

The Relationship between Sunlight Pattern Geometry and Visual Comfort in Daylit Offices

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ABSTRACT: Sunlight in buildings is a multisensory phenomenon that can enhance occupants' comfort, health, and connection with the outside environment through its dynamic luminous and thermal attributes. Current daylighting design guidelines limit sunlight penetration in work environments, reducing both its negative and positive effects on visual comfort and occupants' satisfaction with their indoor environment. One gap in existing literature on sunlight exposure is the lack of addressing the effect of visual interest for both sunlight pattern geometry and its play of brilliants on visual comfort. This paper aims to examine differences in visual comfort and interest assessments under three different sunlight pattern geometries.

This paper 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.

Results showed that visual comfort and visual interest ratings for the Fractal Pattern were higher than those for the Striped Pattern, though the difference was not statistically significant. View ratings for the two patterns were significantly lower than those for No-Pattern ($p < 0.001$). Interestingly, the relationship between the glare metric DGP and visual comfort ratings varied across the three stations. Further, the difference in visual interest between the Striped Pattern and No-Pattern stations was statistically significant ($p < 0.05$). Overall, findings suggest that the visual interest of sunlight patterns and views influenced subjective visual comfort assessments. Implication of this study can inform the design of future facade systems to enhance occupants' visual comfort, interest, and satisfaction with their indoor environment.

KEYWORDS: Sunlight in buildings, visual interest, fractal patterns, glare, view.

1.0 INTRODUCTION

In addition to influencing occupant's visual and thermal comfort, previous studies 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). Therefore, it is essential to effectively manage occupant's sunlight exposure in buildings. In this paper, visual comfort can be defined as the state of mind that expresses satisfaction with the visual environment, including perceptual, e.g. glare perception, and psychological satisfaction.

Sunlight penetration in buildings has been investigated by several researchers to examine occupant's ranges of acceptance and comfort in different space types. Previous studies showed that the main sources of visual discomfort is discomfort glare, which depends on glare source luminance, size, location, and adaptation of the observer (Clear 2012). Previous studies found that 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, and Kensek 2016). 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 their preferred height (Kent et al. 2017; Van Den Wymelenberg and Inanici 2014). In another study, Ne'Eman (1974) found that 73% of occupants considered sunlight a pleasure while 61% preferred a good view over indoor sunlight. 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 the space when it was available. It was argued that adequate luminance variations create a stimulating and interesting environment that improved occupants' preference ratings.

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. 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, and 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 and Boyer 1992).

1.1. Sunlight pattern geometry

Previous studies on sunlight exposure did not investigate whether sunlight pattern geometry influences visual comfort as sunlight pattern geometry is largely determined by shading systems and exterior obstructions. Some of the commonly used shading systems in office buildings include roller shades and venetian blinds which would result in rectangular and striped sunlight patterns, respectively. On the other hand, in buildings with trees nearby, sunlight patterns can be dappled through the leaves, creating fractal-shaped patterns.

People's fascination with nature has been investigated by many researchers who proposed several hypotheses and theories to explain this phenomenon such as Edward Wilson's hypothesis of Biophilia (Wilson 1984), Kaplan's Attention Restoration Theory (Kaplan, 1995), and Ulrich's work on scene type (Ulrich 1981). Most of these hypotheses and theories implied that there are certain characteristics in natural scenes that trigger positive aesthetic and psychophysiological responses (Browning et al. 2012). One approach 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).

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). The prevalence of 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 and Spehar 2016). Overall, previous studies suggested that fractal patterns induce relaxing and restorative effects (Hagerhall et al. 2008), visual preference (Aks & Sprott, 1996; Taylor, 1998; Spehar, Clifford, Newell, & Taylor, 2003), as well as stress recovery benefits (Taylor, 2006). 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. 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 ($D=1.5-1.9$). Two previous studies by the authors (Abboushi et. al., under review) 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. These findings formed the basis of this study.

Regarding Striped patterns, studies suggested that striped patterns are less visually comfortable (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). Another study stated that striped sunlight patterns produced by venetian blinds can have a spatial frequency within the range appropriate for the induction of visual stress (Winterbottom and Wilkins 2009). The contrasting potential effects of striped and fractal patterns on visual comfort and preference makes these patterns ideal for investigating whether visually interesting sunlight patterns, e.g. fractals, influence perceived glare, compared to striped or rectangular sunlight patterns? This study addresses this question by investigating visual comfort and visual interest under three sunlight conditions: Fractal pattern, Striped pattern, and clear (No-Pattern).

1.2. Views

Access to views and view content have been incorporated into LEED v4 to enhance occupant's connection to their outdoor environment, however, the extent to which these variables influence visual comfort has not been comprehensively investigated. Significant differences in subjective evaluations of visual discomfort were found for different views at the same luminance (Shin, Yun, and Kim 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 (Tuaycharoen and 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. Other factors including view type, nature scenes, and aesthetic preferences seemed to influence visual comfort.

1.3. Glare from Daylight

Sunlight is defined as the light of the sun; whereas daylight is defined as the light of the sun and sky during the day (Webster 2016). Generally, different glare metrics have slightly different approaches for estimating glare from daylight. For instance, Daylight Glare Index (DGI), Unified Glare Rating (UGR), and CIE Glare Index (CGI) are all based on the contrast between the luminance of the source and the luminance of the scene. In addition to contrast, the Daylight Glare probability (DGP) metric is influenced by another variable, that is, the amount of light falling on occupant's eye, hereafter vertical illuminance (Wienold and Christoffersen 2006). Vertical illuminance may explain discomfort for occupants seated close to windows (Hirning, Isoardi, and Garcia-Hansen 2017). Jakubiec and Reinhart (2012) found that DGP performs better when direct sunlight is present in the scene and the visible sky from the windows is very bright. To assess glare, a technique that uses high dynamic range images (HDRIs) has been widely utilized in previous studies to analyze the brightness of different surfaces in a scene (Inanici and Galvin 2004).

1.4. Hypotheses

We hypothesized that: 1) Mean view quality rating for the No-Pattern station would be higher than that for the Fractal and Striped patterns. 2) The visual interest of sunlight patterns and view quality might influence visual comfort ratings, therefore, the relationship between the objectively-measured glare level and visual comfort ratings is expected to differ across the three stations. In other words, at the same glare level, occupants might rate their visual comfort differently based on window condition. 3) The Fractal pattern is expected to improve visual comfort and receive higher visual interest ratings, compared to the striped pattern.

2.0 METHODS

2.1. The study setting

This study employed a 3x1 experimental within-subject research design where the same group of subjects experienced three sunlight conditions. Three experimental stations were created in an open-plan office space on the 8th floor of a multi-story LEED Platinum office building in Portland, OR. The three stations were next to each other at the North-east facade, which controlled for view direction and solar orientation across the three stations. The stations exhibited different sunlight pattern geometries which included a fractal pattern (Fractal), a striped pattern (Stripes), and a clear window with no pattern (No-Pattern). The Fractal and the Striped patterns were selected in this study because previous studies suggested that they were associated with positive and negative effects on visual preference and interest, respectively, as outlined in section 1. The No-Pattern condition was included as a base-case for comparison. Main parameters of the study setting are shown in Table 1.

Table 1: Parameters of the study setting.

Setting Parameters	Value
Visible transmittance of glazing (T_{vis})	0.28
Solar heat gain coefficient (SHGC)	0.19
Visible transmittance of pattern	0.04 for black regions and 0.89 for clear regions.
Overall visible transmittance	0.01 through black regions, and 0.25 through clear regions.
Distance between subjects and window	213.3 cm (7 feet)

The different sunlight patterns were produced by panels of clear Mylar with black ink that represented either a fractal or a striped pattern. Each panel was 0.91x1.98 m (3x6.5 feet) mounted on the upper half of a 1.8x1.98 m (6x6.5 feet) window. The roller shades were lowered to create this window size to avoid sunlight patterns on participant's body, particularly at the beginning of the study. For the No-Pattern station, the roller shade was adjusted to a height of 1.37m (54 inches) to ensure that clear areas across the stations are consistent. The three stations had a view of a river 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 (Fig.1).

2.2. Data collection

A total of 22 office workers (13 male and 9 female) volunteered to participate in this study. Participants were given specific instructions and description of the study procedures and asked to sign a consent form prior to starting participation. Subjective and objective indicators of comfort were collected. Subjective comfort data was collected using an offline questionnaire on digital tablets. Table 2 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).

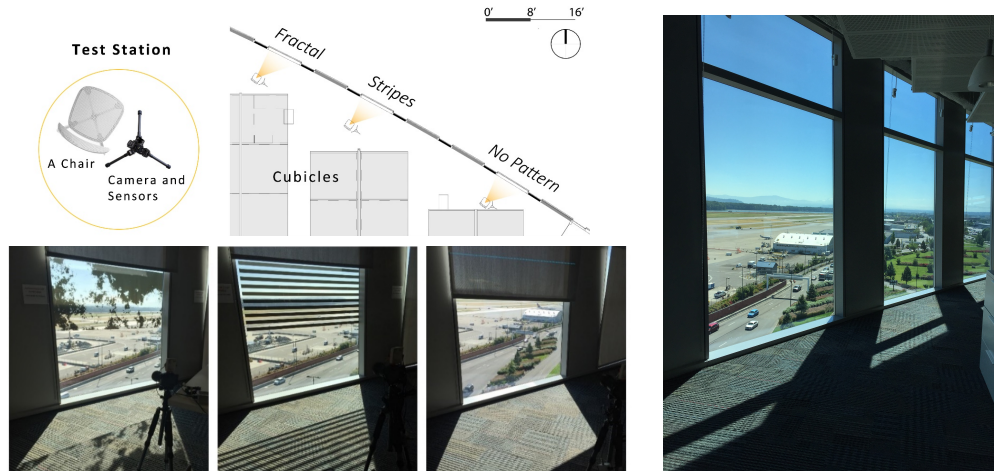


Figure 1: A floor plan of the research setting and test station (top left); pictures of the three stations (bottom left); and an overall picture of the perimeter zone where the study was conducted, prior to adjusting shades (right).

Table 2: The questionnaire and scale used for each question.

Question	Scale
Q1 This is a visually comfortable environment for office work	7-point Likert scale (Strongly Agree (7)-Agree-Somewhat agree-Neither agree nor disagree-
Q2 Sunlight patterns look visually interesting	Somewhat Disagree-Disagree-Strongly disagree (1)).
Q3 I like the view I have from the window	
Q4 Air temperature feels:	7-point semantic differential (Too Warm- Too Cold).

Objective environmental data included vertical illuminance, High Dynamic Range Images (HDRIs), air temperature, relative humidity, and globe temperature. The HDR images were manually captured using Canon G11 cameras equipped with a fisheye lens (Opteka 52mm 0.2x HD Professional Super AF Fisheye) mounted on a tripod and positioned at a height of 142.2 cm (56 inches) to match eye-level position for participants. All other measurements were logged at 5-minute intervals using a series of sensors connected to U-12 Onset HOBO data-loggers. These sensors included; a Licor-210 photometric sensor with a custom voltage amplifier to measure vertical illuminance, and a calibrated NTC Thermistor (10k ohm $\pm 0.1^{\circ}\text{C}$) suspended at the center of a black painted ping pong ball to measure globe temperature. The U-12 Onset data logger provided measurements of air temperature and relative humidity. All sensors, cameras, and amplifiers were calibrated prior to start of the study.

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. The order by which participants completed questionnaires at the three stations was randomized. HDRIs were captured immediately after a participant completed the questionnaire to prevent interference with their perception of the environment. The study took place from 8 to 11 am on summer solstice. Regarding HDRIs, each HDRI comprised of six images combined using 'hdrgen' Radiance command-line (Anywhere Software) using a predetermined response function for each camera. Each HDRI was then analyzed using the 'evalglare' command. Lastly, questionnaire responses were paired with measurements –vertical illuminance, air temperature, globe temperature, relative humidity, and HDRIs using data timestamps.

3.0 RESULTS

The boxplots in Fig.2 show the distribution of responses for visual comfort (Q1), visual interest (Q2), and view quality (Q3) by sunlight condition. Means of visual comfort (Q1), visual interest (Q2), and view (Q3) for the No-Pattern station (5.8, 5, and 6.6 respectively) were higher than those for the Striped (4, 3.9, 3.5) and Fractal (4.6, 4, 3.6) stations. Further, means 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, both patterns received low view quality ratings compared to the No-Pattern condition. As for thermal comfort (Q4), there were no significant differences in subjective responses to Q4. 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 workstations. Mean responses were 4.59, 4.82, and 4.77 for fractal, No Pattern, and Stripes, respectively. Questionnaire responses and the average predictive mean vote (PMV) of -0.2 indicated that no severe thermal discomfort was experienced.

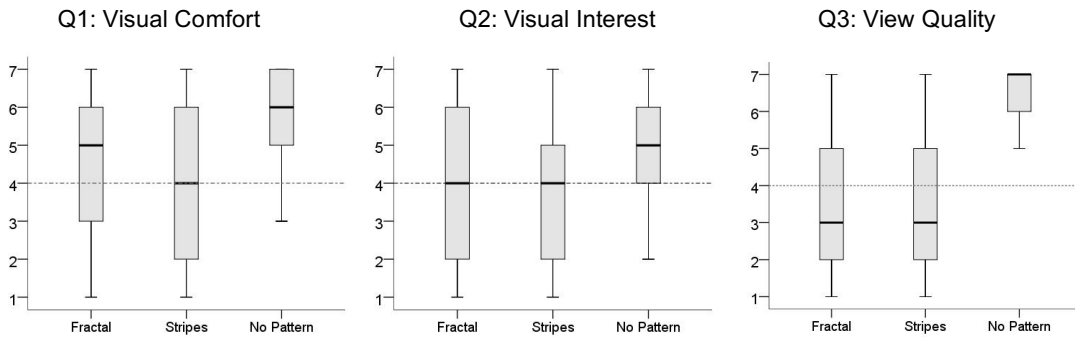


Figure 2: Boxplots of questionnaire responses. Number 7 represents “Strongly Agree”, number 1 represents “Strongly Disagree”, and number 4 is “Neutral”.

Questionnaire responses were analyzed to examine differences among the three stations. Wilcoxon signed ranks test was used. This test was used because Shapiro-Wilk test confirmed that variables violate the normality assumption for the paired T-test. Results showed that visual comfort ratings for the No-Pattern station were significantly higher than those for the fractal ($Z = -2.48$, $p < 0.05$) and the striped patterns ($Z = -3.281$, $p < 0.05$). The difference between visual comfort ratings for 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 only significantly higher ($Z = -2.188$, $p < 0.05$) than those for the striped pattern ($Z = -2.188$, $p < 0.05$). While view area size was consistent across the three stations, the distribution of these areas differed. For instance, in the No-Pattern station, the view area was not interrupted, unlike the Striped and Fractal patterns which included viewing areas within the pattern itself. Participant responses showed that view quality ratings for ‘No Pattern’ were significantly higher than those for Fractal ($Z = -3.753$, $p < 0.001$) and Striped patterns ($Z = -3.742$, $p < 0.001$).

4.0 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, particularly because of the combination of imperceptible glare levels indicated by DGP and the panoramic views. The combination of these factors suggests that participants might be willing to tolerate these low-glare levels in favor of having uninterrupted views, thus neither pattern was deemed important for glare mitigation (Boubekri and Boyer 1992). The importance of shades might be further reduced because participants were not performing a visually critical office task such as typing or reading from a computer screen. Indeed, the preference for unobstructed views was indicated by some participants who mentioned that they preferred to see through the patterns. These findings support our hypothesis regarding a higher view quality rating for the No-pattern station.

Although visual comfort ratings for the Fractal pattern were higher than those for the Striped pattern, the difference was not statistically significant; therefore, our hypothesis regarding a difference between these two was not supported in the current setting with low glare levels. The difference in visual interest between Fractal station and the Striped station was not statistically significant. However, compared to the No-pattern station, only the Striped station significantly reduced visual interest. The expectation to observe a significant difference in visual interest between the two patterns was based on results of previous studies by the authors (Abboushi et al., under review), which suggested that projected fractal light patterns were significantly more visually interesting than rectangular or striped patterns. This study, though, introduced new variables such as glare and views, whose interactive effects with each pattern might have influenced their visual interest.

The relationship between visual comfort ratings and glare levels seemed to differ across the three stations, particularly between the Fractal and Striped stations. Fig.3 shows boxplots of visual comfort ratings and DGP for the three stations. For the Striped and No-Pattern stations, the relationship between visual comfort ratings and DGP followed a linear trend, where higher visual comfort was at lower DGP. In contrast, the plot for the Fractal station showed a quadratic “U” shaped relationship between these two variables. This suggests that the influence of glare on visual comfort was mediated by pattern geometry. This includes effects caused by sunlight pattern geometry and the visual interest thereof, which aligns with results of a previous study (Tuaycharoen and Tregenza 2007) that suggested that discomfort glare cannot be predicted from physical variables alone.

Investigating the visual interest of sunlight patterns should consider the location, geometry, and interactions with room surfaces. The amount of fine-scale detail in fractal sunlight patterns, for instance, varies based on

the distance between the window surface and projection surfaces. Another important topic that warrants further studies are the qualitative aspects of sunlight pattern geometry. These aspects include feelings evoked by the sunlight pattern such as relaxation and excitement (Boubekri, Hull, and Boyer 1991) as well as resemblances associated. To rule out the effects of view quality, future studies would benefit from excluding views in a research setting where participants can sit parallel to the window with limited view of window and outdoor views. This approach would help focus on sunlight patterns to examine the extent to which they influence visual interest and visual comfort ratings.

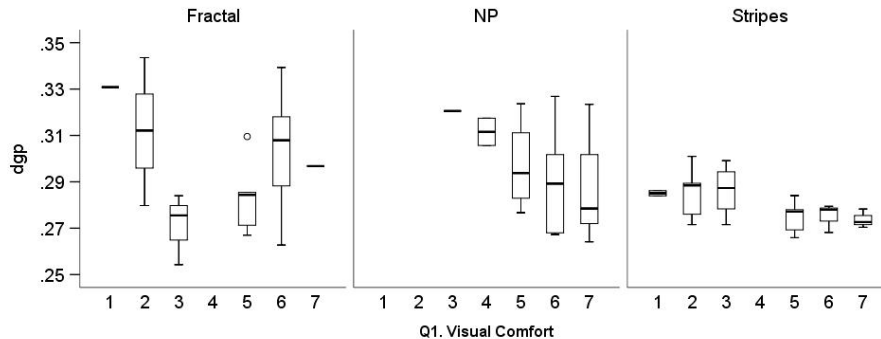


Figure 3: Visual comfort ratings and DGP for the three stations: Fractal (left), No-pattern (middle), and Stripes (right).

Assuming that view quality and the visual interest of sunlight patterns have both contributed to 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 differ under 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 whether visual interest and view quality can offset and reduce perceived glare, and if proved, to what extent. These questions are explored in another forthcoming paper by the authors that examined the same three sunlight conditions at an office building for an extended period and at participants' workstations while performing typical office tasks.

5.0 CONCLUSIONS

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

1. Occupants might be able to tolerate low levels of glare in an office setting when an interesting outdoor view of nature is present. The No-Pattern station received the highest mean ratings for visual comfort and view quality and the differences were statistically significant.
2. The No-Pattern station received the highest mean of visual interest ratings, and the difference was only significant compared to the Striped station.
3. If given a choice between Fractal and Stripped patterned window coverings, occupants might prefer the Fractal coverings and the projected sunlight patterns. The difference in visual interest between the Fractal station and the No-Pattern station was insignificant, whereas the difference in visual interest between the Striped station and No-Pattern station was significant.
4. The predictability of the DGP metric varied across the three stations. This could be due to aspects not addressed by glare metrics such as visual interest and view quality.
5. Visual interest to sunlight patterns in space was well perceived by the occupants and merit further discussion, metrics, and studies. Results showed that ratings of visual interest of sunlight patterns were associated with significant increases in visual comfort ratings.

6.0 LIMITATIONS AND FUTURE WORK

There were several limitations that should be considered when interpreting the results of this study: first, this study took place at an office space where volunteers were recruited for participation; thus, self-selection bias might be present. Second, the north-east facing zone was selected to include a range of sunlight conditions and sunlight profile angles. This, however, limited the timing of the study to when sunlight could be present in the space, hence, the study took place in the morning. Third, window tint and low visible transmittance might have contributed to the low DGP levels, which indicated imperceptible glare levels during the study. This suggests that the results might only be applicable to low glare levels. Beyond the need to refine existing glare metrics for scenes when sunlight is present in space, future studies would benefit from including a wider range of daylighting conditions, corresponding to perceptible to intolerable ranges of glare. It is possible that as glare level increases, the less important the visual interest becomes, hence lessening the difference in visual comfort responses among the three sunlight pattern geometries. This hypothesis warrants further studies to verify or refute it.

The time each participant spent at each station might have lessened annoyance and visual discomfort from potential glare or sunlight exposure. Future studies would benefit from examining visual comfort towards sunlight at participants' desks where a longer monitoring period, different orientations, different view qualities, higher DGP and glare levels, and typical office tasks are considered. Lastly, this study was conducted in a predominantly overcast geographic region which might have influenced occupant's preferences towards sunlight. More studies are needed to delineate regional and seasonal effects on visual comfort and tolerance towards glare from sunlight.

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