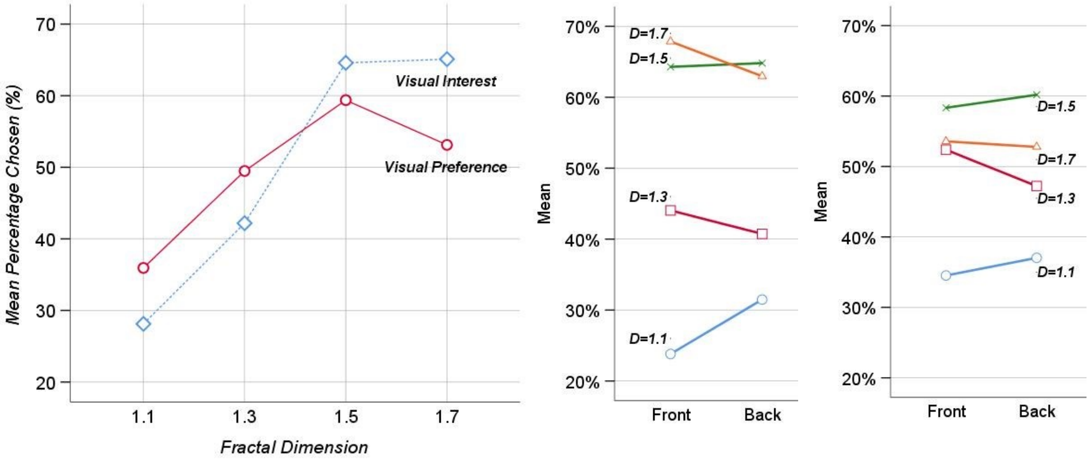


Figure 3.13: Mean percentage chosen for visual interest and preference by fractal dimension (left); mean visual interest by seating group (middle); and mean visual

	DF	Mean Square	F	Sig.
Assessment type	1.00	15.50	3.90	<0.1
Assessment type x Groups	1.00	2.48	0.62	0.435
D	1.48	24565.00	5.93	<0.05
D x Group	1.48	565.75	0.13	0.809
D x Assessment type	2.30	2037.17	3.60	<0.05
D x Assessment type x Group	2.30	82.05	0.14	0.891

Table 3.5: ANOVA results. Assessment type refers to either visual preference or visual interest, and Group refers to the seating group, i.e. front or back.

3.6. General Discussion

Generally, the results suggested that visual interest is dependent on the amount of fine-scale detail perceived by an observer. Overall, the three studies found that visual interest peaked for fractals of D=1.5-1.7, which partially supports the first hypothesis expecting a higher visual interest for mid-complexity fractals. These results of these studies might have been influenced by several factors. First, the use of light as a medium to project the patterns might have influenced visual interest ratings. The possibility of participants associating light patterns with dappled sunlight through trees, particularly in Study 2, was not tested. Examining these associations in future studies can reveal important factors that might influence visual interest of fractal light patterns in interior spaces.

Second, the projection of relatively large-scale fractal light patterns in a lighted space might have affected perceived contrast and complexity. To demonstrate the difference in color brightness between patterns projected on a wall and those viewed on a computer screen, Figure 3.14 shows the differences in color tone for black and white regions when projected on a wall compared to when viewed on a computer screen. This graph suggests that there was a higher contrast between black and white regions of a pattern when viewed on a computer screen.

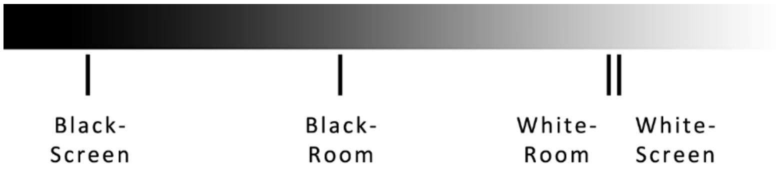


Figure 3.14: Black and white color tones as displayed on screen and as projected on the wall (Study 1) plotted on a gradient scale from black to white.

Third, previous studies that examined visual preference and the three studies reported were conducted in windowless rooms. The provision of view and/or daylight might present competing factors that might influence visual interest. A view of nature through windows might reduce the relative significance of computer-generated fractals. Thus, it would be important to assess whether the presence of windows affects human perceptual response towards fractal patterns. Figure 3.15 shows visual interest results from the three studies.

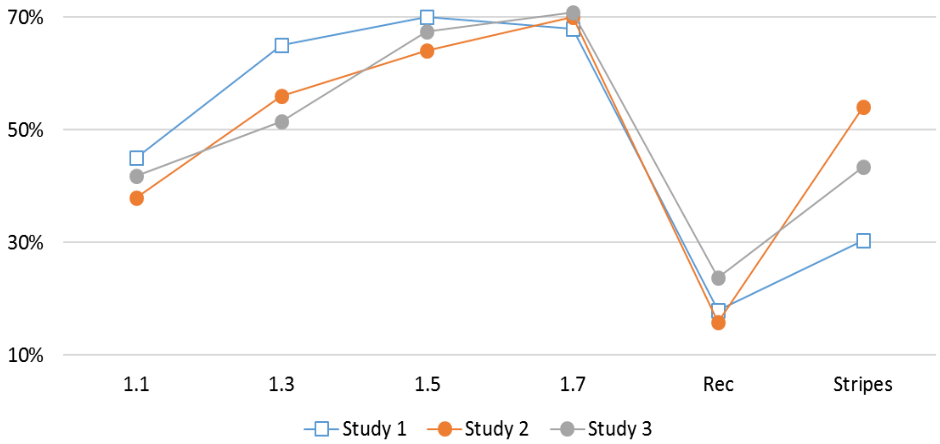


Figure 3.15: Visual interest results from the three studies.

As for visual preference, the results of Study 3 showed a different trend than that reported in previous studies outlined in Section 1.1. While visual preference typically peaked at D=1.3-1.5 with a higher preference for D=1.1 than D=1.7 for the previous studies, Study 3 showed that visual preference peaked at D=1.5 but with a higher preference for D=1.7 than D=1.1. As can be seen in Figure 3.16, the preference curve for previous studies (gray lines) seems to plunge for D higher than 1.3-1.5, in contrast, visual preference results from Study 3 shows a gradual increase up to D=1.5 and then a slight decrease for D=1.7. There were no significant differences in visual preference or interest when examined by seating distance from the projection wall. These results support the third hypothesis regarding a difference in the relationship between fractal dimension and visual preference, but do not support our hypothesis regarding the effect of distance on these preferences.

Regarding mood response, Study 1 showed that fractals maintained a better balance between relaxation and excitement compared to the Striped and Rectangular patterns. On the other hand, Study 2 showed less variability in mood response, which could be due to the use of rendered images instead of directly projecting the patterns in space. Overall, results from Study 1 support the second hypothesis regarding a better maintained balance between relaxation and excitement by fractals compared to Euclidean patterns.

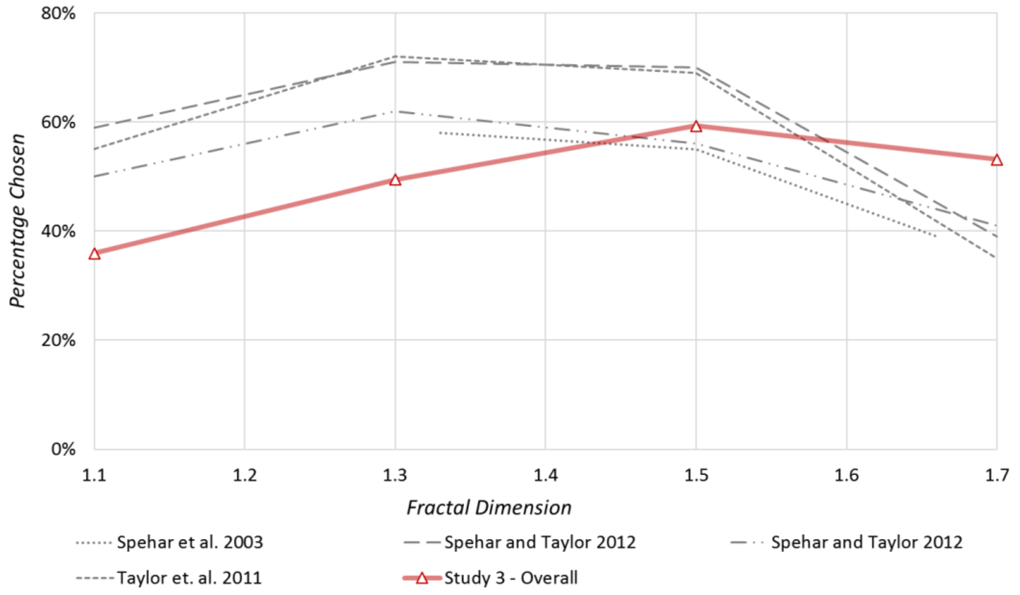


Figure 3.16: Visual preference by D value for previous studies and Study 3.

The fractal pattern D=1.7 and the Striped patterns were consistently significantly different in terms of visual interest, hence were selected for further investigation in the next Chapter by projecting them as sunlight patterns in daylit offices. Particularly, the effect of window and sunlight patterns on visual interest, comfort, and view quality is examined in a pilot study that involved 22 participants.

CHAPTER IV

A PILOT STUDY EXAMINING VISUAL COMFORT, VISUAL INTEREST OF SUNLIGHT PATTERNS, AND VIEW QUALITY

Parts of this Chapter were published in the 2018 ARCC-EAAE International Conference May 16-19, 2018 in Philadelphia, Pennsylvania. Professor Ihab Elzeyadi contributed to this chapter by guiding study design and analyses. The fractal patterns used were developed by Professors Richard Taylor and Margaret Sereno. I was the primary contributor to the studies, conducted data collection and analyses, and wrote the manuscript.

This Chapter reports on the results of a quasi-experiment conducted in an office building in Portland, OR. Three experimental settings (hereafter test stations) were created at the office using different window treatments to create three sunlight geometries –Fractal Pattern, Striped Pattern, and 'No-Pattern'– which were tested and compared for their impact on visual interest, visual comfort, and view quality. The study followed a within-subjects design (same group experienced three different sunlight conditions) where 22 office employees completed a brief questionnaire at each test station, while quantitative environmental data were collected. Participants' responses were paired with physical measurements to examine correlations and visual comfort across the three stations.

Previous studies suggested that sunlight presence in space can improve space quality, occupant's visual and thermal comfort, mood, and health. Current dynamic daylighting metrics and design guidelines, however, limit sunlight penetration in work environments, reducing both its negative and positive effects on visual comfort and space quality. Furthermore, incorporating sunlight in daylighting design has not been comprehensively examined, hence, lacks consensus among researchers and practitioners to embrace its effects in architectural design. Some researchers suggested that sunlight should be greatly limited to avoid potential visual discomfort in offices. While this approach may help limit glare, resultant spaces are likely to be dull with reduced health benefits and visual interest. One gap in existing literature on sunlight exposure is the lack of addressing the effect of visual interest for both sunlight pattern and its play of sparkle on visual comfort. The questions to be answered by this paper are: (1) is there a difference in subjective visual comfort assessments under different sunlight pattern geometries? and (2) what are the positive geometric attributes of sunlight that are preferred by occupants, and should be implemented in daylit office spaces?

4.1. Introduction

Sunlight admission and control in buildings has been examined to delineate occupant's ranges of acceptance and comfort under different sunlight conditions. Studies on occupant's health found that sunlight exposure can expedite recovery for depression patients [Benedetti et al. 2001; Beauchemin and Hays 1996], boost the body's vitamin D supply, and regulate melatonin production (Mead, 2008). Regarding visual comfort, previous studies have highlighted the importance of sunlight control at different building facades. For instance, Elzeyadi & Lockyear [2010] surveyed occupants in a LEED platinum glazed building and found that those in East and West facades reported extreme glare discomfort, compared to occupants in North and South facades that received less sunlight penetration and variations in brightness patterns. Therefore, it is essential to effectively manage occupant's sunlight exposure in buildings to improve their visual and thermal comfort, well-being, and the quality of indoor spaces.

Previous studies focusing on evaluating discomfort glare in offices have not been able to effectively predict occupants' visual comfort when direct sunlight is present in space. Metrics like Daylight Glare Index (DGI), CIE Glare Index, and CIE Unified Glare Rating System (UGR) are only valid for conditions when direct sunlight does not enter the space [Jakubiec and Reinhart 2012; Nazzal 1998; Iwata, Tokura, and Shukuya 1992]. Daylight Glare Probability (DGP) was only able to explain 3 out of 201 scenes that subjects rated as 'just uncomfortable' (Van den Wymelenberg, 2012). This suggests that there might be aspects of sunlight exposure not currently addressed in these metrics such as the visual interest of sunlight patterns, interactional effects between glare and view quality, and related psychological effects. To distinguish between the solar disc and sunlight projections in space, this study defines 'sunlight patterns' as direct sunlight projected onto different surfaces of an interior space.

In a previous study that utilized questionnaires and daylight simulations to investigate the relationship between solar penetration levels and visual comfort (HMG, 2012), it was found that less than 300-350 hours of sunlight exposure per year resulted in positive visual comfort assessments. The resulting annual solar exposure metric ($ASE_{1000,250h}$) recommended that sunlit areas (>1000 lux) should not exceed 10% of floor area for 250 hours per year (IES, 2013). Some researchers may argue that the generalizability of the ASE metric is questionable, particularly because it does not consider shading system type, orientation, view direction of occupants, and shape of sunlight patterns. Indeed, this metric has been critiqued as a strict metric that limits solar exposure and promotes dull spaces [Reinhart 2015]. A recent study found no correlation between annual DGP and ASE (Dutra de Vasconcellos, 2017). Recently, the area requirement of the ASE metrics has been extended for up to 20% of floor area (USGBC, 2017). Various discussions and commentary in scientific conferences and meetings suggest that the ASE metric, though useful in some cases, warrants further studies and explorations to critique its limitations (Heschong, 2017). When sunlight enters a space, occupants react to its various aspects including its thermal, visual, aesthetic, and psychological attributes. Systemically, each one of these aspects influences overall comfort towards sunlight (Elzeyadi, 2002). Therefore, to enhance the usability of current glare and sunlight exposure metrics, it is necessary to investigate not only direct but also the interactional effect of sunlight pattern geometry, glare perception, and their impact on occupant's visual comfort. From the above, it is suggested that the current ASE metric warrants further investigation and refinement.

4.1.1. Visual comfort and glare from sunlight

Previous studies examined the relationship between sunlight and visual comfort in various settings. When occupants composed their long term evaluations of visual comfort, they tended to be most sensitive to direct sunlight [Jakubiec and Reinhart 2013]. Particularly, sunlight is likely to cause visual discomfort if it falls directly on the work plane or the eye, [Jakubiec, Reinhart, and Wymelenberg 2014]. Yet, in several studies, participants preferred to allow sunlight on their desks when asked to adjust blinds to a preferred setting (Kent et al., 2017; Van Den Wymelenberg & Inanici, 2014). Sunlight can contribute to enhancing luminance variability in the field of view, which was found to be associated with perceptions of pleasantness and cheerfulness in libraries (Parpairi, Baker, Steemers, & Compagnon, 2002). Overall, sunlight can influence visual discomfort by increasing the luminance of work surfaces and/or by increasing the contrast between task and surroundings within occupant's field of vision (Suk et al., 2016).

Despite an increased interest in evaluating daylight glare metrics, most existing studies did not use specific sunlight pattern characteristics such as size, shape, geometry, location, and luminance to test visual discomfort, instead, sunlight patterns were assessed using glare indexes such as DGP and DGI that do not provide information regarding sunlight pattern attributes.

Among the few studies that examined sunlight pattern attributes are the large-scale study discussed in the previous section (HMG, 2012), and that conducted by Wang & Boubekri [2010]. Although the later did not find a significant influence of the distance between participants and sunlight pattern on cognitive performance, it concluded that the location of sunlight patterns, window, and activity type affected appreciation and use of the sunlit room.

4.1.2. Aesthetics of sunlight in spaces

In his seminal study, Ne'Eman [1974] found that 73% of occupants considered sunlight a pleasure while 61% preferred a good view over indoor sunlight. Boubekri, Hull, and Boyer [1991] found that optimal sunlight penetration levels that create maximum degrees of relaxation are from 15%-25% of floor area, when positioned sideways to the window. They concluded that sunlight "sparkles" are preferred over large areas of sunlight patches. It was also found that sunlight as manipulated by size, season, time of the day has significant impacts on the affective state of occupants, which influences occupant's satisfaction. In another study, the presence of sunlight was thought to have created cheering and pleasant effects that could have increased glare tolerance (Boubekri & Boyer, 1992). These findings are in line with results of another study which found that façade pattern characteristics influenced perceived spatial ambiance (Chamilothori, Wienold, & Andersen, 2016).

In a controlled experiment following a repeated measures approach, Wymelenberg, Inanici, and Johnson [2010] found that 11 out of 12 participants preferred to allow sunlight patterns into space when it was available. It was argued that adequate luminance variations create a stimulating and interesting environment that improved occupants' preference ratings. These results are in line with another study by Kim [1997], which found that sunlight improved positive emotions more than daylight, in both winter and summer seasons. In a study that examined preference assessments of six façade designs and resulting sunlight patterns (Omidfar, Niermann, & Groat, 2015), it was found that a façade design of low complexity and high order was more preferred than another of high complexity and low order. Overall, such qualitative attributes and environmental aesthetic measures should be used to augment quantitative illumination measurements.

4.1.3. Outdoor views and glare

View type and content have been examined by several researchers to assess their effects on subjective ratings of glare. For instance, significant differences in subjective evaluations of visual discomfort were found for different views at the same luminance (Shin et al., 2012). The same study also found that distant views received lower visual discomfort ratings than close views, which could be due to the sense of extent provided by distant views. These results are in line with results of another study by Tuaycharoen & Tregenza [2007], which found that glare discomfort decreased as interest in view increased at the same mean luminance value. They concluded that the four factors typically used in glare formulae – source luminance, source size, surround luminance and a position index – are not enough to predict visual comfort.

4.1.4. Fractal patterns and visual interest

People's fascination with nature has been investigated by many researchers who proposed several hypotheses and theories to explain this phenomenon. Some of the most prominent of those are Edward Wilson's hypothesis of Biophilia (Wilson, 1984), Kaplan's Attention Restoration Theory [Kaplan, 1995], and Ulrich's work on scene type and psychophysiological responses (R. S. Ulrich, 1981). Most of these hypotheses and theories implied that there are certain characteristics in nature scenes that trigger positive aesthetic and psychophysiological responses.

One approach suggested that these theories can be explained by fractal patterns*,* which are prevalent in nature [Purcell, Peron, and Berto, 2001; Joye and van den Berg, 2011; Hagerhall et al., 2015]. Fractal patterns can be defined as shapes that display a cascade of never-ending, self-similar, meandering detail as observed at various levels of scales [Bovill 1996; Harris 2012]. Many elements in nature, such as trees and clouds, embody fractal patterns. The prevalence of mid-complexity fractals in scenes of nature has caused the human visual system to adapt to efficiently process them. This adaptation is known as the fractal fluency theory (Taylor & Spehar, 2016). Previous studies suggested that fractal patterns induce relaxing and restorative effects [Hagerhall et al. 2008], aesthetic appreciation [Aks & Sprott, 1996; Taylor, 1998; Spehar, Clifford, Newell, & Taylor, 2003], as well as stress recovery benefits [Taylor, 2006]. While these studies were conducted using mathematically generated fractal patterns, the aesthetic preference to fractals was not dependent on their generation process, e.g. mathematically, painted, or generated by nature (Spehar et al., 2003).

Fractals are typically characterized by a variable called the fractal dimension (D), which ranges between 1-2. This parameter quantifies the fractal scaling relationship between the patterns at different magnifications. Behavioral studies confirmed that a rise in D values accompanied by an increase in perceived visual complexity (Taylor & Spehar, 2016). Based on this, fractals can be categorized into low (D=1.1-1.3), medium (D=1.3-1.5), and high complexity (D=1.5-1.9). These thresholds are based on previous studies that consistently refereed to the range D=1.3-1.5 as mid-complexity (Street, Forsythe, Reilly, Taylor, & Helmy, 2016; Taylor et al., 2011). The authors of the current study have accordingly extrapolated thresholds for low and high complexity categories.

In two previous studies by the authors (under review), the fractal fluency theory has been expanded to investigate perceptual response –visual interest and mood– to projected fractal light patterns. Results of these studies suggested that projected fractal light patterns of mid to mid-high complexity were more visually interesting than those in Euclidean shapes such as striped and rectangular patterns. Further, unlike Euclidean shaped light patterns, projected fractal light patterns maintained a better balance between relaxation and excitement (Figure 4.1). These findings formed the basis of this study.

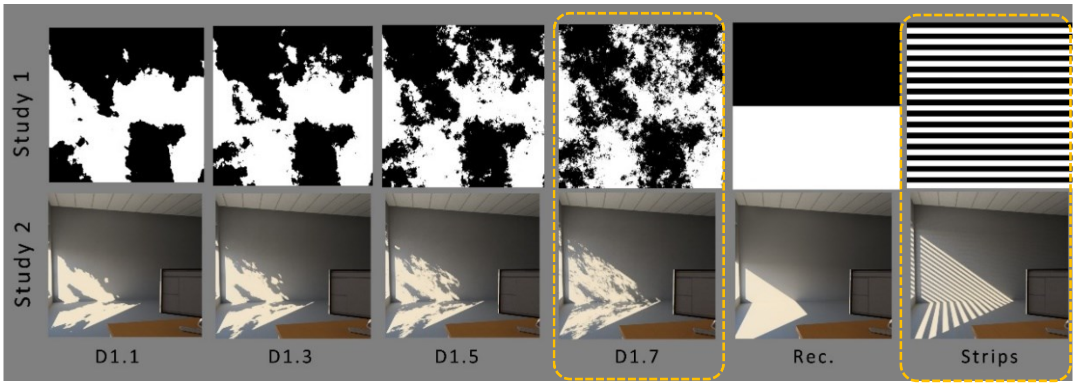


Figure 4.1: The six projected light patterns tested in the previous two studies, with selected patterns highlighted. The D value of fractal patterns is indicated below each pattern.

4.2. The Conceptual Model and Hypotheses

This study conceptualizes the relationship between visual interest and visual comfort from a systemic epistemological perspective. This model hypothesizes that occupant’s visual preference towards sunlight is a result of interactions between two main factors: visual interest and visual comfort (Figure 4.2). The visual preference of sunlight patterns can be thought of as visual comfort mediated by the visual interest of sunlight patterns.

This study examined the effect of sunlight pattern geometry –Fractal, Striped, and No Pattern– on visual comfort, view quality, and visual interest of sunlight patterns. Based on previous studies discussed in sections 1.1 through 1.4, we hypothesized that: 1) the fractal pattern is expected to be associated with a significant increase in visual comfort and visual interest ratings, compared to the striped pattern. 2) View quality ratings through the Fractal pattern are expected to be significantly higher than that for the striped pattern. 3) View quality ratings for the No-Pattern station are expected to be significantly higher than both patterns, assuming tolerable glare levels. 4) Because objective illumination measures including glare metrics do not address the visual interest of glare source, sunlight pattern geometry, or view quality, the relationship between these metrics and subjective visual comfort ratings is expected to differ across the three conditions.

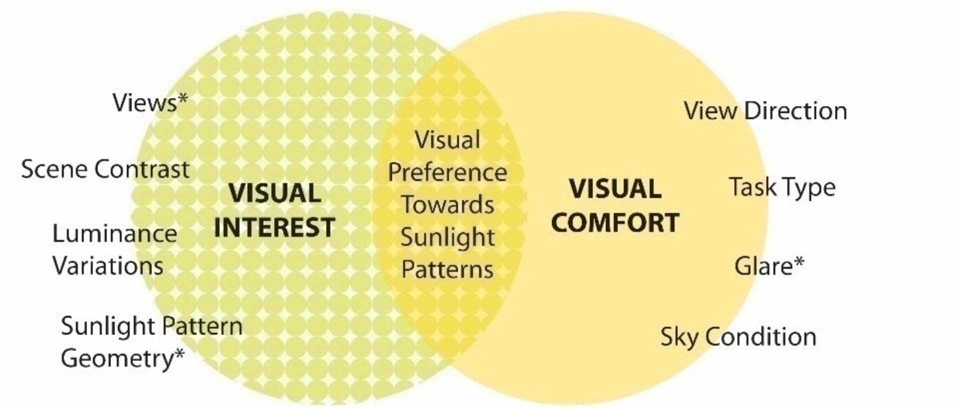


Figure 4.2: The visual preference towards sunlight patterns in work environments. These preferences are a result of visual comfort mediated by the visual interest of sunlight patterns. The list of variables influencing visual comfort or interest is not exhaustive but is meant to highlight main variables involved in the current study (with an asterisk).

4.3. Methods

4.3.1. The experimental setting

This study employed a 3x1 within-subjects quasi-experimental research design. It is referred to as such because it takes advantage of naturally-occurring daylight conditions in an office building, and without a randomized assignment of participant's start time over the course of the study. Three test stations were created in an open-plan office space on the 8th floor of a multi-story LEED Platinum building in Portland, OR. The three stations faced the North-east orientation, which controlled for view direction and solar orientation across the three stations. The stations exhibited different sunlight pattern geometries which included: (1) a statistical fractal pattern with a D=1.7 (Fractal), (2) a striped pattern (Stripes), and (3) a typical clear view window with no patterns (No-Pattern), as can be seen in Figure 4.3.

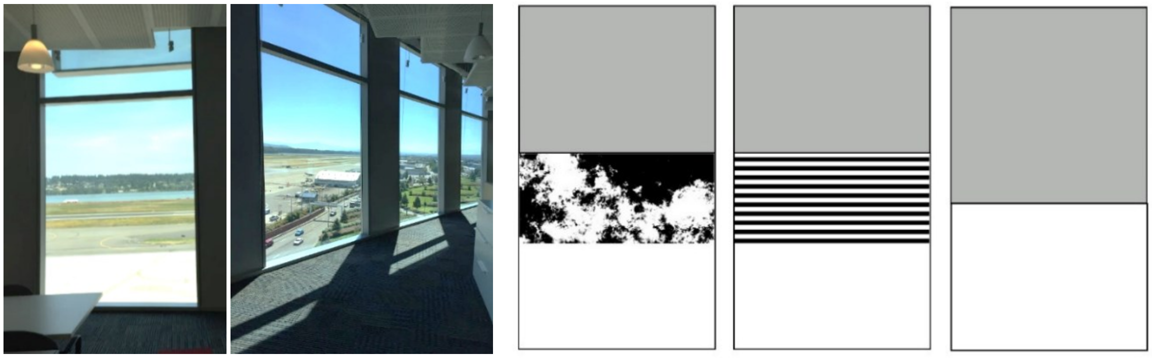


Figure 4.3: Pictures of the view and building zone where the experiment took place (left); and the three window conditions (right). White areas were transparent, black areas were opaque, and gray represents the roller shade.

The different sunlight patterns were produced by panels of clear Mylar with black ink that represented either a fractal or a striped pattern. The size of these patterns was 0.91x1.98 m. (3.0x6.5 feet), which were mounted on the upper half of a 1.8x1.98 m (6.0 x 6.5 feet) window, as can be seen in Figure 4.4. The roller shades were lowered to create this window size to control for excessive glare conditions without obstructing the view, and for avoiding direct sunlight on participant's body at the beginning of the experiment. For the No-Pattern station, the roller shade was adjusted to a height of 1.371 m. (4.5 feet) to ensure that the area of clear regions is consistent across the stations. The three stations had a view of nature composed of a river and mountain ranges in the background and paved roads in the foreground. The space had floor-to-ceiling windows and roller shades, which allowed for controlling view areas within each one of the three windows, and for blocking light from other windows. Visible transmittance (T_{vis}) of the window glazing is 28% and the solar heat gain coefficient (SHGC) is 0.19 as provided by the manufacturer.

The dependent variables tested include visual comfort, the visual interest of sunlight pattern, and satisfaction with view quality. The interest in conducting the study at the north-eastern façade meant that the study had to be conducted in the morning from 8 to 11 am on June 22nd. This allowed for the inclusion of sunlight patterns with different sizes as well as different daylight conditions.

4.3.2. Data collection

A total of 22 office workers (13 male and 9 female) whose ages ranged between 30-60 volunteered to participate in this study. The experimental protocol and instruments were approved by an Internal Review Board (IRB) for the protection of human subjects involved in the study. Participants were given specific instructions and description of the study procedures and asked to sign a consent form prior to starting their participation. Subjective and objective indicators of comfort were collected during the experiment as outlined in the following sections.

4.3.3. Research instruments

Subjective comfort data was collected using an offline questionnaire on a tablet. Table 1 shows the questions and scales used in the questionnaire. Participants interacted with the tablet by pressing on their answer to each question. These questions were selected based on previous studies that examined visual comfort and view quality (HMG, 2012; Van den Wymelenberg, 2012). The questions appeared in the same order as shown in Table 4.1.

Item number	**Question**	**Scale**
Q1	This is a visually comfortable environment for office work	7-point Likert scale (Strongly Agree-Agree-Somewhat agree-Neither agree nor disagree-Somewhat Disagree-Disagree-Strongly disagree).
Q2	Sunlight patterns look visually interesting	
Q3	I like the view I have from the window	
Q4	Air temperature feels:	7-point semantic differential (Too Warm-Neutral-Too Cold).

Table 4.1: The questionnaire and scales used.

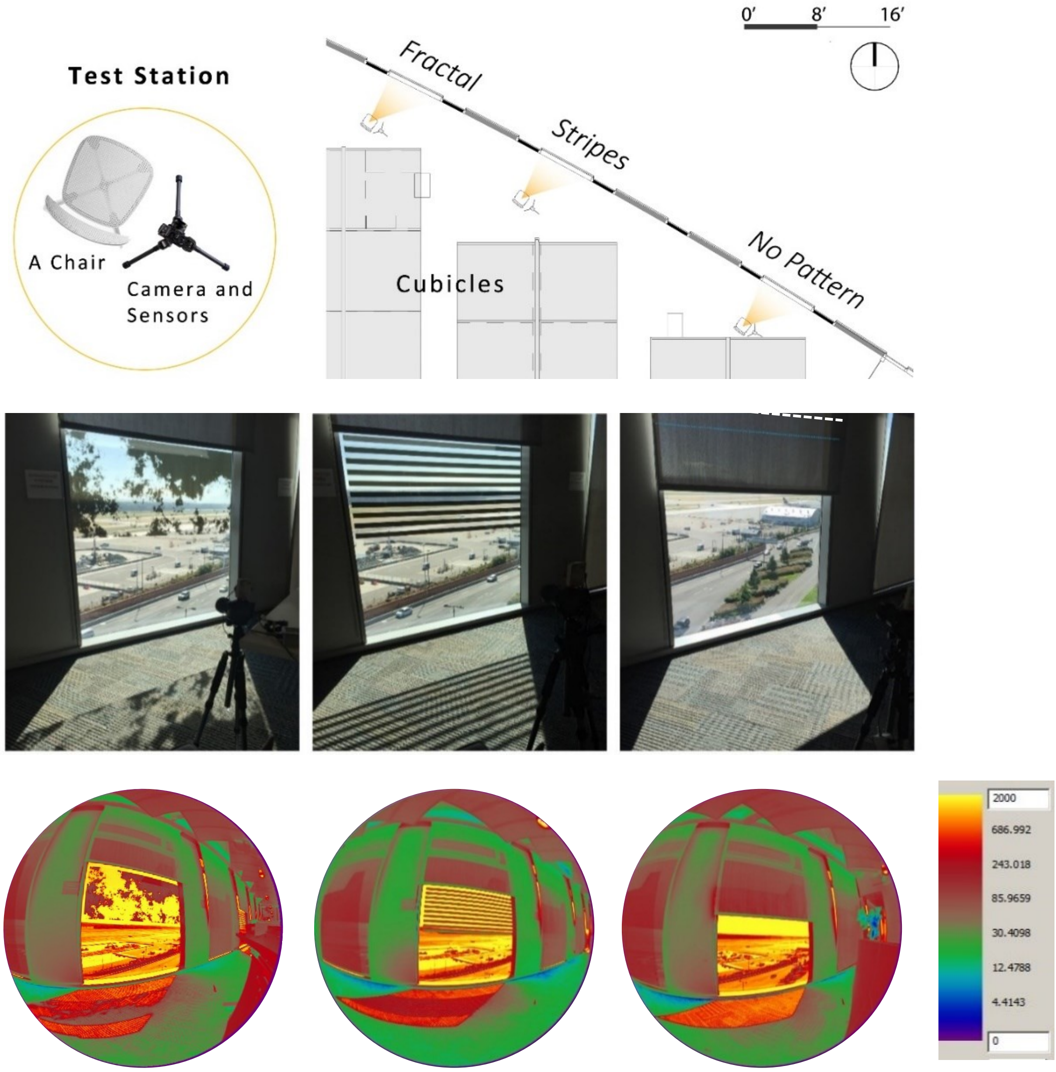


Figure 4.4: A floor plan of the three experimental stations (top); pictures and false color images of the three stations: Fractal (left), Striped (middle), and No-Pattern (right). The dashed line in the No-Pattern image shows shade height at the other two stations. This adjustment was made to ensure that the area of clear areas is consistent across all stations.

Objective environmental data included vertical illuminance (E_v), high dynamic range images (HDRIs), air temperature (T_A), relative humidity ($RH_{\%}$), and globe temperature (T_G). The HDR images were manually captured using a Canon G11 camera equipped with a fisheye lens (Opteka 52mm 0.2x HD Professional Super AF Fisheye) attached to a tripod and located at 142.2 cm (56 inches) to match a typical employee seated eye-level position. The lens projection was angular with a 150° field of view as verified by the researchers. Low dynamic images were captured at ISO 80, white balance was set to daylight, F-stop f/4, and EV=1. Figure 4.5 shows a scatter plot of vertical illuminance as measured and as calculated from HDRIs.

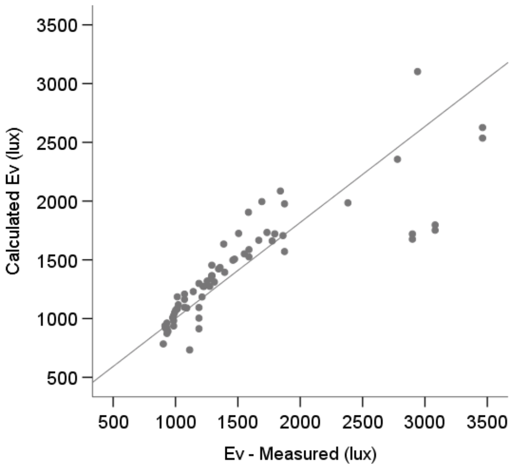


Figure 4.5: Measured vertical illuminance (lux) compared to that calculated from HDRIs. R^2=0.85

All other measurements were logged at 5-minute intervals using a series of sensors connected to a U-12 Onset HOBO data-logger. The environmental sensors included; a Li-Cor-210 photometric sensor with a custom voltage amplifier to measure E_v, a calibrated NTC Thermistor (10k ohm ±0.1°C) suspended at the center of a black painted ping pong ball to measure T_G, in addition to T_A and RH that were both measured using internal sensors of the U-12 Onset Hobo data logger. Figure 4.6 shows the instruments used for data collection.

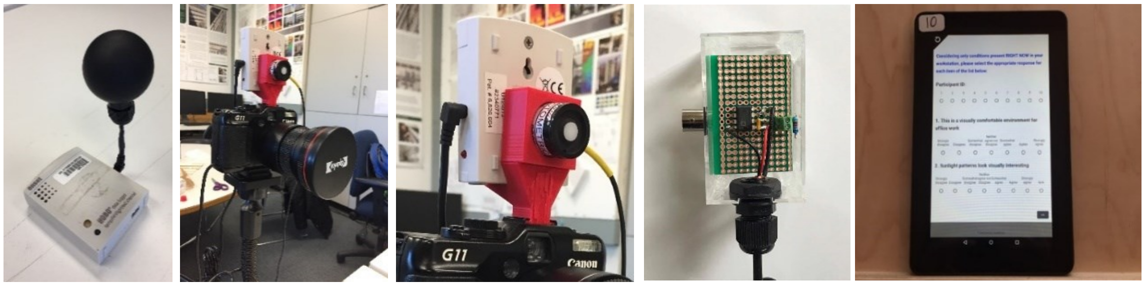


Figure 4.6: Left to right, globe temperature sensor, Canon G11 camera with photometric sensor attached, the signal amplifier used to connect a light sensor to a HOBO data logger, and tablet used for the questionnaire.

4.3.4. Calibration

All light sensors were calibrated prior to start of the experiment. The calibration process was conducted by placing all light sensors (each connected to a U-12 Onset-HOBO data logger) along with a reference light sensor (connected to Li-Cor LI-1400 multi-data logger) next to each other on a desk next to a window. Light measurements were collected from all sensors at a one-minute interval for approximately six hours so that different daylight and electric lighting conditions were included. Regression coefficients were calculated for each one of the three sensors. The error margins were typically within +-5% of the reference sensor as can be seen in Figure 4.7. The calibration procedure and the amplifier used were similar to those employed in previous field studies, e.g. [Konis, 2011].

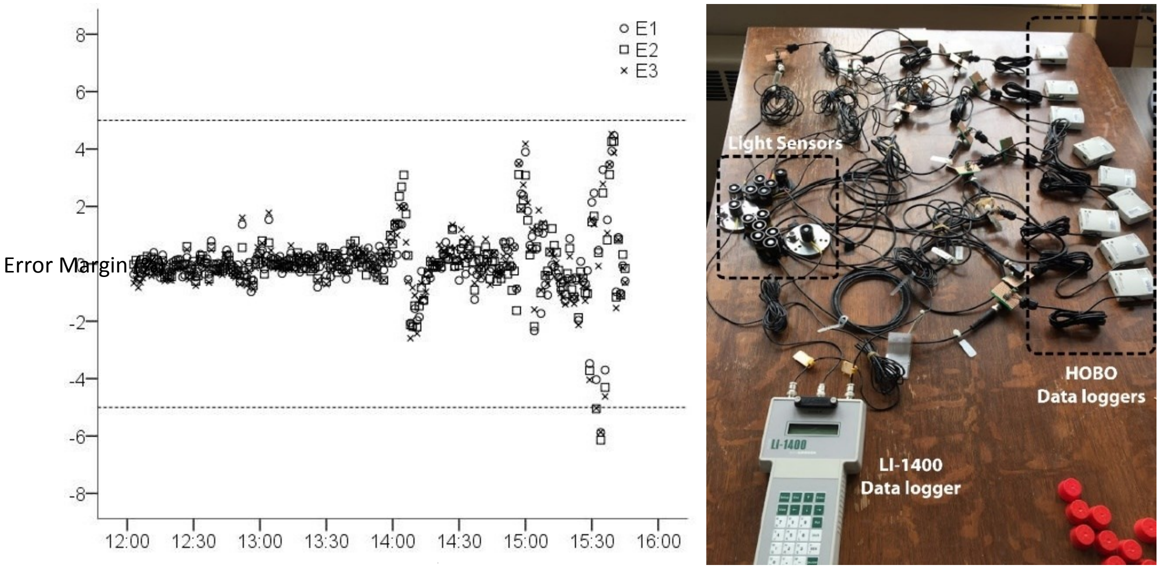


Figure 4.7: The percentage margin of error in E_v measurements for the three light sensors E1, E2, and E3 (left), and the calibration setup (right).

To calibrate HDR images, each camera was used to capture a series of low dynamic range images of a daylit room with sunlight patterns present. The response curve for each camera was then generated using Photosphere software, and used for all subsequent images. Vignetting correction for each camera was determined by taking an HDRI at five degree increments and examining luminance reduction of a gray card across different angles, as described by (Mehlika Inanici & Galvin, 2004). The globe temperature sensor was computed by calculating thermistor resistance, which was then used in the Steinhart-Hart equation to calculate globe temperature.

4.3.5. Experimental procedure

After signing the consent form, each participant was asked to sit at a chair located in each station for approximately two minutes and then answer the questionnaire using the tablet. Each participant was assigned an identification number to allow for questionnaire responses to be paired with recorded environmental conditions and tagged to relate between recorded conditions and questionnaire responses for each participant. The order by which participants experienced the three test stations was randomized across subjects. Generally, each participant started and completed his/her participation at the three stations before another participant began. In other words, the three stations were experienced by each participant within few minutes of each other. HDRIs were captured immediately after a participant completed the questionnaire to prevent interference with their perception of the environment. Figure 4.8 shows E_v as recorded at the end of each questionnaire response.

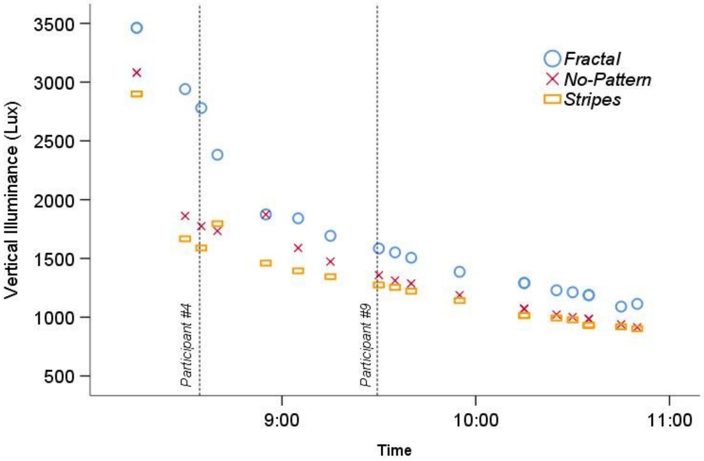


Figure 4.8: Ev at the three stations during the experiment. Each marker represents when a response was recorded at that station. The two dashed lines show that the three assessments were all completed within few minutes for participants number 4 and 9.

4.3.6. Analysis methods

To facilitate statistical analysis, questionnaire responses were recoded into a numerical scale 1-7 such that 7 was ‘Strongly agree’ for questions 1 through 3, and ‘Too warm’ for question 4. Regarding HDRIs, each HDRI comprised of six low dynamic range images combined using ‘hdrgen’ command-line software (Anyhere Software) using predetermined response functions generated by the authors. Each HDRI was then cropped, resized to 800x800 pixels, masked, vignetting corrected, calibrated using the corresponding measured E_v, and evaluated for glare using the 'evalglare' command. The angular lens projection type information was specified in evalglare. This process was automated using a batch file that executed these commands in order. Lastly, questionnaire responses were compiled with physical measurements –E_v, T_A, T_G, $RH_{\%}$, and HDRIs– using data time-stamps for each participant.

4.4. Results

Questionnaire and objective data from the 22 participants was analyzed to investigate two main points: first, differences in visual comfort, visual interest of sunlight patterns, and view quality among the three stations; and second, the relationship between objective measurements and questionnaire responses. The differences were investigated using descriptive statistics, box plots, the Wilcoxon Signed Ranks test, and multiple regression analyses; whereas the relationships were examined using Spearman's rho correlation coefficients.

Regarding sample size, we examined whether the number of participants (n=22) was sufficient to show the differences reported in this study. Considering that this study utilized a repeated-measures approach for the same group of participants, the GLIMMPSE online tool (Kreidler et al., 2013) was used to calculate the ideal sample size as well as the power of the current sample size (Guo, Logan, Glueck, & Muller, 2013). Using a power value of 0.9 and type I error rate of 0.05, the Hotelling-Lawley Trace test showed that a sample of 17 participants would be sufficient. With 22 participants, the same test calculated a power of 0.987, which is higher than the commonly used thresholds of 0.8 and 0.9.

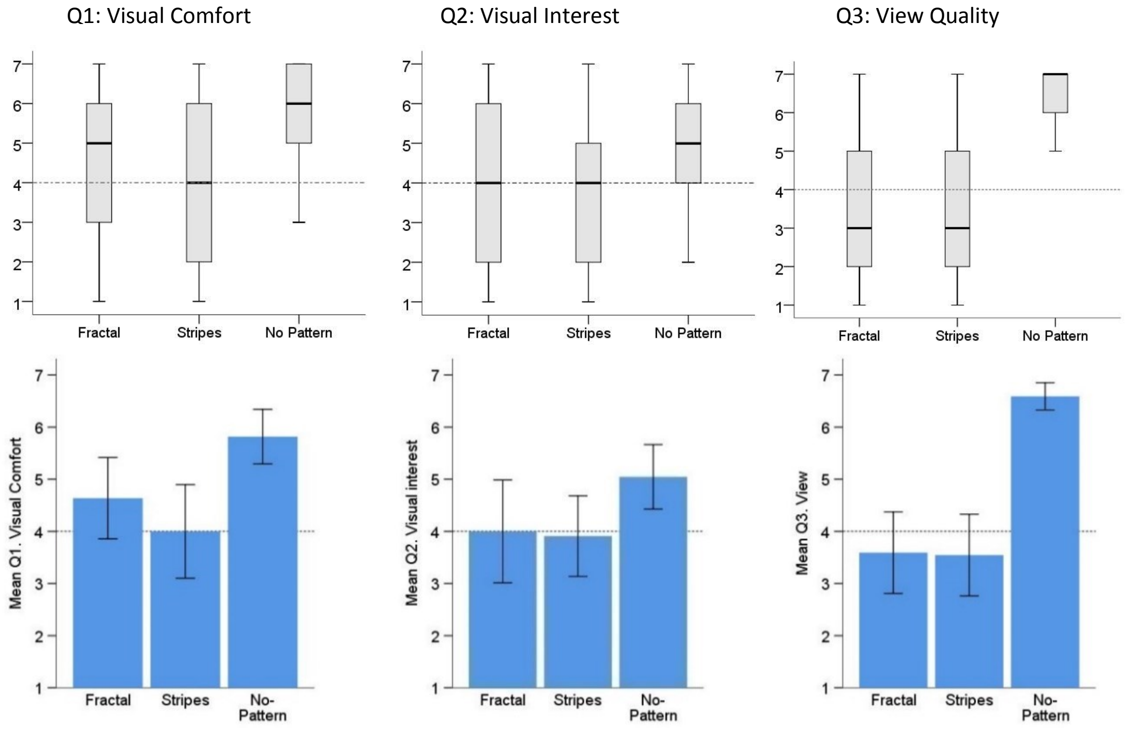
4.4.1. Differences among the three stations

4.4.1.1. Descriptive statistics

The boxplots in Figure 4.9 show that the distribution and means of responses to visual comfort (Q1), visual interest (Q2), and view quality (Q3) varied by station. Means of Q1, Q2, and Q3 for the No-Pattern station were higher than those for the Striped and Fractal stations. Further, means of these questions for the fractal pattern were slightly higher than those for the Striped pattern. There was more variability in visual interest responses for the fractal (SD=2.2) compared to the striped station (SD=1.7). Regarding view quality, both patterns received low view ratings compared to the No-Pattern condition. Table 4.2 shows the means and standard deviations for questionnaire responses.

	Fractal	No-Pattern	Stripes	All Responses
Q1. Visual Comfort	4.64 (1.761)	5.82 (1.181)	4.00 (2.024)	4.82 (1.831)
Q2. Visual Interest	4.00 (2.225)	5.05 (1.397)	3.91 (1.743)	4.32 (1.866)
Q3. View Quality	3.59 (1.764)	6.59 (.590)	3.55 (1.765)	4.58 (2.046)

Table 4.2: Mean and standard deviation for questionnaire responses at each station and for all combined responses. Standard deviation values are in parentheses.


Q1: Visual Comfort

Q2: Visual Interest

Q3: View Quality

Figure 4.9: Boxplots and means of visual comfort, visual interest, and view quality. The error bars in mean graphs represent the 95% confidence interval.

4.4.1.2. Significance of differences in questionnaire responses

Questionnaire responses were analyzed to examine the significance of differences among the three stations. For examining differences, Wilcoxon signed ranks test was used because Shapiro-Wilk test showed that variables violate the normality assumption that is required for the typically utilized paired T-test. For this test, the 0.05 significance level was adjusted to 0.016 using Bonferroni correction to account for the multiple tests conducted using the same data set. As shown in Table 4.3, visual comfort ratings for the No-Pattern station were significantly higher than those for the Fractal (Z= -2.48, p<0.016) and the Striped patterns (Z= -3.281, p<0.016). The difference in visual comfort ratings between the Fractal and the Striped patterns was not statistically significant.

Regarding the visual interest of sunlight patterns, visual interest ratings for the No-pattern were significantly higher than that for the striped pattern (Z= -2.188, p<0.05), but not at the adjusted significance threshold. While view area size was consistent across the three stations, the distribution of these areas differed across stations. For instance, in the No-Pattern station, the view area was uninterrupted, unlike the Striped and Fractal patterns which included viewing areas within the pattern itself. Participant responses showed that view ratings for the No-Pattern station were significantly higher than those for Fractal (Z= -3.753, p<0.016) and Striped patterns (Z= -3.742, p<0.016).

	Fractal – No Pattern	Stripes – No Pattern	Fractal – Stripes
Q1. Visual Comfort	-2.480** (0.013)	-3.281** (0.001)	-1.300 (0.194)
Q2. Visual Interest	-1.595 (0.111)	-2.188* (0.029)	-.202 (0.840)
Q3. View	-3.753** (0.000)	-3.742** (0.000)	-.263 (0.793)
Q4. Thermal Comfort	-.906 (0.365)	-.432 (0.666)	-1.000 (0.317)

Table 4.3: Wilcoxon Signed Ranks test results with significant coefficients highlighted. * represents a significant level <0.05, ** represents a significance according to Bonferroni corrected threshold <0.016. Significance p values are in parentheses.

As for thermal comfort (Q4), differences in subjective responses were not statistically significant. This question was included as a control variable to ensure that no thermal discomfort perceptions arise from sunlight patterns, which may influence overall comfort at any of the three stations. Mean responses were 4.59, 4.82, and 4.77 for fractal, No-Pattern, and Stripes, respectively. Questionnaire responses and the average predicted mean vote (PMV) of 0.11 indicated a slightly warm and near-neutral thermal sensation. The PMV refers to a scale from -3 (cold) to hot (+3) with zero being the neutral thermal state. This is expected as the experimental space is air-conditioned with uniform indoor climate with mean air temperature at 77°F, relative humidity of 41.6%, and radiant temperature of 78.1°F.

Given that there was a difference in vertical illuminance among the three stations, we conducted multiple regression analyses to control for vertical illuminance and examine whether significant differences in visual comfort exist between the two patterns. This was examined by creating a dummy variable for each station and inputting two stations into the regression model while leaving one out as a reference condition. As Table 4.4 shows, when controlling for DGP, the Fractal pattern was associated with a significant increase in visual comfort responses, compared to the Striped pattern station (p<0.1). As shown previously by Wilcoxon Signed Tanks test, the Fractal and Striped patterns were associated with a significant decrease in visual comfort ratings ($p<0.05$) ($p<0.01$), respectively. Other regression models examined differences in the visual interest of sunlight patterns and view quality while controlling for glare level in terms of DGP. The results of these models confirmed results from the Wilcoxon Signed Ranks tests reported in the previous Table 4.3.

	Unstandardized Coefficients		Sig.
	B	Std. Error	
(Constant)	8.121	2.742	.004
DGP	-14.712	9.705	.135
Fractal	.912†	.537	.094
No Pattern	2.021**	.522	.000

Table 4.4: Dependent variable is Q1. Visual Comfort. † represents a significant level <0.1; * represents significant level <0.05, ** represents a significance <0.01.

6.1. *Relationships between Subjective and Objective Measurements*

Spearman's rho correlation coefficients between visual comfort ratings and glare metrics were examined to investigate differences in this relationship across the three stations (Table 4.5). Generally, subjective visual comfort ratings (Q1) significantly correlated with these metrics for the Striped and No-pattern stations, but not at the Fractal station. Visual comfort ratings for the Fractal and Striped stations significantly correlated with sunlight visual interest ratings. When responses for the three stations were collectively examined, the visual comfort ratings were significantly associated with view quality (Spearman's rho coefficient = 0.43, $p<0.01$) and the visual interest of sunlight patterns (Spearman's rho coefficient = 0.50, $p<0.01$). Similarly, visual interest of sunlight patterns significantly correlated with view quality (Spearman's rho coefficient = 0.37, $p<0.01$).

	Q1. Visual Comfort		
	Fractal	No-Pattern	Stripes
Visual Interest of Sunlight Pattern (Q2)	.588**	0.029	.660**
View ratings (Q3)	0.359	.485*	-0.026
40° Band Mean Luminance	0.069	-0.410	-.525*
40° Band Luminance Max	0.086	-.557**	-.479*
DGP	0.094	-0.395	-.487*
Mean luminance	0.081	-0.395	-.507*
Ev	0.012	-.450*	-.494*
Background Luminance	0.071	-.435*	-.488*
Source Luminance	0.073	-0.395	-.474*
Omega of Sources	0.022	.452*	0.389
Ratio (95th percentile to Mean)	-0.004	-0.370	0.295
Coefficient of variation for the 40° Band	0.009	-.487*	0.394

Table 4.5: Spearman's rho correlation coefficients between Q1 (visual comfort) and visual comfort metrics. The significance of the relationship is represented by * for $p<0.05$ or ** for $p<0.01$.

6.1.1.Glare and Visual Comfort Ratings

While DGP values ranged between 0.25-0.35 indicating imperceptible glare levels, DGI values ranged between 16.67-23.9 indicating glare levels ranging from imperceptible glare to intolerable glare. However, because DGI did not correlate with visual comfort ratings at any of the stations, this metric was not used for further investigation in this study. Overall, 28.8% of responses indicated visual discomfort, and 68.2% indicated that they were visually comfortable, which aligns with the DGP results. Therefore, the DGP metric was used to examine relationships with visual comfort ratings.

It is important to note that DGP was developed using a four-point semantic differential scale: imperceptible, perceptible, disturbing, and intolerable (Wienold & Christoffersen, 2006), which is different and does not relate directly to the seven-point Likert scale used in the current study. Although it can be argued that ‘imperceptible’ represents comfort while the other three levels represent different degrees of visual discomfort, this study does not aim to relate the two scales, but instead, it takes advantage of the fact that both scales exhibit a linear transition from visual comfort to discomfort. This linearity allows for relationships between DGP and visual comfort responses to be investigated even with a seven-point Likert scale, as shown in a previous study (Van Den Wymelenberg & Inanici, 2016).

Interestingly, there was a variation in the relationship between DGP and visual comfort ratings across the three stations, as illustrated by Figure 4.10. This shows that participants reported visual comfort ratings of ‘Somewhat disagree’ or ‘Somewhat agree’ at DGP values lower than anticipated. Particularly, when compared to the No-Pattern and Striped stations that show a gradual decrease in DGP value ranges as visual comfort rating increases. These results are not specific to DGP, examining visual comfort ratings by vertical illuminance showed similar results. This suggests that visual comfort ratings close to neutral (with no strong preference) at the Fractal station were influenced by other factors such as visual interest and overall preference for the fractal pattern.

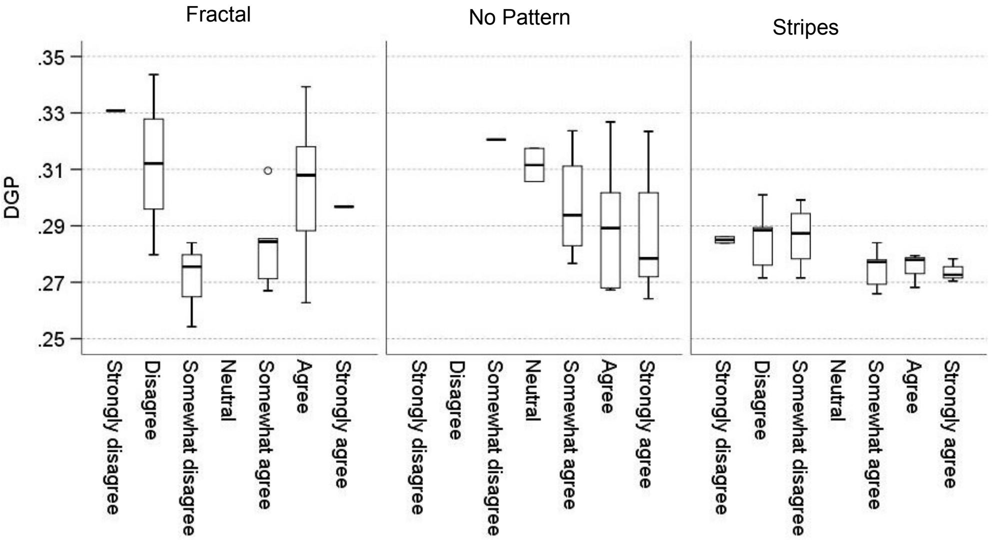


Figure 4.10: Differences in the relationship between DGP and visual comfort ratings (Q1) for Fractal (left), No-Pattern (middle), and Stripes (right).

Different window patterns might influence the size of glare sources, thus, we examined glare source size across the three stations. Mean glare source size for the Fractal and Striped stations were 0.34 and 0.32, respectively, whereas mean glare source for the No-Pattern station was 0.23. The luminance of the 95th percentile within the 40° band for the No-pattern station was 3686.8 cd/m^2, which was higher than that for the Fractal (3289.2 cd/m^2) and the striped statins (2609.6 cd/m^2). Overall, the two patterns were similar in terms of glare source size and 95th percentile, which suggests that the discriminating factor between the two is the geometry of glare sources and sunlight patterns. Figure 4.11 shows false-color images of the three stations at four different times during the experiment.

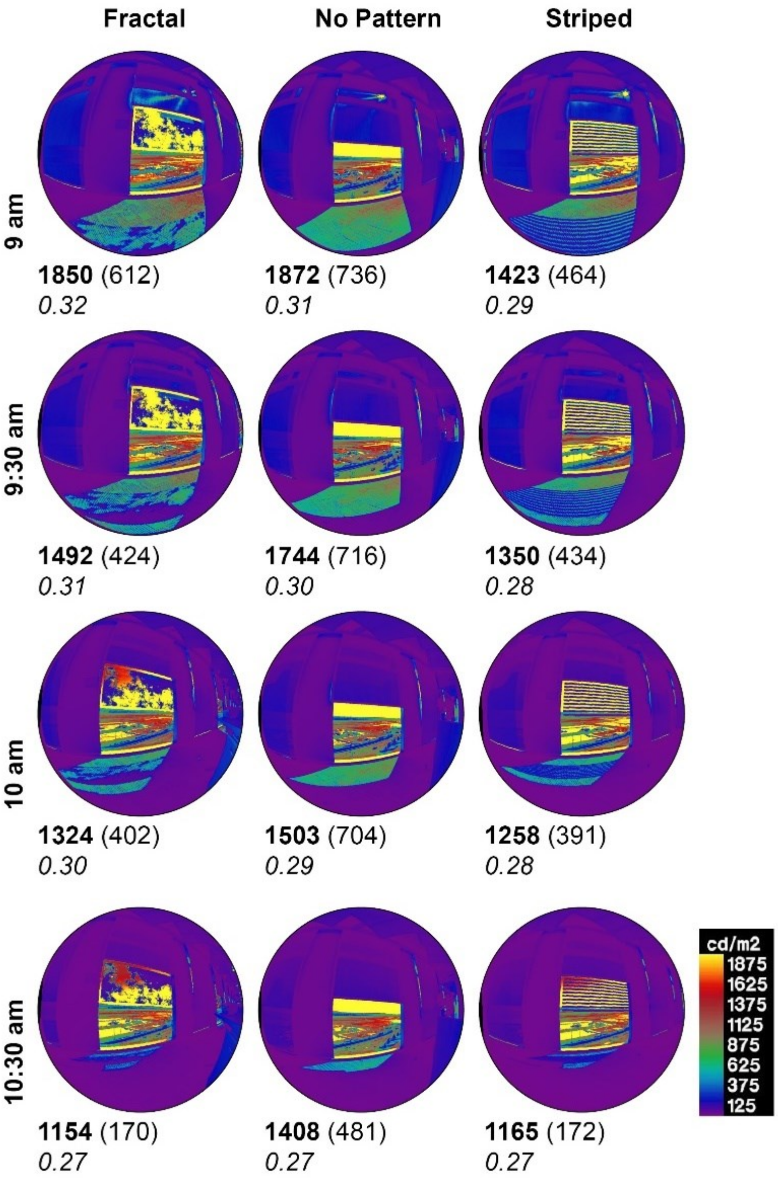


Figure 4.11: False colored images representing luminance distribution over part of the study duration. Mean window luminance in bold, mean sunlight pattern luminance in parentheses, and DGP in italic are included for each scene.

4.5. Discussion

Visual comfort and view quality ratings for the Fractal and Striped stations were significantly lower than those of the No-Pattern station. This suggests that view quality might have influenced visual comfort assessments; particularly because of the imperceptible glare levels indicated by DGP values below 0.38, questionnaire responses showing that 68.2% were satisfied with visual comfort, and the panoramic outdoor views. The combination of these three factors suggests that participants maybe were willing to tolerate these glare levels in favor of having uninterrupted views, thus neither pattern was deemed important. The preference for unobstructed views was indicated by some participants who mentioned that they preferred to see through the patterns. On the other hand, the two patterns received similar ratings for view quality and visual interest of sunlight patterns. These findings support our hypothesis regarding a higher rating for clear views over the two patterns, but do not support our hypothesis that view quality at the Fractal station is higher than that at the Striped station.

Multiple regression analyses allowed for controlling glare level in terms of DGP. Although only at the 10% level, the results showed that visual comfort ratings at the Fractal station were higher than those at the Striped station (Table 4.4). While the difference in visual interest of sunlight patterns between the Fractal and Striped stations was not significant, responses showed different distributions as shown by Figure 4.9. Therefore, it is possible that the visual interest of sunlight patterns or that of the patterns mounted on windows have contributed to the difference in visual comfort ratings. Because the importance of sunlight pattern geometry seems to be influenced by outdoor views and window patterns, future studies should explore the visual interest of sunlight patterns in scenes without a visual access to patterns on windows or outdoor views.

Interestingly, the visual interest of the rectangular sunlight pattern at the No-Pattern station was significantly higher than that for the Striped pattern. This finding contradicts the result of a study by the authors (under review), which showed that the visual interest of the Striped sunlight pattern was higher than that of the rectangular in renderings. This suggests that outdoor view quality might influence visual interest ratings of sunlight patterns.

When shade perforations are uniformly distributed, which is the case for typical commercial roller shades, view clarity was found to be dependent on perforation size and shade visible transmittance (Konstantzos et al., 2015). In addition to view clarity, a preliminary study using virtual reality found that perforation pattern –stripes, regularly spaced rectangles, and irregularly spaced rectangles– to have significantly influenced perceived pleasantness, complexity, and excitement (Chamilothori et al., 2016). It is expected that view clarity scores to be influenced by view content and the ability of occupants to reconstruct outdoor views as seen through perforations. Future studies should examine view clarity scores and mood response for shades with an irregular distribution of perforations, such as the fractal patterns. Particularly, to examine whether the distribution of perforations, e.g. uniform or irregular, influences view clarity.

While a previous study by the authors (under review) suggested that projected fractal light patterns are significantly more visually interesting than rectangular or striped patterns, this experiment found that visual interest ratings for the No-Pattern station were significantly higher than those for the Striped pattern station. This could be due to variables in this study that were not considered in the previous one such as glare and outdoor views, whose interactive effects with each pattern might have influenced visual interest ratings. The results of this study do not support our hypothesis regarding a higher visual interest for Fractal sunlight patterns, compared to Striped sunlight patterns.

Assuming that the view quality and the visual interest of sunlight patterns have both influenced visual comfort ratings, the questions to be asked are: 1) what are the relative importance of these two factors for visual comfort; 2) how would the relationships observed in this study be influenced by higher glare levels. These questions warrant further studies that expand the levels of glare experienced to include perceptible, disturbing, and intolerable levels. This step is important to delineate the extent to which visual interest and view quality can offset and reduce perceived glare.

4.6. Conclusions

We summarize the conclusions of this study using the following points:

- The visual interest ratings of Striped sunlight patterns were significantly less than those for the No-Pattern station ($p<0.05$). The difference in visual interest between the Fractal and No-pattern stations was not statistically significant.
- While controlling for vertical illuminance, the Fractal pattern was associated with a significant increase in visual comfort, compared to the Striped station ($p<0.1$).
- The No-Pattern station received the highest mean ratings for visual comfort and view quality and the differences were statistically significant compared to the two patterns ($p<0.016$).
- The relationship between glare level and visual comfort ratings varied across the three stations.
- Occupants might be willing to tolerate low glare levels in an office setting when an interesting outdoor view of nature is present.
- The visual interest of sunlight patterns in space was well perceived by the participants and merits further discussion, metrics, and studies. Results showed that ratings of visual interest of sunlight patterns were associated with significant increases in visual comfort ratings.

4.7. Limitations and Future Work

This study took place at an office space where volunteers were recruited for participation; thus, self-selection bias might be present. Order bias might also be present because questionnaire questions were not randomized across participants. The timing of the experiment was limited to when sunlight could be present in the space (summer morning). Regional and seasonal variability in occupant's visual reaction were not within the scope of this study but might have influenced occupant's responses. Investigating such variability can inform how daylighting design guidelines in general, and sunlight exposure guidelines specifically can be tailored to different regions and seasons.

Although sunlight patterns were admitted into space, DGP values remained below 0.38 throughout the study, this could be due to window tint and low T_{vis}. Another limitation was that participants were not involved in an office task at the test stations. It is expected that interacting with the questionnaire on the tablet for two minutes did not require a level of visual concentration nor generated potential visual fatigue as much as typing or reading on a computer screen for prolonged periods of time. It would be beneficial to investigate the possibility of incorporating the duration of exposure and the visual load of different tasks into visual comfort indexes as mediators of visual comfort. Overall this approach might strengthen and facilitate comparisons between results of field studies and those from controlled experiments.

The presence of a panoramic view of a river from the 8th floor might have influenced the relationship between visual comfort and sunlight pattern visual interest ratings. Based on the results of this paper, it is hypothesized that the two patterns covered part of the view and their aesthetics did not outweigh that of the view. This hypothesis, however, requires further testing utilizing views of different aesthetic qualities and ratings.

Given these limitations, the study outlined in the next Chapter explores occupant's visual comfort, visual interest of sunlight patterns, and view quality during typical work days at an office building. The study included different façade orientations, different view directions/ office layouts, and longer exposure time.

CHAPTER V

INVESTIGATING OCCUPANT’S VISUAL COMFORT, VISUAL INTEREST OF SUNLIGHT PATTERNS, AND VIEW QUALITY IN A DAYLIT OFFICE SPACE

A portion of this Chapter was published in the IES Research Symposium 2018: Light + Human Health Symposium held April 8-10 in Atlanta, GA. Professors Ihab Elzeyadi and Kevin Van Den Wymelenberg contributed to this work by guiding study design and analyses. Professor Grant Jacobsen aided with statistical analyses. The fractal patterns used were developed by Professors Richard Taylor and Margaret Sereno. I was the primary contributor to the studies, conducted data collection and analyses, and wrote the manuscript.

Sunlight is a multisensory phenomenon that can enhance occupant’s comfort, health, and connection with the outside environment through its dynamic luminous and thermal attributes. Current daylighting metrics (IES-LM-83-12) and practice guidelines (IES RP-5-13) limit sunlight penetration in work environments, reducing both its negative and positive effects on visual comfort and spatial quality. One gap in existing literature on sunlight exposure is in addressing effects of the visual interest for sunlight patterns and their play of brilliants on visual comfort. The term ‘sunlight patterns’ refers to direct sunlight projections in interior spaces. The questions to be answered are: is there a difference in subjective visual comfort assessments under sunlight conditions of different visual interests? And if proved, what are the positive geometrical attributes of sunlight that should be implemented in daylit office spaces to reduce occupant’s perceived glare?

To address this gap, this Chapter employed a within-subjects design where 33 office workers were subjected to three sunlight patterns: Fractal Pattern, Striped Pattern, and Clear at an office building in San Francisco, CA over a five-week period. Occupant’s perceived visual and thermal comfort responses and physical environmental measurements in terms of vertical illuminance, high dynamic range images, air temperature, relative humidity, and globe temperature were collected and paired with each other.

5.1. Introduction

Sunlight in buildings influences occupant's visual and thermal comfort as well as their psychophysiological response. Previous studies found that sunlight causes melatonin rhythm phase advancement which can be effective against seasonal affective disorder and insomnia (Mead, 2008). Further, the exposure to daytime bright light was found to improve psychomotor vigilance performance and sleep quality (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; Figueiro & Rea, 2014). Studies on visual comfort found that sunlight exhibits cheering and pleasant attributes that influenced occupants visual comfort (Boubekri et al., 1991). When sunlight is admitted into space, it creates projections of sunlight patterns on different surfaces in space that can improve the appearance of that space (Ne'Eman, 1974). The qualitative attributes of these patterns such as geometry and visual interest have not been examined for their impact on visual comfort. Examining the effect of these variables and incorporating it into daylighting design can help in creating visually interesting and comfortable environments.

Current daylighting practices limit sunlight patterns to reduce the possibility of glare for occupants. While this approach might help in limiting glare, it promotes dull and visually monotonous environments with reduced sunlight benefits (Reinhart, 2015). Such practices, to some extent, reflect challenges that have inhibited the incorporation of sunlight in daylighting design. One of these challenges is the lack of a glare metric that can reliably predict occupant's visual comfort when sunlight patterns are present in space. For instance, the daylight glare index (DGI), CIE unified glare rating System (UGR) are only valid for conditions when direct sunlight does not enter the space (Jakubiec and Reinhart 2012; Nazzal 1998; Iwata, Tokura, and Shukuya 1992). The daylight glare probability (DGP) was developed under stable and clear sky conditions (Wienold & Christoffersen, 2006) and was found to be a better predictor than DGI, however, it exhibits several limitations (Hirning et al., 2014; Van Den Wymelenberg & Inanici, 2014). Other aspects like thermal comfort, views, and privacy may influence visual comfort ratings (E. Lee et al., 2005; N. Wang & Boubekri, 2010) but their direct and interactive effects have not been comprehensively assessed.

Another challenge is manifested by the lack of studies that examined qualitative aspects of sunlight and effects on occupant's visual comfort. This is particularly important because of the established psychophysiological effects associated with sunlight. Incorporating these aspects into daylighting design can help in creating visually comfortable and interesting environments (S. Rockcastle et al., 2017).

Among different space types, offices are visually critical spaces where occupants typically spend a considerable amount of their time performing computer-based tasks in fixed view directions. Nonetheless, they experience a wide and dynamic range of daylight conditions throughout the day (Elzeyadi & Lockyear, 2010). The current annual sunlight exposure metric, $ASE_{1000,}$250h, requires that sunlit area not to exceed 10% of floor area for 250 hours a year before operable shades or blinds are deployed to block sunlight (IES 2013). Supporting research (HMG, 2012) did not include enough variety in sunlight penetration patterns by different façade orientations, shading systems, and climates (IES, 2013). This metric was found to overpredict the occurrence of glare and warrants further refinement (Dutra de Vasconcellos, 2017). Therefore, there is a need for studies that examine various aspects that influence occupant's preferences towards sunlight patterns.

5.1.1. Cheering effects of sunlight

Boubekri et al., (1991) found that a sunlit area of 15%-25% of floor area created maximum levels of relaxation when occupants were parallel to the window. They concluded that sunlight sparkles are preferred to large floods for enhancing emotional well-being. It was also found that sunlight, as manipulated by size, season, time of the day, has significant impacts on the affective state of occupants, which influences their satisfaction. This study suggests that the illuminance of sun patterns exceeds that needed for visibility in offices, so, other qualitative aspects of sunlight patterns and view quality should also be considered to understand how occupants form overall preferences towards sunlight patterns. These results are in line with another study (Kim (1997), which found that sunlight improved positive emotions more than daylight, both in winter and summer seasons in classrooms. This finding might be partially explained by the enhanced connection to nature promoted by direct sunlight.

Results of a study in England (Ne'Eman, 1974) showed that 73% of office occupants considered sunlight a pleasure while 24% considered it a nuisance. When asked to choose between a good view or sunlight patterns with an unpleasant view, 61% preferred a good view, and 36% preferred sunlight patterns with unpleasant views. Ne'Eman developed a qualitative scale for occupant's reaction to sunlight patterns, and included sunlight sparkle and improved appearance of interiors as pleasant and liked effects.

Wang & Boubekri, (2010) examined subjects' seating preferences in a sunlit space and found that most subjects chose to sit close to or within the sunlight patterns where average horizontal illuminance ranged from 527-14052 lux, which is relatively a high range for paper-based tasks. Other factors, i.e. sense of control, privacy and views, were identified to have had influenced seating preferences. Another study suggested that 11 out of 12 participants chose to let sunlight patterns into space, which suggests that carefully positioned sunlight patterns can enhance occupant's satisfaction (Van den Wymelenberg et al., 2010).

5.1.2. View quality

Previous studies found that views of nature were associated with higher satisfaction and positive physiological benefits. For example, an unobstructed view of natural surroundings was associated with improvements in self-reported physical and mental health during a residential rehabilitation program (Raanaas et al., 2011). Although the desire for views is well established, the characteristics that make it more or less desirable are not as well understood (Collins, 1975). Ulrich (1981) concluded that scenes of nature had a more positive influence on the psychophysiological states than urban scenes. In a subsequent study, Ulrich (1984) found that patients in rooms with windows looking out on a natural scene had shorter postoperative hospital stays and took fewer potent analgesics than those in similar rooms with windows facing a brick wall. Another study (P. Leather et al., 1998) found that a view of natural elements buffered the negative impact of job stress on intention to quit.

A study that compared simulated views of a green roof to views of a concrete slab found that viewing a green roof was associated with a more consistent responding to the task and fewer omission errors, compared to viewing a concrete roof (Lee, Williams, Sargent, Williams, & Johnson, 2015). In addition to view content, previous studies showed that the distance of view elements influences visual comfort ratings (Shin et al., 2012). Some researchers suggested that an interesting view is associated with a less visual discomfort rating compared to a less interesting view (Tuaycharoen & Tregenza, 2005, 2007). However, another study (Aries et al., 2010) found that nature views increased discomfort directly. Aries et. al. suggested that the visual interest evoked by view might have influenced these ratings. Overall, these studies showed that satisfaction with views influences visual comfort, therefore, creating a balance between maintaining views while mitigating glare would help improve visual comfort.

5.1.3. Fractal patterns

Existing literature shows that natural scenes are more preferred, than urban scenes, (Purcell, Peron, and Berto 2001) and are believed be associated with many positive psychophysiological responses such as a higher alpha activity (higher relaxation effects), a positive emotional state (Ulrich 1981), and less sick leaves in offices (Elzeyadi 2012). Kaplan (1995) proposed the attention restoration theory which implies that natural environments are particularly rich in the characteristics necessary for restorative experiences. The question, therefore, is what are these characteristics that exist in natural environments? Many researchers suggested that the effects of natural scenes on attention restoration can be explained by the geometrical characteristics of fractal patterns which are prevalent in nature (Purcell, Peron, and Berto 2001; Joye and van den Berg 2011; Hagerhall et al. 2015; (Mandelbrot, 1983).

Fractal geometry can be defined as shapes that display a cascade of never-ending, self-similar, meandering detail as observed at various levels of scales (Bovill 1996; Harris 2012). These patterns are often characterized by their roughness and irregularity (Spehar et al., 2003) and can be found in trees, clouds, rivers, and other natural elements. The prevalence of fractal patterns in nature might have caused the visual system to adapt to efficiently process them, hereafter the fractal fluency theory (Taylor & Spehar, 2016).

Fractal patterns are quantified and characterized based on a variable called the fractal dimension (D). This parameter quantifies the fractal scaling relationship between the patterns observed at different magnifications (Spehar et al., 2003). For fractal patterns, this value lies between 1 and 2 and determines the complexity of the pattern. Fractal patterns are mainly classified into two categories based on the manner in which the patterns repeat at different scales (Hagerhall et al. 2015); these two categories are statistical, and exact fractals. Statistical fractals are found in nature and exhibit randomness and variety in sizes at different scales, therefore, they look similar at different scales so that only the pattern's statistical qualities repeat (Taylor and Spehar 2016). On the other hand, exact fractals look exactly the same as observed at different magnifications (Fairbanks & Taylor, 2011).

Fractal patterns were found to elicit a positive perceptual response. For instance, Taylor (1998) conducted an experiment where participants were shown pictures of fractal and non-fractal patterns and found that 95% of participants preferred fractals to non-fractal patterns.

Fractal patterns were also found to enhance stress recovery compared to a non-fractal pattern, which increased stress levels by 13%. These results suggest that fractal patterns elicit a positive perceptual and physiological response compared to non-fractals. On the other hand, striped patterns were more likely to cause visual discomfort because they have Fourier amplitude spectra that depart maximally from those of natural scenes (A. J. Wilkins, 2016). A study that examined visual comfort in schools suggested that Venetian blinds can cause pattern glare because of the spatial frequency of sunlight patterns projected through them (Winterbottom & Wilkins, 2009). Despite the prevalence of Venetian blinds and subsequently striped light pattern, there has been a lack of studies that investigated differences in visual comfort between fractal and non-fractal light patterns.

Previous studies showed that visual interest ratings typically peaked for mid-complexity fractals when the pattern was viewed on a computer screen. In two previous studies by the authors (Abboushi et al., 2017) the fractal fluency theory has been expanded to investigate perceptual response –visual interest and mood– to spatially projected fractal light patterns. Results of these studies suggested that projected fractal light patterns of mid to mid-high complexity (D=1.5-1.7) were more visually interesting than those in Euclidean shapes such as striped and rectangular patterns. Further, unlike Euclidean shaped light patterns, projected fractal light patterns maintained a better balance between relaxation and excitement. These findings formed the basis of this study. Figure 5.1 shows the patterns examined in these two previous studies and the selected patterns that were used in the current study.

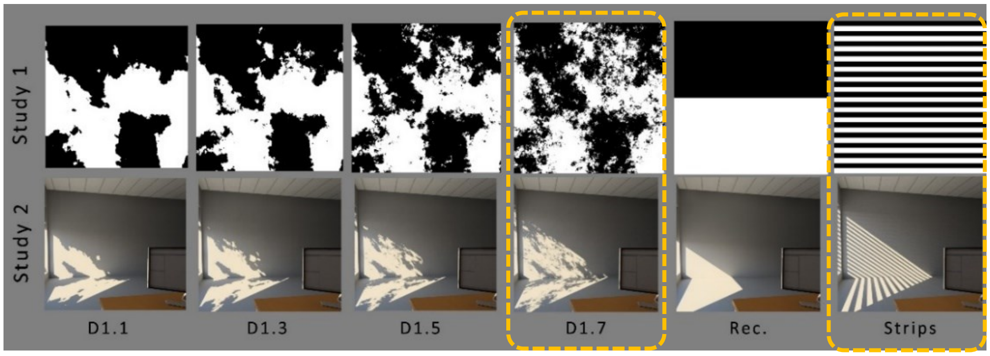


Figure 5.1: The six projected light patterns tested in the previous two studies, with selected patterns highlighted.

5.2. The Conceptual Model and Hypotheses

Based on the literature reviewed in sections 1.1 through 1.3, this study hypothesizes that the visual interest of sunlight patterns and visual comfort would have an influence on visual preferences towards sunlight patterns (Figure 5.2), following the idea that occupants perceive and react to their environments in a systemic manner (Elzeyadi, 2002). We hypothesize that: 1) the Fractal pattern to be associated with a significant increase in visual comfort ratings, compared to the Striped pattern and clear conditions; 2) the Clear condition to be associated with significantly lower visual comfort ratings compared to the two patterns; 3) the Fractal pattern to be associated with a significant increase in visual interest, compared to Striped and Clear conditions; 4) mean view quality ratings for the Clear condition to be higher than that for the Fractal and Striped conditions. In addition to direct effects, this study aims to explore indirect and interactive effects, such as those between views and different window conditions.

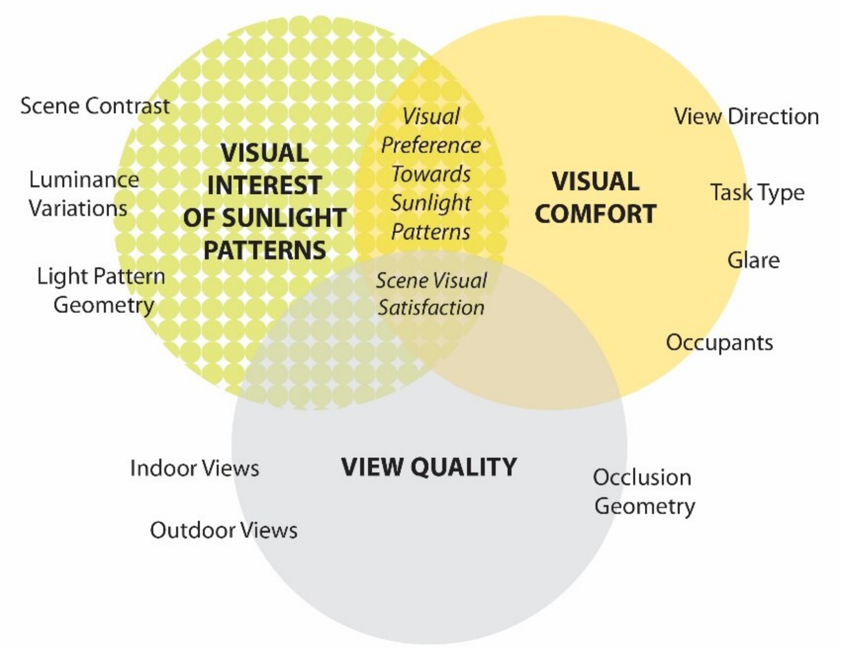


Figure 5.2: A conceptual model shows the relationship between visual interest, visual comfort, and visual preferences towards sunlight in office environments. Visual preference towards sunlight patterns is visual comfort moderated by the visual interest of sunlight patterns.

5.3. Methods

5.3.1. Research setting

The study was conducted at an office building in San Francisco, CA over a period of five weeks (June.27-July.27) during the summer of 2017. The building is a 20-story Class A office building with a LEED Platinum certification (Figure 5.3). Within this building, cubicles located on floors 13-18 on the South-East (SE) or South-West (SW) facades constituted the sample frame from which participants were recruited and selected. This allowed for different sunlight conditions to be examined and increased the number of potential participants (Figure 5.4). Prior to the start of this study, overshadowing by nearby buildings was examined using SunEye 210 Shade Tool (of Solmetric Inc.) to ensure that all windows of selected cubicles have an unobstructed sunlight access. The office is based on an open-plan layout with 152.4cm (5 feet) high partitions. The selected cubicles were adjacent to exterior windows, which had light gray roller shades (manufacturer) with an openness ratio of 3%. The windows varied slightly in size, however generally each window measured 1.98 x 1.98 m (6.5 x 6.5 feet). Figure 5.5 shows images of the cubicle layouts.

Figure 5.3: A picture of the SW main façade (Left); southern corner (Middle); and an aerial view showing surrounding buildings and urban context (Right).

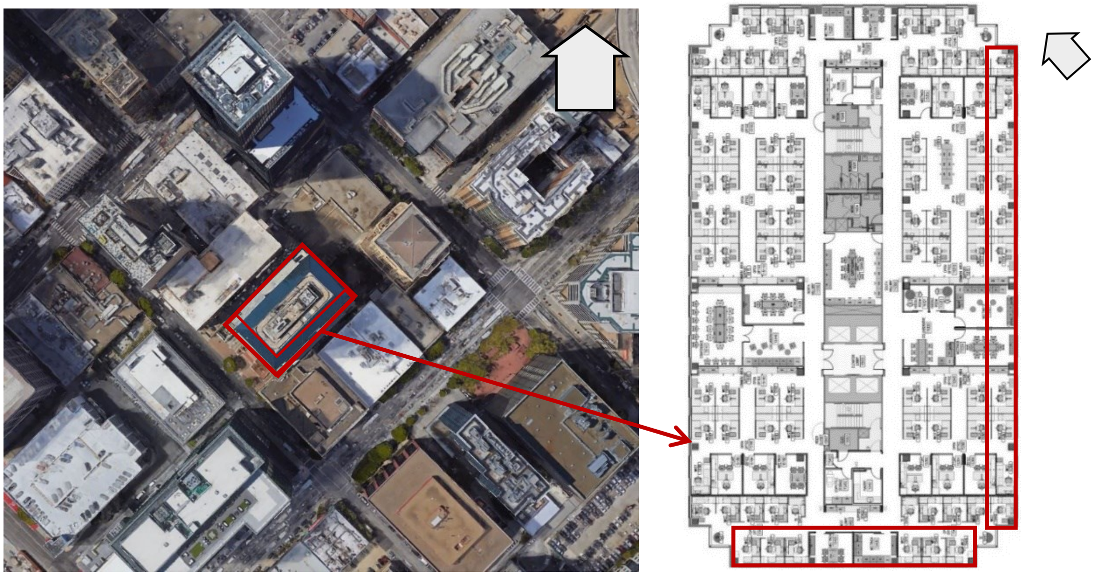


Figure 5.4: Building location and surroundings (left), and a typical floor plan of the offices (right). Workstations on SE and SW facades are circumscribed.

Figure 5.5: Representative workstation layouts: perpendicular to the window (left and middle), and parallel to the window (right).

5.3.2. Window conditions

Three window conditions were created by mounting a plastic film on participant's window: a Fractal pattern, Striped pattern, and Clear conditions. The two patterns which were printed on a clear plastic film. Each pattern measured 198x91 cm (6.5x3 feet) and was mounted on the lower part of participants' windows. The fractal pattern is a medium-high complexity with (D=1.7), which was shown in a previous study (under review) to be significantly more visually interesting than the striped pattern. On the other hand, the striped pattern consisted of clear and black horizontal stripes (Figure 5.6).

Window shades were adjusted at a height of 91 cm (3 feet) to reduce the possibility of intolerable glare being experienced for a long duration by participants. This was implemented to ensure that glare levels do not impede the ability of participants to conduct their work, which may lead to their withdrawal from the study. Further, the resultant pattern size made it more convenient for the researcher to swap the patterns. None of the participants stopped their participation amid the study.

Figure 5.6: The three-sunlight condition at a participant's workstation.

5.3.3. Participants

Participation in this study was voluntary. The recruitment process started by sending an email to occupants in workstations directly next to a window on the SE or SW facades to explain the study and to identify potential participants. Those that expressed interest in participating were sent a consent form that outlined different aspects of the study. A total of 33 participants whose ages ranged from 30-70 years completed the study. Most participants (51.5%) were 50-59 years of age. As for gender, 48.5% were male and 51.5% were female. Workstations were either perpendicular to the window (15 on SE, 3 on SW) or parallel to the window (5 on SE, 10 on SW). Figure 5.7 shows the number of responses received each week (left) and percentage of participants within each age group (right).

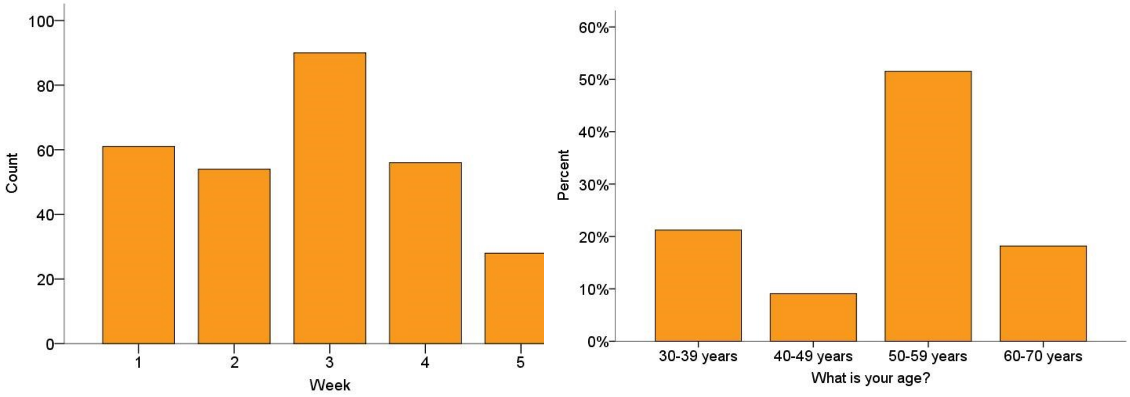


Figure 5.7: Questionnaire responses collected each week (left); and participants' age percentages (right).

To explain study procedure, showcase the sensors, and demonstrate interaction with the questionnaire, a 1-hour orientation session was scheduled with participants prior to the start of the study. This session helped answer questions about participant's role and participation times they are required to take the questionnaire. In this session, participants chose the weeks in which they would be available to participate. This helped coordinate with participants for different study weeks such that a maximum of ten participants were scheduled for a given week. The decision to schedule a maximum of 10 participants per week was determined based on the available 10 data collection stations. This also helped ensure that there is enough time for the researcher to retrieve data and relaunch data loggers and cameras.

5.3.4. Data collection

Physical measurements, as well as visual and thermal comfort assessments by occupants, were collected throughout the study. These two datasets were then paired with each other using the time stamps.

5.3.4.1. The questionnaire

The questionnaire was displayed and answered on a tablet that utilized an offline application to collect responses at three times a day: 9 am, 11 am, and 3 pm. The participants were notified of these three times by a quiet alarm that would stop when a questionnaire was completed, or can be snoozed for 10 minutes. These three times were selected to examine different sunlight exposure conditions. In addition to these times, participants were encouraged to take the questionnaire at any other time. Participants were informed that in case he/she is away for a meeting or not at his/her desk at these times, they can take the questionnaires before leaving or after arrival. The questionnaire comprises of 4 questions (Table 5.1). Each participant was assigned a unique identifier which he/she selected prior to answering each questionnaire. The same identifier was used to identify the tablet as well as the camera and all other sensors. A total of 289 responses were collected, 126 of which were taken when sunlight was present in space.

Item number	Question	Scale
Q1	This is a visually comfortable environment for office work	7-point Likert scale (Strongly Agree-Agree-Somewhat agree-Neither agree nor disagree-Somewhat Disagree-Disagree-Strongly disagree).
Q2	Sunlight patterns look visually interesting	
Q3	I like the view I have from the window	
Q4	Air temperature feels:	7-point semantic differential (Too Warm-Neutral-Too Cold).

Table 5.1: The questionnaire instrument and scales used.

5.3.4.2. Physical measurements

Physical measurements included vertical illuminance (Ev), high dynamic range images (HDRIs), air temperature, globe temperature, and relative humidity. All measurements were logged at a 5-minute interval except for the HDRIs, which were automatically captured every 10 minutes. The cameras used were 5 Canon PowerShot G11 and 5 Canon PowerShot G15 equipped with a 150° fisheye lens (Opteka 0.2x HD Professional Super AF Fisheye). The HDRI capturing process was automated using a script (Ultimate Intervalometer CHDK script) that took 9 images at different shutter speeds typically ranging 1/60 – 1/4000 at F-stop=2.8 from 8 am to 5 pm.

To generate a reliable luminance response curve, each camera was used to capture a series of low dynamic range imagers of a daylit room that included sunlight patterns. The response curve for each camera was then derived using ‘Photosphere software’ (Anyhere software), and then used for all subsequent HDRIs captured by that camera. The Hdrgen Radiance command line (Anyhere software) was used to automate the HDRI creation process. Lens vignetting correction for each camera was determined by taking an HDRI at 5° increments and examining luminance reduction of a gray card across different angles compared to the HDRI taken at 0°, as described by Inanici (2006). The resultant values were plotted as a function of the angle to extract the fit line polynomial equations. These equations were then used to create a grayscale (.TIF) image that was used for vignetting correction.

The photometric sensors were of Licor-210 type connected to a HOBO data logger via a custom amplifier. The amplifier was used to amplify the small signal of the sensor (30 µA per 100 klux) to a voltage 0-2.5v that can be recorded by the HOBO data logger via its external channel. All light sensors were calibrated prior to the start of the experiment. The calibration process was conducted by placing all light sensors (each connected to a HOBO data logger) along with a reference light sensor (connected to LI-1400 logger) next to each other on a desk next to a window. Light measurements were collected from all sensors at a 1-minute interval for approximately 6 hours so that different daylight and electric lighting conditions were included. Regression coefficients were calculated for each one of the 10 sensors. The error margins were typically within +-5% of the reference sensor. The calibration procedure and the amplifier used were similar in design to those used by Konis (2011).

Lastly, the globe temperature was collected using thermistors (NTC Thermistor 10k ohm ±0.1°C) suspended at the center of a black painted ping pong balls. The fabricated sensor was connected to a HOBO data logger via its external channel. Measurements were recorded as volts (0-2.5 v) which were used to calculate globe temperature using Steinhart's equation. Figure 5.8 shows equipment setup.

Figure 5.8: Typical equipment setup.

5.3.5. Study schedule

The study was conducted over a five-week period. Each week, a maximum of 10 participants were recruited. Each participant experienced the three different sunlight conditions over three consecutive days (one condition/day). The two patterns were randomized across participants for Days 1 and 2. For example, some participants started with the Fractal pattern while others started with the Striped pattern. The third day was consistently for the Clear condition. Swapping between these three window conditions was typically conducted at the end of work day after which no questionnaire responses were recorded in that day. Table 5.2 shows study weekly schedule and tasks performed on each day.

Day	Description	Notes
0	Equipment setup	Pattern 1 is mounted on the window in preparation for day 1.
1	Pattern 1 (Fractal or Stripes)	Pattern 2 is mounted at end of the workday in preparation for day 2.
2	Pattern 2 (Fractal or Stripes)	All patterns are removed at the end of the workday in preparation for day 3.
3	Clear	
4	Equipment retrieval	All data were downloaded prior to relocating equipment to a new participant.

Table 5.2: Schedule of data collection procedures followed each week. Data collection was conducted on days 1, 2, and 3. The two patterns were randomly counterbalanced across all participants.

5.3.6. Data cleaning and analysis

Data were initially collected from 35 participants, however, the HDR cameras were accidentally unplugged for two participants, hence were excluded from analyses. Extensive spot checking was conducted to verify the accuracy of dataset merging processes. Responses collected on equipment setup day, those collected after 5 pm, as well as additional responses provided outside the three experimental days were excluded from analyses. Data analyses were conducted with a focus on sunlight patterns and view direction.

5.4. Results

Three statistical analyses were utilized in this study: first, descriptive statistics were used to examine general differences and similarities in physical measurements and questionnaire responses among the three window conditions; second, Spearman's rho correlation coefficients were utilized to examine correlations between subjective visual comfort ratings and illumination measurements; third, multiple regression analyses were conducted to examine associations between window condition, visual comfort, visual interest of sunlight patterns, and view quality ratings. Specifically, multiple regression analyses allowed for statistically controlling certain variables such as glare level while examining differences among different window conditions.

In multiple regression analyses, two window conditions, Fractal and Clear, were entered as dummy variables whereas the third window condition, Stripes, served as a reference group. The selection of the reference group was due to the interest in assessing whether there were differences between the Fractal and the Striped patterns. The DGP metric was entered in multiple regressions to control for variability in daylighting conditions across all study days. A total of 289 responses were included in the analyses, 114 of which were completed with sunlight patterns present in space.

5.4.1. Descriptive statistics

Participants located in workstations at the SE and SW facades experienced a wide range of daylight conditions exemplified by variations in vertical illuminance (E_v) and DGP over the course of the day. Given solar orientation, E_v values were typically higher in the morning for SE participants and lower in the afternoon, compared to those on the SW façade. Overall, E_v ranged from 104.6 to 9589.9 lux, with a Mean of 1710.1 lux and a standard deviation (SD) =1584.1 lux. As can be seen in Figure 5.9(left), E_v range was higher at the Clear condition, compared to the two patterns, which exhibited similar E_v ranges. Generally, E_v values were higher at the SE façade (Mean= 1987.2 lux) than at the SW façade (Mean= 1265.7 lux), particularly under the two patterns. As for glare levels, DGP exhibited more variation under the Clear condition (SD=0.12) compared to the Striped and Fractal conditions (SD=0.06). Mean DGP values were 0.26, 0.32, and 0.26 for the Fractal, Clear, and Striped conditions, respectively. Figure 5.9/ middle shows a boxplot of DGP values by window condition.

Regarding thermal comfort during the study, air temperature generally ranged from 68° F to 82° F with a Mean of 74.5° F. Relative humidity ranged from 32.2% to 62.2% with a mean of 50.5%. The two patterns had similar air temperature distributions and means (74.2°F for the Fractal, and 74.1°F for the Striped pattern), whereas it was slightly higher for the Clear condition at 75.3°F.

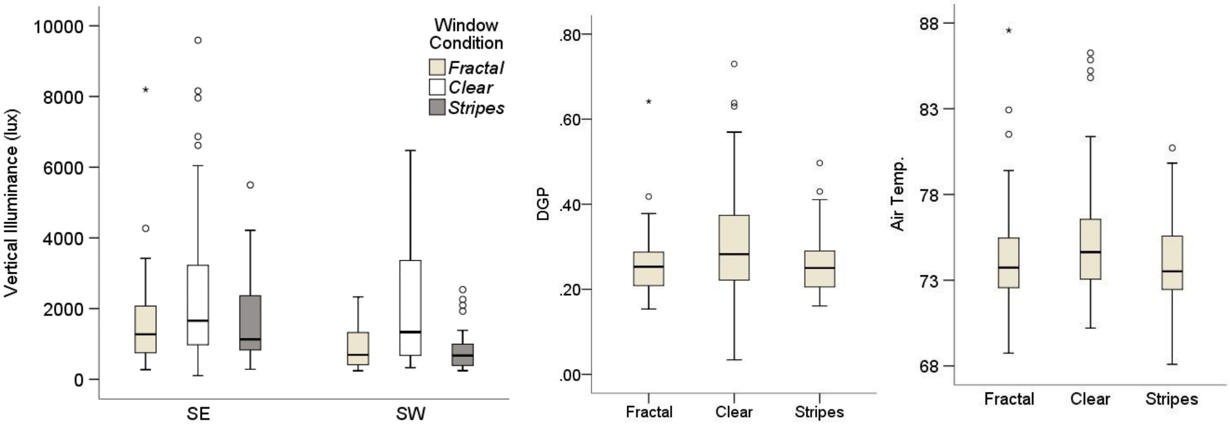
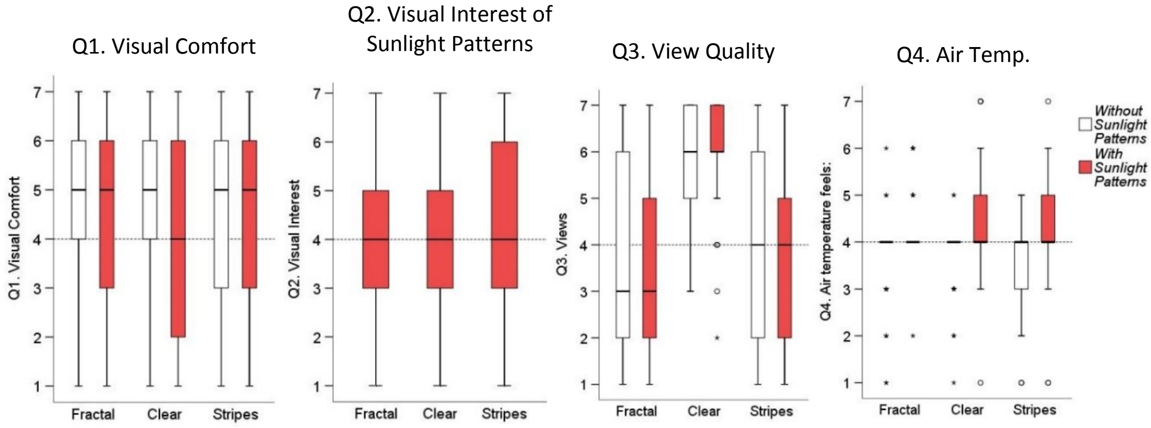


Figure 5.9: A boxplot of vertical illuminance for all participants by façade orientation and window condition (left); a boxplot of DGP (middle) and air temperature in Fahrenheit (right) across the three

Questionnaire responses varied across the three window conditions. Visual comfort responses were slightly lower when sunlight patterns were present in space (mean=4.19, SD=1.85), compared to responses without sunlight pattern (mean=4.79, SD=1.72). Expectedly, view ratings (Q3) for the clear condition (mean=6.01, SD=1.13) were notably higher than those for the two patterns (mean=3.55, SD= 2.10; mean=3.78, SD=1.98 for the Fractal and Striped patterns respectively). Further, median view rating for the striped condition was higher than that for the Fractal pattern condition (Figure 5.10). Because illumination and thermal conditions varied across participants and across the three test days for each participant, these box plots were only utilized to infer general trends like that of the higher ratings for Clear views compared to the two patterns. To examine differences among the three window conditions in questions 1-3, there is a need to control for glare, which is addressed by multiple regression analyses. Table 5.3 shows a summary of descriptive statistics for questionnaire responses and physical measurements across the three window conditions.


Q1. Visual Comfort

Q2. Visual Interest of Sunlight Patterns

Q3. View Quality

Q4. Air Temp.

Figure 5.10: Box plots for visual comfort, visual interest, views, and air temperature by window condition and presence of sunlight patterns. For Q1, Q2, and Q3: 1=Strongly disagree, 7=Strongly agree. For Q4, 1= Too cold, 7= Too warm, and 4= neutral.

	Fractal				Clear				Stripes			
	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD
Questionnaire												
Q1. Visual Comfort	1.0	7.0	4.5	1.6	1.0	7.0	4.5	1.9	1.0	7.0	4.6	1.9
Q2. Visual interest	1.0	7.0	4.1	1.6	1.0	7.0	4.1	1.6	1.0	7.0	4.2	1.9
Q3. Views	1.0	7.0	3.6	2.1	2.0	7.0	6.0	1.1	1.0	7.0	3.8	2.0
Q4. Air temp.	1.0	6.0	3.9	0.9	1.0	7.0	4.1	1.0	1.0	7.0	3.9	1.0
Physical Measures												
Air Temp.	68.7	87.6	74.2	2.8	70.2	90.9	75.3	3.6	68.1	80.7	74.1	2.4
Relative Humidity	32.3	60.3	51.2	4.6	32.5	62.3	49.4	4.7	41.4	59.5	51.0	4.1
MRT	63.7	83.2	73.0	3.3	59.6	99.6	74.4	5.7	67.8	86.9	73.6	3.6
E_v	243	8195	1336	1130	105	9590	2438	2053	247	5498	1314	1059
Mean luminance	79	2454	361	322	24	2788	645	546	70	1625	349	288
DGP	0.15	0.64	0.26	0.07	0.03	0.73	0.32	0.12	0.16	0.50	0.26	0.07

Table 5.3: Descriptive statistics for questionnaire responses and physical measurements across the three window conditions.

5.4.2. Visual comfort

Overall, visual comfort ratings varied by façade orientation, view direction, sunlight presence, and window condition. To examine differences in visual comfort across the three window conditions, two multiple regression analyses were conducted. The first model divided responses by 'presence of sunlight patterns' and view direction to examine general differences in visual comfort that are common to all participants on both façade orientations. The second model delved into examining differences by façade orientation to account for differences in daylight conditions between the SE and SW façades.

Results from the first model (Table 5.4) showed no significant differences in visual comfort ratings when sunlight patterns were present in space. Significant differences were only observed in scenes without sunlight patterns and for those perpendicular to window, where the Clear and Fractal conditions were associated with a significant increase in visual comfort ($p<0.05$ and $p<0.1$, respectively). Interestingly, the relationship between DGP and visual comfort ratings was only significant for those parallel to the window regardless of the presence of sunlight patterns.

To account for differences in daylight conditions on each façade, multiple regression analyses were conducted including façade orientation in the second model (Table 5.5). The results showed that on the SE façade, and in scenes without sunlight patterns, the Fractal pattern was associated with a significant increase in visual comfort for those perpendicular to window ($p<0.01$). The Striped pattern, on the other hand, was associated with a significant increase in visual comfort, compared to the Fractal condition, for those parallel to window in scenes with or without sunlight patterns ($p<0.1$).

For participants on the SW façade, there were no significant differences among the three window conditions under either view direction, hence results for the SW façade were not included in Table 5.5. Overall, these results suggest that view direction and façade orientation influenced visual comfort ratings under the different window conditions. Figure 5.11 shows mean visual comfort ratings for participants on the SE façade for both view directions.

			Unstandardized Coefficients	
			B	Std. Error
Without sunlight patterns	Perpendicular to window	(Constant)	4.055	.743
		DGP	.880	2.705
		Fractal	.790*	.418
		Clear	1.049**	.432
	Parallel to window	(Constant)	7.782	1.166
		DGP	-12.964**	5.067
		Fractal	-.519	.485
		Clear	.097	.538
With sunlight patterns	Perpendicular to window	(Constant)	5.086	.727
		DGP	-2.391	1.861
		Fractal	.186	.569
		Clear	-.244	.522
	Parallel to window	(Constant)	7.566	.935
		DGP	-11.182**	3.310
		Fractal	-.729	.590
		Clear	-.166	.609

Table 5.4: The dependent variables is the Visual Comfort (Q1). The reference window condition is the Striped pattern condition. All models are estimated through ordinary least squares. One, two, and three stars indicate 10 percent, 5 percent, and 1 percent significance, respectively.

				Unstandardized Coefficients	
				B	Std. Error
South-East Facade	Without Sunlight Patterns	Perpendicular to Window	(Constant)	3.262	.798
			DGP	2.360	2.825
			Fractal Pattern	1.218***	.453
			Clear	1.526***	.460
		Parallel to Window	(Constant)	7.479	2.450
			DGP	-5.773	10.489
			Fractal Pattern	-1.514*	.861
			Clear	-.679	.851
	With Sunlight Patterns	Perpendicular to Window	(Constant)	4.566	.781
			DGP	-1.501	1.960
			Fractal Pattern	.246	.595
			Clear	.284	.572
		Parallel to Window	(Constant)	9.236	1.008
			DGP	-14.014***	3.527
			Fractal Pattern	-1.190*	.658
			Clear	-.228	.652

Table 5.5: The dependent variables is the Visual Comfort (Q1). The reference window condition is the Striped pattern condition. All models are estimated through ordinary least squares. One, two, and three stars indicate 10 percent, 5 percent, and 1 percent significance, respectively.

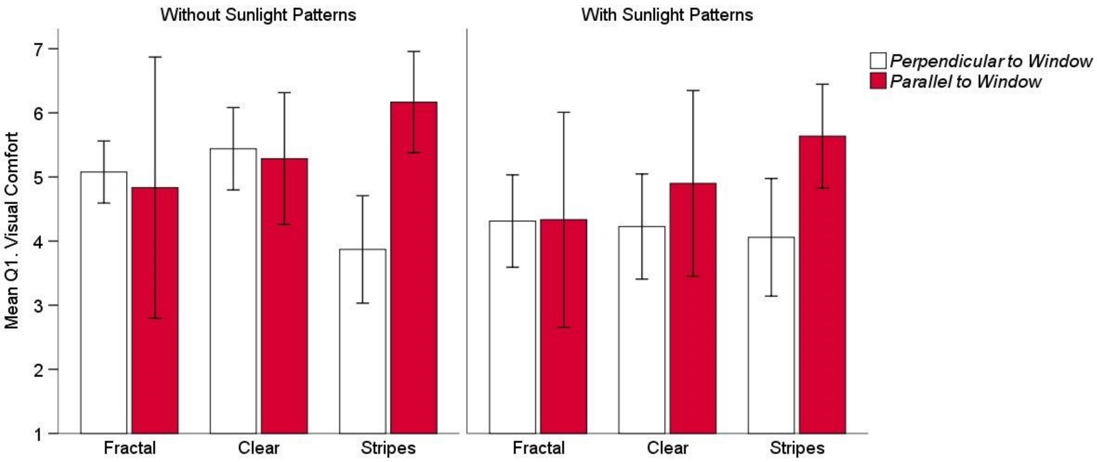


Figure 5.11: mean visual comfort rating for participants on the SE façade divided by the presence of sunlight patterns and view direction. The error bars represent 95% confidence intervals.

5.4.3. Correlations

Spearman's rho correlation coefficients were examined between subjective visual comfort ratings (Q1) and objective illumination metrics. These correlations showed that there wasn't one metric that consistently showed significant correlations across different window and sunlight conditions. Further, when sunlight patterns were present in space, no significant correlations were found under the Fractal or Striped conditions, whereas there were several significant correlations under Clear condition. Among the metrics that significantly correlated with the Clear condition in sunny scenes are vertical illuminance, mean luminance, and DGP. Responses were examined by view direction to investigate differences. For those perpendicular to the window, DGP showed a significant correlation (-0.16, $p<0.05$) but vertical illuminance and DGI did not. On the other hand, for those parallel to the window, vertical illuminance, DGI, and DGP showed significant correlations with visual comfort ratings (-0.34, -0.36, -0.42, $p<0.01$), respectively.

When all responses were collectively examined, most objective measures showed significant correlations with visual comfort ratings. Specifically, the DGP and Discomfort Glare Rating (DGR) metrics, which showed highest correlations coefficients (0.26, $p<0.01$). Because the DGP metric incorporates vertical illuminance, a component that may explain discomfort for occupants seated close to windows (Hirning et al., 2017), it was chosen to control for glare level in multiple regression analyses in the previous visual comfort analyses and those in next sections.

		Q1. This is a visually comfortable environment for office work						
		Without Sunlight Pattern			With Sunlight Patterns			All
		Fractal	Clear	Stripes	Fractal	Clear	Stripes	
Vertical Illuminance		-0.26	.37**	-.36**	-0.14	-.34*	-0.27	-.22**
Mean luminance		-0.22	.38**	-.27*	-0.10	-.38**	-0.23	-.21**
Mean Luminance weighted by position index		-.30*	.33*	-.36**	-0.16	-.33*	-0.297	-.24**
Median luminance		-0.04	.44**	-0.03	-0.08	-.33*	-0.09	-.12*
Median luminance weighted by position index		-0.08	.45**	-0.04	-0.02	-.32*	-0.19	-.14*
Omega of sources		-0.15	-.44**	-.34*	-0.16	-0.05	-0.05	-.19**
40° Band	Mean luminance	-.29*	.34*	-0.23	-0.15	-.32*	-0.22	-.19**
	Max. luminance	-0.06	0.09	0.10	-0.12	-.32*	0.09	-0.10
	Median luminance	-0.24	.46**	0.13	-0.10	-.32*	-0.24	-0.11
	75th percentile	-0.19	.35*	-0.20	-0.08	-0.27	-0.27	-.15**
	95th percentile	-0.22	0.20	-0.19	-0.13	-.34*	-0.14	-.21**
	Standard deviation	-0.18	0.17	-0.11	-0.17	-.33*	-0.10	-.18**
CIE Glare Index (CGI)		-0.26	-.35*	-0.26	-0.18	-0.24	-0.08	-.24**
Discomfort Glare Index (DGI)		-0.20	-.41**	-0.25	-0.04	-0.25	0.03	-.22**
Discomfort Glare Probability (DGP)		-.33*	0.21	-.37**	-0.18	-.34*	-0.28	-.26**
Unified Glare Probability (UGP)		-0.24	-.40**	-0.24	-0.18	-0.23	-0.07	-.23**
Unified Glare Rating (UGR)		-0.24	-.40**	-0.24	-0.18	-0.23	-0.07	-.23**
Visual Comfort Probability (VCP)		.28*	.36*	.30*	0.25	0.23	0.09	.25**
Discomfort Glare Rating (DGR)		-.28*	-.36*	-.30*	-0.25	-0.23	-0.09	-.26**

Table 5.6: Spearman's rho correlation coefficients between visual comfort (Q1) and objective illumination measurements and metrics. In addition to correlations with all responses, responses are divided by presence of sunlight and window condition. One, two and three stars indicate 10 percent, 5 percent, and 1 percent significance, respectively.

5.5. Discussion

The analyses described in the results section showed that differences in visual comfort ratings varied by window condition, view direction, and presence of sunlight patterns. Consistently, both models 1 and 2 showed a significant reduction in visual comfort for the Fractal pattern, compared to the Striped pattern, for those parallel to the window. Further, the results showed that the Fractal pattern was associated with a significant increase in visual comfort for those perpendicular to the window and in scenes without sunlight patterns. These differences between the Striped and Fractal patterns could be due to differences in luminance distributions, reflections on computer screen for those parallel to window, the visual interest of the window patterns, the duration of time spent looking outdoor through the window, and/or view quality. Particularly, qualitative differences in daylight conditions could be the discriminating factor because glare level, as measured and represented using DGP, was controlled for in these comparisons. Overall, these results suggest that the Fractal pattern might contribute to improving visual comfort for large-sized and relatively uniform glare sources when looking perpendicular to window, e.g. under overcast sky conditions. However, this hypothesis requires further studies to verify it. The following sections examine differences in visual interest and view ratings to help understand how visual interest and views might have influenced visual comfort ratings.

5.5.1. Visual interest of sunlight patterns

Visual interest ratings varied by view direction such that mean visual interest for the Fractal sunlight patterns was higher for participants perpendicular to the window, compared to those parallel to the window. To investigate the significance of differences in visual interest ratings (Q2), multiple regression analyses were utilized. The results showed that, compared to the Striped pattern, the Fractal pattern was associated with a significant increase for those perpendicular to the window and a significant decrease for those parallel to the window (Table 5.7). There were no significant relationships between the Clear condition and visual interest ratings for both view directions.

		Unstandardized Coefficients	
		B	Std. Error
Perpendicular to Window	(Constant)	4.988	.737
	DGP	-2.699	1.961
	Fractal	1.020*	.525
	Clear	.436	.506
Parallel to Window	(Constant)	5.265	.922
	DGP	-3.754	3.308
	Fractal	-1.067*	.547
	Clear	-.440	.612

Table 5.7: The dependent variable is the Visual Interest of Sunlight Patterns (Q2). Reference window conditions is the Striped pattern. All models are estimated through ordinary least squares. One star indicates 10 percent significance.

When visual interest ratings were examined by façade orientation, the Fractal pattern condition was associated with a significant increase ($p<0.1$) for those parallel to the window, and a significant decrease for those parallel to the window ($p<0.05$) on the SE façade. No significant differences were found on the SW façade (Table 5.8). This could be due to differences in sunlight pattern size and geometry in workstations on the SW compared to those on the SE façade. In this study, one set of the three daily responses was collected when sunlight patterns can access the SW workstations (at 3:00 pm), which resulted in relatively shorter sunlight penetration and smaller sunlight patterns compared to the SE façade, as can be seen in Figure 5.12.

			Unstandardized Coefficients	
			B	Std. Error
South-East Facade	Perpendicular to Window	(Constant)	4.685	.795
		DGP	-2.024	2.083
		Fractal Pattern	1.006*	.539
		Clear	.642	.568
	Parallel to Window	(Constant)	7.517	1.114
		DGP	-9.444**	4.001
		Fractal Pattern	-1.682**	.640
		Clear	-.187	.759

Table 5.8: The dependent variable is the Visual Interest of Sunlight Patterns (Q2). Reference window conditions is the Striped pattern. All models are estimated through ordinary least squares. One or two stars indicate 10 percent, 5 percent significance, respectively.

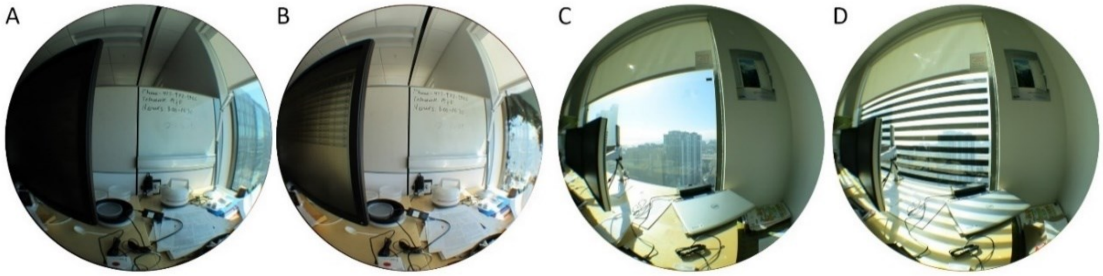


Figure 5.12: Sunlight patterns on the SW façade at 3:00 pm (A, B); and on the SE façade at 9-9:30 am (C, D).

Figure 5.13 shows mean visual interest ratings on the SE façade by window condition and view direction. While the visual interest for Fractal sunlight patterns was significantly higher than that for the Striped ones, this was not associated with a significant increase in visual comfort as discussed in Section 3.2. On the other hand, the visual interest for the Striped pattern outperformed the Fractal for those parallel to window, which is like the relationships found in visual comfort analyses. This suggests that visual interest ratings from those parallel to

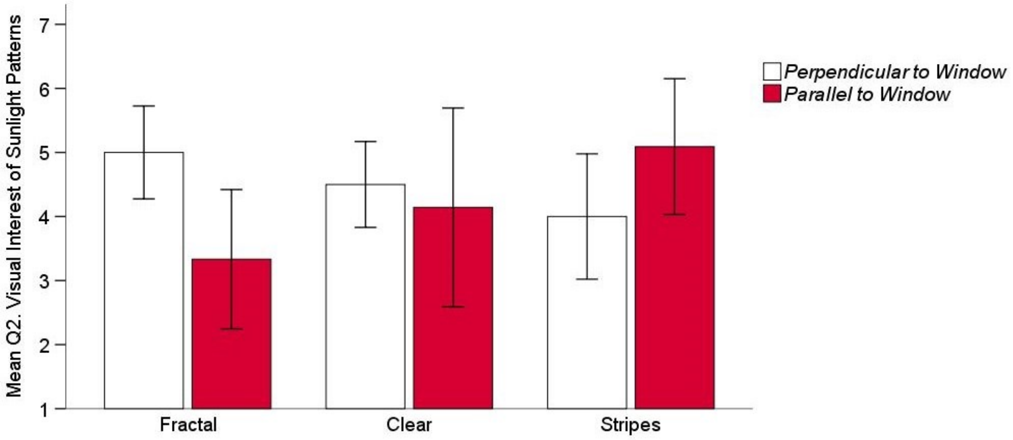


Figure 5.13: Mean visual interest rating for the three window conditions by view direction on the SE facade. The error bars represent 95% confidence intervals.

window could be associated with their visual comfort assessments. It is unclear, however, whether the visual interest influenced visual comfort or vice versa, and the extent of this interaction.

5.5.2. View quality

Generally, view quality ratings were higher for participants perpendicular to the window compared those parallel to the window, as can be seen in Figure 5.14. This suggests that view quality ratings could be influenced by occupant's view direction. Means of view quality for those perpendicular to the window were 4.18, 6.18, and 3.8 which are consistently higher than for those parallel to the window with means of 2.84, 5.75, and 3.76 for the Fractal, Clear, and Striped condition, respectively. Because of the differences in view quality by view direction and presence of sunlight, these two factors were considered in the analyses.

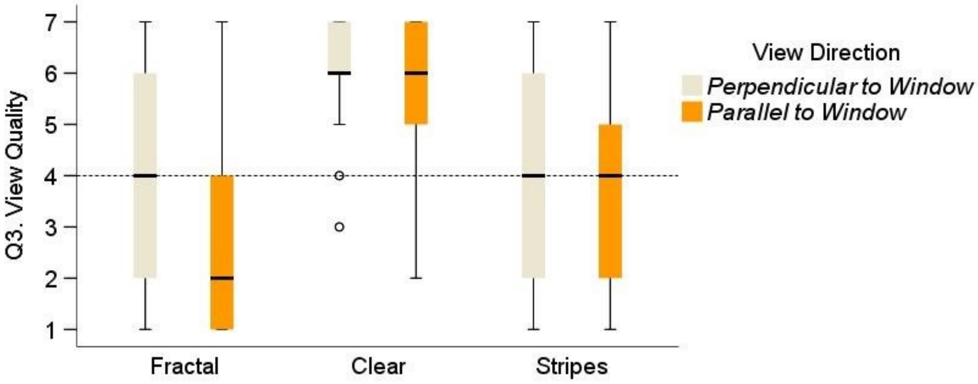


Figure 5.14: A boxplot of view quality ratings by occupant's view direction.

To investigate the significance of differences in view quality ratings, multiple regression analyses were used. First, view quality was examined only by view direction. The results showed that, expectedly, compared to the Clear condition, both patterns were associated with a significant decrease in view ratings ($p<0.01$). Further, compared to the Striped pattern, the Fractal pattern was associated with a significant decrease in view quality for those parallel to the window ($p<0.05$). Second, when responses were broken down by the presence of sunlight patterns (Figure 5.15), this negative association between the Fractal pattern and view quality was specific to responses when sunlight patterns were present in space (Table 5.9). No significant differences in view quality were found between the Fractal and Striped patterns when sunlight patterns were not present.

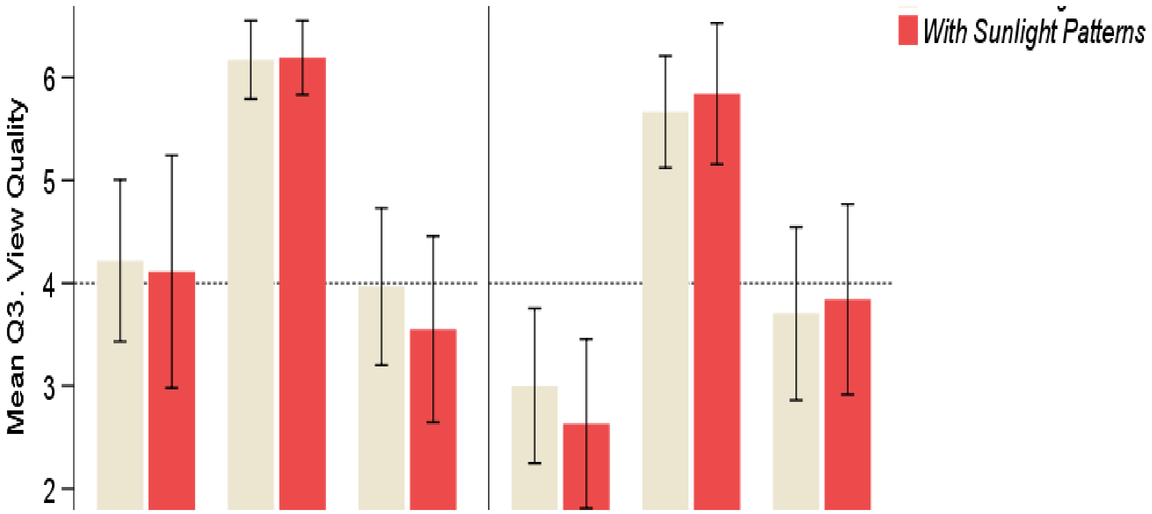


Figure 5.15: Mean view ratings by desk layout and sunlight condition: without sunlight patterns (top), and with sunlight patterns (bottom). * denotes a significant difference at the p<0.05 level. The error bars represent 95% confidence intervals.

			Unstandardized Coefficients	
			B	Std. Error
Without Sunlight Patterns	Perpendicular to window	(Constant)	3.448	.834
		DGP	2.062	3.035
		Fractal	.261	.469
		Clear	2.161***	.484
	Parallel to window	(Constant)	5.608	1.184
		DGP	-8.643*	5.143
		Fractal	-.699	.493
		Clear	2.264***	.547
With Sunlight Patterns	Perpendicular to window	(Constant)	3.292	.704
		DGP	.785	1.804
		Fractal	.566	.551
		Clear	2.583***	.506
	Parallel to window	(Constant)	4.796	.870
		DGP	-3.769	3.078
		Fractal	-1.172**	.549
		Clear	2.175***	.566

Table 5.9: The dependent variable is View quality (Q3). All models are estimated through ordinary least squares. One, two, and three stars indicate 10 percent, 5 percent, and 1 percent significance, respectively.

When view quality was examined by façade orientation (Table 5.10), the Fractal pattern on the SE façade was associated with a significant increase in view quality for those perpendicular to the window (p<0.1), whereas it was associated with a significant decrease in view quality for those parallel to the window (p<0.1). No significant differences in view quality were found between the Fractal and the Striped conditions on the SW façade. On the SE façade and for those perpendicular to the window, mean view quality ratings were 4.21, 6.21, and 3.55

compared to 2.67, 5.88, and 3.76 for those parallel to the window at the fractal, Clear, and Striped conditions, respectively. When the results of the two models are collectively examined, they suggest that the Fractal pattern reduces view quality ratings for those parallel to window on the SE façade or with sunlight patterns in space.

The relationship between view direction and view quality through the two patterns could have been influenced by the duration of time spent looking outdoors through the window pattern. For example, those seated parallel to the window were more likely to spend less time looking towards the window. This hypothesis, however, requires further testing to verify it.

			Unstandardized Coefficients	
			B	Std. Error
South-East Façade	Perpendicular to Window	(Constant)	3.224	.517
		DGP	1.117	1.488
		Fractal Pattern	.674*	.393
		Clear	2.607***	.390
	Parallel to Window	(Constant)	4.336	1.022
		DGP	-2.316	3.775
		Fractal Pattern	-1.119*	.619
		Clear	2.196***	.612

Table 5.10: The dependent variable is View quality (Q3). All models are estimated through ordinary least squares. One, two, and three stars indicate 10 percent, 5 percent, and 1 percent significance, respectively.

Unlike the Striped pattern, the fractal pattern exhibits an irregular distribution of clear and opaque areas. Although clear areas were consistent across the two patterns, it can be argued that the Striped pattern allowed for more uniform and consistent viewing compared to the Fractal pattern. These results highlight an important process in psychological research called ‘masking’ which relates to the reduction in visibility of the one stimulus (views) by another stimulus or mask (window pattern) (Bachmann, 1984). Particularly, the Fractal pattern relates to noise masking, a random dot pattern, whereas the Striped pattern relates to structure masking, shapes similar to view content (Agaoglu, Agaoglu, Breitmeyer, & Ogmen, 2015). Overall, it is possible that the ability of occupants to reconstruct obstructed view regions under the Fractal pattern was lower, compared to the Striped pattern for those seated parallel to the window (Figure 5.16). This effect can be referred to as ‘outdoor view reconstructability’, which is different from the view clarity index (Konstantzos et al., 2015) in that the former is concerned with overall view quality whereas view clarity assessed the ability to distinguish individual elements such as sky condition or color of cars.

Figure 5.16: Participant's views through the Clear (left), Fractal (middle), and Striped (right) window conditions.

A key difference between the clear condition and the two patterns is that each pattern was another stimulus that framed the outdoor views. This poses an important question of whether the pattern becomes part of the view and the extent to which the pattern influences view quality ratings. In this study, we did not collect visual interest ratings of the window pattern itself. Nonetheless, it is expected that view interest ratings would differ from those discussed in section 1.3, mainly because the visual interest of outdoor views would compete with that of the pattern that is occluding it. For example, when patterns are viewed on a white background, the pattern is the sole potential source of visual interest, however, when outdoor views are present, the pattern might be viewed as a distraction that reduces the visual interest of the views. Therefore, when multiple stimuli are present, it is important to consider the visual interest of the overall composite view and not of each stimulus separately.

5.5.3. The Borderline between comfort and discomfort

To explore whether the borderline threshold between comfort and discomfort (BCD) differs among the three window conditions, visual comfort responses were categorized into comfortable (strongly agree, agree, and somewhat agree) or uncomfortable (strongly disagree, disagree, and somewhat disagree). Figure 5.17 shows a boxplot of vertical illuminance by visual comfort response and view direction. Overall, occupants seated parallel to window were visually uncomfortable at lower vertical illuminance ranges compared to those perpendicular to the window. This also lowers the borderline threshold for those parallel to the window in terms of vertical illuminance and DGP.

The BCD values, in terms of vertical illuminance and DGP, were calculated using the midpoint method which calculates the mean of (strongly agree, agree, and somewhat agree) and the mean of (strongly disagree, disagree, and somewhat disagree), then calculates the mean of these two values. The results show only slight differences in BCD between the Fractal and Striped patterns, with notably higher BCD values for the Clear condition, as shown in Table 5.11.

The BCD values for vertical illuminance under the two patterns in the parallel view direction are in line with results of a previous study that identified BCD to be 1250 lux (Van Den Wymelenberg & Inanici, 2014).

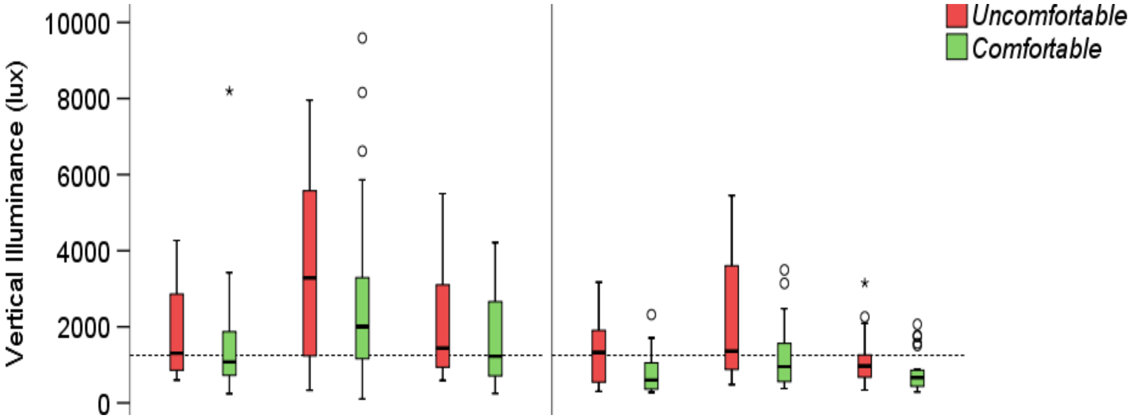


Figure 5.17: Vertical illuminance (lux) Log $_{\text{base 10}}$ ordered by value for each window condition. The x axis represents response number. The dashed line shows the borderline threshold between comfort and discomfort of 1250 lux identified by (Van Den Wymelenberg & Inanici, 2014).

Table 5.11 showed that BCD in terms of vertical illuminance and DGP for under the two patterns were consistently lower those under the Clear condition. This could be due to occupant's adapting to a wider range of daylight conditions under the Clear condition, which might have influenced their visual comfort assessments. In other words, the range of daylight conditions experienced by occupants might have influenced what they considered a visually uncomfortable condition. Examining this hypothesis further can inform the methodological approaches used in future studies. Another potential explanation for the difference is that the relatively higher view quality under the Clear condition might have increased tolerance to glare. This suggests that view quality should be incorporated into glare prediction models.

	Fractal	Stripes	Clear
Perpendicular	1726.4 (0.28)	1829.4 (0.29)	3105.3 (0.35)
Parallel	1028.1 (0.24)	977.6 (0.24)	1760.2 (0.28)

Table 5.11: Vertical illuminance in lux and (DGP) borderline values between comfort and discomfort for each window condition and in two view directions. These values were calculated using the midpoint method as described above.

To examine the influence of visual comfort on visual interest, visual comfort responses were transformed into a binary rating: comfortable and uncomfortable. Figure 5.18 shows mean visual interest ratings by visual comfort. Generally, visual interest ratings were less under visually uncomfortable conditions, compared to visually comfortable ones. Focusing on visually uncomfortable scenes, it can be noticed that mean visual interest of fractal sunlight patterns was higher than that of the Striped pattern for those perpendicular to window. Although the number of responses is reduced, a multiple regression model showed that this difference was significant at the 10% level. On the other hand, the visual interest of fractal and striped sunlight patterns were similar and relatively lower for those parallel to window. These results suggest that fractal patterns might be particularly effective in reducing perceived glare for those perpendicular to window. Further studies are warranted to explore the interdependencies between visual interest, visual comfort, and view quality.

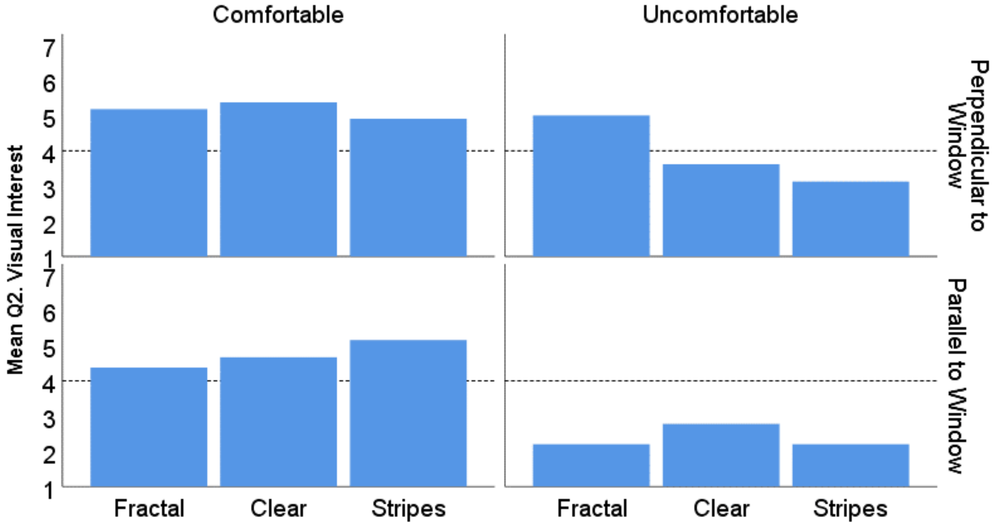


Figure 5.18: Mean visual interest by visual comfort, view direction, and window condition.

In addition to the difference in sunlight pattern size, there were several differences in daylight conditions between the two facades. For instance, in the mornings, sun disc was typically visible through the roller shades on the SE façade but not on the SW façade (Figure 5.19). Particularly because the sun only accessed the SW façade in the afternoon and participants were asked to respond to questionnaire at 3 pm. This might have contributed to the absence of significant differences between the two patterns on the SW façade.

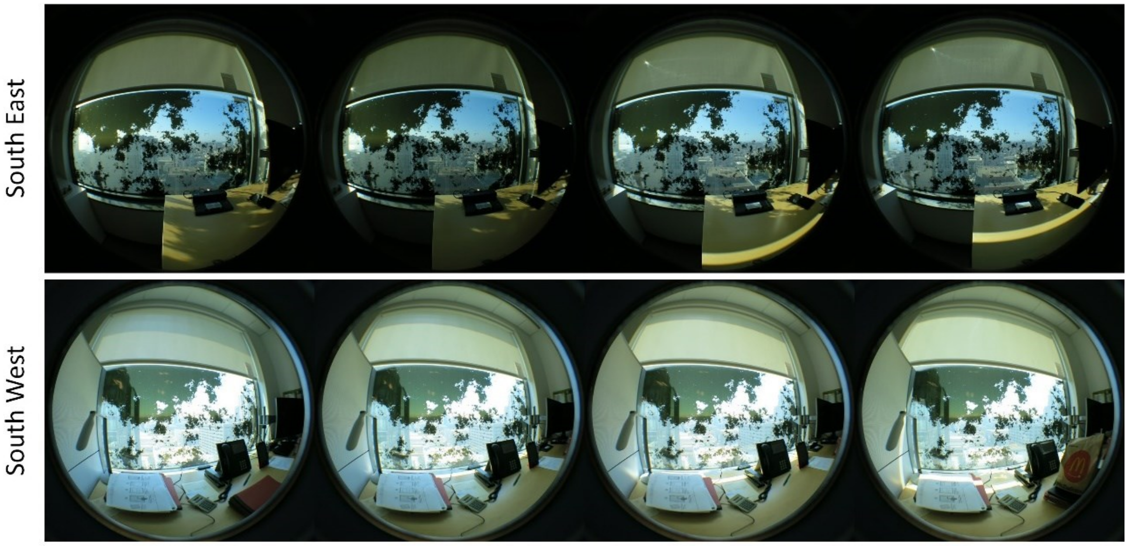


Figure 5.19: Daylight conditions at the south east in the morning and at the south west façade in the afternoon.

5.6. Conclusions

We summarize the conclusions of this study with the following points:

- The Striped window condition was associated with a significant increase in visual comfort ($p<0.1$) over the Fractal pattern condition for those parallel to window on the SE façade and in scenes with sunlight patterns.
- The Fractal pattern was associated with a significant increase in visual comfort ($p<0.01$), compared to Striped condition, for those perpendicular to the window on the SE façade and without sunlight patterns in space.
- Visual interest of sunlight patterns varied by desk layout and façade orientation such that on the SE façade the Fractal pattern was associated with a significant increase in visual interest ($p<0.1$) for those perpendicular to the window, and a significant decrease in visual interest ($p<0.01$) for those parallel to the window.
- Both patterns were associated with a significant decrease in view quality ratings ($p<0.01$).
- Compared to the Striped pattern, the Fractal pattern was associated with a significant decrease in view quality ratings for those parallel to the window ($p<0.1$), whereas it was associated with a significant increase in view quality for those perpendicular to window ($p<0.1$).
- There were no significant differences in visual comfort, view quality, or visual interest of sunlight patterns on the SW façade.

5.7. Limitations

There are several limitations that should be considered when interpreting the results of this study. First, this study was conducted during the summer in San Francisco, CA. and did not include winter sunlight conditions, which might create higher glare levels particularly during early morning and late afternoon periods. Another limitation was the naturally occurring variations in sky conditions, which reduced the possibility of a paired comparison within each subject.

Each window condition was only experienced by each subject for one day. Further, the number of times that each participant completed the questionnaire each day was limited to three times to avoid interrupting their work. Further, the shades were fixed at three feet high to reduce the possibility of participants stopping their participation before completing the study. While none of the participants stopped their participation, the position of the shades mitigated glare levels. Because this is an inherited limitation in field studies, higher glare levels might be more easily explored in controlled experiments.

Most participants (51.5%) in this study were 50-59 years of age, hence their sensitivity to brightness might be different than those in other age groups. Lastly, in this study, we did not apply luminous overflow correction to adjust for peak luminance limitations because the procedures to correct for this are evolving and have not been validated.

CHAPTER VI

SUMMARY OF CONTRIBUTIONS AND FUTURE WORK

This dissertation identified two main goals: first, to examine the perceptual response of projected light patterns; and second, to investigate differences in visual comfort, visual interest of sunlight patterns, and view quality under different window conditions. These two goals were investigated through a series of four studies that addressed different topics related to these goals. When the results of these studies are collectively examined, the results provide insights on the effects of sunlight pattern geometry on occupant's visual interest, comfort, and satisfaction with view quality. The following sections summarize main contributions related to each goal.

6.1. Examining the Perceptual Response of Projected Light Patterns

This goal was examined in Studies 1, 2, and 3 (Chapter 3 and 4) by assessing visual interest and mood response to four fractal light patterns of varying complexities and two non-fractal light patterns. In Study 1, light patterns were directly projected on a wall whereas in Study 2, renderings of an interior space that included simulations of light patterns on the wall and floor of a room were projected. Study 3 examined the effect of distance, between observer and projection wall, on visual interest and visual preference. Overall, results showed that fractal light patterns of medium to medium-high complexity were significantly more visually interesting, as compared to other light patterns. It is possible that visual interest ratings were influenced by spatial variables such as room surfaces and lighting. Study 3 showed that distance did not significantly influence visual interest or visual preference. Regarding mood response, it was found that fractal light patterns provided a better balance between relaxation and excitement compared to Striped and Rectangular patterns.

Results of study 1 suggested that the mid-complexity fractal light pattern D=1.5 was significantly more visually interesting compared to fractal light patterns of D=1.1, D=1.3, D=1.7, and the two Euclidean patterns. The fractal light pattern of D=1.7 was slightly less visually interesting than D=1.5. In Study 2 when light patterns were shown as light patterns in renderings, the fractal pattern with D=1.7 was significantly more visually interesting than all other patterns. Interestingly, the striped pattern was significantly more visually interesting than the fractal with D=1.1. Lastly, the rectangular pattern was significantly less visually interesting than all other patterns.

Results of Study 3 suggest a shift in visual interest compared to results of previous studies. As can be seen in Figure 6.1, there is a difference in the relationship between visual interest and the fractal dimension. This difference was hypothesized to had been influenced by spatial and environmental variables, this hypothesis, however, requires further testing.

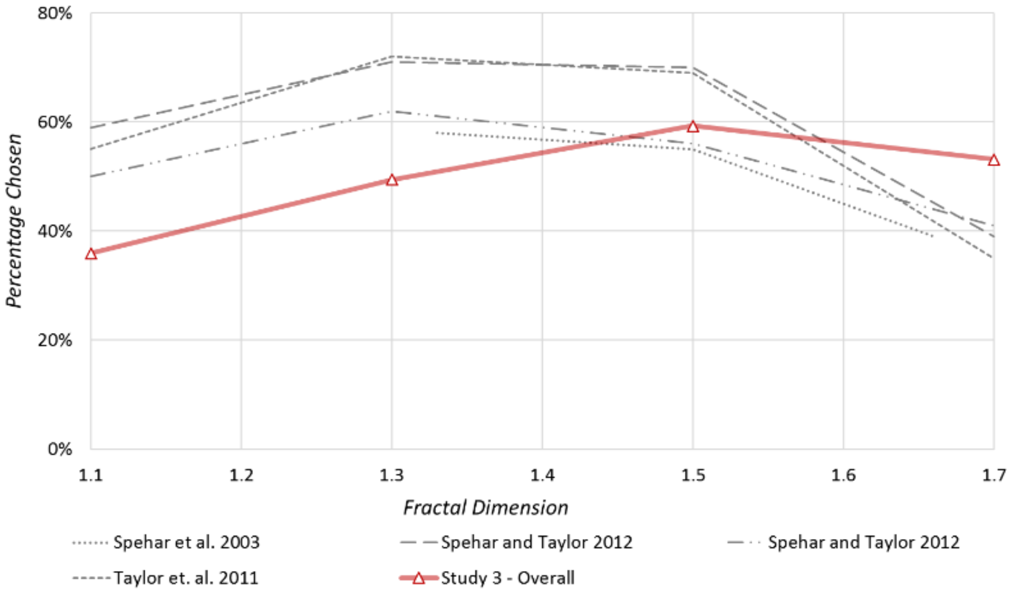


Figure 6.1: Visual preference by D value for previous studies and Study 3.

6.2. Investigating Differences in Visual Comfort, Visual Interest of Sunlight Patterns, and View Quality under Different Window Conditions

This goal was investigated through two studies described in Chapter 5 and Chapter 6. Generally, the results suggest that regardless of the visual interest of the pattern mounted on windows, view quality ratings were significantly reduced under Fractal or Striped patterns compared to the Clear condition. When sunlight patterns were present in space, no significant differences in visual comfort were found between the Fractal and Striped patterns. There were some differences in the visual interest of sunlight patterns when compared to the Clear condition and when examined by view direction.

Study 3 illustrated that the visual interest ratings of the Striped pattern were significantly less than those for Clear condition. It was also suggested that occupants might be able to tolerate low levels of glare in an office setting when an interesting outdoor view of nature is present. The Clear condition received the highest mean ratings for visual comfort and view quality and the differences were statistically significant compared to the two patterns. Overall, this study showed that the visual interest of sunlight patterns was associated with significant increases in visual comfort ratings.

Study 4 concluded that compared to the Striped pattern, the fractal pattern was associated with a significant increase in visual comfort for participants perpendicular to the window and without sunlight patterns in space. It was also found that the visual interest of sunlight patterns was influenced by view direction such that the Fractal pattern was associated with a significant increase in visual interest for those perpendicular to the window, whereas the Fractal pattern was associated with a significant decrease in visual interest for those parallel to the window. While both patterns were associated with a significant decrease in view quality, the Fractal pattern was associated with a significant decrease in view quality for those parallel to the window and when sunlight patterns were present in space.

6.3. Applications

The findings of this dissertation might have implications for improving visual comfort and interest in different fields and industries. The following sections discuss the application of fractal patterns in build environments, the automotive industry, and

6.3.1. The built environment

Fractal patterns can be utilized in shading and daylight systems, e.g. blinds, screens, glazing, etc.; to manipulate the geometry of sunlight patterns and improve occupant's visual comfort, visual interest of sunlight patterns, and view quality. Altering sunlight pattern geometry might be possible with emerging dynamic glazing systems such as electrochromic or thermochromic glazing. With further studies on human perceptual response, it is possible that the visual interest of sunlight patterns or mood response to become additional criteria for the design and control of these systems.

In addition to perimeter building zones that have direct access to sunlight and outdoor views, the findings may have implications for windowless rooms where sunlight patterns can be transferred using various technologies and projected on interior surfaces. For instance, the geometry of sunlight from a light tube can be manipulated, as still projections or dynamic ones that vary based on sky condition, for example. This can enhance the sense of connection to outside environments in these spaces.

While fractal patterns and sunlight in space can independently enhance a sense of connection to nature, fractal sunlight patterns mimic sunlight dappled through trees, hence they might provide a higher sense of connection to nature and be associated with biophilic effects (Browning et al., 2012). Particularly, as found in Studies 1, 2, and 3 mid to mid-high complexity fractals were more visually preferred and interesting than other complexities. This might have implications for occupant's well-being and indoor comfort.

6.3.2. The automotive industry

Maintaining visibility and reducing eye fatigue are some of the main requirements for car glazing systems, particularly windshields. The use of patterned tint stripes in the upper area of windshields might help reduce visual discomfort, maintaining interest, and enhancing stress recovery (Taylor, 2006). This might have implications on the safety and well-being of drivers and passengers, particularly long commuters and shipping truck drivers.

6.4. General Limitations

There are several limitations to the approach, methods, and findings that should be considered when interpreting the studies reported. First, while the use of remote polling proved helpful for efficiently collecting responses from all participants at the same time, there were variations among participants in terms of seating location, distance, and view direction. Although Study 3 showed that distance did no significantly influence visual preference and interest, it remains unclear how the combination of distance, luminance distribution, contrast, and seating location might have influenced preference and interest.

Second, the patterns examined in Studies 4 and 5 were printed on a clear transparency to simulate fractal and striped patterns. The visual response to these patterns might be different than that to actual objects being simulated. For instance, although trees include fractal patterns, the visual response to printed fractal patterns might be different from that to trees adjacent to building. Similarly, the visual response to printed stripes might be different than that of venetian blinds. Other properties like color, texture, and material might have influenced these responses.

Third, the ability to gain access to office buildings to conduct field studies is inherently challenging. This limited the location and number of potential buildings available for investigation. As a result of this limitation, Studies 4 and 5 were conducted in two different climate zones where occupants might have had different preferences and prejudgments related to the presence of sunlight patterns in space. Further, the desire for continuous and uninterrupted data collection during sunny and clear sky conditions has limited Study 4 to summer months. Therefore, occupant's visual reaction during winter or spring months was not investigated.

Fourth, the selection of window pattern size (3x6 feet) was driven by cost, ease of mounting in an office space, and by the desire to limit intolerable glare occasions. The later was based on concerns over workers being able to perform their daily tasks, which could lead to the possibility of participants stopping their participation. While none of the participants stopped their participation, the size of patterns might have reduced the impact of occupant's visual response compared to covering the whole window.

6.5. Future Work

6.5.1. Visual interest and view clarity

Previous studies that examined perceptual responses to fractal patterns were mainly conducted in windowless rooms, including the first two studies in this dissertation. The provision of view and daylight in the room might present competing factors that might influence visual interest. Specifically, a view of nature through windows might reduce the relative significance of computer-generated fractals. Thus, future studies should examine whether the visual interest of projected light patterns is influenced by the presence of these two variables.

Another research area that warrants further exploration is related to investigating view clarity through different patterns. It is hypothesized that the adequacy of window patterns for improving view clarity depends on the relationship between view type and pattern geometry. For instance, it might be possible that fractal patterns reduce visibility the most while looking at a scene of nature. The results of such efforts can help inform the selection of window patterns to improve visual interest and view quality.

6.5.2. Visual interest of sunlight patterns

In studies 3 and 4, view quality was consistently higher for the clear condition, therefore, to isolate the effects of views, future studies should examine visual comfort and visual interest of sunlight patterns when parallel to the window without access to outdoor views. This would help determine whether sunlight pattern geometry can be potentially used to enhance visual interest and visual comfort in windowless rooms.

Future studies should examine tradeoffs and interactions between views, visual interest of sunlight patterns, and visual comfort to examine whether the visual interest of sunlight patterns increases tolerance to glare as suggested by previous studies (Tuaycharoen & Tregenza, 2005). Further, to explore the extent to which outdoor view is maintained despite glare. These research areas can be investigated by examining occupant's behavioral responses, e.g. shade control, under different sunlight conditions.

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