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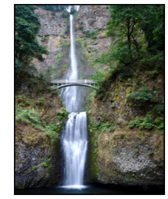

Fractals in architecture: The visual interest, preference, and mood response to projected fractal light patterns in interior spaces

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ABSTRACT

The visual patterns of fractal stimuli on a computer screen and the brightness patterns of light projected onto room surfaces have independently been shown to influence human perceptual responses. It is not clear, however, what effect would result if the same fractal patterns were projected as light patterns on room surfaces. This paper reports on the results of three studies investigating 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 results suggest that fractal light patterns of medium to medium-high complexity (quantified by the fractal dimension $D = 1.5–1.7$) were significantly more visually interesting than other patterns. Crucially, viewing distance did not significantly influence visual interest or visual preference. Based on these studies, the use of medium to medium-high complexity fractal light patterns in interior spaces may be useful for enhancing occupants' visual interest and mood.

People's appreciation for the visual characteristics of 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, 2003). Another theory was proposed by Kaplan, 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). Regarding these hypotheses and theories, a logical question to ask is: What characteristics in natural scenes elicit such positive responses? Another related question is: What mechanism of visual perception underlies this positive response?

In an attempt to identify these characteristics and the visual perceptual mechanism employed, one approach suggested that the positive effects of natural scenes can be explained by fractal patterns, which are prevalent in natural scenes (Purcell, Peron, & Berto, 2001; Joye & Van den Berg, 2011; Hagerhall et al., 2015; Hagerhall, Purcell, & Taylor, 2004; Spehar, Clifford, Newell, & Taylor, 2003). Examples include trees, mountains, rivers, clouds and lightning. Fractal objects display a cascade of self-similar patterns over a range of magnification scales (Fairbanks & Taylor, 2011; 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 et al., 2018; Taylor & Spehar, 2016). This theory was selected as a basis for the three studies presented in this paper because of its relation to the Attention Restoration theory and the Biophilia hypothesis. This is an attempt to answer an important, yet unexplored dimension of environmental stimuli related to the relationship between the inherent structure of the stimuli and the mechanism used to attribute responses to it. Further, the ability to accurately generate environmental stimuli using fractal patterns of specific complexities and densities was advantageous for controlling certain study variables, such as brightness. The term 'density' hereafter refers to the ratio between black- and

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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; Spehar et al., 2003; Taylor, 1998), heightened pattern recognition (Taylor et al., 2017a,b, 2018), increased navigation skills (Juliani, Bies, Boydston, Taylor, & Sereno, 2016), as well as stress recovery benefits (Taylor, 2006). These effects might be mediated by the positive visual preference of environmental stimuli, 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 of art works. 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).

Building upon previous research studies in environmental psychology, visual interest and preference toward patterns in interior spaces can be conceptualized as a result of direct and interactive effects among four variables: 1) pattern type, for example, fractal or Euclidean; 2) pattern complexity; 3) the medium used to present the patterns, for example, light projections; and 4) spatial variables such as viewing distance and scale of pattern. The current study adopts this conceptualization, which highlights the importance of considering other stimuli and their effects on visual interest and preference toward patterns in interior spaces.

Most previous studies, however, examined perceptual responses to fractals using two-dimensional visualizations on a computer screen (Bies, Blanc-Goldhammer, Boydston, Taylor, & Sereno, 2016; Hagerhall et al., 2004; Hagerhall et al., 2008; Spehar et al., 2003; Spehar & Taylor, 2013; Taylor, Spehar, Hagerhall, & Van Donkelaar, 2011). Thus, the applicability of findings to actual environmental stimuli and indoor brightness patterns is yet to be explored. This is mainly because the impacts of spatial projection of patterns, lighting, room 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 the perceptual and physiological benefits found when fractals were viewed on a computer screen. To address this gap in behavioral application of the fractal fluency theory, the studies presented in this paper focus on the visual interest and preference for projected light patterns in space.

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 contributions of the fine scale patterns grow, 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 (Fairbanks & Taylor, 2011; Hagerhall et al., 2015). Exact fractals also exhibit a different aesthetic dependence on D (Bies et al., 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 the fractal dimension range of 1.3–1.5 (Spehar & Taylor, 2013; Taylor et al., 2005). Spehar et al. (2003) examined visual preferences for three types of fractals that were generated using different methods: Natural, computer-generated, and human-produced fractals. The results showed that preferences congregate within the range $D = 1.3$–1.5, regardless of the generation method. Fig. 1 shows examples of fractals generated with different methods. Aks and Sprott (1996) found that participants preferred patterns with a D value between 1.17 and 1.38 and suggested that aesthetic preference may reflect stable individual differences and traits, such as creativity.

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).

In addition to visual appeal, the $D = 1.3$–1.5 range was also found to significantly reduce stress by 60% − stress level was determined by skin conductance measurements (Taylor, 2006). This was a unique study because rather than displaying the fractal patterns on a computer screen, they were mounted, each measuring 3.2×6.5 feet (1.0×2.0 m), on a wall in front of participants. In a subsequent study that examined brain activity using electroencephalograms, statistical fractal patterns were found to induce an alpha response (Hagerhall et al., 2008), which is an indicator of a wakefully-relaxed state. Furthermore, statistical fractals generated the highest beta response in the parietal cortex, which means that they generate 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 showed benefits related to stress recovery and brain response, Studies 1 and 2 in this paper examined mood response to determine whether a similar positive effect is reflected in mood response when environmental stimuli in the form of fractal light patterns are projected on surfaces such as walls.

Participants' profiles and sampling criteria varied across previous studies. Some studies included undergraduate students at the University of New South Wales either 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 ranges between 17 and 31 (Aks & Sprott, 1996). Large-scale studies (Draves & Al, 2008; Taylor & Sprott, 2008) included 20,000 people who voted while a computer screen saver was active.

2. Environmental perception

A previous study showed that natural environments were more likely to be considered restorative, compared to urban environments, and received positive evaluations of recovery, which appeared to explain the higher preference for forest slides over the city slides projected on screens (Staats, Kieviet, & Hartig, 2003). Another study (Hartig, Evans, Jamner, Davis, & Gärling, 2003) found that positive affect increased after walking through a nature reserve and decreased after walking in an urban environment. The latter 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. Another study (Brooks, Ottley, Arbuthnott, & Sevigny, 2017) concluded that both actual and pictorial nature contact benefits mood, though actual nature is more effective. The affective restoration of natural environments substantially accounted for their preference over built environments (van den Berg, Koole, & van der Wulp, 2003).

A recent study that examined eye movements while viewing natural or urban scenes concluded that the visual processing of nature scenes required smaller cognitive effort (Franěk, Šefara, Petružálek, Cabal, & Myška, 2018). This aligns with the fractal fluency theory (Taylor et al., 2018), which explains the ease in navigating landscapes of low to mid complexity fractals (Juliani et al., 2016). In addition to the reduced cognitive effort, connectedness with nature was found to be associated with higher holistic and innovative thinking styles (Leong, Fischer, & McClure, 2014).

While arguably related, visual interest and visual preference may be different concepts. Generally, visual preference is more commonly assessed in psychological studies that examined fractal patterns, whereas

Fig. 1. Natural, computer-generated, and human-produced fractals (left to right). Courtesy of Richard Taylor.

visual interest appears more prominently in environmental aesthetic studies perhaps driven by the desire to create visually interesting spaces and avoid dull spaces. Hence, the current study examines visual interest and preference for various patterns projected on a wall (rather than viewed on a computer screen) with viewers seated at varying distances to the wall, to establish a reference for future studies in architecture and environmental spatial perception.

Light perception. Light is one of the main environmental stimuli that can influence people's perception and mood in interior and outdoor spaces. Previous studies examined the 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 (John Flynn, Spencer, Martyniuk, & Hendrick, 1973). For instance, impressions of visual clarity, spatial complexity, contrast, spaciousness, and relaxing vs. tension-inducing space were considered. A recent study found a link between contrast and visual interest in architectural renderings (Rockcastle, Amundadottir, & Andersen, 2016). Another study found that light correlated color temperature (CCT) significantly affected spatial brightness perception, visual comfort, satisfaction, and self-reported productivity (Knez, 1995; Wei et al., 2014).

Not only does the perception of light influence emotions, a previous study found that the observer'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 of stimuli: 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 & Powerll, 1993). They associated each type of lighting stimuli with certain behaviors and sensations. For example, they argued that play of brilliants had potential to excite the optic nerve and stimulate the body (Fig. 2).

Given the demonstrated effect of light on information in the visual field, we argue that the effect of fractal patterns is likely to be influenced if light was used to project and represent the same patterns. Therefore, the three studies presented in this article focused on projected light patterns, as opposed to light patterns viewed on a screen or on a poster.

3. Summary of studies and hypotheses

In general, three studies were conducted and were tied closely to four hypotheses. Studies 1 and 2 examined the visual interest and mood response to black and white patterns projected onto a surface, and to projected patterns in renderings of an interior space, respectively. The patterns included four fractal patterns and two Euclidean patterns. For these two studies, we hypothesize that: 1) fractal light patterns will be more visually interesting than non-fractal light patterns; 2) fractal compared to non-fractal light patterns will enhance both Relaxation and Excitement.

Study 3 examined visual interest and visual preference for two groups of participants seated at different viewing distances to investigate whether visual interest and preference are rated similarly or differently, and to study whether viewing distance influences these two ratings. We hypothesize that: 3) visual interest and preference ratings will be similar; 4) the distance between observers and patterns will influence visual preference for the fractal dimension of the projected light patterns in space, and hence, visual preference is expected to be different from preference for those patterns viewed on a computer screen.

Fig. 2. Dappled sunlight patterns through trees is an example of play of brilliants. Courtesy of Steven Holl Architects/Susan Wides.

4. Study 1: The visual interest and mood response to projected light patterns

4.1. Methods

Participants. Participants were recruited from a pool of students enrolled in a human-factors course in the department of architecture. 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

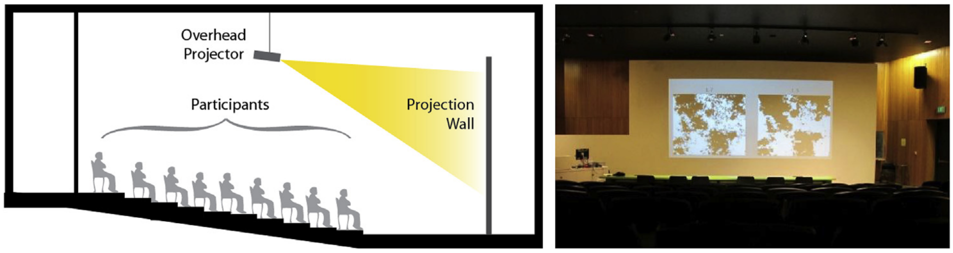

Fig. 3. A section drawing (left) and a picture (right) of the lecture room used in this study.

experiment were given 5 min 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. All participants signed a consent form and, upon completion, received an extra participation credit in that course.

Study setting. The experiment was conducted in a lecture hall at noon during the Winter term of 2017 (Fig. 3). The dimensions of the room were 49.7 × 52.8 × 18.0 feet (15.1 × 16.0 × 5.4 m). An overhead projector was used to project different patterns on a white wall located in front of the participants. The projection area of each light pattern was 8.0 × 8.0 feet (2.4 × 2.4 m). 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 17.0 feet (5.1 m) away, and the farthest person was 46.0 feet (14 m) away. The projector (Panasonic PT-DZ6700U) had a resolution of 1920 × 1200 pixel, and a brightness of 6000 Lumens. Lighting in the room was set to allow a clear view of both the light pattern projections and room surfaces, and remained constant for the duration of the experiment. The luminances 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 the vertical illuminance at the projection wall, excluding the lighting contribution from the projector, was 23 Lux.

Visual stimuli. Black and white fractal and non-fractal patterns were used in this experiment. The selected fractal patterns included four statistical fractal patterns (D = 1.1, 1.3, 1.5, and 1.7) and two non-fractal patterns, a rectangular and a striped pattern (Fig. 4). 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 was paired with every other pattern in the set, and presented twice, once on each side of the projection wall (for the visual interest assessment). Stimulus order was randomized. To evaluate the impact of the projected light patterns on mood, the 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.

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 used successfully in previous studies of visual preference (Spehar et al., 2003, 2015). For assessing mood, a rating procedure was used on individual images. This procedure involved 24 image 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 Fig. 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 (Boubekri, Hull, & Boyer, 1991; Russell & Pratt, 1980). Only four parameters were selected so that participant fatigue was reduced. The two indices were utilized following Russel and Pratt's conceptualization of affective meaning as a two-dimensional bipolar space.

Participants were given 17 s 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 to 20 s would ensure that responses were received from all participants and recorded by the polling station receiver. After each assessment, a neutral gray color was shown for 5 s. Responses were collected from all participants at the same time. The time required to complete viewing and assessments was 40 min. Prior to the start of the experiment, practice questions were presented to ensure the clarity of the questions and the experimental procedure. In response to the question “Which light pattern is more visually interesting?”, each participant selected the letter A/B of the pattern that was more visually interesting. In response to questions addressing the observer's feelings (for example, “Does this light pattern make you feel peaceful?”), letters A-E were used to label the following levels: “Not at all”, “a little”, “moderately”, “quite a bit”, and “extremely”.

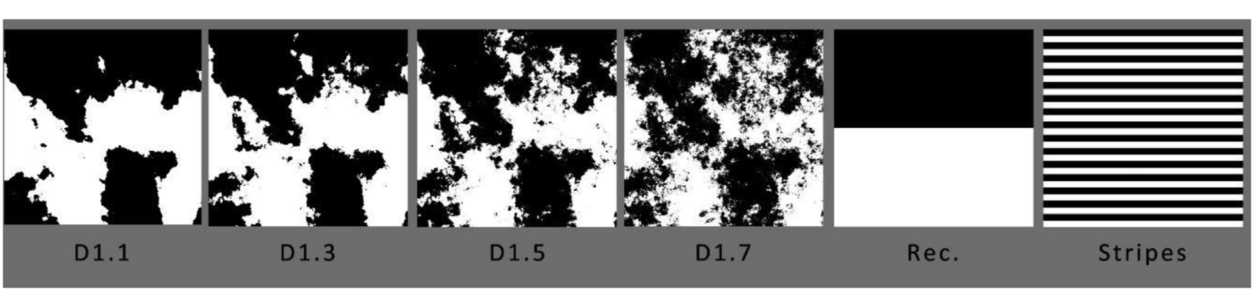

Fig. 4. The four fractal patterns were selected to convey various levels of fractal complexity, whereas the non-fractals were selected to mimic light patterns of a venetian blind (Stripes) and a roller shade (Rectangular). Fractal patterns are courtesy of Cooper Boydston, Richard Taylor, and Margaret Sereno.

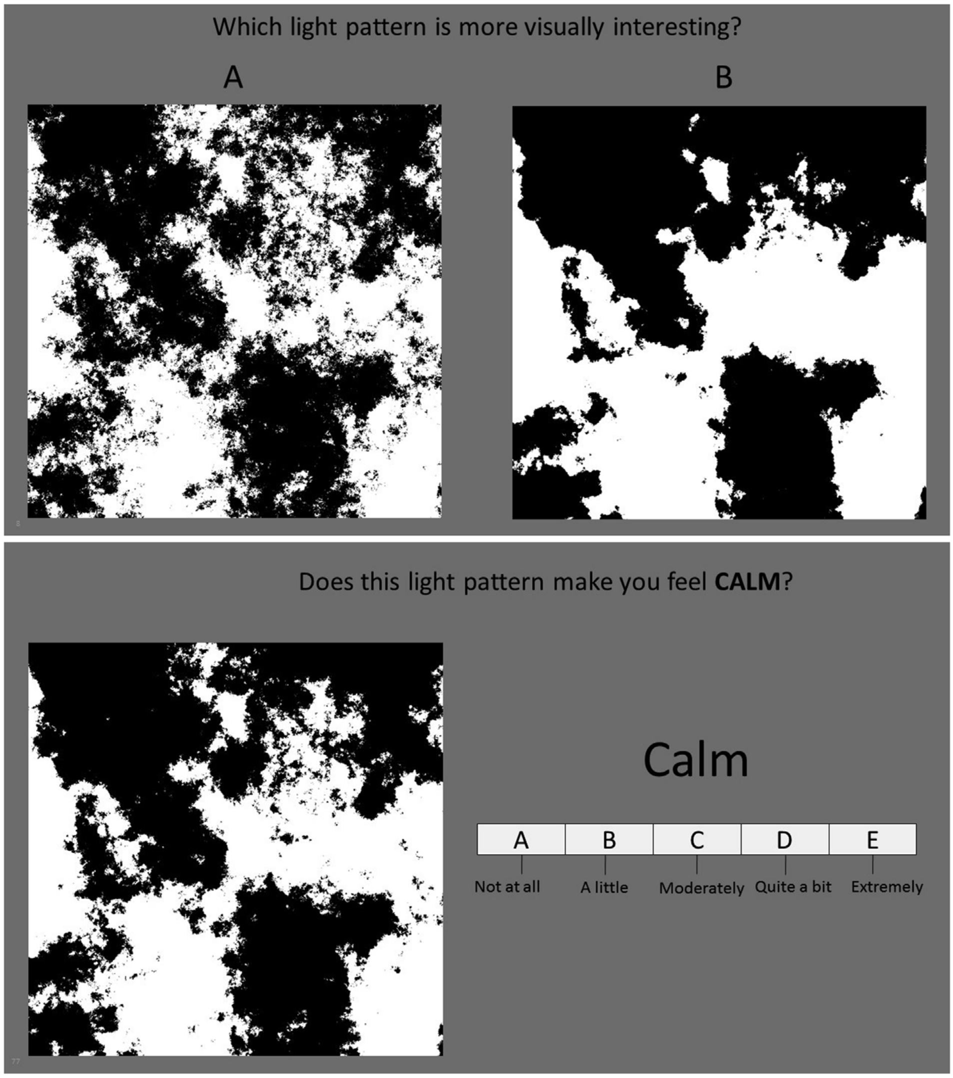

Fig. 5. Example stimuli as presented: visual interest assessment (top), and mood assessment (bottom).

4.2. 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 (Fig. 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. The 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.

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 fractals of $D = 1.7$ (Mean = 68.2%, SD = 27.3) and $D = 1.3$ (Mean = 65%, SD = 17.5) were not significantly different. Generally, the two non-fractal patterns, rectangular and the stripes, were significantly less visually interesting than all of the fractal patterns. In addition, there was a significant difference ($Z = 3.056$, $p < 0.01$) between the 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 five 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 of $D = 1.5$ and $D = 1.7$, respectively (Fig. 7). The only pattern for 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 the fractal dimension increased. Interestingly, the ‘Excited’ line resembled the visual interest curve found in previous studies.

The four mood variables for each light pattern were factor-analyzed to confirm the two main indices proposed by Russell and Pratt (1980). Exploratory factor analysis using Principal Components Analysis for factor extraction and Varimax with Kaiser Normalization as a rotation method were used. These analyses were separately conducted on each pattern. The factor loadings indicated the existence of two underlying indexes, Relaxation and Excitement, with eigenvalues generally higher than 1 as recommended by Berman and Wang (2012). Table 1 shows load bearings of the mood variables on each index, and the eigenvalues. 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 to 0.93, while the ‘Excited’ and ‘Stimulated’ variables had high load bearings on the ‘Excitement’ index ranging from 0.77 to 0.93.

Generally, it was found that as D increased, the Excitement

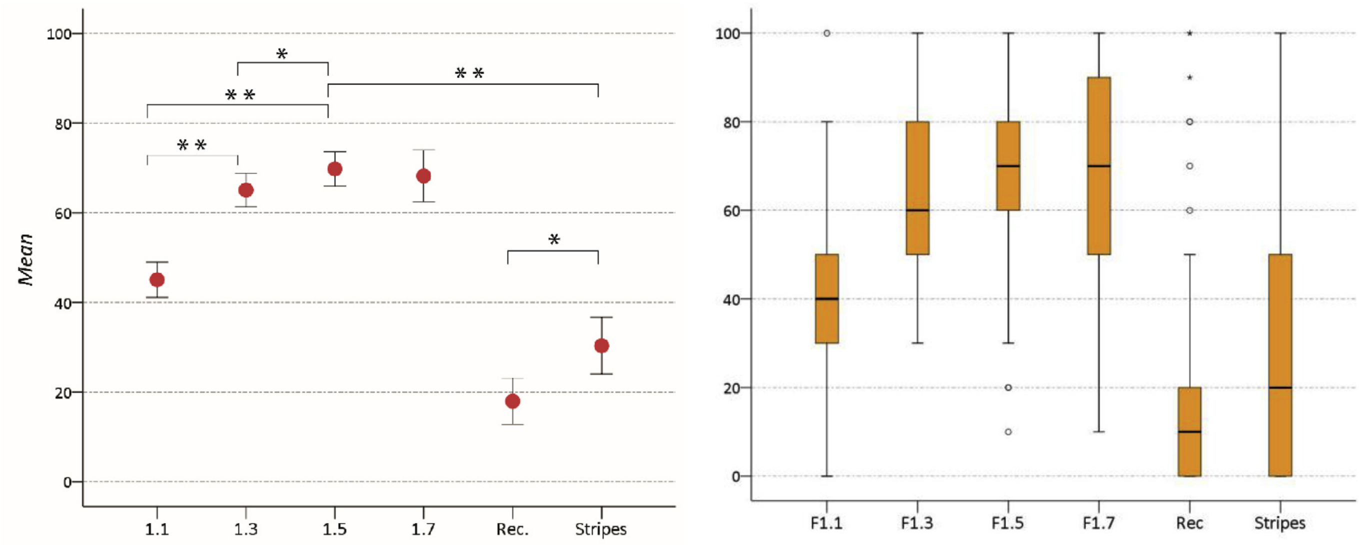

Fig. 6. Mean percentage chosen for each light pattern (left), error bars represent standard error; and boxplot shows corresponding distribution. * represents $p < 0.05$, ** represents $p < 0.01$.

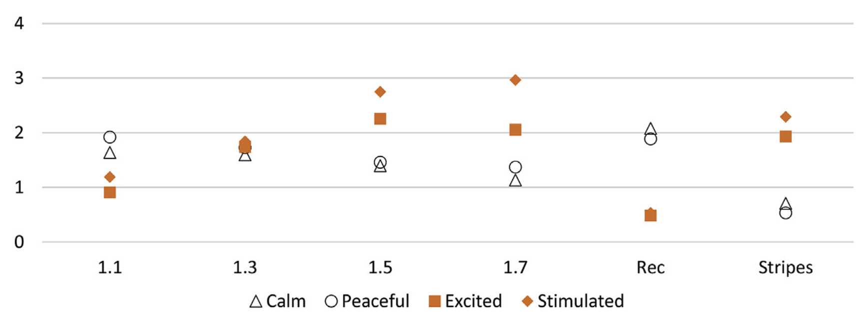

Fig. 7. Means of the four mood responses. The Y axis shows level to which participants felt that a certain pattern made him/her feel such that 0 = Not at all,1 = A little, 2 = Moderately, 3 = Quite a bit, 4 = Extremely.

increased, and feelings of Relaxation slightly decreased. Fractals 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), the fractal patterns maintained more balance between Relaxation and Excitement (Fig. 8). Table 2 summarizes the Wilcoxon signed-rank test results in terms of the Z statistic and significance level (2-tailed).

4.3. Discussion

The results of Study 1 are in line with the results of previous studies which suggested that fractal patterns are more preferred than non-fractal ones (Taylor, 1998). The two Euclidean patterns were significantly less visually interesting than all fractal patterns. Furthermore, there is a range of fractal complexity that is ideal for enhancing visual interest: As the *D* value increases from *D* = 1.1 to *D* = 1.5 visual interest increases. After that, visual interest slightly decreases for *D* = 1.7.

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 the 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, 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 et al. (1991), it can be inferred that fractal light patterns of *D* = 1.5 and

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

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
Eigenvalues	1.6	1.2	2.1	0.9	1.8	1.6	1.8	1.4	1.9	1.6	1.7	1.7

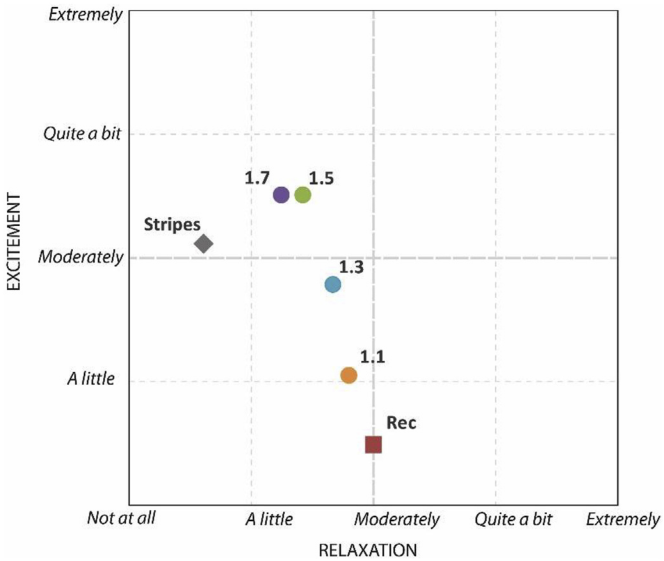

Fig. 8. A boxplot of mean Excitement and Relaxation for each pattern.

Table 2
Wilcoxon signed-rank test results for Visual Interest, Relaxation, and Excitement. * represents $p < 0.05$, ** represents $p < 0.01$.

		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**

$D = 1.7$ 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 perceived as being rather dull because it was rated low in Excitement and moderate in Relaxation. The use of a differential scale would help examine these inferences.

The higher visual interest of fractal patterns over Euclidean ones is consistent with the higher preference for nature views compared to urban scenes (Ulrich, 1981). Further, the enhancement of mood achieved by nature views was also demonstrated in Study 1 through the fractals' balance between Relaxation and Excitement, compared to Euclidean patterns. These results suggest that viewing fractal light patterns in interior spaces may elicit restorative and biophilic benefits similar to those of nature scenes (B. Browning et al., 2012; W. Browning, Ryan, & Clancy, 2014). Future applications of this finding are important to be explored spatially in three-dimensional compositions of light and space.

5. Study 2: The visual interest and mood response to renderings that included light patterns

While Study 1 suggests that certain fractal light patterns are more visually interesting than others, the results cannot yet be extended to actual architectural spaces: For example, daylight patterns through

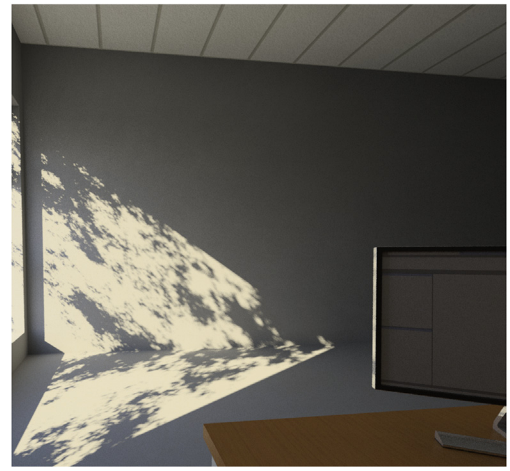

Fig. 9. An example of the rendered space showing fractal pattern D = 1.7 projected on room surfaces. Although the window itself is not shown in the renderings, its presence is depicted.

windows, which represent a major source of light projection in interior environments. Hence, the aim of Study 2 was to examine whether the findings of Study 1 extend to the more realistic case of light patterns cast by fractal window shades. To do this, the stimuli of Study 2 consisted of computer renderings of sunlight patterns falling on façade systems of an office space (Fig. 9). These were then projected on the lecture room wall to conduct the visual interest and mood assessments.

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.

5.1. Methods

This study followed the same participant recruitment and seating, presentation procedure, assessment, and timing as in Study 1. Study 2 was conducted in an afternoon of a subsequent academic term to Study 1 with the subject pool from an environmental control systems class. For mood assessment, the six images were presented one at a time while participants assessed four mood parameters for each. These renderings were generated by placing the six 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 building information modelling (BIM) software (version 2016) and were of an office space with a side window through which sunlight patterns penetrated and were cast on the room's floor and opposite wall. Fig. 10 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), 78% were 18–29 and 18% 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.

5.2. Results

Similar to Study 1 results, Study 2 found that visual interest increases as fractal dimension increases (Fig. 11). 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

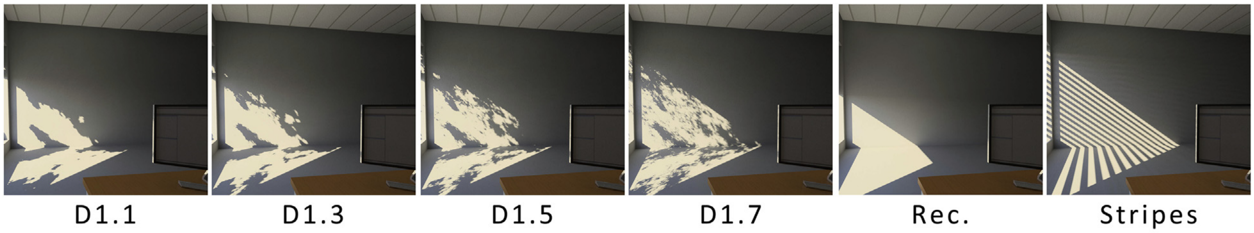

Fig. 10. The same patterns from Study 1 were used to create these renderings. The view is selected so that only sunlight pattern projections are visible and not the pattern on the window. Fractal patterns are courtesy of Cooper Boydston, Richard Taylor, and Margaret Sereno.

in line with the 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).

The four mood responses were assessed on a scale ranging across '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 (Fig. 12). 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), 'Calm' and 'Peaceful' were used to calculate a 'Relaxation' index, whereas 'Excited' and 'Stimulated' were used to calculate an 'Excitement' index.

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 for 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 $D = 1.7$ (Fig. 13). Table 4 summarizes the Wilcoxon signed-rank test results in terms of the Z statistic and significance value (2-tailed).

5.3. Discussion

The previous behavioral studies of fractal patterns displayed on computer screens found a peak visual preference in the range $D = 1.3$–1.5. In contrast, Studies 1 and 2 found that visual interest peaked at higher D values (1.5 and 1.7 respectively). One possible explanation for the shift to higher D values might originate in the increased viewing distance associated with projecting the fractal light patterns on the wall (15.1–14 m) as compared to, for example, 60 cm (Spehar, Walker, & Taylor, 2016) (Fig. 14).

To explain how a reduction in perceived light pattern detail (due to increased viewing distance) might have caused the observed shift in D, it is important to recall that the perceived visual complexity of a fractal is determined by the contribution of fine-scale structure; with more fine structure generating higher complexity. This complexity is determined by the D value, which controls the ratio between fine and coarse structure, and by the range of scales over which the fractal is observed. Increasing this range increases the visual complexity. Considering these two factors, it is possible that a low D fractal observed over a large scaling range will have the same perceived visual complexity as a high D fractal observed over a smaller scaling range (Fig. 15). For this reduced scaling range, a higher D value might be required to generate the same perceived visual complexity. Whereas previous studies showed that perceived complexity correlated linearly with D value (Spehar et al., 2016), in future studies we plan to demonstrate that perceived complexity also depends on scaling range.

To examine the relationship between the size of the smallest detail and the ability of participants to perceive it, the smallest detail is assumed to occur at the pixel separation distance of the pattern. Because participants with 20/20 vision can resolve details that occupy a visual

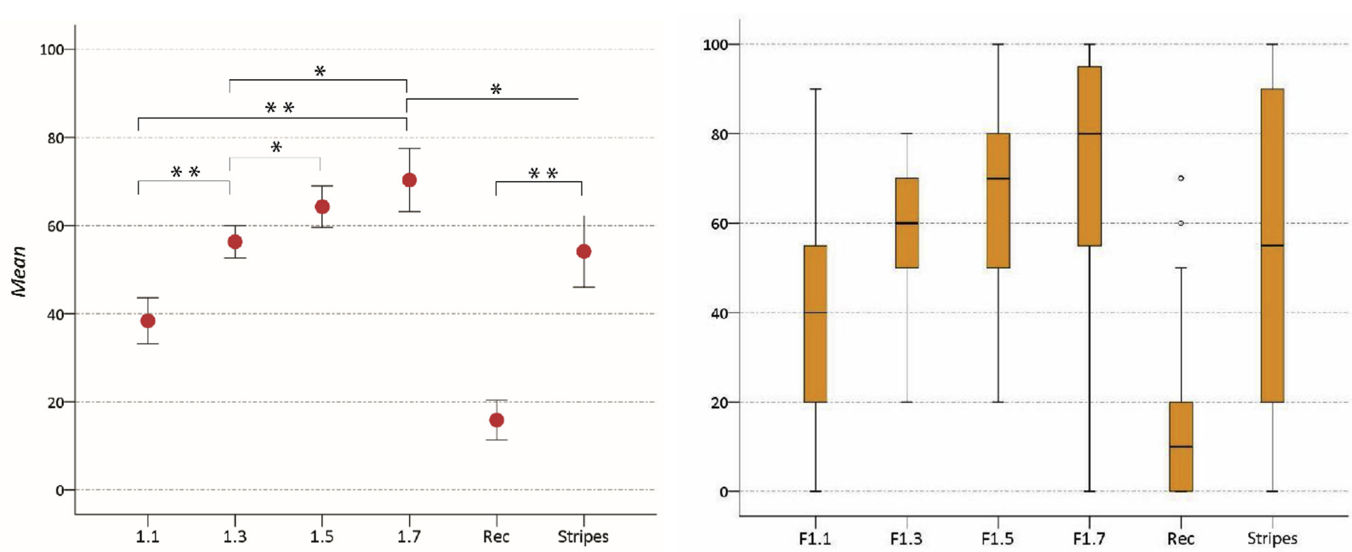

Fig. 11. Visual interest ratings: mean percentage chosen as a function of pattern type (left); whiskers represent standard error. Box plots of visual interest ratings (right). * represents $p < 0.05$, ** represents $p < 0.01$.

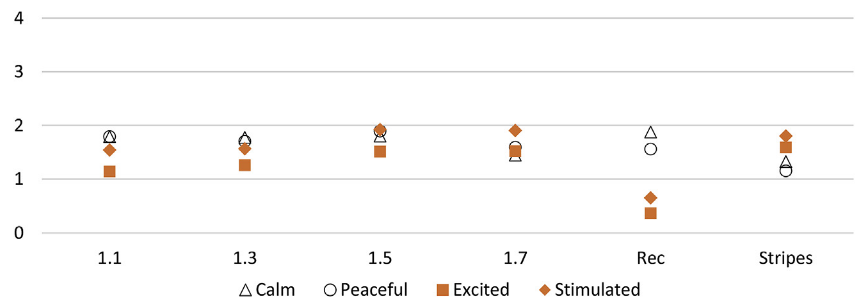

Fig. 12. Means of the four mood responses. The Y axis shows the level to which a certain pattern made the observer feel, such that 0 = Not at all,1 = A little, 2 = Moderately, 3 = Quite a bit, 4 = Extremely.

angle of (1/60)°, the smallest resolvable sizes for participants in different seat rows were calculated using this equation (the smallest resolvable size = tan(1/60)*distance from the pattern). Fig. 16 shows a scatter plot of this relationship. According to this plot, out of the 10 seat rows that were occupied during Studies 1 and 2, only participants in the first three rows could resolve the finest detail. Thus, it is possible that the reduction in observed fine detail was responsible for the behavioral shift to higher *D* for the projected images.

This would also explain why the shift is larger for Study 2 than for Study 1. The rendered sunlight patterns in Study 2 were distorted because of the orientation of projection surfaces in the rendered room, for example, the wall and floor. The further the surface from the window, the greater the edge blurriness (Fig. 17). 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.

In terms of the mood assessment, the responses for Study 2 congregated in low excitement compared to the results of Study 1. We hypothesize that this muting effect is due to the change in medium, specifically the use of renderings. Therefore, the relative difference not the absolute value is what should be examined.

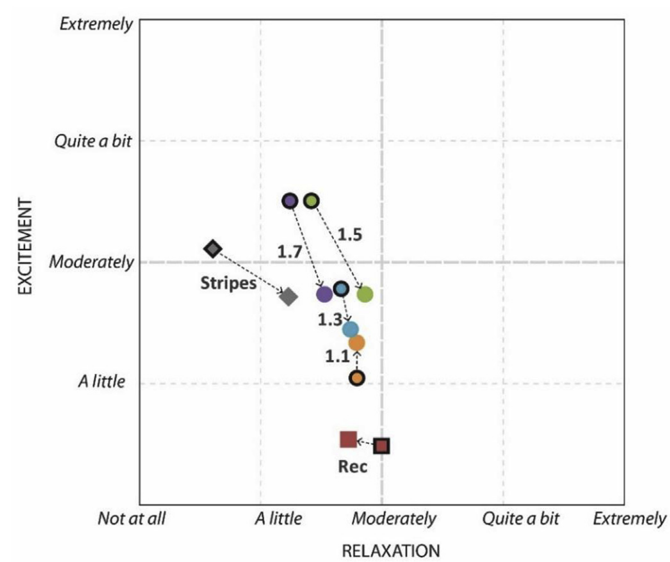

Fig. 13. Boxplot of mean Relaxation and Excitement values for the six patterns showing Study 2 results (markers without a black border) compared to those from Study 1 (markers with a black border).

6. Study 3: The visual interest and preference for projected light patterns viewed at different distances

The purpose of Study 3 was to investigate the effect of viewing distance (near/far) to determine whether the associated reduction in perceived fine-scale detail might have caused the shift to higher *D* observed in Studies 1 and 2 relative to previous studies. Given that participants in Studies 1 and 2 rated visual interest rather than preference used in previous studies, Study 3 also compared assessment type (interest/preference) on participant choice responses to determine if this was the origin of the shift to higher *D*.

6.1. Methods

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 for 26 participants was 18–29 years.

6.2. Results

A 3-way mixed ANOVA (Distance (front, back) x Fractal Dimension (1.1, 1.3, 1.5, 1.7) x Assessment Type (Interest, Preference)) was performed on the response choice data for the fractal patterns, with Distance as a between-subjects' variable and fractal dimension and

Table 3
Factor loadings after Varimax with Kaiser Normalization for each mood variable on the two indices Relaxation (1) and Excitement (2).

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
Eigenvalues	1.9	1.5	2.0	1.4	3.3	1.8	3.0	1.8	3.0	1.0	2.2	1.4

Table 4
Results of the Wilcoxon signed rank test for visual interest, Relaxation, and Excitement. * represents p < 0.05, ** represents p < 0.01.

		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**

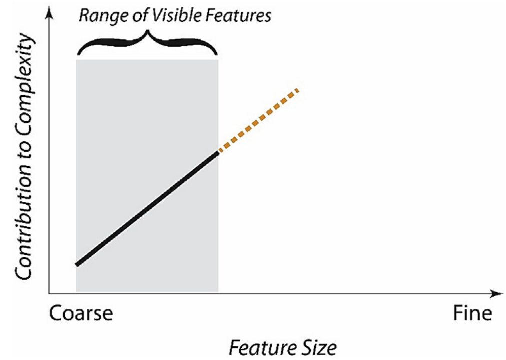

Fig. 15. The contribution of dashed orange part of a fractal pattern does not contribute to perceived complexity because it falls outside the range of visible features (note that D sets the gradient of the line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

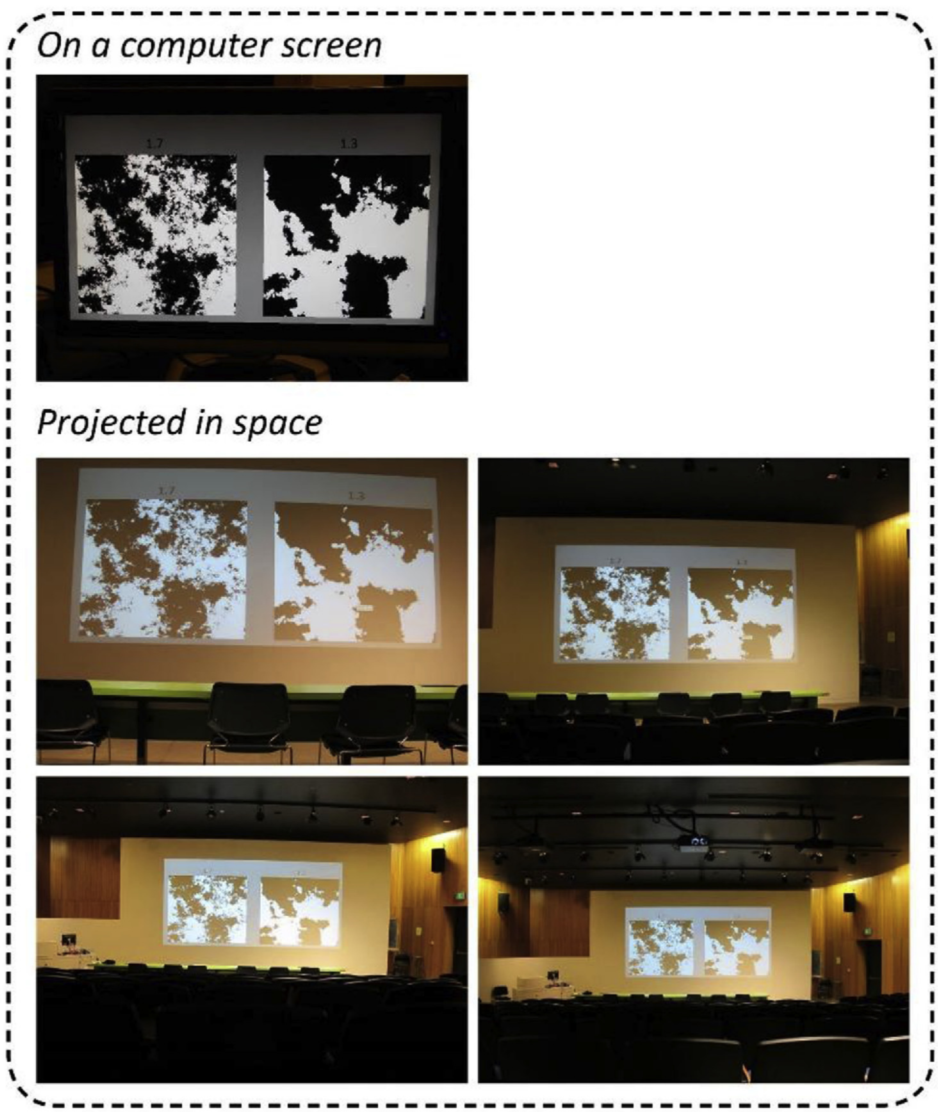

Fig. 14. A comparison of view sheds between viewing on a computer screen vs. projected on a wall and viewed at 5.1 m, 8.2 m, 11.2 m, and 14 m away from projection wall.

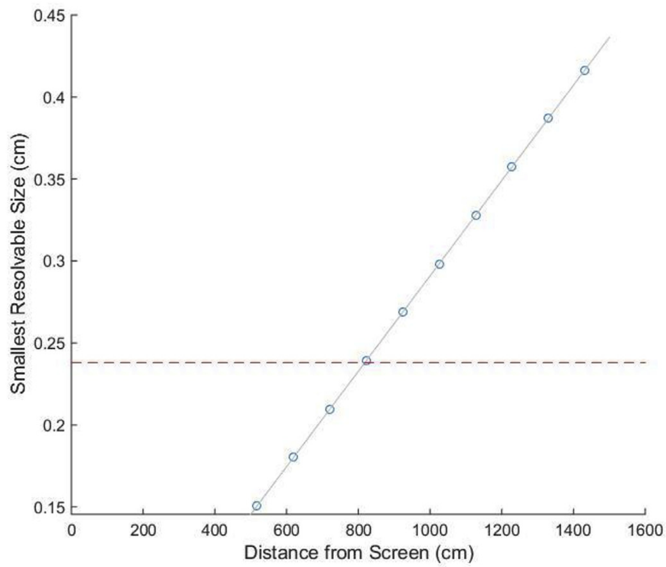

Fig. 16. A scatter plot shows the relationship between distance from screen and smallest resolvable size. The dashed red line represents the actual size of the smallest detail. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

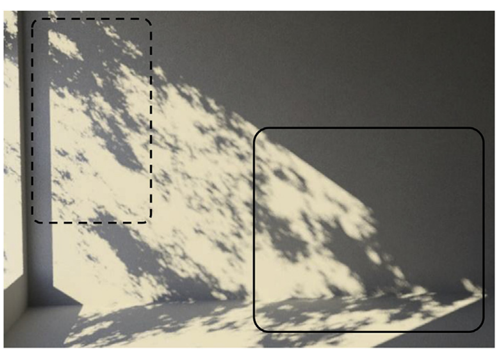

Fig. 17. The two highlighted regions are different in terms of blurriness for the fractal shadow of D = 1.7. The region marked with the continuous line looks blurrier than the region marked with dashed lines.

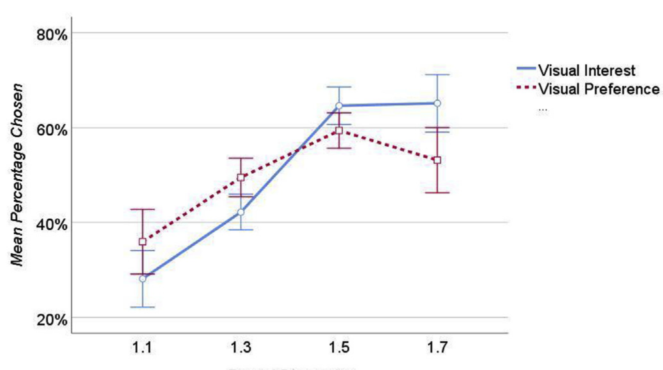

Fig. 18. Mean percentage chosen for visual interest and preference by fractal dimension (left). The error bars represent ± 1 Standard Errors.

assessment type as within-subjects' variables. Mauchly's test indicated a violation of the assumption of sphericity for Fractal Dimension $\chi^2(5) = 52.93$, $p < 0.001$ and the interaction between Fractal Dimension and Assessment Type $\chi^2(5) = 15.97$, $p = 0.007$. Therefore, Greenhouse-Geisser corrected values are reported. There was a main effect of Fractal Dimension $F(1.48,44.43) = 5.94$, $p = 0.010$, and an interaction between Fractal Dimension and Assessment Type $F(2.30,69.06) = 3.61$, $p = 0.027$. Within-subject contrasts of the interaction showed a significant linear trend $F(1,30) = 6.61$, $p = 0.015$. The interaction indicates that response choice was different across the levels of Fractal Dimension depending on Assessment Type (visual interest or visual preference). While visual preference peaked at $D = 1.5$ (mean = 59.3, SD = 21.1), visual interest peaked from $D = 1.5$ (mean = 64.5, SD = 22.3) to $D = 1.7$ (mean = 65.1, SD = 34.2), as can be seen in Fig. 18. Interestingly, there were no significant differences in response choices related to seating Distance from the screen ($F(1,30) = 0.63$, $p = 0.435$) (Fig. 19).

6.3. Discussion

Similar to the results of Study 1 and Study 2, Study 3 found that visual interest increases as fractal dimension increases. Study 3 explicitly compared visual interest and visual preference responses to the four fractal patterns when viewed at widely different distances. The results demonstrate that fractal complexity does affect visual interest and preference choice responses differently with visual interest peaking at slightly higher *D*-values than visual preference. Finally, while viewing distance has a large effect on the visual angle of the projected fractal stimuli as well as the ability to see the smallest levels of recursion and finest detail in the fractal patterns (see Figs. 14–16), this does not affect the assessments of visual interest and preference.

Conclusions

When collectively examined, the results show that the behavioral responses to projected fractal light patterns are dependent on the amount of complexity perceived by the observer. All three studies showed that visual interest peaked for fractals in the range $D = 1.5–1.7$ (Fig. 20) and Study 3 showed that visual preference also peaked in this range. Overall, in line with previous studies (Hagerhall et al., 2004; Spehar et al., 2003), we found that visual interest and preference varied by pattern type (fractal or Euclidean) and by fractal dimension. Further, there is a clear shift in preference towards higher *D* values compared to previous results. Assuming that the transition from computer screens to projected stimuli similarly influences visual interest, the results shown in Fig. 18 suggest that, if the previous studies had rated visual interest, an equivalent shift to higher D for projected versus computer images would have been seen for visual interest.

In contrast to our hypothesis that distance would impact visual preference and interest, no significant effect was found. This robustness to blurring of the finest details in the fractal pattern is confirmed by the fact that the results are not impacted if the responses from participants who required vision correction but did not wear spectacles are included in our analysis. By showing that the fine scale patterns do not need to be visually resolved by the observer, this further emphasizes one of the findings of the original computer-based studies – that only a limited magnification range is necessary for the observer to perceive the fractal scaling properties of the patterns.

Having ruled out distance as the cause for the shift to higher *D*, there remain several factors that differ between the computer-based and projector-based experiments. First, unlike viewing the pattern on a computer screen, the image projected on the wall becomes integrated into the environment of the room. In particular, participants view the whole scene consisting of a complex fractal pattern surrounded by the less complex Euclidean space. We suggest that this addition of a less complex visual component adds a tolerance for higher complexity of the fractal itself, thus inducing the shift to a higher *D* for preference and visual interest. This environmental factor further explains why the shift is slightly more prominent for Study 2 compared to Study 1 – the renderings used in Study 2 feature a fractal embedded into a Euclidean office space which, when projected, is then embedded in the Euclidean

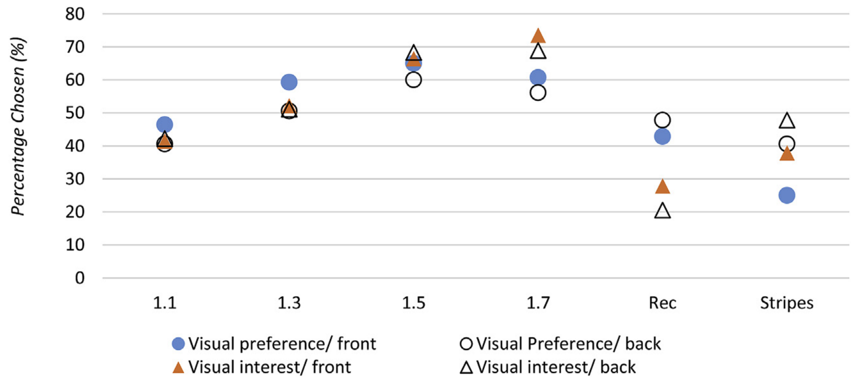

Fig. 19. Visual preference and interest by viewing distance.

space of the lecture room.

This difference between computer-based viewing and room-based viewing can be further explained by figure-ground segregation. When patterns are viewed on a computer screen, the screen is the figure that attention is paid to, while the room becomes the background, which tends to be ignored. Whereas when patterns are projected on a wall, there is less separation between these two elements (figure and ground) which leads to the focus of attention being on both the pattern and the room (Fig. 14). This figure-ground relationship is associated with an object-based attention (Egly, Driver, & Rafal, 1994) which suggests that the room receives higher attention and enhanced visual processing in room-based studies.

This effect emphasizes the impact of the room in which the experiments are performed. In particular, previous studies that examined visual preference and the three studies reported here 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. More generally, we note that this environmental effect has important consequences for the field of biophilic space design (W. Browning et al., 2014; Wilson, 2003). The results of our three studies demonstrate that it is not sufficient to study the human response to nature. It is important to study how this response changes when the natural pattern is embedded in the human-made built environment (Korpela, De Bloom, Sianoja, Pasanen, & Kinnunen, 2017; Lee, Williams, Sargent, Williams, & Johnson, 2015; Taylor et al., 2017a,b; Van Renterghem & Botteldooren, 2016).

The second difference between the computer and projected images is their light intensity, which will affect the perceived contrast. 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 et al., 2016). To demonstrate the difference in color brightness between patterns

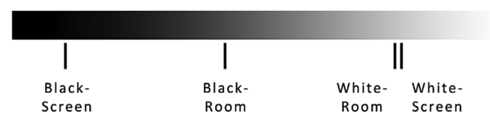

Fig. 21. Black and white color tones as displayed on screen and as projected on the wall (Study 1) plotted on a gradient scale from black to white.

projected on a wall and those viewed on a computer screen, Fig. 21 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 figure suggests that there was a higher contrast between the black and white regions of the pattern when viewed on the computer screen which might increase the observer's ability to resolve the fine-scale patterns of the fractal. The reduced role of the fine-scale detail in the projected pattern might induce a shift to higher *D*. However, above we demonstrated that distance (which has an analogous impact on the fine-scale patterns) did not have a significant impact on the preferred *D*.

The third possible difference between the computer and projected images lies in participants possibly associating the projected light patterns with the shadows of fractals seen in our daily experiences, such as the dappled sunlight through trees or the shadows from clouds. However, neither of these examples have higher *D* values compared to other commonly observed fractals and so this doesn't explain the shift to higher *D*.

The three studies demonstrate that visual interest and preference vary by fractal dimension when examined in an architectural context. Because of the importance of fractal dimension, the potential shift to higher *D*-values has major implications if fractal patterns were to be used in interior spaces to enhance visual preference. Particularly, the Euclidean architectural surroundings seem to have influenced the relationship between visual preference and pattern fractal dimension.

The difference in the way *D* influences visual preference and visual interest ratings suggests that these two concepts are different. We

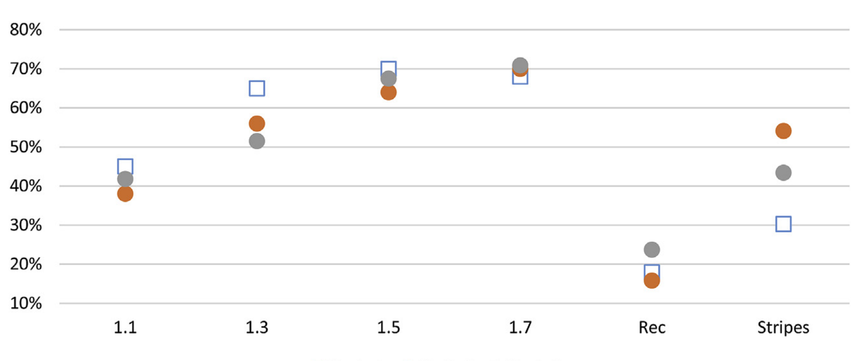

Fig. 20. The visual interest in terms of percentage chosen for the three Studies.

conceptualized visual preference as a broader concept that includes and is influenced by visual interest. Therefore, the relationship between visual interest and preference (Fig. 18) shows some similarities in the overall trend yet differences as well, specifically lower values of visual interest for $D = 1.1$ and $D = 1.3$ and higher values for $D = 1.5$ and $D = 1.7$. These differences could also be due to visual preference being driven by factors other than visual interest, such as the ease of visual processing as suggested by the fractal fluency theory. Thus, a pattern that is of higher visual interest does not necessarily signify higher preference. We suggest that the selection of which concept to use for assessment should consider these differences.

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, the results from Study 1 support the second hypothesis regarding a better maintained balance between Relaxation and Excitement by fractals compared to Euclidean patterns.

Previous studies showed that lighting can influence mood (Boubekri et al., 1991; Je; Flynn, Hendrick, Spencer, & Martyniuk, 1979; Knez, 1995), and that fractal patterns were more visually preferred (Spehar et al., 2015; Taylor et al., 2011, 2017a,b). Our experiments expand empirical evidence regarding projected fractal light patterns and their applicability to explain preference to light and indoor space interactions. The results show potential for utilizing mid to mid-high complexity fractal patterns to enhance occupants' visual interest, visual preference, and mood. This might have further implications for the design of façade systems, particularly shading systems such as roller shades and perforated screens (Chamilothori, Wienold, & Andersen, 2016). Typically, the perforations in these systems are regularly spaced to achieve an overall openness factor (typically 3–17%) that does not consider the benefits of manipulating sunlight pattern geometry. Enhancing visual interest, preference, and mood is crucial for occupants who spend most of their time indoors (Rockcastle, Amundadottir, et al., 2016). Further, the demonstrated benefits of fractal light patterns may interact and influence occupants' visual comfort to increase tolerance under glary conditions, for example. This can increase occupants' satisfaction with their indoor environments.

We end with a few general comments. One of the limitations of our studies 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, for example, $D = 1.1$, $D = 1.4$, etc. However, to compare results to previous studies, the 0.2 increment between D values was utilized.

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 occupants' mood but also to improve the quality of interior spaces.

Our studies highlight 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 implication of such studies can inform the design of future daylighting and shading systems to enhance occupants' visual comfort and satisfaction with their indoor environment.

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