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# Assessing the Visual Comfort, Visual Interest of Sunlight Patterns, and View Quality under Different Window Conditions in an Open-Plan Office

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## ABSTRACT

Sunlight is a multisensory phenomenon that can enhance occupant's comfort, health, and connection to the outside environment through its dynamic luminous and thermal attributes. One gap in the existing literature on sunlight exposure is in addressing the visual interest of sunlight patterns and its potential effects on visual comfort. This study employed an experimental procedure where 33 office workers were subjected to three different window and sunlight patterns: *fractal pattern*, *striped pattern*, and *clear* at an office building over three days (one condition per day). Subjective ratings and physical environmental measurements were collected and analyzed to understand differences among the three conditions. Results showed no significant differences in visual comfort or visual interest of sunlight patterns among the three conditions. Desk layout influenced visual interest and view quality ratings. The fractal and striped patterns negatively influenced view quality compared to the clear condition. These results suggest that the shape of window and sunlight patterns might have limited to no impact on visual comfort and interest in offices when workers are preoccupied performing typical office work.

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## KEYWORDS

Daylighting; sunlight in buildings; visual interest; visual comfort; sunlight patterns

## 1. Introduction

Light can serve as a zeitgeber for the human clock (Morrow and Roenneberg 2001), and can help regulate melatonin suppression and phase shifts (Boyce et al. 2003; Duffy and Czeisler 2009). The lack of short wavelength light in the morning was shown to delay dim light melatonin onset (Figueiro and Rea 2010). Daylight in buildings influences occupant's visual and thermal comfort as well as their psychophysiological state. Previous studies suggested that daylight can improve cognitive and visual performance (Heschong 2002; Chellappa et al. 2011; Viola et al. 2008). Other studies found that exposure to bright light can promote alertness (Smolders et al. 2015; Souman et al. 2018). Daylight consists of light from the sun, i.e. sunlight, and from the sky (Mardaljevic et al. 2009). The projections of sunlight onto different surfaces in space, hereafter "sunlight patterns" might influence occupants visual comfort through its pleasant and cheering attributes (Boubekri and Boyer 1992).

Current daylighting practices, however, limit the presence of sunlight patterns promoting dull and visually monotonous environments (Reinhart 2015). One of the challenges for incorporating sunlight in daylighting design might be the lack of a robust, consistent, and reliable glare metric for predicting occupant's visual comfort when sunlight patterns are present in space. For instance, the daylight glare index (DGI) and the CIE unified glare rating system (UGR) are only valid for conditions when direct sunlight does not enter the space (Iwata et al. 1992; Jakubiec and Reinhart 2012; Nazzal 1998). The daylight glare probability (DGP) was developed under stable and clear sky conditions (Wienold and Christoffersen 2006) and was found to be a better predictor than DGI, however, it exhibits several limitations including underpredicting glare when sunlight is within the task region (Hirning et al. 2014; Van Den Wymelenberg and Inanici 2014). Other aspects like thermal comfort, type of light source, and view quality may influence visual comfort ratings

(Knoop et al. 2019; Lee et al. 2005; Wang and Boubekri 2010) but their effects have not been fully assessed.

Another challenge for incorporating sunlight in daylighting design is the lack of studies that examined qualitative aspects of sunlight patterns, and their effects on occupant's visual comfort and overall satisfaction. This is particularly important because of the established psychophysiological effects associated with sunlight. Hence, carefully incorporating controlled amounts of sunlight indoors can help in creating visually comfortable and interesting interior environments so long as glare can be managed (Boubekri and Boyer 1992; Van den Wymelenberg et al. 2010).

Offices are visually critical spaces because occupants spend a considerable amount of time performing computer-based tasks in fixed view directions. Nonetheless, occupants in daylit offices often experience a wide range of light conditions throughout the day (Elzeyadi and Lockyear 2010). The current Annual Sunlight Exposure ( $ASE_{1000 \text{ lux}, 250 \text{ hours}}$ ) metric documented in LM-83-2012 stated that spaces with more than 10% of floor area exposed to sunlight for more than 250 hours a year were "judged to have unsatisfactory visual comfort" (IES 2013). The document recommends that occupants have easy access to control window brightness using blinds or shades. The document also acknowledges that the supporting research (HMG 2012) "... did not include enough variety of sun penetration patterns by various orientations, space types, shading device types or climate zones to fully understand how occupants' preferences vary by these factors" (IES 2013). The Illuminating Engineering Society later stressed that the ( $ASE_{1000 \text{ lux}, 250 \text{ hours}}$ ) metric should presently be used as an indicator for glare potential, and suggested that rating organizations, such as the Leadership in Energy and Environmental Design (LEED), might consider awarding compliant spaces an exemplary performance credit while requiring spaces that exceeded 20% of floor area to utilize dynamic facades to respond to the dynamic character of daylight. A follow-up study suggested that the metric may overpredict the occurrence of occupant perceived glare and that further refinement is warranted (Dutra de Vasconcellos 2017). For these reasons,

there is a need for studies that examine various aspects that influence occupant's preferences toward sunlight patterns.

Currently, there is no consensus on what questions and scales should be used for assessing visual comfort (Allan et al. 2019). For example, a previous study used the phrase: "This is a visually comfortable environment for office work" assessed on a seven-point Likert scale (Van Den Wymelenberg and Inanici 2016). This rating scale measures the broad concept of visual comfort, compared to other scales that focus on visual discomfort. For example, another study asked participants to rank their visual comfort: "Comfortable," "Perceptible Discomfort," "Disturbing Discomfort," or "Intolerable Discomfort" (Jakubiec and Reinhart 2013). Other studies used the Glare Sensation Vote: "Just Perceptible," "Just Noticeable," "Just Uncomfortable," and "Just Intolerable" which was shown graphically to participants (Altomonte et al. 2016), or to which participants responded vocally (Kent et al. 2019).

### 1.1. Sunlight in buildings

Compared to diffuse daylight, direct sunlight can better improve positive emotions both in winter and summer seasons in classrooms (Kim 1997). Another study found that a sunlit area of 15%-25% of floor area created maximum levels of relaxation when occupants were in a seating position parallel to window (Boubekri et al. 1991). Boubekri et al. concluded that sunlight sparkles were preferred over large areas of sunlight for enhancing emotional well-being. It was also suggested that sunlight, as manipulated by size, season, time of the day, has significant impacts on the affective state of occupants, which influences their satisfaction. Given that the illuminance level provided by direct sunlight exceeds that needed for visibility in offices, qualitative aspects of sunlight patterns might play a critical role in forming overall preferences toward sunlight in offices (Chamilothori et al. 2016; Omidfar et al. 2015).

Results of a study in England showed that 73% of office occupants considered sunlight a pleasure while 24% considered it a nuisance (Ne'Eman 1974). Furthermore, 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 an unpleasant view. Wang and 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. Other factors, i.e. sense of control, privacy, and views were identified to might have had influenced seating preferences. Another study found that 11 out of 12 participants chose to let sunlight patterns into space, which suggests that carefully controlled sunlight patterns can enhance occupant's satisfaction (Van den Wymelenberg et al. 2010).

When reviewing existing literature, a clear distinction should be made between viewing the solar disk through a window, viewing sunlight patterns in space, and being in sunlight patterns. Each condition is likely to call attention to certain variables and concerns. For instance, the high luminance of solar disc is often associated with glare (Konis 2011), whereas sunlight patterns in space are often examined in relation to esthetics and mood (Boubekri and Boyer 1992).

### 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). 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 to a natural scene had shorter postoperative hospital stays and took fewer potent analgesics than those in similar rooms with views of a brick wall. Views of nature buffered the negative impact of job stress on blue-collar employees' intention to quit (Leather et al. 1998). A comprehensive review concluded that views of nature and daylight can positively influence mood (Beute and de Kort 2014). Lastly, in a study of a work space, daylighting and preferred views of nature were associated with a 50% reduction in sick leave of office employees (Elzeyadi 2012).

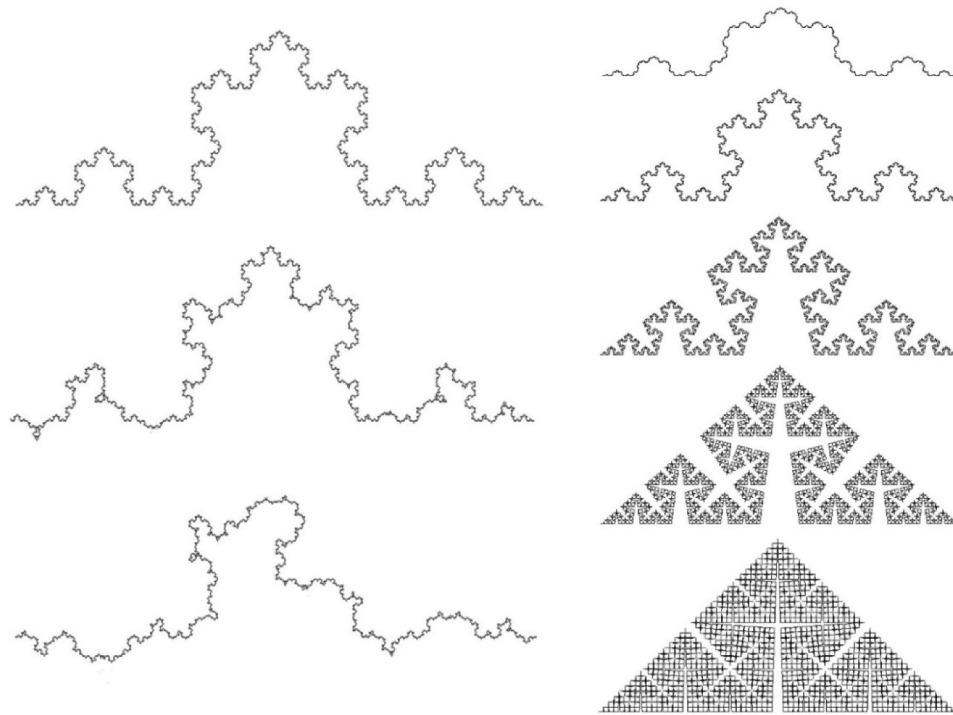
Viewing renderings of nature seem to carry some of the benefits. A previous study that used simulated views found that viewing a green roof was associated with a more consistent task response and fewer omission errors, compared to viewing a concrete roof (Lee et al. 2015). Not only view elements are important, the distance of view elements can influence visual comfort ratings (Shin et al. 2012).

Several studies suggested that view quality can influence visual comfort. For instance, researchers concluded that an interesting view was associated with lower visual discomfort ratings compared to a less interesting view at the same mean luminance (Tuaycharoen and Tregenza 2005, 2007). Another study found that better quality views were associated with lower visual discomfort (Aries et al. 2010). It should be noted that none of these studies explored the view of sunlight patterns in space.

### 1.3. Fractal patterns

Although the desire for an outdoor view is well established, the characteristics that make views more or less desirable are not as well understood (Collins 1975). The attention restoration theory implied that natural environments are particularly rich in the characteristics necessary for restorative experiences (Kaplan 1995). Many researchers suggested that one of these characteristics is fractal geometry (Hagerhall et al. 2015; Joye and Van den Berg 2011; Mandelbrot 1983; Purcell et al. 2001). 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 can be seen in trees, clouds, coastlines, and other natural elements. The prevalence of fractal patterns in nature might have caused the human visual system to adapt to efficiently process them, hereafter the fractal fluency theory (Taylor and Spehar 2016).

In Fig. 1, we use a coastline to demonstrate the intrinsic visual properties of fractals. As shown in the left column, fractals can be divided into two categories – “exact” (top image) and “statistical” (bottom image). Whereas exact fractals are built by repeating a pattern at different magnifications,



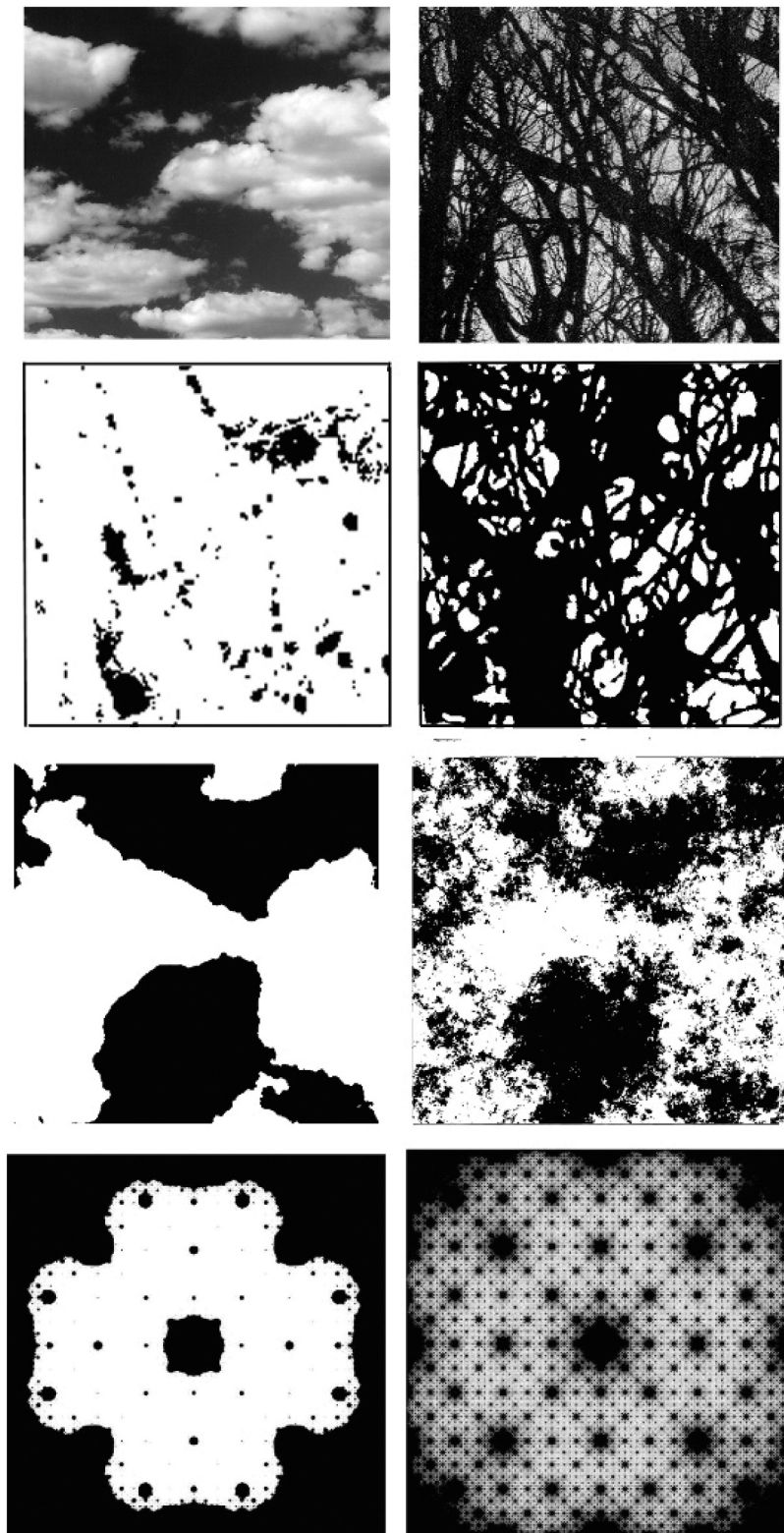
**Fig. 1.** Left column: A computer-generated coastline based on exact fractals (top) is morphed into a statistical fractal coastline (bottom) by introducing randomness. For the top fractal, all of the headlands point upward. For the bottom fractal, half point downward and the positions of the up and down headlands are randomized. Note the  $D$  value (1.24) is preserved for all 3 patterns (top, middle and bottom). Right column: The effect of increasing  $D$  is shown for 5 exact coastlines. Each of the coastlines is built using the same coarse scale pattern. Increasing the contributions of the fine scale patterns causes the coastlines to occupy more of the 2-dimensional plane, thus raising their  $D$  values: 1.1 (top), 1.3, 1.5, 1.7 and 1.9 (bottom).

“statistical” fractals introduce randomness into their construction. This disrupts the precise repetition so that only the pattern’s statistical qualities (e.g., density, roughness, complexity) repeat. Consequently, statistical fractals simply look similar at different size scales. While exact fractals display the cleanliness of artificial shapes, statistical fractals capture the “organic” signature of natural objects. To quantify the rich visual intricacy of the fractals, we adopt a traditional measure employed by mathematicians – the pattern’s fractal dimension  $D$ . This is calculated using a procedure called the box counting method (Spehar et al. 2003). This parameter describes how the patterns occurring at different magnifications combine to build the resulting fractal shape. For a smooth line (containing no fractal structure)  $D$  has a value of 1, while for a completely filled area (again containing no fractal structure) its value is 2. However, the repeating patterns of the fractal line cause the line to begin to occupy space. As a consequence, its  $D$  value lies between 1 and 2. By increasing the amount of fine structure in the

fractal mix of repeating patterns, the line spreads even further across the two-dimensional plane (see the right column of Fig. 1) and its  $D$  value, therefore, moves closer to 2.

Figure 2 demonstrates how a fractal’s  $D$  value has a powerful effect on its visual appearance. This figure includes images from nature, art, and mathematics. For each of the rows, the image in the left column has a lower  $D$  value than that in the right column. Clearly, for the low  $D$  fractals, the small content of fine structure builds a very smooth sparse, shape. However, for fractals with  $D$  values closer to 2, the larger amount of fine structure builds a shape full of intricate, detailed structure. More specifically, because the  $D$  value charts the ratio of fine to coarse structure, it is expected that  $D$  will serve as a measure of the visual complexity generated by the repeating patterns. Behavioral research confirms that the complexity perceived by observers does indeed increase with the image’s  $D$  value (Spehar et al. 2016).





**Fig. 2.** Fractal complexity in nature, art and mathematics. The different rows summarize the variety of fractal images (see text for details). In each case, the left column shows examples of low  $D$  fractals and the right column show the equivalent high  $D$  fractals.

Previous studies showed that visual interest ratings peaked for mid-complexity fractals when the pattern was viewed on a computer screen

(Hagerhall et al. 2008; Spehar et al. 2003; Spehar and Taylor 2013; Taylor et al. 2005). In a recent study, the fractal fluency theory was extended to

investigate visual interest and mood while viewing spatially projected fractal light patterns (Abboushi et al. 2019). Results suggested that projected fractal light patterns of mid to mid-high complexity ( $D = 1.5\text{--}1.7$ ) were more visually interesting than those in striped and rectangular patterns (Fig. 3). These findings formed the basis of the current study.

Fractal patterns were found to elicit a positive perceptual response. For instance, Taylor (2006) 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 (Wilkins 2016). For example, Venetian blinds can cause pattern glare because of the spatial frequency of sunlight patterns projected through them (Winterbottom and Wilkins 2009). Despite the prevalence of Venetian blinds and subsequently striped light patterns, there has been a lack of studies that investigated the effects of striped patterns on visual interest and comfort.

#### 1.4. The hypotheses

This study aims to investigate differences in visual comfort, visual interest of sunlight patterns, and

view quality under three different window and sunlight patterns in an office environment. The three patterns included: (1) a fractal pattern, (2) a striped pattern, and (3) a clear window. We hypothesized that the visual interest of fractal patterns might influence occupant's visual comfort and view quality, following the idea that occupants perceive and react to their environment including both direct and interactional effects (Elzeyadi 2002). Specifically, we hypothesized that: 1) the fractal pattern would be associated with the highest visual comfort and interest ratings; 2) view quality ratings for the clear condition would be higher than both patterns.

## 2. Methods

The study was conducted in an office building in San Francisco, CA over a five-week period during the summer of 2017. Each participant experienced three different window conditions over three consecutive days (one condition per day). The three window conditions included two window patterns and a clear condition (Fig. 4). The two patterns were a “fractal pattern” and a “striped pattern,” which were mounted on participant's window and randomized across participants for days 1 and 2 (fractal-striped or striped-fractal). The third day was consistently set as the “clear condition.” Participants rated visual comfort, visual interest of sunlight patterns, view quality, and thermal comfort three times a day.

The office had an open-plan layout with 152 cm (5 feet) high partitions and manual light gray roller shades with an openness ratio of 3% (Fig. 5). Prior to the start of the study, overshadowing by nearby

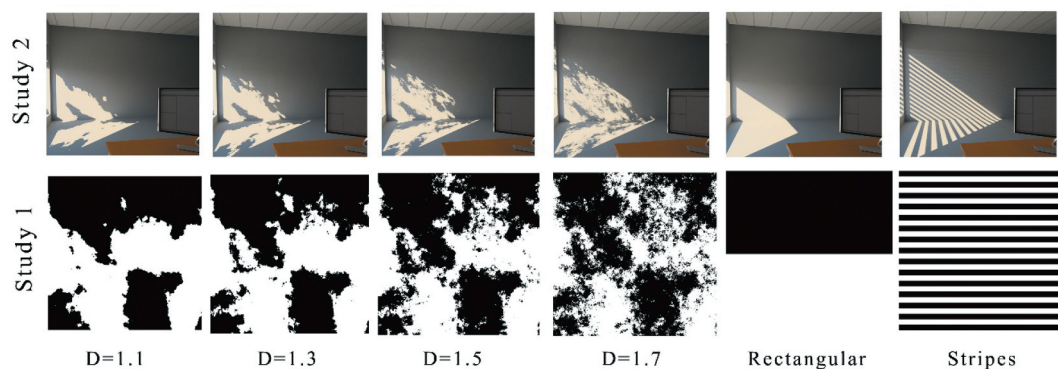


Fig. 3. The six patterns examined in a previous study (Abboushi et al. 2019).



**Fig. 4.** The three window conditions including the fractal pattern  $D = 1.7$  (left), clear condition (middle), and striped pattern  $D = 1$  (right).



**Fig. 5.** A picture of a workstation showing camera location (left), and a typical floor plan highlighting workstations on the SW and SE facades (right).

buildings was examined to ensure that all participant windows had unobstructed access to sunlight. Both patterns were printed using black ink on clear films. The visible transmittance values were 0.89 and 0.04 for clear and black areas, respectively.

Windows in the office measured 198 cm wide x 198 cm high (6.5 x 6.5 feet) and the films were 198 cm wide x 91 cm high (6.5 x 3 feet). Hence, the films were mounted covering only the lower part of participant's window. The remainder of the window area (198 x 107 cm) remained shaded throughout the study to reduce the possibility of intolerable glare, since this might affect participation and number of responses in the study.

The intention behind using window films was to directly expand upon previous studies following the fractal fluency theory, and using the same type of stimuli (Abboushi et al. 2019; Spehar and Taylor 2013; Taylor et al. 2011). Adding thickness, for example, to either pattern would have

influenced their complexity in a way that was not previously examined.

### 2.1. Dependent variables

Given the need for repeated assessments, the questionnaire was designed to be brief (Table 1). The questions and scales used were based on previous studies using a seven-point Likert scale (HMG 2012; Painter et al. 2010; Van Den Wymelenberg

**Table 1.** The questionnaire instrument and scales used.

Question	Scale
Q1 This is a visually comfortable environment for office work.	Seven-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:	Seven-point semantic differential scale (Too Warm-Neutral-Too Cold).



**Fig. 6.** Sky coverage in Oktas from a weather station near the office building for the year 2017. Courtesy of San Francisco Bay Area Weather Forecast Office.

that explained the study in further detail. Regarding age, six participants were 60–70 years of age, 17 participants were 50–59 years of age, and 10 participants were 30–49 years. As for gender, 16 were male and 17 were female. Questionnaire responses and physical measurements were collected from a total of 33 participants.

Participants were located on floors 13–18 on the Southeast (SE) or Southwest (SW) facades. On the SE façade, 15 participants had a desk layout with a view perpendicular to the window and five participants had a desk layout with a view parallel to the window; compared to three perpendicular views and 10 parallel views on the SW façade. The final dataset consisted of 265 responses, 105 of which were taken when sunlight was present in scene (Table 2). Spot checking was conducted to verify the accuracy of dataset merging processes.

## 2.4. Experimental procedure

This study was approved by the institutional review board at the authors' university. Prior to the start of study, an orientation session was held with participants to explain the study. The session described the study procedure and the types of data that were collected. The participants were instructed not to change blind position and to complete the questionnaire three times a day. The participants were informed that they could complete the questionnaires at their earliest convenience if they were away from their desk, e.g. in

a meeting. The participants were informed that they could provide additional responses at any time and were asked not to make any changes to their work schedule because the intention was to capture their responses during a typical workday. No compensation was provided to participants.

The questionnaire was answered on a tablet at three times a day: 9:00, 11:00, and 15:00. These times were selected to ensure that all participants were present at their workstations and to avoid arrival, lunch, and departure times. A quiet alarm sounded as reminder but could be snoozed for 10 minutes. Responses collected on equipment setup day, those collected after 17:00, as well as additional responses provided outside the three experimental days were excluded from analyses. In cases when multiple responses by the same participant were within 30 minutes of each other, the response closer to 9:00, 11:00, or 15:00 was kept and the other response was removed. Figure 7 shows response times for each participant by time of the day.

Each participant was assigned a unique identifier that was used to combine subjective responses with physical measurements. To combine questionnaire responses with physical measurements, the closest measurement was matched with each questionnaire response. The mean difference in time between captured HDR image time and questionnaire completion time was 2 min. The mean difference in time between  $E_v$  measurements and questionnaire completion times was 1 min.

## 2.5. Overview of analysis methods

Statistical analyses included descriptive statistics and linear mixed models. The IBM SPSS 26 software was used to generate these models. Linear mixed models are widely used when there is no independence in the data, e.g. correlated, while setting fixed variables and allowing the model to vary by a random variable. A model was generated for each of the dependent variables (visual comfort, visual interest of sunlight patterns, and view quality).

# 3. Results

## 3.1. Descriptive statistics

Over the course of the study, participants experienced a wide range of light conditions exemplified

**Table 2.** An overview of the distribution of participant responses.

			Sunlight	No sunlight	
Façade orientation	Desk layout	Window condition	in the scene	in the scene	All
SE	Perpendicular	Clear	14	28	42
		Fractal	14	25	39
		Stripes	17	21	38
	Parallel	Clear	7	7	14
		Fractal	9	5	14
		Stripes	10	5	15
SW	Perpendicular	Clear	5	4	9
		Fractal	2	6	8
		Stripes	3	6	9
	Parallel	Clear	8	14	22
		Fractal	8	19	27
		Stripes	8	20	28
Total			105	160	265

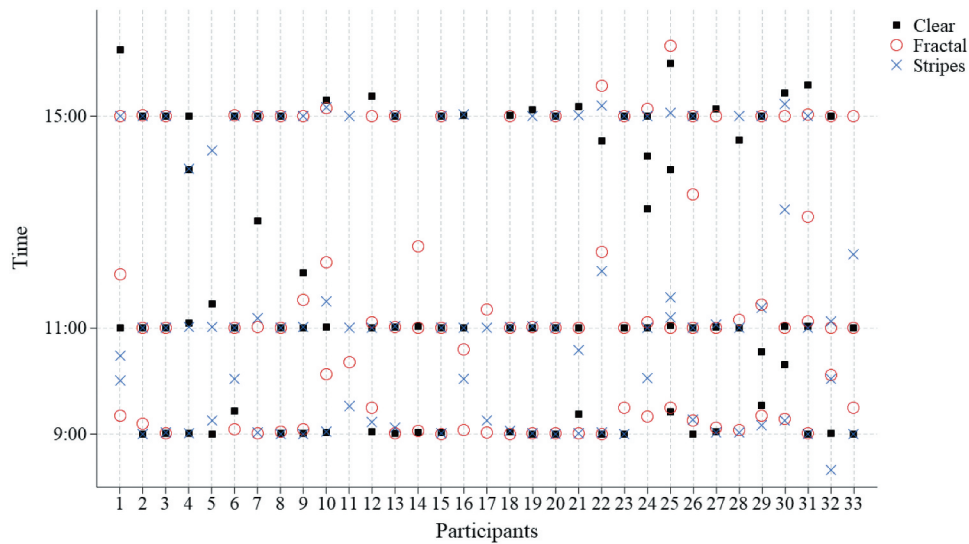


Fig. 7. Response times plotted by participant and window condition.

by variations in DGP (Fig. 8/right). Given solar orientation, DGP values were typically higher in the morning and lower in the afternoon for SE participants, compared to those on the SW façade. Overall,  $E_v$  ranged from 105 to 9590 lux ( $M = 1694$  lux,  $SD = 1596$  lux) and DGP ranged from 0.03 to 0.72 ( $M = 0.27$ ,  $SD = 0.09$ ). DGP levels were mainly within the imperceptible category ( $<0.35$ ) for 84% of cases, with only 7% of cases within the intolerable category ( $\geq 0.45$ ).

Though the office space was air-conditioned and did not feature operable windows, air temperature ranged from 20°C to 27°C with a mean of 23.5°C. Relative humidity ranged from 41% to

61% with a mean of 51%. Though thermal discomfort might have occurred in a few cases (4.5% answered with “too cold” or “too warm”), no responses were excluded because we did not confirm whether thermal discomfort affected visual comfort, visual interest, and view quality.

Regarding questionnaire responses, there were slight variations in the visual interest of sunlight patterns and in view quality (Fig. 8/left). There was a noticeable variation in view quality ratings among the three window conditions. Table 3 shows the mean and standard deviation of questionnaire responses and physical measurements.

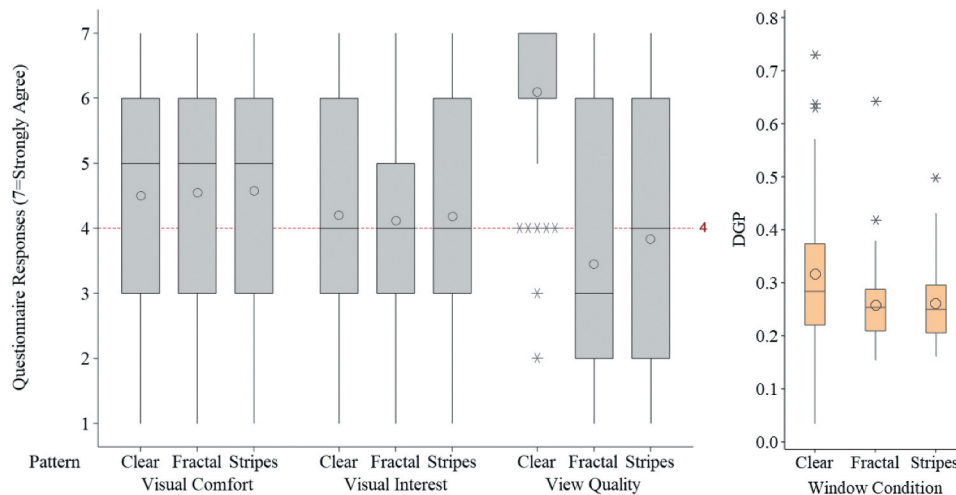


Fig. 8. A boxplot of questionnaire responses (left), and a boxplot of daylight glare probability (right). The boxplots show minimum, 25<sup>th</sup> percentile, median, 75<sup>th</sup> percentile, maximum, and outliers. The circles within each boxplot represent the means.

**Table 3.** Descriptive statistics of questionnaire responses and main physical measurements.

	Clear		Fractal		Stripes	
	Mean	SD	Mean	SD	Mean	SD
Visual Comfort	4.5	1.8	4.5	1.7	4.6	1.9
Visual Interest	4.2	1.6	4.1	1.6	4.2	1.9
View Quality	6.1	1.0	3.5	2.1	3.8	2.0
Thermal Comfort	4.2	1.0	3.9	0.9	3.9	1.0
Air Temp (F)	75.1	3.3	74.2	2.8	74.1	2.4
Vertical illuminance	2443	2103	1325	1146	1331	1085
DGP	0.32	0.13	0.26	0.07	0.26	0.07

### 3.2. Linear mixed models

Linear Mixed Models (LMM) were used to examine occupant's ratings of visual comfort, visual interest of sunlight patterns, and view quality. The assumption of normality for dependent variables and residuals was verified using probability plots. Fixed variables included window condition, desk layout, façade orientation, presentation order, DGP, and an interaction term window condition x desk layout. Participant identifier was added as an independent random variable. All post hoc comparisons were adjusted using the Bonferroni correction. Estimated marginal means (EMM) and standard error (SE) are reported to show the direction of the effects.

#### 3.2.1. Visual comfort

No significant differences in visual comfort were found among the three window conditions [ $F(2, 256) = 0.22$ ;  $p = .80$ ]. Furthermore, no significant effect was found of desk layout [ $F(1,256) = 2.32$ ;  $p = .12$ ] or façade orientation [ $F(1,256) = 3.70$ ;  $p = .05$ ] on visual comfort. The DGP metric showed a significant effect on visual comfort [ $F(1,256) = 14.20$ ;  $p < .01$ ]. Though presentation order was randomized, it had a significant effect on visual comfort [ $F(1,256) = 3.98$ ;  $p = .04$ ] with a higher visual comfort for striped-fractal order ( $EMM = 4.7$ ;  $SE = 0.16$ ) than fractal-striped order ( $EMM = 4.2$ ;  $SE = 0.16$ ). The effect of the interaction term window condition x desk layout was not significant.

#### 3.2.2. Visual interest of sunlight patterns

Overall, there were no significant differences in visual interest ratings across the three window conditions [ $F(2,96) = 0.17$ ;  $p = .84$ ]. The effect of façade orientation was not significant [ $F(1,96) = 1.49$ ;  $p = .22$ ]. Desk layout significantly

affected the visual interest of sunlight patterns [ $F(1,96) = 7.42$ ;  $p < .01$ ]. Specifically, visual interest was higher for participants with a desk layout perpendicular to window ( $EMM = 4.58$ ;  $SE = 0.26$ ), compared to participants with a desk layout parallel to window ( $EMM = 3.57$ ;  $SE = 0.25$ ). Effects of presentation order [ $F(1,96) = 0.07$ ;  $p = .79$ ] and DGP [ $F(1,96) = 3.09$ ;  $p = .08$ ] were not significant. The effect of the interaction term window condition x desk layout on visual interest was not significant.

#### 3.2.3. View quality

Regarding view quality, as shown in Fig. 8, the clear condition was significantly better ( $EMM = 6.10$ ,  $SE = 0.19$ ) than the fractal pattern ( $EMM = 3.42$ ;  $SE = 0.19$ ) and the striped pattern ( $EMM = 3.83$ ;  $SE = 0.19$ ) [ $F(2,256) = 55.57$ ;  $p < .01$ ]. No differences were found between the fractal and the striped patterns. The influence of desk layout on view quality was significant [ $F(1,256) = 10.41$ ;  $p < .01$ ] with higher view quality ratings for participants perpendicular to window ( $EMM = 4.87$ ;  $SE = 0.17$ ) compared to participants parallel to window ( $EMM = 4.0$ ;  $SE = 0.17$ ). The effects of façade orientation [ $F(1,256) = 0.48$ ;  $p = .48$ ] and presentation order [ $F(1,256) = 3.88$ ;  $p = .05$ ] on view quality were not significant. DGP did not have a significant effect on view quality [ $F(1,256) = 0.22$ ;  $p = .64$ ]. The effect of the interaction term window condition x desk layout on view quality was not significant.

## 4. Discussion

In this study, our hypothesis regarding the fractal pattern being associated with the highest levels of visual comfort and interest was not supported. It was found that desk layout (parallel or



perpendicular to window) affected ratings of visual interest of sunlight patterns and view quality. This result is in line with findings of a previous study where differences in relaxation and excitement (under different windows and sunlight conditions) were dependent on view direction (Boubekri et al. 1991). These results suggest that desk layout in relation to window is an important factor when examining the visual environment.

In contrast to the current study results on visual comfort and visual interest, previous studies reported differences in visual comfort and visual interest under different window conditions. For example, Tuaycharoen and Tregenza (2007) found that glare discomfort from windows decreased as interest in outdoor view increased, this study acknowledged that it was not clear whether the reduction in visual discomfort would persist with continued exposure. A previous study found that ratings of visual comfort and visual interest of sunlight patterns were higher for a clear window condition, compared to a striped pattern (Abboushi and Elzeyadi 2018). It is important to note that participants did not conduct any office task while viewing the patterns and only spent a short duration observing the different window conditions.

Another study used virtual reality to simulate sunlight in a space, and showed that an image of the simulated space was perceived as more interesting under irregular window screen and sunlight patterns, compared to regular patterns (Chamilothori et al. 2019). It should be noted that mean exposure time to each scene in this study was 68 seconds, and that the scene included sunlight covering a large area of a side wall. In the current study, the size of sunlight patterns was relatively small given that the study was conducted in summer months, and that computer monitors and other items on participant's desk might have obstructed viewing these patterns.

There are important methodological differences between these previous studies and the current study. Participants in the current study were exposed to window conditions for a longer duration in their office (three days in the current study, compared to a few minutes) and performed typical daily office tasks, which might have mediated the influence of light pattern geometry on visual

comfort. In the current study, participants might have directed their attention to performing office tasks, compared to solely observing window and sunlight patterns. A previous study found that task difficulty influenced temporal glare responses (Altomonte et al. 2016). It is therefore expected that viewing a visual stimulus while performing a task would affect visual comfort differently, compared to leisurely viewing a visual stimulus without performing any tasks.

While the clear window condition allowed more sunlight in the space, compared to the two patterns, there were no differences in visual comfort. This finding is in line with previous studies and supports the notion that the presence of sunlight in a space can be appreciated in work environments (Boubekri and Boyer 1992; Van den Wymelenberg et al. 2010).

Compared to other previous studies (Abboushi et al. 2019; Taylor and Spehar 2016), one of the main differences was the background of the patterns (white background in previous studies compared to clear areas through which outdoor view is seen in the current study). We did not collect visual interest ratings of the window pattern itself, which might differ from the visual interest of sunlight patterns, mainly because the visual interest of outdoor views would compete with the visual interest of the pattern that is occluding it.

While previous studies suggested that striped patterns are more visually uncomfortable because they deviate maximally from natural patterns (Wilkins 2016; Winterbottom and Wilkins 2009), this study did not find any differences in visual comfort or interest of sunlight patterns between the striped pattern and the fractal pattern. The different results may be due to differences in environmental contexts, e.g. pattern on a window in an office compared to viewing a stimulus on a computer screen with a white background (Penacchio and Wilkins 2015). It should be noted that the current study focused on visual comfort for conducting office work and not while specifically looking at the pattern.

Following the figure-background concept in perception (Wagemans et al. 2012), when patterns are viewed on a white background, the pattern is the sole stimulus and 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 stimuli and not of each stimulus separately.

Regarding view quality ratings, the preference for unobstructed views is in line with previous studies (Abboushi and Elzeyadi 2018; Omidfar et al. 2015). A key difference between the two patterns is in view composition. This poses important questions on the extent to which window patterns influenced view quality ratings, and on the interaction between indoor and outdoor views for view quality assessments. The fact that the fractal pattern exhibits irregular clear and translucent areas, compared to the repetition in the striped pattern, did not make a difference in view quality. While the effect of regular shades and openness factor has been studied (Konstantzos et al. 2015), there is a lack of studies examining outdoor view quality seen through regular and irregular openings.

Although there were differences in view quality between the clear condition and the two patterns, these differences did not seem to influence visual comfort. This result is in line with a previous study (Aries et al. 2010) that did not find a significant relationship between view quality and/or type and environmental utility, specifically glare problems.

The use of window patterns and their shape highlights an important process in psychological research called “masking” which relates to the reduction in visibility of one stimulus (views) by another stimulus or a 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

et al. 2015). Overall, it is possible that the ability of occupants to reconstruct obstructed view regions under both patterns was reduced, compared to the clear condition (Fig. 9). 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.

There were several limitations that should be considered when interpreting the results and conclusions of this study. This study was conducted during the summer months in San Francisco, CA, which might have limited sunlight pattern size and influenced occupants’ preferences toward sunlight. The window conditions affected the location of sunlight patterns as well as view areas. The shade position was fixed to reduce the possibility of participants experiencing intolerable glare and stopping their participation. While none of the participants stopped their participation, the position of the shades mitigated glare levels. These confounding factors are inherent to field research assessing different façade designs and might have influenced the results of this study.

Regarding participants, the number of participants was limited and most participants (23 out of the 33 participants) were 50–70 years of age, hence their sensitivity to brightness might be different than those of other age groups. In this field study, the timing and frequency of the questionnaire were limited to avoid interrupting participant’s daily office work as that was thought to might influence their participation and response rates. The duration of exposure to each window condition was limited to one day. Occupant’s familiarity with the clear condition, presentation



**Fig. 9.** Participant’s views through the clear (left), fractal (middle), and striped (right) window conditions.

order (clear was always set as third condition), and the non-randomized order of questionnaire items might have influenced the results.

Another limitation in the current study is related to the use of a broad visual comfort ratings (this is a visually comfortable environment for office work) along with DGP, which was originally developed using a scale that measures discomfort (Wienold and Christoffersen 2006). It is unclear whether this issue affected the results of the current study.

Because thermal comfort was not fully investigated in this study, it is unclear whether thermal discomfort affected participants' responses to visual comfort, visual interest of sunlight patterns, or view quality. Hence, no responses were removed. This issue might have affected a small number of responses given that the office was air-conditioned.

Considering these limitations, the current study raises questions on façade screens, e.g. perforated metal screens where some level of view occlusion is unavoidable. We did not find differences in visual comfort or visual interest of sunlight patterns. This suggests that the shape of window and sunlight patterns might have limited to no influence on visual comfort or visual interest of sunlight patterns in offices where workers are preoccupied performing typical daily tasks.

Future studies should examine the effect of performing a task on visual interest assessments in work environments. The effect of window shades with irregular openings on view quality is another important area that warrants further studies.

## 5. Conclusions

This study examined occupant's visual comfort, visual interest of sunlight patterns, and view quality under three different window conditions through a field study in an office building. This investigation relates to the shape of perforations in window screens and shades. Previous literature on this topic did not examine sunlight patterns in a realistic setting while participants are performing typical daily tasks. This difference should be considered while interpreting the outcomes of the current study. We summarize the conclusions of this study with the following points:

There were no significant differences in visual comfort or visual interest ratings among the fractal pattern, striped pattern, and clear condition.

The fractal and striped patterns were associated with a significant decrease in view quality, compared to the clear condition.

View direction significantly influenced visual interest of sunlight patterns and view quality ratings.

There were no significant differences in view quality between the fractal pattern and the striped pattern.

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