Stress and Space:
Investigating the Use of Fractals to Reduce Stress in the Built Environment

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Abstract

This paper explores the relationship between psychology and architecture, and how the two intersect in the built environment. This project investigates how fractals, or forms with elements repeated at different scales, can be used to reduce stress in urban areas. The first study successfully reproduced the finding that fractal images relieve stress in an experimental setting. The second study, which is ongoing, investigates the ability of fractals to decrease perceived stress in a public transit context. If the results show that fractals are effective at stress relief, the study will add to the scientific foundation for improving the design of public spaces using fractal imagery.

Introduction

Knowing how the environment around us affects our moods and behaviors can help us appreciate it and change it for the better in big and small ways, whether we are designers or inhabitants of that environment. The interaction is reciprocal: our brains shape buildings and buildings shape our brains. Awareness of how the brain responds to certain features of the environment can help architects to design environments best suited to humans, and psychologists and neuroscientists should more often consider the brain in relation to its environment because the primary purpose of the brain is to respond to its environment.

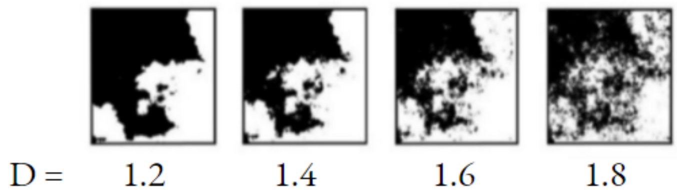
While scientific study dedicated to these topics is only a few decades old (see Canter and Craik, 1981, for a history of environmental psychology), the topics themselves are not. Architects have designed buildings to evoke certain feelings and experiences in their occupants for centuries. Take, for example, the Hagia Sophia, built in the 6th century AD, renowned for its soaring interior which was designed to enhance the spiritual experience of worshippers through shimmering gold mosaics and undulating marble, creating otherworldly acoustic reverberation (Pentcheva, 2011). Architects will never be able to perfectly predict or control the way occupants react to a building since they are bound to have different associations with different spaces, along with different needs and priorities. Still, neuroarchitecture can help to inform techniques and principles of good design based on the similarities of brain functioning across populations.

One widely beneficial principle is the incorporation of nature into design. Biophilia, meaning the human affinity for nature, could explain the widespread creation of gardens as a place of pleasure and relaxation. The human species evolved surrounded by nature, and as such our brains are primarily adapted to natural settings. There is a common psychological preference for natural environments over urban ones (Van der Berg, Hartig, and Staats, 2007) and in fact, cities can take a toll on mental health. In particular, city living, with its noise, crowding, and pollution, is a cause of chronic stress, which can lead to mental disorders such as depression (Matheson et al., 2006). It is not surprising, then, that as long as cities have existed, humans have brought nature into them.

Across many studies measuring physiological, behavioral, and self-reported effects, natural environments consistently relieve stress (Berto, 2014). Fractal geometry is hypothesized to be a key element of nature responsible for this phenomenon. Fractals, or shapes repeated at different scales, are ubiquitous throughout nature (Mandelbrot, 1982). For example, each branch of a large tree has smaller branches protruding from it such that branches could be considered “mini trees,” and so on. Examples are plentiful in nature; snowflakes, clouds, mountain ranges, and coastlines are all fractal.

All fractals, whether they are exact forms repeated at different scales (mathematical fractals) or forms with random variation (statistical fractals), can be defined by the ratio of complexity at different scales, called fractal dimension, D (Lorenz 2002). D can range from 1, representing a straight line, increasing in complexity up to 2, a completely filled space (see Figure 1). One way of defining D is the box-counting method, which divides an image into progressively smaller squares, counting the number of boxes containing a relevant feature of the image - perhaps a window edge for an architectural image. When calculated across a range of box sizes, this yields the fractal dimension (Lorenz 2002).

Figure 1. *Graphical examples of fractal dimension, adapted from Taylor 2021.*



A re-analysis of the results of a NASA study on stress relief found that an artificial abstract pattern increased stress compared to control, while fractal patterns decreased stress whether they were natural or hand-made (Taylor, 2006). In the original 1986 study on physiological response to art, participants completed a series of tasks designed to induce physiological stress. On the wall of the room was either a picture of a forest, an artistic rendering of a tree in a savannah, an abstract pattern, or a blank control surface. Participants' skin conductance, which correlates with stress response, was measured throughout the experiment. During recovery periods between tasks, participants who completed the study in the room with the forest image had a 3% greater decrease in skin conductance than the control group, while participants in the savannah artwork group had a 44% greater decrease in stress than the control group. The re-analysis found that the forest image had a fractal dimension D of 1.6, the savannah artwork had a D of 1.4, and the abstract pattern was not a fractal (Taylor, 2006). Critically, the fractal quality of the image was more important than realistic representation of nature (Salingaros, 2017).

Other indirect evidence that fractals induce a physiological stress relief response comes from an electroencephalogram (EEG) study that found that fractals with $D = 1.3$ produced the largest alpha response in frontal regions of the brain (Hagerhall et al., 2008). Alpha waves are associated with a wakeful but relaxed state. Interestingly, the study found that the same fractal dimension also produced the strongest beta response in the parietal lobe. The authors suggest, if this is due to activity in the fronto-parietal network, that fractals may also be effective at holding attention. This fits with the Attention Restoration Theory (ART; Kaplan and Kaplan, 1989). According to the ART, nature provides a respite from the draining work of sustaining attention on a task; it is stimulating enough to engage attention in a broad manner while restoring attentional faculties worn down by the focus required in daily life. The ART links stress and attention, positing that depleted attention causes a feeling of stress that stems from a feeling of having inadequate mental resources to process one's surroundings. It proposes that nature can restore the capacity of directed attention after it has been exhausted by a task, which has been demonstrated in numerous empirical studies (e.g., Lee et al., 2015).

The fractal dimension D reveals a quantifiable connection between nature and the human mind. D is a key predictor of preference for scenes; humans prefer fractals with a dimension of 1.3-1.5, which matches those typically found in nature (Taylor, 2021). Taylor proposes the "fractal fluency" model as a neuroscientific explanation of preference for mid-complexity fractals. The human visual system seems to have adapted to process the fractals present in the natural world by first analyzing scenes in a fractal manner. Eye-tracking analysis revealed that participants' eyes followed fractal ($D = 1.4$) routes when looking at an image, with the gaze establishing larger points of interest and then making smaller saccades around those points to gather details (Taylor 2021). This is the most efficient way of parsing a scene, which would have been critical, for example, to early humans scanning for predators in the wild.

Evidence from fMRI studies has identified brain regions whose activation responses are D-dependent (Taylor, 2021), with further studies being conducted on the parahippocampal region, which is involved in spatial and scene recognition. If the activation of parahippocampal gyrus and related regions are correlated with fractal dimension, this could explain increased performance in visual tasks when participants are exposed to fractal stimuli. Taylor (2021) summarizes a variety of findings in this domain, including increased detection and discrimination sensitivity for mid-*D* fractals and enhanced navigation through mid-complexity landscapes. Collectively, these findings indicate that humans have indeed evolved to be “fluent” with fractals.

Not only does fractal fluency increase efficiency in processing, it produces a positive emotional response as a result. Perceptual fluency is “the ease with which people process information” (Oppenheimer & Frank, 2008), and leads to positive affect (Reber, Winkielman, & Schwarz, 1998). With fractals, Joye et al. (2016) found that participants solved puzzle tasks faster and more accurately when viewing a highly self-similar (fractal) block structure than a less self-similar structure, and rated the high-fractal trials as easier and more enjoyable to solve. Positive affect caused by fractals could be one reason why humans enjoy looking at nature, why we hang pictures of mountains, clouds, and trees on our walls, build elaborate gardens, and walk to city parks. Over our history, across civilizations, we have also built architecture with fractal geometry, to consciously or unconsciously mimic the natural world.

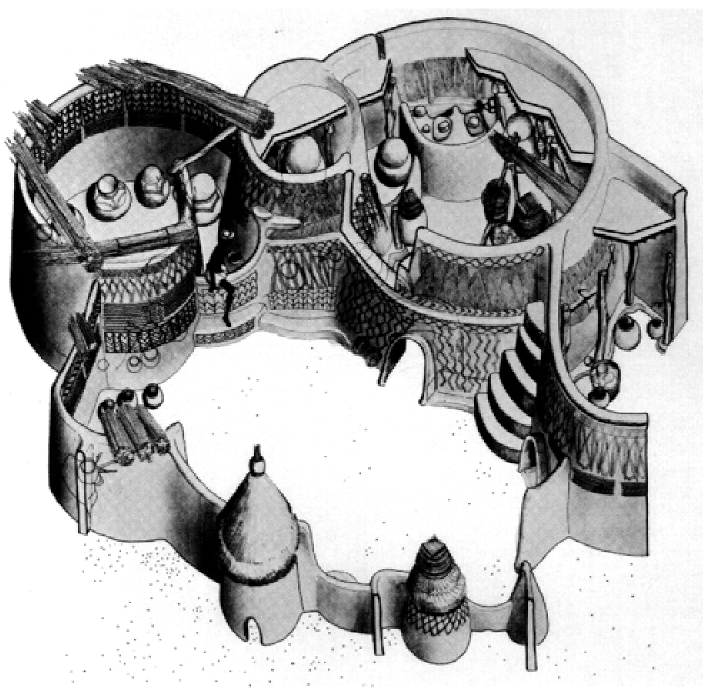
Fractal architecture has been used for centuries, and modern designers can look to history for a rich well of wisdom. Hindu temples, commonly consisting of large domes surrounded by radially symmetric smaller domes at many scales, are one of the most profound examples. In this case, fractal architecture arises out of the Hindu cosmology that each part of a whole contains the whole within itself (Joye, 2007), leading to incredible detail and decoration at both large and small scales. Gothic architecture, with its intricately detailed facades, is another example of highly self-similar architecture (Joye, 2007). Repeated motifs such as pointed arches and the floral patterns of rose windows add to the fractal nature, and thus, it seems, to the long-standing appeal of these buildings.

Figure 2. *Fractal Architecture: Kandariya Mahadev Temple, Khajuraho, India.*

Jain, Nish. (2011). *Kandariya Mahadev Temple at Khajuraho*. Creative Commons BY-SA 3.0 license.

In Africa, many different cultures use fractal architecture as well as fractal art and music to express specific cosmological concepts related to recursion. One example is the Nankani, an ethnic group in northern Ghana whose spirituality prioritizes interconnectedness with the ecosystem (Amenga-Etego, 2016). Nankani villages are made up of a series of family compounds, which in turn are made up of a series of scaled rooms along the perimeter of a courtyard. The same cylindrical and domed shapes are repeated throughout, and are purposefully repeated at even smaller scales, in stacks of earthenware bowls called "zalanga" (Allentuck, Davis, and Roach, 2009).

Figure 3. *Fractal Architecture: A Nankani Home*



From Roy (2003), cited by Allentuck, Davis, and Roach (2009).

Much Islamic architecture employs fractal geometry. For example, in many mosques such as the Dome of the Rock, a geometric dome structure is repeated with radial symmetry at smaller and smaller scales. Above the many mosque entrances is a muqarnas, an ornamented vault which often displays a fractal structure, and is meant to draw attention to the transition between spaces.

The common thread of these historical examples of fractal architecture is that they exhibit complexity across large and small scales. Modern architecture is generally much less complex, due to both stylistic and economic reasons. Given that humans seem to prefer mid-level visual complexity over simple forms, one way to relieve stress in urban environments might be to incorporate more fractal art and architecture, which is a cost-effective way to bring natural elements into places where they are lacking.

While the literature on fractal stress relief and its applications in architecture and urban design is expanding (see for example Fatni, 2014; Hadley, 2020; Joye, 2007; Smith et al., 2020; Taylor, 2021), the original study which reported the fractal stress relief effect (Taylor, 2006) did not establish a causal effect since the independent variable, fractal dimension, was not randomly manipulated. In addition, the results of that study have not, to this author's knowledge, been replicated, and the data and analysis are not available to the public. Given that it was not originally conducted to measure the effect of fractals on stress response, it is critical that fractal stress relief is demonstrated in a psychological context with stimuli controlled for their fractal complexity and other visual characteristics.

Experiment 1 was designed to address the lack of replication of the fractal stress relief effect. By comparing two stimuli with similar high-level visual attributes, it attempts to isolate the effect of fractal geometry on self-reported stress response. Experiment 2, which is still in progress, investigates whether the fractal stress relief effect holds in an actual urban context. Both experiments also measure subjective responses to the fractal and non-fractal stimuli as a way to distinguish between the stress relief effect and a positive emotional response to the fractal itself.

Experiment 1: Replicating Stress Response and Subjective Response to Fractals in an Online Setting

The experiment, in the form of an online questionnaire, was designed to test the following hypotheses: 1) Participants who view a fractal image will report they are less stressed and feeling less worried, tense, or anxious than participants in the non-fractal group. 2) Participants will rate the fractal image more relaxing, pleasant, and similar to nature than the non-fractal image. Conversely, participants will rate the non-fractal image more overwhelming, but also boring.

Method

Participants

30 undergraduate students ages 18-21 were recruited from a Psychology Research Participant Pool at Carnegie Mellon University in Pittsburgh, PA. 21 participants were female, 8 participants were male, and 1 identified as non-binary. The only incentive to participate in our study was a class credit for the psychology department. Data was collected between 3/2/22 and 4/15/22.

Design

Participants were randomly assigned to view the fractal (n = 15) or non-fractal (n = 15) image and were asked to rate the image on a scale of 1-10 for five subjective metrics: boring, overwhelming, pleasant, relaxing, and similarity to nature (adapted from Omidfar Sawyer and Chamilothori, 2019). Next, participants were asked to assess their current stress state with two items on a scale of 1-10. Self-reported responses were used for feasibility of data collection. Real-time stress measures have been validated as part of the

Ecological Momentary Assessment (EMA) literature (Shiffman, Stone, and Hufford, 2008). The first self-reported stress item simply asked “How stressed are you feeling right now?” (adapted from Chin et al., 2019). The second was “Are you worried, tense, or anxious right now?” (based on Lindsay et al., 2018). Two items were used as a slightly more nuanced measure, but a longer questionnaire was avoided to limit the duration of the experiment. An additional questionnaire collected demographic information such as age, gender, ethnicity, and estimated lifetime exposure to nature.

Materials

The fractal stimulus (Figure 4a) was generated in Python using a Levy flight (Smith et al., 2020) with the packages matplotlib and scipy.stats. The flight’s path was created by first generating an arbitrary starting point and moving in a random direction with a distance sampled from the levy distribution (alpha = 1.4, beta = 1) 500 times, such that there are many small segments along the path and few large ones. Hexagons were then plotted at each vertex on the path, with the radii proportional to the preceding path segment. The non-fractal stimulus (Figure 4b) was created by randomizing the locations of these 500 hexagons.

Procedure

The entire experiment was conducted online without interaction with the experimenter. Participants were directed to the Gorilla Experiment Builder website through the Carnegie Mellon Psychology Research Participant Pool system. After indicating their consent to continue with the experiment, participants were prompted to complete the questionnaire.

Figure 4. *Fractal and Non-fractal Stimuli in Image Questionnaire*

a) fractal **b)** non-fractal

Results

All participants completed each section of the experiment. For the purpose of this analysis, outliers were included since they were very small in number and were not estimated to have an impact on the results.

Analysis was conducted to determine if responses to fractals and non-fractals were significantly different for two stress metrics, as well as five subjective metrics (boring, overwhelming, pleasant, relaxing, similar to nature), on a scale of 1-10. Table 1 summarizes the descriptive statistics for the image questionnaire and denotes where the differences between the fractal and non-fractal groups were significant.

Table 1. *Fractal vs. Non-fractal Online Questionnaire Responses: Descriptive Statistics*

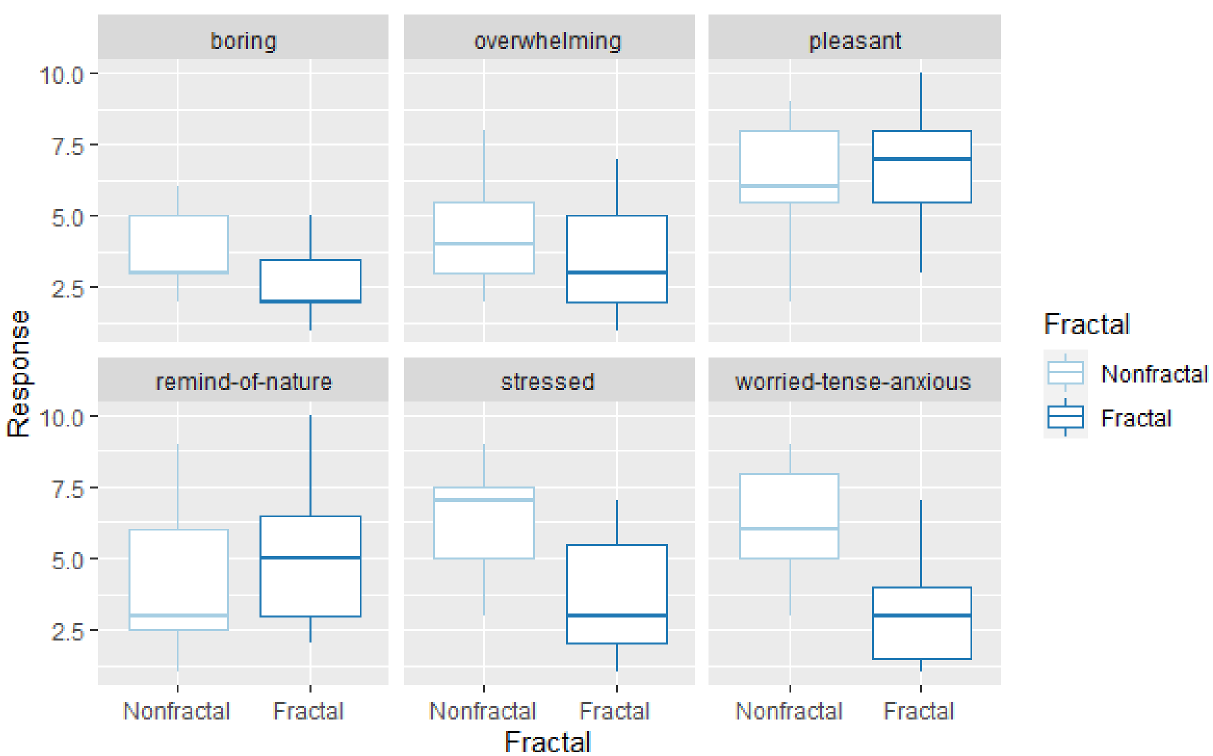
Question	Response: Non-Fractal (scale of 1-10, n = 15)	Response: Fractal (scale of 1-10, n = 15)
Stress**	6.2 ± 2.0	3.6 ± 2.2
Worried, Tense, or Anxious***	6.3 ± 1.9	3.2 ± 1.9
Boring*	3.9 ± 1.4	2.8 ± 1.4
Overwhelming	4.4 ± 1.9	3.6 ± 2.1
Pleasant	6.2 ± 2.1	6.8 ± 1.9
Relaxing	5.6 ± 1.8	6.5 ± 1.6
Similar to Nature	4.1 ± 2.3	5.4 ± 2.6

"*" denotes p-value below .05, "**" below .01, "***" below .001.

Simple linear regression was used to test if responses to fractals and non-fractals were significantly different for each metric. Participants who viewed the fractal image reported feeling less stressed than those who viewed the non-fractal image. The fitted regression model for the self-reported stress response was 6.20 - 2.60 * (fractal). The model was statistically significant ($R^2 = .30$, $F(1,28) = 11.83$, $p^{**} = .002$). For the item which asked how worried, tense, or anxious participants were, the fitted regression model was: Response = 6.27 - 3.07 * (fractal). This model was highly significant ($R^2 = .31$, $F(1,19) = 8.38$, $p^{***} < .001$).

The subjective responses to the fractal image were, on average, more positive than to the non-fractal image (see Fig. 5), but most were not significantly so. The fitted regression model for "Boring" was: Response = 3.87 - 1.07 * (fractal). The regression model was statistically significant ($R^2 = .14$, $F(1,28) = 4.59$, $p^{*} = .041$). For "Overwhelming," the fitted regression model was: Response = 4.40 - 0.80 * (fractal). This model was not statistically significant (R^2 = .04, $F(1,28)$ = 1.21, p = .281). For "Pleasant," the fitted regression model was: Response = 6.20 + 0.60 * (fractal). This model was not statistically significant (R^2 = .02, $F(1,28)$ = 0.67, p = .420). For "Relaxing," the fitted regression model was: Response = 5.60 - 0.93 * (fractal). This model was not statistically significant (R^2 = .07, $F(1,28)$ = 2.249, p = .145). For "Similarity to Nature," the fitted regression model was: Response = 4.13 - 1.27 * (fractal). This model was not statistically significant (R^2 = .07, $F(1,28)$ = 1.97, p = .172).

Figure 5. *Fractal vs. Non-fractal Online Questionnaire Responses*



In summary, participants in the fractal group reported lower stress and felt significantly less worried, tense, or anxious compared to the non-fractal group. Participants who viewed the fractal image rated it significantly less boring than participants who viewed the non-fractal image, but the rest of the subjective response metrics did not produce significantly different responses. Data collection is still in progress, so smaller effects may appear with the planned sample size of 60 participants.

Discussion

The purpose of Experiment 1 was to validate the finding that fractal images relieve stress (Taylor, 2006) and to investigate subjective response to fractals. The first hypothesis, that fractal images would evoke lower self-reported stress responses than non-fractal images, was supported by the results. However, the results did not strongly support the second hypothesis about subjective response, as there was not a significant difference in response for most of the metrics, with the exception that participants found the fractal image more interesting. These findings are consistent with Abboushi et al. (2019)'s work, from which the questionnaire items were partially developed. That series of studies found that mid-complexity fractal images (D = 1.5) had the highest visual interest. Notably, Abboushi et al. report that "'Calm' and 'Peaceful' ratings gradually dropped as the fractal dimension increased," which is in line with the lack of significant differences in response for the "Relaxing" and "Overwhelming" metrics.

The difference in results between subjective responses and stress responses is noteworthy. Most striking is that there is a clear reduction of stress caused by the fractal image, and yet participants did not find the fractal image significantly more pleasant than the non-fractal image. Perhaps the stress response is mediated by a subconscious mechanism. This hypothesis is supported by the observation that the stress response to fractals does not require direct attention to the fractal (Taylor, 2006). However, It is important to note that this is a preliminary study, so additional significant effects in the overwhelming, pleasant, and similarity to nature subjective response metrics may appear with a larger sample size.

There are a number of limitations in the design of this study. Though self-reported stress response is an accepted measure, it has the potential to be unreliable and biased, and is a limited measure regardless. A critical follow-up to this study would include a measure of physiological stress such as Heart Rate Variability (HRV). This would make a within-subjects experiment possible, where the real-time physiological effect of fractal stress relief could be directly measured. Another limitation is that only one image was used for each group. This design was chosen so that results would be comparable to the results of Experiment 2, but a more ideal study would make use of multiple fractal and non-fractal images for a more robust representation of the effect of fractals. A limitation to construct validity arises from the format of the questionnaire, which forces participants to focus their attention on the stimulus. Effects weaken or disappear without attention or reflection on the image, which is more likely outside of the experimental setting.

Other limitations come from the participant recruitment method. All participants were undergraduate students, and thus the external validity of the study is questionable. Thus one of the goals of Experiment 2 was to reach beyond the university population, and future studies in this field should explore possible demographic differences in response to fractals, including the effects of short-term and long-term prior exposure. In addition, the gender ratio of this study was expected to be relatively balanced, but in fact many more participants were female than male, which could be an issue if there are significant gender differences in perception of visual complexity. This has not been widely examined, but one study found that boys preferred more complex website designs than girls (Hsiu-Feng, W, 2014), so it is possible that the gender ratio of the current study impacted the results. Since there were only 8 male participants, analysis of gender effects was not conducted.

Experiment 2: Stress Response and Subjective Response to Fractals in an Urban Setting

With Experiment 1 having validated the stress relief effect of the fractal stimulus, the aim of Experiment 2 was to measure if the effect holds in a potentially stressful environment. Bus transit was chosen as the setting for this experiment since it is a common urban context where passengers are likely to have time to answer a short survey. Two posters, one fractal and one non-fractal, were displayed at bus stops, with a link to an online questionnaire in the same format as Experiment 1. As in Experiment 1, the central hypothesis of the study was that participants who viewed the fractal poster would report less stress than participants who viewed the non-fractal poster. The secondary hypothesis was that participants would rate the fractal poster more positively on the subjective metrics, that is more pleasant and similar to nature, and less boring and overwhelming, than the non-fractal poster. This experiment has not revealed any significant results, but preliminary descriptive statistics and results are reported.

Method

Participants

Members of the public in the Pittsburgh area were invited to participate in the study through large poster advertisements at bus stops in the Oakland neighborhood of Pittsburgh. 23 participants were female, 16 participants were male, and 4 participants identified as nonbinary. There was no incentive given to participate in the study.

Design

Same as Experiment 1, without random assignment to fractal ($n = 40$) or non-fractal ($n = 4$) group, and with the exception that the "Relaxing" metric is not included. For clarity, this study is described as the second experiment, but was designed before Experiment 1 and thus "Relaxing" was added in the later experiment.

Materials

Same as Experiment 1, except that the fractal and non-fractal stimuli were embedded in posters (43" x 64") explaining the study to participants and linking to the online questionnaire, with a colorful background (see Figure 6).

Procedure

Posters displayed in bus shelters at various intersections in the Oakland neighborhood of Pittsburgh included an overview of the experiment and link and a QR code to an online survey on the Jotform questionnaire platform. Participants were asked to indicate their consent and then were instructed to fill out a survey in response to the artwork on the poster.

Figure 6. *Posters Displayed in Bus Shelters*

a) Fractal

b) Non-fractal

c) Example of Bus Shelter Location

Results

As in the previous experiment, outliers were included since they were very small in number and were not estimated to have an impact on the results.

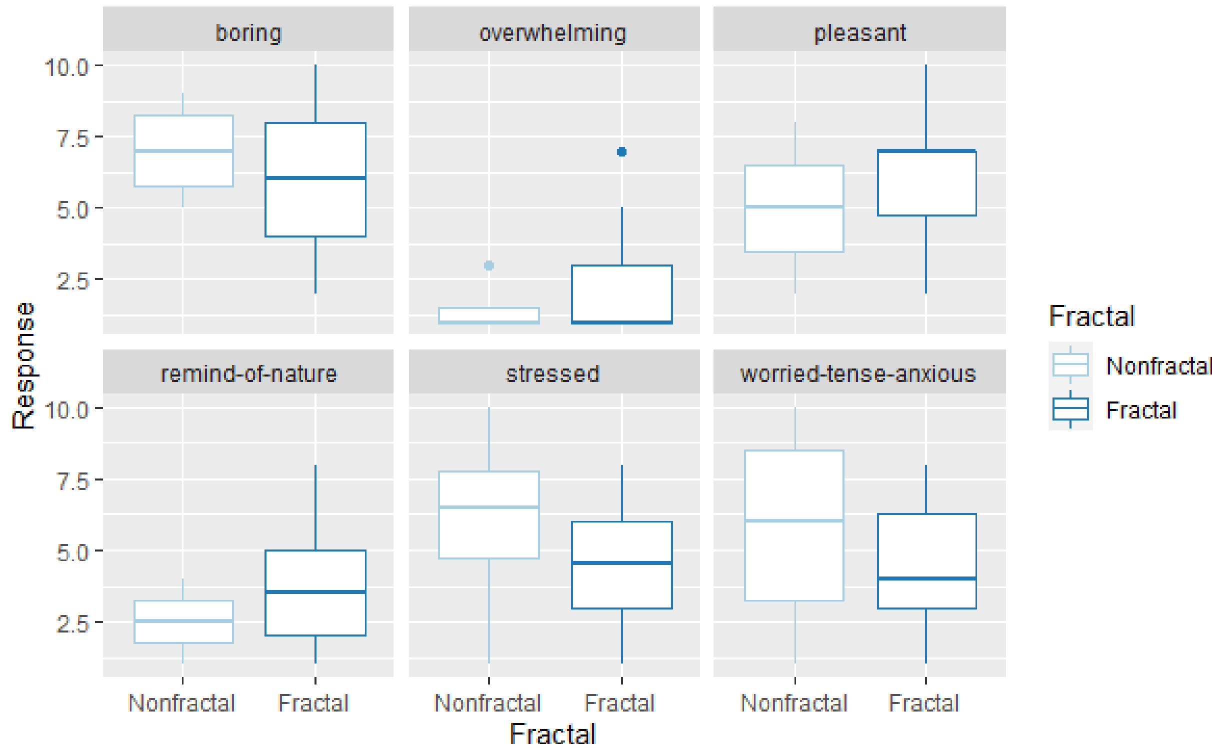
As before, analysis was conducted to test if responses to fractals and non-fractals were significantly different for five subjective metrics (boring, interesting, overwhelming, pleasant, similar to nature), as well as two stress metrics, on a scale of 1-10. Table 2 summarizes the descriptive statistics for the questionnaire.

Table 2. *Fractal vs. Non-fractal Bus Questionnaire Responses: Descriptive Statistics*

Question	Response: Non-Fractal (scale of 1-10, n = 4)	Response: Fractal (scale of 1-10, n = 40)
Stress	6.00 ± 3.74	4.38 ± 2.06
Worried, Tense, or Anxious	5.75 ± 4.03	4.30 ± 2.11
Boring	7.00 ± 1.83	6.03 ± 2.54
Overwhelming	1.50 ± 1.00	2.00 ± 1.40
Pleasant	5.00 ± 2.58	6.08 ± 1.90
Similar to Nature	2.50 ± 1.29	3.65 ± 2.01

Simple linear regression was used to test if subjective responses to fractals and non-fractals were significantly different for each metric. There were no significant differences in subjective or stress responses (see Fig. 7).

Figure 7. *Fractal vs. Non-fractal Bus Questionnaire Responses*



Discussion

It is unsurprising that there was no significant difference between stress responses or subjective responses to the fractal and non-fractal bus stop posters given the current sample size and distribution. The fractal poster was displayed in a much more highly-trafficked area than the non-fractal poster for the majority of the data collection period. Since there were only 4 responses to the non-fractal poster and 40 to the fractal poster, no conclusions about the fractal stress relief effect in this context can be drawn yet. However, the current means of each group suggest the possibility that the stress relief effect will hold to some extent in the bus stop context, and that participants will rate the fractal poster somewhat more positively on the subjective response measures.

A limitation of this study in comparing the fractal stress relief effect across the online and bus shelter contexts is the difference in stimuli format. The stimuli for the online study were composed of only the fractal and non-fractal designs, while the bus shelter posters contain additional written information and colored backgrounds. This could influence the subjective responses to the posters and make comparison between the online and bus contexts unreliable.

Another limitation is that the posters were displayed in only the Oakland neighborhood of Pittsburgh, PA, which has a large university student population. Though one of the goals of the study was to include a diverse range of participants beyond the typical undergraduate population used in psychology experiments, the Oakland neighborhood was chosen because it has the highest bus ridership rates in the area. A future iteration of this study could address this limitation and also control for the characteristics of the bus stop locations by having many posters dispersed throughout Pittsburgh and other cities.

Even with its limitations, this study has the potential to demonstrate that public art with fractal patterns has the capacity to reduce stress, which would add to the growing literature supporting the use of biophilic patterns in urban areas as a way to combat the stress that these areas cause. Finally, once data collection is complete, analysis of the difference between subjective responses to the bus shelter posters and the images used in the online questionnaire may provide insight into demand characteristics in studies of subjective preference, as participants in the bus study rated both stimuli more boring, less overwhelming, less pleasant, and less similar to nature than participants in the online study.

Conclusion

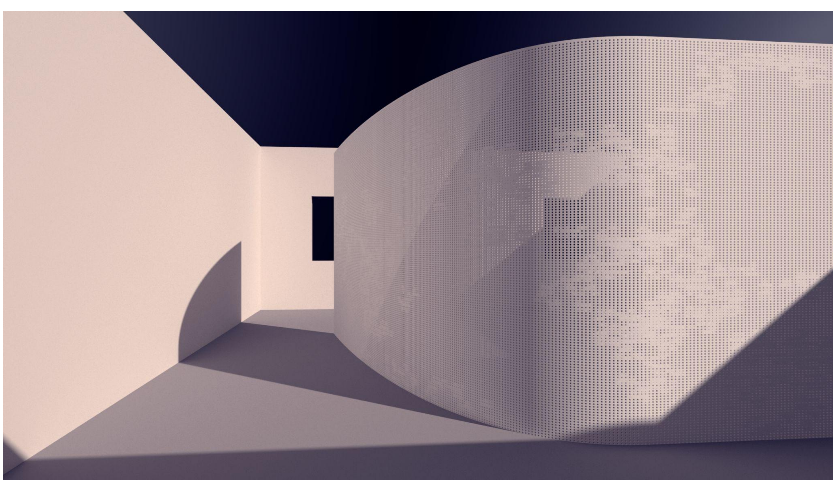
The results of this research support the hypothesis that fractal images reduce self-reported stress. Experiment 1 was successful in demonstrating the fractal stress relief effect with two images that differ in terms of their fractal structure, but not in terms of low-level visual characteristics. Unexpectedly, the subjective responses to each image did not significantly differ, except that participants rated the fractal image significantly less boring than the non-fractal image. Data collection for Experiment 2 is still in progress, and definitive conclusions can not be drawn at this time due to the sample size of the non-fractal group.

A remaining question is whether fractal geometry is intrinsically beneficial and appealing to the human brain, or whether fractals happen to achieve the levels of complexity we tend to prefer. It could be, for example, that as long as there is a balance of complexity at large and small scales, then the repetition of the same form is unnecessary. The preference for mid-level visual complexity has been demonstrated even in infants (Kidd, Piantadosi, & Aslin, 2012), there is some evidence that humans exhibit "dendrophilia," or the tendency to impose hierarchical recursive structures on sequential information, while animals do not (Ferrigno et al., 2020). To address the question of complexity versus fractal geometry, future iterations of this study would benefit from implementation of measures of informational complexity. If both the fractal and non-fractal stimuli share the same level of complexity, the stress relief effect size, if the effect occurs at all, would be hugely informative.

An experiment that was planned as part of this thesis project but has not yet been implemented is the investigation of the fractal stress relief effect in immersive architectural stimuli. Abboushi et al. (2019) note that most studies involving fractals used two-dimensional stimuli, and that "the applicability of findings to actual environmental stimuli has yet to be explored." They begin to rectify this problem by testing participant preferences for projected tree-like shadow patterns with varying complexity in interior spaces, finding that those with *D* = 1.5-1.7 were the most "visually interesting". While these studies measured preference as a function of fractal dimension in an architectural setting, no study has directly measured the effect of fractal architecture on stress.

This study will compare participants' responses to a virtual space with a fractal (see Figure 8) or non-fractal pattern. The central hypothesis, similar to the above studies, is that participants in the fractal group will report lower stress and higher subjective ratings of the space than participants who view the same space with a similar but non-fractal pattern.

Figure 8. *Virtual Architectural Space with Fractal Pattern*



The space is designed as a room with a screen separating two areas. The fractal pattern appears in a series of perforations through the screen. Architectural model developed by Bea Spolidoro of Fisher ARCHitecture.

This experiment attempts to bridge the gap between studies in the field of architecture that measure occupant preference for fractals without specifically measuring stress response and studies in cognitive neuroscience that measure relaxation responses to simple, non-immersive fractal stimuli.

A next step for this branch of inquiry is to investigate the impact of different implementations of fractals in architecture. The above experiment proposes the use of a fractal pattern as a decorative feature of an otherwise non-fractal space. However, much of the fractal architecture built throughout history makes its fractal geometry integral to its form. That is, the spaces within the buildings themselves make up a three-dimensional fractal shape, and the building as a whole would look completely different without fractal geometry. One question that has yet to be investigated is whether the fractal stress relief effect is heightened in these types of highly fractal spaces compared to spaces with only two-dimensional fractal patterns. Another question is whether the stress relief effect holds when the fractal is not visible from a single vantage point. If, for example, the plan of a building is fractal, as in Frank Lloyd Wright's Palmer House, then memory and spatial reasoning are required in order to "perceive" the fractal. Whether this type of fractal would produce a stress relief response has yet to be investigated.

Another branch of inquiry, also discussed as an extension to Experiment 1, is to use physiological stress measures such as Heart Rate Variability (HRV), in addition to more immersive methods of stimuli presentation such as Virtual Reality (VR). The combination of these methods would shed light on the experience of fractals in realistic contexts and would be incredibly beneficial for the design of fractals for public spaces.

The experiments conducted as part of this thesis add to the literature on the stress relieving effect of fractals and how they can be implemented in urban areas. The online experiment is the first to validate the effect of fractal geometry on stress relief discovered by Taylor (2006). The application of fractals to an urban context in the bus transit experiment presents an example of low-cost fractal ornamentation which could be implemented to improve the quality of life in cities. Much more work is needed to understand the physiological effect of fractals and the ways in which the surrounding context and environment impacts their perception, but this work will give us the power to optimize the complexity of our environment to suit our brain's natural processes.

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