THE ROLE OF FRACTAL FLUENCY ON VISUAL PERCEPTION

by

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DISSERTATION ABSTRACT

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From quarks to galaxies, the natural world is organized with fractal geometry. Fractal fluency theory suggests that due to their omnipresence in our visual world, fractals are more fluently processed by the visual system resulting in enhanced cognitive performance and aesthetics. However prior research has yet to define the boundaries of fractal perception. Thus, the present dissertation aims to explore 1) how individual differences and 2) inclusion of additional structure impact fractal perception, as well as define the unique contribution of fractal statistics on 3) visual judgments in Euclidean space and 4) memory performance. In four empirical chapters, I demonstrate robust trends in fractal perception across wide variation in viewing conditions. Moreover, fractals are shown to be perceived as definitively unique compared to nonfractal images. Together these findings provide insight into how the visual system handles self-repeating patterns and reaffirms the vast potential of fractal installments for occupant wellbeing.

This dissertation includes previously published and unpublished co-authored material.

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CHAPTER I

INTRODUCTION

From quarks to galaxies, the natural world is organized with fractal geometry (Mandelbrot, 1982; Falk & Balling, 2010; Taylor, 2021; Brielmann et al., 2022). Self-similar repetition not only serves as an efficient function for biological growth (Mandelbrot, 1982) but also as a common theme present in items of beauty (Viengkham & Spehar, 2018; Taylor et al., 2011; Taylor, 2003; Taylor et al., 2007; Rawls et al., 2021; Lukman et al., 2007; Graham & Field, 2008; Forsythe et al., 2017; Beauvois, 2007). Though fractal structure had been long discussed in the world of mathematics (Segal, 1978), Mandelbrot (1978) popularized the term with his creation of a recursive set of self-similar patterns and direct acknowledgement of fractal structure being intertwined throughout nature (Mandelbrot, 1968; Mandelbrot, 1982). Further investigation of fractal organization emerged from the study of aesthetics to show that fractal structure is not only associated with beautiful natural formations (Falk & Balling, 2010; Hagerhall et al.,2018) but also human-made art (Taylor, 2003; Beauvois, 2007; Lukman et al., 2007; Graham & Field, 2008; Graham & Redies, 2010). Furthermore, even the pattern in which a viewer's eyes move when scanning a scene or evaluating beautiful works reflects fractal organization (Guastello & Gregson, 2016). The prevalence of fractals in the observable surroundings has compelled researchers to probe the connection between these abundant patterns and a seemingly universal response to their presence (Spehar et al., 2003; Falk & Balling, 2010; Taylor & Spehar, 2016).

Regardless of whether they are viewed as a two-dimensional (2D) surface, three-dimensional (3D) form, or even a dynamic texture; fractal patterns are composed of a unique set of internal factors. The combination of the pattern's fundamental configuration (referred to as the “seed pattern”), exactness of pattern repetition, level of recursion, presence of symmetry, and ratio of coarse-to-fine structure (known as fractal dimension referred to as “*D*-value”) create the distinctive character of any given fractal (Boselie & Leeuwenburg, 1985). Multiple procedures exist for generating fractal seed patterns, including inverse-Fourier and midpoint displacement for segment perturbation, as well as specific methods of pixel deletion or addition (Bies et al., 2016; Smith et al., 2020; Friedenberg et al., 2021). Repetition of fractal seed patterns across scales typically occurs in either a statistical manner (Mandelbrot, 1982) (sometimes referred to as “natural fractals” due to their prevalence in the natural world such as tree-branches, coastlines, etc.) or an exact manner (Hagerhall et al., 2015; Bies et al., 2016) which may also integrate a degree of symmetry to the pattern. The fractal seed can then be grown to occupy a greater amount of space and repeat at finer scales which can be measured as the individual pattern’s *D*-value (or also be measured in terms of alpha, the slope of the amplitude spectrum). Variations across these factors produce consistent alterations in viewer perceptions (Bies et al., 2016); with greater predictability and processing efficiency through arrangement simplicity, exactness of repetition, and symmetry (Hagerhall et al., 2015; Friedenberg et al., 2021). This ease of processing is posited as the underlying factor for positive viewer experiences and general aesthetic preference for fractal patterns (Falk & Balling, 2010; Spehar et al., 2015; Taylor & Spehar; 2016; Robles et al., 2021).

Fractal Fluency Theory relies on the prevalence of fractals and their self-similar structure to suggest that the visual system is tuned to process fractal patterns more efficiently (Taylor & Spehar, 2016). By being able to distill complex patterns down to their smallest representative elements, the overall pattern can be understood without the visual system expending additional metabolic energy to repeatedly process the same information projected at various scales (Isherwood et al., 2017). Peak processing fluency coincides with fractal patterns that are most often encountered in the natural environment, particularly those of low-moderate complexity (Spehar et al., 2003; Sprott, 1993; Taylor et al., 2005). Although further research is required to determine whether this tuning is created through exposure during a critical period of development or due to evolutionary processes (Robles et al., 2020; Falk and Balling, 2010; Taylor et al., 2018; Hagerhall et al., 2008), Fractal Fluency Theory is supported by behavioral findings of improved performance on navigation (Juliani et al., 2016), object-naming (Rogowitz & Voss, 1990), and attention maintenance (Hagerhall et al., 2015) for natural fractal patterns of a low-moderate complexity. Furthermore, robust literature demonstrates that experiences of visual appeal also peak with fractals of this complexity (Taylor et al., 2011; Taylor & Sprott, 2008, Spehar et al., 2003). Through more fluent processing of the constant stream of visual information coming from the environment, reserved metabolic energy can be better devoted to deeper processing and engagement with the stimuli on a higher level to drive aesthetic perceptions.

Despite a general sense of agreement with individual interpretations of the surrounding visual world, individual differences are documented to influence viewer perceptions (Forsythe et alk., 2017; Güçlütürk et al., 2016; Hagerhall et al., 2018; Pyankova, 2019; Rezaei et al., 2020; Spehar et al., 2016; Spehar et al., 2015; Street et al., 2015). Variations in typical perception are often associated with factors impacting the speed and effortfulness of an observer's processing abilities. Extent of pattern experience and understanding accumulate with observer age allowing the individual to learn successful handling of contextual information (Roder et al., 2000; Billington et al., 2008). It is suggested that the viewer incrementally acquires an understanding of greater complexity in their surroundings, possibly encouraging a shift in preference towards patterns with the greatest comprehensible complexity (Kidd et al., 2012). Besides typical development, the occurrence of atypical processing strategies apparent with cognitive disorders coincides with variations in natural pattern perception. For example, individuals scoring higher on the Autism Spectrum can maintain a greater visual perceptual load (Bayliss & Kritihos, 2011) and be less impacted by global context (Hadad, 2018; Grinter et al., 2009) which results in a tolerance for higher visual complexity. Conversely, individuals with age induced neurodegeneration (Forsythe et al., 2017) and schizophrenia (Rezaei et al., 2020) appear to be more easily overwhelmed by additional complexity. Beyond internal cognitive factors, familiarity with environments of different spatial scaling may additionally weight viewer fractal experiences to prefer complexities that coincide with more commonly encountered spatial frequencies (Hagerhall et al., 2018). The effects of experience and cognitive variations cannot be removed from an observer's perception. Thus, the first goal of the current dissertation is to assess fractal perception across a broad sampling of viewers in order to isolate the impact of individual differences on visual experiences.

Fractal patterns are omnipresent in nature, but rarely are individual fractal patterns perfectly arranged without overlapping forms or contextual elements of differing configuration in any given view of a landscape (Mandelbrot, 1982). Correct interpretation of the surrounding environment requires not only being able to successfully process this cacophony of individual visual patterns, but also to account for relationships between these patterns across changes in viewing condition and angle (Renning et al., 2013; Vishwanath et al., 2005; Lee & Saunders, 2013). Variation in visual processing can modify viewer experience, particularly the ease with which the viewer can simplify a given pattern or stimulus to a representative element that requires lower effort to interpret (Billington et al., 2008; Rezaei et al., 2020). With even the slight increase in predictable order, particularly with respect to symmetry (Bies et al., 2016) and exactness of repetition across scales (Robles et al., 2020), pattern processing is facilitated, leading to a tolerance for overall pattern complexity and thus a shift in observer preference towards more complex images (Bies et al., 2016; Hagerhall et al., 2016; Güçlütürk et al., 2016). Beyond internal variations of pattern structure, visual order surrounding an image is also factored into viewer interpretation (Aboushi et al., 2019; Sereno et al, 2020). Considering the above factors, the second aim is to evaluate how the inclusion of additional structure yields a composite pattern impacting observer perceptions.

The impact of divergent composition is never more evident than the amalgamation of humanmade Euclidean design (e.g., built environments) with natural fractal patterns. Unlike the self-similar fractal relationships found in natural landscapes, Euclidean arrangements appear starkly artificial. These humanmade configurations of regular straight lines are exemplified by the indoor spaces in which most people spend the majority of their time. Whereas the human visual system is adept at handling natural configurations of spatial frequencies, additional effort is required to process Euclidean arrangements (O'Hare & Hibbard, 2011; Penacchio & Wilkins, 2015; Le et al., 2017). Moreover, this expenditure of additional energy from managing unnatural visual statistics is correlated with an overall increase in occupant stress levels producing negative psychological experiences and decreased general well-being, manifesting in symptoms of discomfort, visual strain, and prevalence of headaches (Penacchio & Wilkins, 2015; O'Hare & Hibbard, 2011; Ogawa & Motoyoshi, 2020). Increasing exposure to nature and natural patterns such as fractals is shown to benefit observer well-being (Burtan et al., 2021; Hagerhall et al., 2015; Ulrich, 1981) and have a restorative effect on attention (Berman et al., 2008; Hagerhall et al., 2015; Kaplan & Kaplan, 1989; Kaplan & Kaplan, 1982). Installments of fractal-based design may mitigate the effects of unnatural visual processing strain as they can be added into existing built environments to decrease visual strain without sacrificing the functionality of the space (Smith et al., 2020; Roe et al., 2020; Abboushi et al., 2019; Taylor & Sprott, 2008). Fractal installations inject elements of natural configurations into manufactured spaces and serve as a break from the visually draining surroundings, lowering levels of visual processing effort to facilitate occupant relaxation (Hagerhall et al., 2015; Smith et al., 2020). Building off results from the second aim, the third aim of this dissertation is to define how perception is systematically altered with the integration of fractal arrangement into simple Euclidean structure. Findings from this line of research will functionally serve to inform selection of fractal designs tailored to the purpose of a space, in addition to furthering scientific awareness of the unique impact of underlying fractal structure on perception of the visual world.

The ability to understand a fractal pattern in its entirety from the comprehension of a subset of its components is an underlying tenet of Fractal Fluency Theory (Taylor & Spehar, 2016) and is theorized to be responsible for peaks in performance coinciding with low-moderate fractal complexity (Juliani et al., 2016, Taylor et al., 2017; Hagerhall et al., 2015). The self-similar arrangement inherent to fractal statistics has been suggested to make these complex patterns easier to understand. However, it is not well understood whether this increase in processing fluency occurs at a detriment to encoding pattern distinctiveness. Although recognition of natural scenes is driven by global structure (Greene & Olivia, 2009), success of image discrimination and recognition is impacted by the structural features of a target, including number of shared local elements in an item or scene (Schurgin et al., 2020). Despite the human-eye being highly sensitive to alterations within a given pattern (Spehar et al., 2015; Isherwood et al., 2017; Isherwood et al., 2021), the shared features fundamental to fractals (ie. seed, recursion, black-white ratio) greatly increases the difficulty in discriminating between patterns. With the arrangement of many simple local elements being repeated to create a global pattern, fractals could be processed in a similar manner on both local and global scales. In line with other aspects of cognitive performance, memory performance for fractal patterns may be reflective of a general fractal fluency and expose how encoding and retrieval may vary with fractal arrangement. The final aim of this dissertation is to explore how fractals are encoded and represented in long term memory. Results from this research will further our understanding of how fractals are processed in the visual system and can be applied to decisions on design implementation.

Overview of the Dissertation

The goals of this dissertation are to 1) assess the impact of individual differences on perception of fractal patterns, 2) evaluate how the inclusion of additional structure integrates into overall pattern perception, 3) define the unique contribution fractal structure imparts on visual judgements in Euclidean space, and 4) probe the relationship between fractal perception and memory performance. In four empirical studies, I will show that trends in fractal perception are established early in life (Chapter 2), can be modulated through the incorporation of artistic elements (Chapter 3), as well as Euclidean structure (Chapter 4), and that variations in pattern structure can impact memory abilities (Chapter 5). Importantly, these chapters will demonstrate how visual fractal structure in our surroundings contributes to shared perceptual experiences. Together, this series of studies add to a growing literature of Fractal Fluency Theory including the utility of integrating fractal designs into human-made environments and furthers our understanding of the role the statistics of nature play in our perceptions of the visual world.

Chapter 2 will address the broad generalizability of fractal preference across a wide span in development, exposure, and individual cognitive differences. Previous work in the field has heavily focused on the perception and preferences of neuro-typical young adults to conclude a common preference for statistical fractal patterns with low-moderate complexity (Bies et al., 2016; Spehar et al., 2016; Street et al., 2016; Pyankova et al., 2019) and exact fractal patterns with high complexity (Bies et al., 2016; Hagerhall et al., 2015; Friedenberg et al., 2021). However, trends are shown to shift in the presence of cognitive variations associated with older-aged populations (Forsythe et al., 2017). Furthermore, the manner in which an individual integrates contextual information critical in pattern perception varies across development (Hadad, 2018), as well as with processing tendencies due to exposure and familiarity of a given pattern complexity (Roder et al., 2000), or with the degree to which the individual processes pattern features (Billington et al., 2008). Thus, it is unclear whether these well-established trends in fractal preference are present in younger individuals with lower levels of exposure and understanding of novel fractal structure. Chapter 2 of the dissertation will address this gap in the literature by comparing fractal preference of children and adults. Importantly, it will demonstrate how these major factors of individual differences in processing style or years of exposure are not driving forces behind fractal preferences. Moreover, it will show that preference for both statistical and exact fractal patterns is stable across a wide range in age and cognitive differences and reflects a likely fluency of fractal processing established earlier in development.

The broad findings of a stable fractal preference from the previous chapter then inspires Chapter 3 to address the perceptual effects of fractal design installments in shared spaces. Previous studies have determined the ability of fractal patterns to alter the experience of a given object or space (Juliani et al., 2016; Taylor et al., 2018; Abboushi et al., 2019; Roe et al., 2020; Spehar & Stevanov, 2021) suggesting that these patterns can be utilized to mitigate negative health effects associated with Euclidean spatial structure (O'Hare & Hibbard, 2011; Ogawa & Motoyoshi, 2020). To effectively incorporate fractal designs, the space's overall function and design must be considered in addition to the desired psychological experience of the occupant. To address these facets, Chapter 3 will test how perceptions of various fractal designs change with alterations to overall image design and arrangement. Fractal inspired carpet designs which incorporate various design elements, fractal elements, and arrangements into their composition (Smith et al., 2020) will be assessed with ratings of broad psychological effects to determine how fractal-inspired-design can balance aesthetic and psychological goals of a space. Furthermore, viewer subpopulations which have been shown to exist amongst well-established trends in fractal preference (Street et al., 2016; Hagerhall et al., 2018; Spehar et al., 2016; Güçlütürk et al., 2016) will be explored in order to more thoroughly consider which designs should be selected to produce the most positive psychological impact for the greatest number of occupants in a shared space. Consistent with Chapter 2, stable trends driven by complexity of pattern components are uncovered across a large sample, with consistent small subpopulations that systematically vary. Overall aesthetic preference for these fractal designs is demonstrated to be derived from the balance of contrasting psychological needs for increased arousal and decreased tension. Furthermore, the incorporation of design elements provides additional order in the patterns and shifts average viewer ratings toward moderate-high complexity patterns to maintain stronger preference in most viewers without incurring distaste from subgroups. Results from this chapter suggest that installment of specific fractal designs can predict and possibly modulate occupant perceptions of common Euclidean surroundings.

Building upon Chapter 3, which explores the effects of a specific fractal design, Chapter 4 will define the unique impact of fractal structure as a whole on pattern perception to disentangle how fractal organization interacts with contrasting Euclidean configurations. Findings from this research will fill a critical gap of outlining the distinct effect fractal statistics have on visual perception as a whole and how the introduction of Euclidean structure must be handled to optimize the utility of fractal design incorporation in human-made spaces. Whereas previous research supports the potential of fractal installations to promote positive psychological experiences of a space (Taylor & Sprott, 2008; Aboushi et al., 2019; Robles et al., 2021) no studies have directly confirmed the extent to which an underlying fractal structure is the driver of these consistent trends in perception as opposed to stylistic features of the image such as general complexity or black-white ratio. This study is the first to compare viewer perception of fractals and statistically equivalent patterns with fractal structure removed to definitively confirm the distinctive role of fractal order on the human visual experience further, reinforcing the utility of studying these natural patterns. Established trends of fractal perceptions have been heavily assessed in contextual isolation, with stimuli serving as a singular visual surface (Bies et al., 2016; Spehar et al., 2003; Spehar et al., 2015). However, in the visual world fractal items rarely appear as two-dimensional surfaces devoid of additional composition or surrounding components. Chapter 4 answers the fundamental question: how does fractal perception change with the integration of additional non-fractal structure? This study examines how even the most basic Euclidean structure, reminiscent of a prototypical surrounding three-dimensional space, alters viewer perceptions of fractal patterns and must be accounted for to predict the efficacy of fractal design in human-made spaces. Findings from this chapter serve as an imperative step in comprehending how fractals produce predictable perceptions.

Chapter 5 branches away from the previous measurements of subjective perceptions to investigate the impact of underlying fractal structure on more objective cognitive abilities, specifically how underlying fractal structure is processed during memory tasks. The distinct structure of fractal arrangement allows these patterns to be processed in an efficient and low-effortful manner (Taylor & Spehar, 2016). This fluency of processing has been demonstrated to facilitate viewer comprehension that promotes object-naming (Rogowitz & Voss, 1990) and navigational abilities (Juliani et al., 2016). In both instances, observers are quicker to process lower complexity fractal patterns as a whole and rely on features of low-moderate complexity for greater success in their given task, thus lending more support to an underlying processing fluency for these patterns. Can Fractal Fluency Theory then account for fractal pattern memory as a whole? Chapter 5 seeks to determine how fractal structure impacts whole pattern recognition and if these patterns are encoded on a holistic or component basis. The first study investigates participant memory for fractal stimuli compared to mathematically matched non-fractal images to identify the utility of fractal structure for whole-pattern memory. This study suggests that the self-similar nature of fractal arrangement promotes more effective visual encoding than visually comparable non-fractal images without negating distinct internal features necessary to differentiate between similar stimuli. To further probe how self-similarity in pattern features can affect visual component memory, study two assesses source memory for elements within fractal and non-fractal images. This chapter extends the understanding of Fractal Fluency Theory to show how the viewer can efficiently reduce fractal images to their fundamental structure to promote whole pattern recognition. These findings provide a more nuanced view of fractal processing and its impact on image distinctiveness which should be accounted for when informing decisions on pattern utility. Finally, chapter 6 will integrate findings from across the studies to synthesize a broader understanding of fractal perception across variations in individuals, contexts, and tasks and provide a general discussion that ties them to the broader literature of Fractal Fluency Theory.

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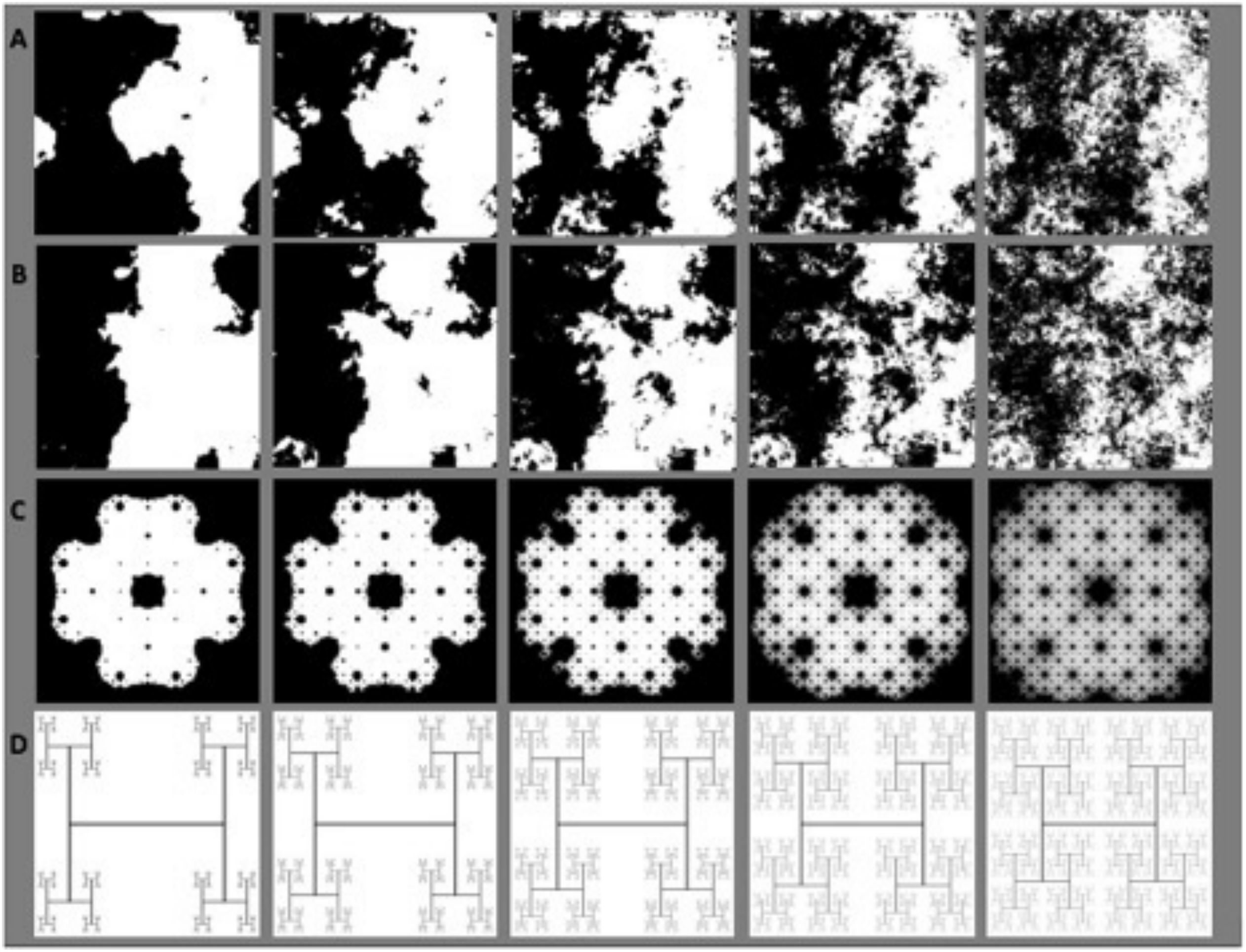
CHAPTER II

A SHARED FRACTAL AESTHETIC ACROSS DEVELOPMENT

From Robles, K. E., Liaw, N. A., Taylor, R. P., Baldwin, D. A., & Sereno, M. E. (2020). A shared fractal aesthetic across development. *Humanities and Social Sciences Communications*, *7*(1), 158. https://doi.org/10.1057/s41599-020-00648-y

The aesthetics of nature are influenced by fractal complexity (Mandelbrot, 1982; Taylor et al., 1999). Recursion (the number of pattern repetitions across scales) and fractal dimension *D* (the rate of pattern shrinkage between repetitions) set the relative contributions of coarse-to-fine structure for the overall fractal pattern, thus determining its visual complexity (Boselie & Leeuwenburg, 1985; Eysenck, 1942). The character of the pattern repetition ("statistical" versus "exact") further influences perceived complexity, as does the degree of the pattern's spatial symmetry (the presence of invariant geometric transformations such as reflections and rotations). The dependence of aesthetic preference on complexity has been established for both statistical (Fig. 2.1A, B) (Hagerhall et al., 2015; Taylor et al., 2011 as a review) and exact (Bies et al., 2016a) (Fig. 2.1C, D) repetitions of fractal patterns.

Statistical fractals are prevalent in natural scenery (e.g. trees, mountains, clouds, rivers) (Mandelbrot, 1982) and preference for them has been shown to peak at low–moderate complexity (approximately D = 1.3–1.4 on a scale between D = 1.1 and 1.9) and steadily decrease with additional complexity (Taylor et al., 2011; Taylor & Sprott, 2008). The paintings of Jackson Pollock reflect these findings in that the artist's layering of paint establishes a fractal structure (Taylor et al., 1999, 2007), and preference for cropped black and white versions of these works peaks at mid-complexity (Spehar et al., 2003). Moreover, traditional and contemporary art from diverse cultures contain fractal properties (Graham & Field, 2008;



Graham & Redies, 2010), suggesting a universal preference for patterns of low- moderate

Figure 2.1. Fractal stimuli. A-D. Examples of the two statistical **A** and **B** and two exacts **C** and **D** seeds used in the experiment. The sequence of images depicts the progression from low (*D*=1.1 on the far left) to high (*D*=1.9 on the far right) complexity.

perceived complexity with subgroups of preference for different *D*-values (Bies et al., 2016a; Spehar et al., 2016; Street et al., 2016; Pyankova et al., 2019). Notably, an analysis of famous artworks indicates preference for lower *D*-values with age-related conditions including Alzheimer's and Parkinson's diseases (Forsythe et al., 2017). Contrasting the overall preference for low–mid-complexity statistical fractals, increased tolerance of fractal complexity elicited by the symmetries and precise repetition of exact fractals generates preference for higher *D*- values (Bies et al., 2016a).

Previous research indicates that heightened preference and psychophysical performance are associated with common low–moderate natural patterns (Spehar et al., 2003; Sprott, 1993; Taylor et al., 2005) reminiscent of savanna scenes (Falk & Balling, 2010). Fractal Fluency theory suggests the visual system is tuned, either through repeated exposure or evolutionary mechanisms, to better process complexities most encountered in the surrounding natural environment (Falk & Balling, 2010; Taylor et al., 2018, Hagerhall et al., 2008) and it is this efficiency that leads to fractal preference. In contrast, unnatural Euclidean patterns and environments have been linked to increased strain on the visual system producing headaches (Penacchio & Wilkins, 2015) and lower aesthetic preference (Taylor, 1998). Additional studies recommend installations of naturalistic low–moderate *D* fractals to reduce occupants' stress levels in built environments (Hagerhall et al., 2015; Taylor et al., 2005). Combined, the above studies highlight the importance of understanding fractal fluency for optimizing our visual environments across all age groups.

Impact of individual differences and age

Perceptual integration of contextual information varies across development and can impact susceptibility to visual illusions (Hadad, 2018). Differences in general perceptual strategies or age-related handling of contextual information may alter the perception of patterns, either by influencing the degree to which local compared to global features of patterns are processed (Billington et al., 2008), or the degree of contextual experience and familiarity an individual has with different pattern complexities (Roder et al., 2000). A local bias reflecting a predilection for small-scale, detailed structure might guide preference for more complex patterns, whereas a global bias may produce a preference for larger scale structure which is more discernable in patterns with low–mid range complexity. Likewise, the so-called Goldilocks effect may account for changes in preference (Kidd et al., 2012). Beginning in infancy, an individual incrementally acquires knowledge of more complicated and novel aspects of the surrounding environment, thus gradually learning how to comprehend more complex patterns and concepts. After decades of exposure to natural patterns, this theory suggests that understanding of visual patterns will have deepened compared to that of early childhood, shifting preference towards the most complex patterns an individual can process (Roder et al., 2000; Kidd et al., 2012). To define the impact of these factors on fractal aesthetics, it is vital to consider a wider sample of participant ages (children as well as adults) and account for the impact of individual perceptual biases (determined by assessing Systemizing Quotient (SQ) scores (Baron-Cohen et al., 2001) and susceptibility to global context effects in the Ponzo Task (Hadad, 2018), see Fig. 2.2 (Walter et al., 2008)). Overall, if robust trends found in adults are present in children (especially since few tasks result in steady performance across a wide age gap (Stevenson, 1972)), it would support the conclusion that these preferences are likely resulting from a common visual tuning established earlier in life. This would be of notable interest in part because early life is often largely spent in Euclidian shelters, which are inherently less complex than nature's fractal environments (Clements, 2004).

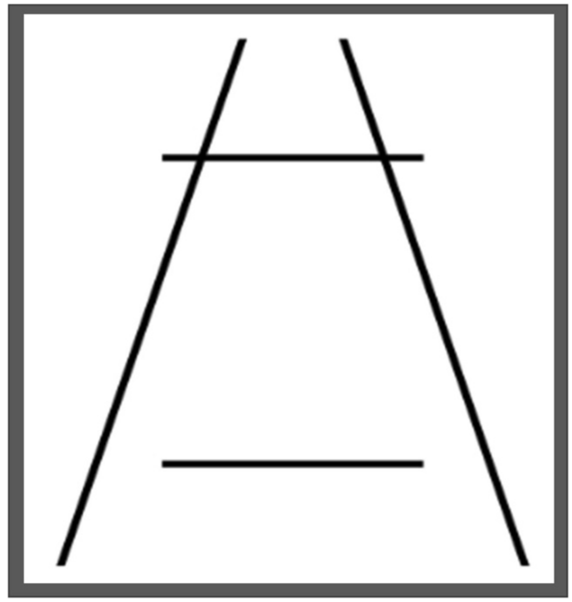


Figure 2.2. Depiction of the Ponzo Task. Depiction of the Ponzo Task. Surrounding contextual information provided by the vertical lines influences the accuracy of length judgments of the horizontal lines. Greater susceptibility to this illusion is related to a global processing bias.

Methods

Participants

To examine the extent to which preference for complexity in fractal patterns may change across development, 178 participants comprised of students from the University of Oregon and guests of the Eugene Science Center were recruited for the current study. Eighty-two of the participants were adults recruited through the University of Oregon's SONA participant pool system (75 females, age ranging between 18 and 40 years, mean age 20 years old), and the other 96 participants were children between the ages of 3 and 10 years old (43 females, mean age 6.5 years old) who visited the Eugene Science Center. We sampled roughly equal numbers of male and female children from each age range (3–4, 5–6, 7–8, and 9–10 years old), and at least 20 children were recruited for each age group. Adult participants received class credit for their participation in the current study, whereas child participants received either stamps or stickers for their time. Informed consent was acquired following protocol approved by the Institutional Review Board at the University of Oregon. Consent for child participants was obtained through a consent form signed by the child's parent or legal guardian in addition to verbal consent from the child, whereas adult participants completed a single consent form.

Visual displays

Stimuli were displayed on a Microsoft Surface- Pro touch screen electronic tablet which was placed on a table in front of participants and propped up at an angle within reaching distance ~25 cm from the participants. Questionnaires given to adult participants were presented on an additional hand-held touch screen electronic tablet (iPad) while child participants completed perceptual tasks.

Stimuli and tasks

Fractal stimuli and preference task. Fractals are complex because they possess structural similarity across scales. Exact fractals are built by precisely repeating a pattern at different magnifications. In contrast, statistical fractals are built by introducing randomness into their construction which disrupts the precise repetition such that only the pattern's statistical qualities repeat across scales. Two sets of statistical (Fig. 2.1A, B) and exact (Fig. 2.1C, D) fractals were used. Exact midpoint displacement fractals (Fig. 2.1C) were generated according to an algorithm described by Fournier (Fournier et al., 1982; Bies et al., 2016a, b). Exact H-tree fractals (Fig. 2.1D) repeat an H-pattern at increasingly fine size scales. The statistical fractals were created using a variant of the midpoint displacement method (Fournier et al., 1982; Bies et al., 2016b). Two different sets of statistical fractals of varying complexity were generated from two different seeds. The complexity of a fractal pattern is determined by the rate at which the exact or statistical pattern deceases in size with each iteration of the repetition process (Mandelbrot, 1982; Taylor et al., 2011). The rate is set by the pattern's fractal dimension or "*D*", which ranges from 1.1 to 1.9 (1.1, 1.3, 1.5, 1.7, and 1.9) in our stimulus sets (see Fig. 2.1 for an example stimulus set).

Participants viewed either exact or statistical fractal patterns presented in two randomized blocks, with each block consisting of only one fractal pattern stimulus set (exact midpoint displacement or H-tree; statistical midpoint displacement seed #1 or #2). Each stimulus set consisted of five unique patterns of different complexity or *D*-value (e.g., Fig. 2.1A). A two-alternative forced choice task was used, resulting in 10 trials (10 fractal pairs) per block. All fractal pattern complexities were paired once within a block, resulting in each complexity being presented four times within a block. Stimulus pairing and presentation order were random with the constraints that (1) all fractal pattern complexities were paired only once, (2) half of the 10 trials consisted of patterns with higher complexity on the right side and half on the left side, and (3) each pattern of a given complexity appeared on both left and right sides. Between trials, a smiley face icon served as a fixation point that had to be touched to produce the next pair of images.

Ponzo stimuli and task. Following the fractal preference task, participants completed 10 trials of a Ponzo task. In this task participants were presented with vertical lines angled towards the center of the screen and two horizontal lines placed between the slanted vertical lines in the upper and lower halves of the screen (see Fig. 2.2 for an example stimulus). The length of each horizontal line was randomly generated such that it did or did not intersect the vertical lines, and each horizontal line was larger or smaller than the other. Participants adjusted the lower line to match the length of the upper line. Accuracy and directional bias of adjustments were measured as a difference in pixels between the upper and lower-line segments and whether these adjustments overestimated or underestimated the target length.

Questionnaire

After the fractal preference and Ponzo tasks, all adult participants completed the SQ questionnaire. The quotient was determined based upon participants' ratings of the degree to which the statements were like or unlike themselves, which provided a score of overall systemizing and emotional tendencies (Baron-Cohen et al., 2001). A children's SQ (Auyeung et al., 2009) was completed by parents or guardians on a separate electronic tablet while child participants completed the fractal preference and Ponzo tasks.

Procedure and design

Participants were presented with either exact or statistical fractals and completed three practice trials prior to two blocks of two alternative forced choice decisions. The practice stimuli were different than the experimental stimuli. Participants were instructed to touch the fixation image to initiate the presentation of pairs of fractal patterns. Image pairs remained on the screen until participants made a selection by physically touching the image they preferred ("liked best"). Upon completion of the fractal preference task, participants were presented with a Ponzo illusion task. In this task participants were instructed to drag their finger along a line segment to adjust its length until it matched the length of a parallel line segment positioned above it. Adult participants completed an online questionnaire that contained demographic questions as well as the SQ. Parents or guardians of child participants completed a children's version of this questionnaire while the child completed the other tasks. Throughout the experiment, researchers sat next to child participants and encouraged children to maintain focus on the tasks. At the conclusion of the experiment all participants were compensated and debriefed according to the protocols approved by the Institutional Board at the University of Oregon.

Results

Data from 82 adult participants (between 18 and 33 years old) and 96 child participants (between 3 and 10 years old) were retained from the 83 adults and 118 children who participated in the experiment. Data were excluded due to failure to (a) complete the study, (b) comprehend instructions, or (c) maintain focus during the experiment.

Fractal preference task

A three-way mixed 5 × 2 × 2 ANOVA (*D*-value (1.1, 1.3, 1.5, 1.7, 1.9) × age (3–10-year-old children, and 18 years and older adults) × Fractal-Type (statistical, exact)) was performed using IBM SPSS Statistics for Macintosh, Version 25.0) on preference data for the fractal patterns (recorded as proportion of trials a given pattern was chosen in a two- alternative forced choice pairing), with *D*-value as a within- subjects variable and Fractal-Type and Age as between-subjects variables (see Table 2.1). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value ($\chi^2(9)=292.18$, $p< 0.001$**). Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = 0.521$). As indicated by a single asterisk for statistical significance of $p < 0.05$ and double asterisk for significance of $p<0.001$, only a significant main effect of *D*-value emerged in the analysis ($F(2.08, 362.67) = 3.79$, $p = 0.02$*, 95% CI [0, 0.06], $\eta_p^2 = 0.02$), [Age ($F(1, 174)=0.001$, $p=0.97$, 95% CI [0, 0.001], $\eta_p^2<0.001$) and fractal-type ($F(1, 174) = 2.13$, $p = 0.15$, 95% CI [0, 0.06], $\eta_p^2=0.01$)]. Furthermore, no significant interactions appeared between *D*-value and age ($F(2.08, 362.67) = 2.37$, $p = 0.09$, 95% CI [0, 0.04], $\eta_p^2 = 0.01$), fractal-type and age ($F(1, 174) = 0.001$, $p=0.97$, 95% CI [0, 0.001], $\eta_p^2<0.001$), or among *D*-value, fractal-type and age ($F(2.08, 362.67) = 0.36$, $p = 0.71$, 95% CI [0, 0.02], $\eta_p^2 = 0.002$). The sole significant interaction was between *D*-value and fractal-type ($F(2.08, 362.67) = 2.94$, $p = 0.05$*, 95% CI [0, 0.05], $\eta_p^2 = 0.02$) (see Fig. 2.3). A follow-up three-way mixed 5 × 4 × 2 ANOVA (*D*-value (1.1, 1.3, 1.5, 1.7, 1.9) × age (3–4, 5–6, 7–8, and 9–10-year-old children) × fractal-type (statistical, exact)) was performed on child participant data (see Table 2.2). Once again, Mauchly's test indicated a violation of the assumption of sphericity for *D*-value ($\chi^2(9) = 88.30$, $p < 0.001$**), thus degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = 0.634$). No significant main effects were uncovered [*D*-value ($F(2.54, 223.28)=2.35$, $p=0.08$, 95% CI [0, 0.07], $\eta_p^2=0.03$),

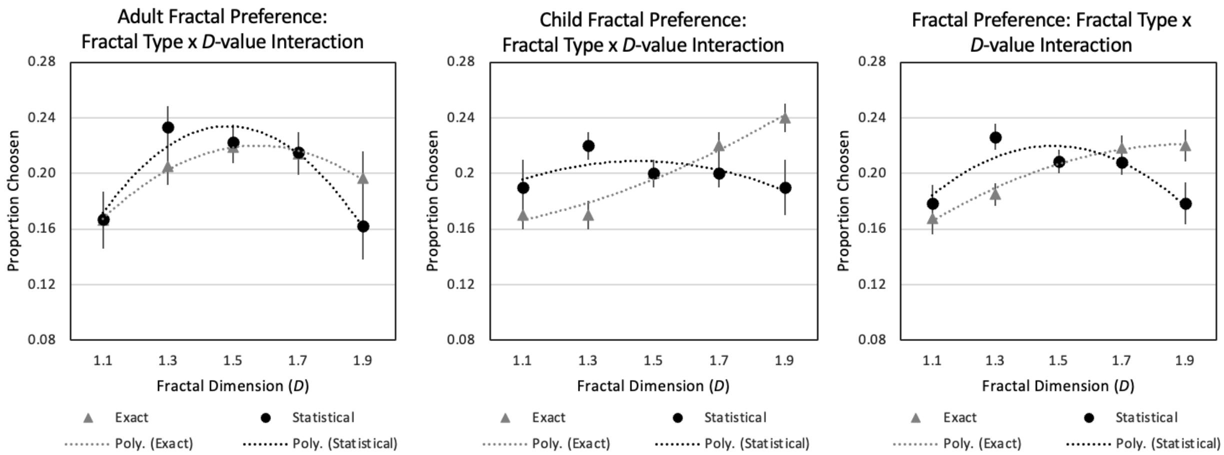


Figure 2.3. Participant data demonstrating interaction between *D*-value and fractal-type. Adult (left panel), child (middle panel), and all (right panel) participant data demonstrating an interaction between *D*-value and fractal-type. Fractal preference for both children and adults rose steadily for exact fractal patterns and peaked at higher complexity. Preference for statistical fractals peaked at low-moderate complexity (*D*= 1.3) and decreased with additional complexity. All sets of data were fit with second-order polynomial functions (dashed lines).

Table 2.1: Mixed ANOVA across *D*-value, Age, and Fractal Type

	df numerator	df denominator	*F*	*p*	η_p^2	95% *CI*
D-Value (1.1, 1.3, 1.5, 1.7, 1.9)	2.08	362.67	3.79	.02*	.02	0, .06
Age (adult or child)	1	174	0.001	.97	<.001	0, .001
Fractal-Type (exact or statistical)	1	174	2.13	.15	.01	0, .06
D-Value * Age	2.08	362.67	2.37	.09	.01	0, .04
D-Value * Fractal-Type	2.08	362.67	2.94	.05*	.02	0, .05
Age * Fractal-Type	1	174	0.001	.97	<.001	0, .001
D-Value * Age * Fractal-Type	2.08	362.67	0.36	.71	.002	0, .02

*p<.05 are statistical significance

age ($F(3, 88)$=1.05, p= 0.38, 95% CI [0, 0.11], $\eta_p{}^2 = 0.03$) and Fractal-Type ($F(1, 88) = 0.97$, p = 0.33, 95% CI [0, 0.09], $\eta_p{}^2 = 0.01$)]. The only significant interaction was between D-value and fractal-type ($F(2.54, 223.28) = 3.49$, $p = 0.02$*, 95% CI [0, 0.09], $\eta_p{}^2 = 0.04$) (see Fig. 2.3, middle panel).

***Table 2.2*:** Mixed ANOVA across *D*-value, Ages, and Fractal Type

	df numerator	df denominator	F	p	$\eta_p{}^2$	95% *CI*
D-Value (1.1, 1.3, 1.5, 1.7, 1.9)	2.54	223.28	2.35	.08	.03	0, .07
Ages (3-4, 5-6, 7-8, 9-10, +18)	3	88	1.05	.38	.03	0, .11
Fractal-Type (exact or statistical)	1	88	.97	.33	.01	0, .09
D-Value * Ages	7.61	223.28	1.49	.17	.48	0, .08
D-Value * Fractal-Type	2.54	223.28	3.49	.02*	.04	0, .09
Ages * Fractal-Type	3	88	1.05	.38	.03	0, .11
D-Value * Ages * Fractal-Type	7.61	223.28	0.36	.76	.02	0, .02

*p<.05 are statistical significance

A series of planned comparisons on the full data set explored the locus of the significant interaction between D-value and fractal-type. Average preference for statistical fractals ranged from a low of 0.18 (SD = 0.14) for D = 1.9 to a high of 0.23 (SD = 0.09) for D = 1.3. Paired samples t-tests revealed that mean preference differed significantly between D = 1.1 (M = 0.18, SD = 0.12) and 1.3 (M = 0.23, SD = 0.09) [$t(85)=-4.55$, $p< 0.001$**, 95% CI [−0.17, −0.07], d = 0.45], D = 1.3 and 1.9 (M = 0.18, SD = 0.14) [$t(85) = 2.03$, $p = 0.046$*, 95% CI [−0.002, 0.24], d = 0.41], as well as D = 1.7 (M = 0.21, SD = 0.09) and 1.9 [$t(85) = 2.26$, $p = 0.027$*, 95% CI [0.01, 0.14], d = 0.24]. Seen in Fig. 2.3—right panel, across the five fractal complexities, preference for statistical patterns peaked with low–moderate D and decreased with more extreme D-values. Regarding exact fractals, average preference increased with additional complexity from a low of 0.17 ($SD = 0.11$) for $D = 1.1$ to 0.22 ($SD = 0.11$) for $D = 1.9$. Preference for exact patterns differed significantly between $D = 1.1$ ($M = 0.17$, $SD = 0.11$) and 1.5 ($M = 0.21$, $SD = 0.07$) [$t(91) = -2.83$, $p = 0.006$*, 95% CI [−0.18, −0.03], $d = 0.44$], $D = 1.1$ and 1.7 ($M = 0.22$, $SD = 0.09$) [$t(91) = -2.73$, $p = 0.008$*, 95% CI [−0.22, −0.03], $d = 0.49$], $D = 1.1$ and 1.9 ($M = 0.22$, $SD = 0.11$) [$t(91) = -2.59$, $p = 0.011$*, 95% CI [−0.23, −0.03], $d = 0.48$], $D = 1.3$ (M=0.18, SD=0.08) and 1.5 [$t(91) = -2.15$, $p = 0.034$*, 95% CI [−0.12, −0.005], $d = 0.32$], as well as $D = 1.3$ and 1.7 [$t(91) = -2.11$, $p = 0.038$*, 95% CI [−0.16, −0.005], $d = 0.38$] (see Table 2.3). Paired independent samples t-tests between preference for exact and statistical patterns across the five D-values demonstrated that preference for only two D-values were significantly impacted by fractal-type, $D = 1.3$ ($t(176) = -3.30$, $p < 0.001$**, 95% CI [0.22, 0.8], $d = 0.52$) and $D = 1.9$ ($t(159.28) = 2.18$, $p = 0.030$*, 95% CI [−0.62, −0.03], d=0.32). For $D = 1.3$, exact fractal patterns elicited a significantly lower preference score ($M = 0.18$, $SD = 0.08$) than statistical patterns ($M =$

Table 2.3: Independent Samples t-Tests across D-value and Fractal Type

	D=1.1		*D*=1.3		*D*=1.5		*D*=1.7		*D*=1.9	
	Statistical Patterns	Exact Patterns	Statistical Patterns	Exact Patterns	Statistical Patterns	Exact Patterns	Statistical Patterns	Exact Patterns	Statistical Patterns	Exact Patterns
D=1.1	-	-	*t*= -4.55* (*d*=.45)	*t*= -1.72 (*d*=.19)	*t*= -1.53 (*d*=.29)	*t*= -2.83* (*d*=.44)	*t*= -1.38 (*d*=.28)	*t*= -2.73* (*d*=.49)	*t*= -.002 (*d*=0)	*t*= -2.59* (*d*=.48)
D=1.3			-	-	*t*= 1.51 (*d*=.21)	*t*= -2.15* (*d*=.32)	*t*= 1.04 (*d*=.21)	*t*= -2.11* (*d*=.38)	*t*= 2.03* (*d*=.41)	*t*= -1.94 (*d*=.37)
D=1.5					-	-	*t*= .04 (*d*=.01)	*t*= -.65 (*d*=.10)	*t*= 1.47 (*d*=.27)	*t*= -.70 (*d*=.11)
D=1.7							-	-	*t*= 2.26* (*d*=.24)	*t*= -.18 (*d*=.02)
D=1.9									-	-

*p<.05 are statistical significance

0.23, *SD* = 0.09). Conversely, for *D* = 1.9, exact fractal patterns engendered a significantly higher preference score (*M* = 0.22, *SD* = 0.11) than that of statistical patterns (*M* = 0.18, *SD* = 0.14).

To summarize, in a direct comparison of preference for exact and statistical fractals of differing complexity, our findings confirmed the established trends of a preference for low–moderate complexity *D*-values for statistical fractals (Taylor et al., 2011) and higher *D*-values for exact fractals (Bies et al., 2016a). Importantly, the lack of a significant effect of age on preference for *D*-values (no age × *D*-value interaction) suggests that preferences for fractal patterns are stable by early childhood. While the effect sizes for the *F*-tests are generally small, they are in alignment with results from previous research (Street et al., 2016) which demonstrate a wide range of effect sizes for preference tasks.

Individual differences tasks

The Ponzo task was completed by 82 adult and 29 child participants. Task accuracy was recorded as average difference in pixels (error) between the adjusted and target line lengths. Overall participant error was 33.24 pixels (*SD* = 37.11). Average adult error was 24.82 pixels (*SD* = 24.38), while average child error was 41.66 pixels (*SD* = 45.09). SQ scores were recorded as point totals for agreement with a series of statements regarding systemizing tendencies. SQ scores for adults can range from 0 to 150, whereas the children's version of the questionnaire is roughly half the length with scores ranging from 0 to 56. Adults averaged an SQ score of 63.7 (*SD* = 20.68) points, while children averaged 25 (*SD* = 8.15) points.

We completed independent samples t-tests comparing adults' and children's Ponzo and SQ scores and a correlational analysis between SQ scores and Ponzo errors, since previous work links susceptibility to visual illusions that rely on context (including the Ponzo illusion) to lower

SQ scores (Billington et al., 2008; Walter et al., 2008). Child and adult SQ scores were first standardized since they were recorded on different scales. A *t*-test comparing standardized SQ scores for adults versus children revealed no significant age-related differences in systemizing tendencies [$t(109)=0$, $p=1.0$, 95% CI [−0.42, 0.42], $d=0.00$]. After log transforming Ponzo scores to address their non-normal distribution, a t-test comparing Ponzo scores for these groups showed significant age-related differences in Ponzo task accuracy [$t(162) = -4.91$, $p < 0.001$**, 95% CI [−1.08, −0.45], $d = -0.77$] (see Table 2.4). Distributions of the child data may have been particularly affected by attrition (due to inadequate comprehension of Ponzo task instructions by some child participants and lack of SQ completion by parents). No significant correlation was detected between SQ and Ponzo scores ($r = -0.12$, $p = 0.22$) likely explained by prior research regarding age-related differences in illusion susceptibility (Hadad, 2018). A one-tailed correlational analysis on SQ scores and Ponzo error in adult participants alone (n = 82) detected a significant correlation ($r = -0.21$, $p = 0.028$*) (with higher SQ scores relating to reduction in Ponzo errors), and was performed since the link between visual illusion susceptibility and SQ scores was previously established only in adult participants (Walter et al., 2008) and attrition of child participants (n = 23) reduced the data available.

Table 2.4. Independent Samples *t*-Test across Age-Category and Perceptual-Task

	Child Ponzo error (in pixels)	Child Systemizing Quotient (SQ)
Adult Ponzo error (in pixels)	$t(162)=-4.91$** $d=-.77$	–
Adult Systemizing Quotient (SQ)	–	$t(109)=0$ $d=.00$

*$p<.05$ are statistical significance

To determine if individual differences in perceptual strategies (measured by either the SQ or Ponzo test) could significantly explain variance in fractal preference, we performed a 2-step multiple linear regression analysis to predict fractal preference from fractal-type, *D*-value, SQ score, and Ponzo error (see Table 2.5). The first step of the model, including fractal-type,

Table 2.5: Two-Step Regression predicting Fractal Preference

	df numerator	df denominator	*F*	*p*	R^2	95% *CI*
Fractal Preference ~ Fractal Type and *D*-Value	3	886	5.98	<.001 *	.02	.0, .04
	Step 1:		Beta	*t*	*p*	95% *CI* for Beta
		Constant	.24	3.82	<.001 *	.12, .36
		Fractal Type	.29	3.24	<.001 *	.12, .47
		D-Value	.08	2.64	<.001 *	.01, .25
		Fractal Type* *D*-Value	-.2	-3.30	<.001 *	-.31, -.08

	df numerator	df denominator	*F*	*p*	R^2	95% *CI*
Fractal Preference ~ Fractal Type, *D*-Value, SQ Score, and Ponzo Error	5	519	.66	.66	.01	.0, .02
	Step 2:		Beta	*t*	*p*	95% *CI* for Beta
		Constant	.35	3.61	<.001 *	.16, .55
		Fractal Type	.16	1.30	.19	-.08, .41
		D-Value	.10	1.80	.07	-.01, .20
		Fractal Type* *D*-Value	-.11	-1.33	.19	-.27, .05
		SQ Score	<.001	.001	.99	-.02, .02
		Ponzo Error	<.001	.00	.99	-.07, .07

*p<.05 are statistical significance

D-value, and the interaction of the two variables, significantly explained variance in preference ($F(3, 886) = 5.98$, $p < 0.001$**, $R^2 = 0.02$, 95% CI [0.0, 0.04]). The second step, adding SQ scores and Ponzo error to the model, was unable to significantly account for additional variance in fractal preference ($F(5, 519) = 0.66$, $p = 0.66$, $R^2 = 0.01$, 95% CI [0.0, 0.02]).

Table 2.6: Regression predicting Adult Fractal Preference

	df numerator	df denominator	*F*	*p*	R^2	95% *CI*
Adult Fractal Preference ~ SQ Score and Ponzo Error	2	407	.00	.99	.01	.0, .0
			Beta	*t*	*p*	95% *CI* for Beta
		Constant	.5	8.46	<.001 *	.38, .62
		SQ Score	<.001	.001	.99	-.03, .03
		Ponzo Error	<.001	.00	.99	-.09, .09

**p*<.05 are statistical significance

To rule out the impact of possible differences in data due to child participant attrition and SQ test dissimilarities, an additional regression was completed to predict adult preference alone, with a model containing SQ score and Ponzo error $F(2, 407) = 0.00$, $p = 0.99$, $R^2 < 0.001$, 95% CI [0.0, 0.0]) (see Table 2.6). This model also failed to significantly explain variance in fractal preference. Thus, despite the robust measurement of processing bias in our sample, no significant linear relationship emerged between these factors and fractal preference.

Discussion

Fractal patterns that recur in a statistical manner are prevalent in natural environments (Spehar et al., 2003; Taylor et al., 2018; Hagerhall et al., 2008) and both statistical and exact fractals are found in the art of many cultures (Graham & Redies, 2010). Preference is shown to peak at low–moderate fractal complexity (*D*) for statistical fractals and at higher *D*-values for exact patterns (Bies et al., 2016a) (since simplicity is introduced into these patterns though symmetry and exact repetitions), supporting a Fractal Fluency model in which common natural patterns are most fluently processed. In the first direct comparison of preference for statistical and exact fractals, the current study bolsters previous findings by confirming these robust preference trends and establishes that these preferences are apparent by early childhood, suggesting that this common fractal aesthetic is formed earlier in development.

We investigated the degree to which individual differences in processing style (assessed using the SQ and Ponzo task) might account for trends in fractal preference. The presence of a local or global processing bias could alter preference for pattern complexity by shifting preference toward higher complexity patterns containing more fine-scale/local detail for a local bias, or, for a global bias, toward lower complexity patterns in which larger scale forms are more apparent. Despite a wide range in SQ scores and Ponzo task performance and replication of a systematic relationship between these two assessments for adult participants (higher SQ scores correlate with lower Ponzo task error), no relationship was found between processing bias and preference for fractal complexity. The non-significant relationship between processing style and trends in fractal preference might be indicative of a developmentally early-emerging and broadly universal aesthetic that reflects the environmental complexity of early-humans as opposed to the more Euclidian environment experienced by most modern day children. However, these findings may have been impacted by underpowered sample sizes (in which the child sample suffered from attrition on these two assessments), prompting replication in larger samples to further substantiate this result.

Prior to this study, exposure to and facility in processing fractal patterns might have been expected to vary across the lifespan due to environmental and developmental factors. If fractal aesthetics reflected the most commonly encountered complexities across repeated exposure, differences would be expected to arise between individuals who differ in decades of experience (particularly since typical early life is primarily spent within Euclidian structures of low visual complexity) (Clements, 2004). Additionally, change in preference across childhood from simpler to more complex fractal patterns would have been expected if pattern comprehension changed incrementally with age. Instead, our finding of consistent preference trends across childhood and through adulthood suggests a stable fractal aesthetic is established early in life. This leaves open the possibility that an early biological or evolutionary mechanism optimizes the visual system for processing fractals—the most common spatial structure (of low–moderate complexity) found in nature (Falk & Balling, 2010), supporting a universal Fractal Fluency theory. In addition to defining possible sub-group behaviours in preferences across the lifespan (Bies et al., 2016a; Street et al., 2016), future studies must examine earlier stages of development (from infancy to 3 years of age) to further define the impact of experience with fractal patterns on visual tuning and the development of what may be a universal aesthetic preference. Addressing the developmental impact on fluency of fractal processing is vital to understanding and regulating aesthetic experiences in both natural and built environments.

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CHAPTER III

AESTHETICS AND PSYCHOLOGICAL EFFECTS OF FRACTAL BASED DESIGN

From Robles, K. E., Roberts, M., Viengkham, C., Smith, J. H., Rowland, C., Moslehi, S., Stadlober, S., Lesjak, A., Lesjak, M., Taylor, R. P., Spehar, B., & Sereno, M. E. (2021). Aesthetics and Psychological Effects of Fractal Based Design. *Frontiers in Psychology*, *12*, 3413. https://doi.org/10.3389/fpsyg.2021.699962

Driving nature's aesthetics, fractal patterns are prevalent across both microscopic and global structures in natural environments (Mandelbrot, 1982; Taylor, 2021). Fractals are comprised of self-similar patterns repeating across scale, with varying levels of recursion (number of repetitions across scales) and fractal dimension "*D*-value" (rate of pattern shrinkage between repetitions) that drive perceptions of pattern complexity by determining the relative contributions of coarse-to-fine structure for the overall pattern. Additionally, the nature of pattern repetition (occurring in either an exact or statistical manner) also impacts perceptions of pattern preference and complexity (Taylor et al., 2005, 2011; Taylor & Sprott, 2008; Hagerhall et al., 2015; Bies et al., 2016). The aesthetic quality of fractal patterns has been well observed (Spehar et al., 2003) and can be highlighted by its appearance in art (Taylor et al., 1999, 2018; Graham & Field, 2008; Graham & Redies, 2010; Viengkham & Spehar, 2018). Across diverse cultures, fractal patterns are present in both contemporary and traditional artworks. Exemplified by the fractal structure created by the layering of paint in paintings of Jackson Pollock (Taylor et al., 1999, 2007; Taylor, 2003), fractal patterns can elicit highly aesthetic responses through changes in complexity.

Furthermore, fractal patterns have the prospect of altering more than just the aesthetic experience of a given object (Juliani et al., 2016; Taylor et al., 2018; Abboushi et al., 2019; Roe et al., 2020; Spehar & Stevanov, 2021). Fractals can be installed into larger Euclidean spaces to mitigate the effect of unnatural spatial frequency content that can lead to visual strain and discomfort (O'Hare & Hibbard, 2011; Ogawa & Motoyoshi, 2020). The increasing amount of time people spend indoors surrounded by Euclidean architecture produces visual strain because of the additional visual effort required to process more artificial spatial frequencies is suggested to lead to detrimental effects such as increased rates of headaches (Penacchio & Wilkins, 2015). Beyond alleviating physical discomfort, occupant stress levels can be minimized through fractal installations reminiscent of nature by reducing cognitive and visual strain produced by surrounding unnatural spatial frequencies (Taylor, 2006; Hagerhall et al., 2008; Le et al., 2017). These positive impacts of viewing fractals can be considered within the context of biophilia (Wilson, 1984) which recognizes the inherent need of humans to connect to nature. In particular, it is possible that the stress-reduction (Ulrich, 1981; Ulrich et al., 1991; Kellert, 1993) and attention restoration (Kaplan & Kaplan, 1982, 1989) impacts studied in pioneering investigations of viewing nature might be induced through nature's fractals by easing visual processing.

To utilize the beneficial effects of natural geometry, the *ScienceDesignLab* (*SDL*) was formed in 2017 to generate patterns informed by the psychology of aesthetics (Smith et al., 2020). To transform the patterns into the built environment, SDL collaborated with the *Mohawk Group* - one of the world's largest flooring manufacturers. Floors represent a common, expansive space for exposing people to aesthetic patterns. Known as *Relaxing Floors*, the designs were launched in Spring 2019 and have since received ten awards for human-focused design. The designs were composed from fractal patterns based on the hypothesis that fractals are responsible for the positive impacts of viewing nature's scenery.

Whereas most studies of nature's statistical fractals focus on images of individual objects, typical scenes feature 'fractal composites' in which individual objects merge to form an overall pattern. In addition to more closely capturing the essence of nature, *Relaxing Floors* exploited the extra flexibility offered by the composition process to develop patterns that were intriguing from a design perspective. To describe the compositional principle underpinning these fractals, we considered the analogy of individual fractal trees combining to create a fractal forest. Fractal trajectories called 'Lévy flights,' featuring flights with multiple length scales, were used as the starting point for these designs (Scott, 2005; Ferreira et al., 2012; Figure 3.1A). Much like a bird dropping a seed whenever it lands, the seeds then grow into fractal trees at the locations between the flight trajectories. For simplicity, the seeds shown in Figures 3.1B–D have a circular shape. The seed's size can be scaled relative to the length of the previous flight, thus transferring the flight trajectory's scaling properties to the dropped seed (Figure 3.1D).

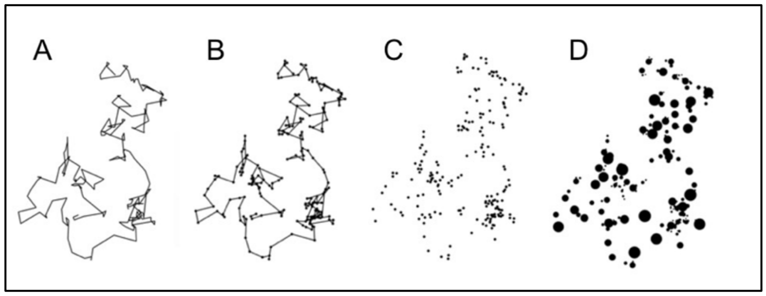

Figure 3.1. Fractal flights. **(A)** Lévy flight trajectories; **(B)** circular seed patterns are added to the 'landing' locations between these trajectories; **(C)** the trajectories are removed; **(D)** the sizes of the circles are scaled based on the length of the previous flights.

Figure 3.2 shows the seed growth process that replaces each circle in Figure 3.1 with a 'tree' pattern based on a traditional fractal called the Sierpinski Carpet. This fractal grows from a square-shaped seed by repeating the square at multiple size scales (note that while Figure 3.2B shows three levels of repetition for demonstration purposes, the patterns used in the carpets typically feature 2 levels). In principle, the square-shaped seeds can be replaced with any shape, providing designers with considerable flexibility for future designs. Similarly, the black background can be replaced by various pattern textures including the lines used in the design that we will study here (Figure 3.2D). To convert the design from an exact to statistical pattern, randomness is introduced into the lengths of the black lines and also in the positions of the white squares (Figures 3.2E–H). The rate at which the seed changes size between the repetition levels

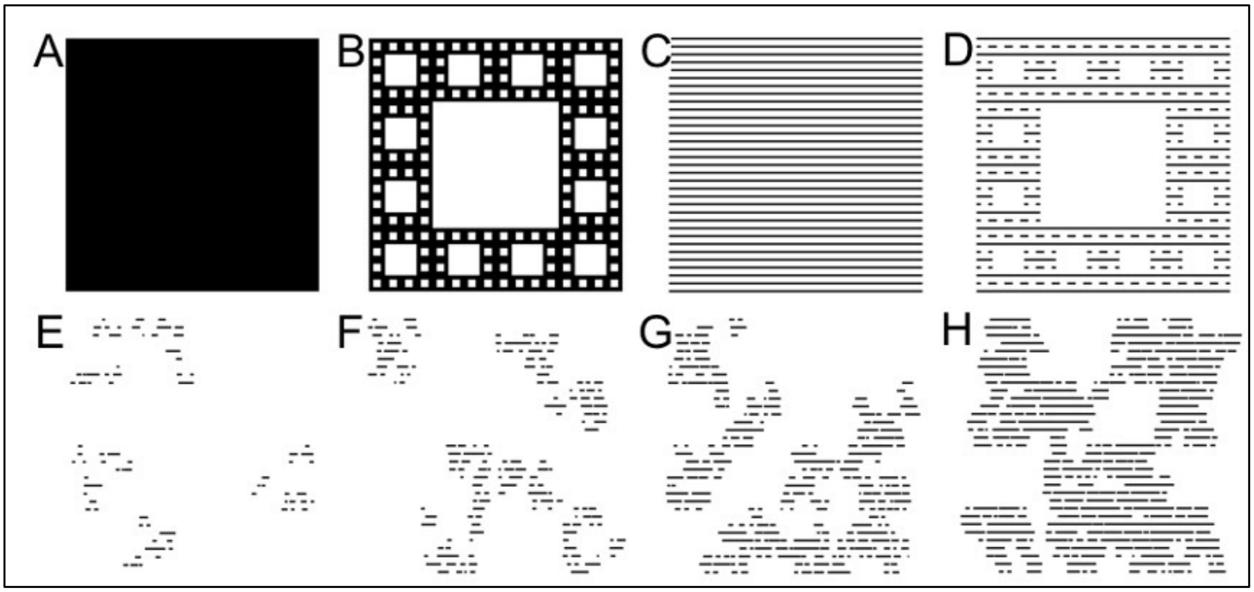

Figure 3.2. Fractal trees. **(A)** The tree growth starts out with a filled square; **(B)** a square-shaped seed is used to grow a Sierpinski pattern with *D*=1.8; **(C)** the black background is replaced with a line construction; **(D)** a square-shaped seed is used to grow a Sierpinski pattern superimposed on this lined background. The patterns are then randomized to morph the exact fractal into a statistical fractal. The *D*-value of the final fractal is inputted during this growth process. Four examples are shown here **(E)** 1.2, **(F)** 1.4, **(G)** 1.6, **(H)** 1.8.

can then be adjusted using *D*-value (Methods) – Figures 3.2E–G shows examples of fast (Figure 3.2E) to slow (Figure 3.2H) rates, each with a different randomization. The resulting fractal trees are then embedded at the landing sites between the fractal flights (Figure 3.3A). This design strategy therefore has the potential to incorporate fractal scaling in three key ways: (1) the fractal spacing between the trees (determined by the flights), (2) the distributions of the tree sizes (again set by the flights) and (3) the fractal growth of the seeds into trees.

A second motivation for the ‘bird flight’ composition strategy is that when viewing fractal patterns eye movements have been found to follow fractal trajectories (Taylor et al., 2011). This is because if the eye’s gaze is directed at just one location within the fractal scenery the peripheral vision only has sufficient resolution to detect coarse patterns. Therefore, the gaze shifts position to allow the eye’s fovea to detect the fine scale patterns at multiple locations. This allows the eye to experience the coarse and fine scale patterns necessary for confirmation of the fractal character of the stimulus. The reason the eye adopts a fractal trajectory when performing this task can be found in studies of animals such as birds foraging for food in their natural terrains. Their foraging motions are also fractal. For example, the short trajectories allow a bird to look for food in a small region and then to fly to neighboring regions and then onto regions even further away, allowing efficient searches across multiple size scales. The eye adopts the same motion when 'foraging' for visual information. These designs therefore place the tree locations using the same fractal statistics that the eye adopts when viewing them.

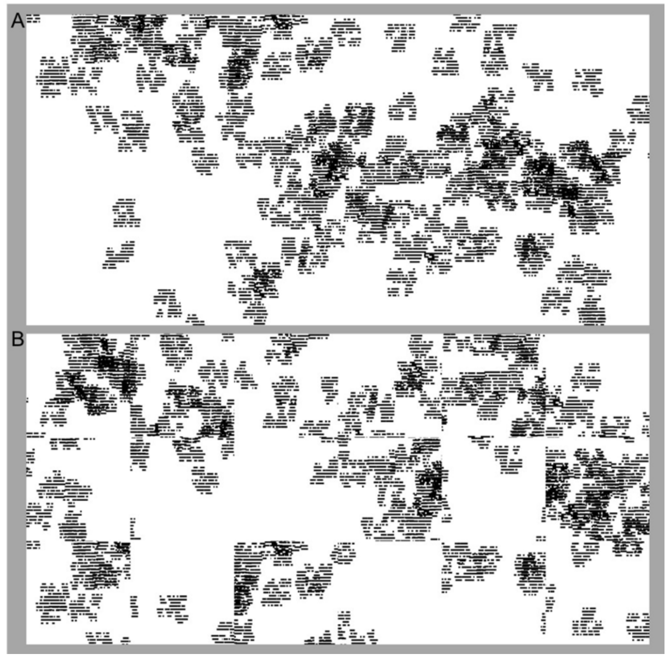

Figure 3.3. Fractal 'forests.' The forests integrate the flights of Figure 3.1 with the seed design of Figure 3.2. **(A)** is an image of the original (i.e., Before randomization) forest pattern with $D = 1.6$; **(B)** shows the same forest after it has been divided into tiles and the tiles randomized.

One challenge remained. For manufacturing demands, the 6ft (15 cm) by 12ft (30 cm) pattern of Figure 3.3A is divided into either 2ft by 2ft 'tiles' or 1ft by 3ft 'planks,' which will then be randomly re-assembled when installed in order accommodate the unique layout of any given space without altering the fractal *D*-value of the installation. We therefore had to simulate this division process to ensure that it did not disrupt the design aesthetic (in particular, that any discontinuities at the tile or plank edges fit well within the overall pattern) nor the fractal aesthetic (that the discontinuities did not alter the forest fractal's *D* value). Figure 3.3B shows an example of the randomized flooring pattern. Figure 3.4 (left image) shows the patterns as they appear on the carpets. In addition to this tuning of pattern characteristics to achieve the fractal aesthetics, the patterns also need to translate well to the carpet format seen in Figure 3.4A. The tufted carpet background had to be textural enough to hide the tile edges without creating a pattern that would alter the intended *D*-value. New tufting techniques which hide unused yarns to create controlled texture were used to achieve an optimized construction for aesthetics. The *Relaxing Floors* collection featured three fractal forests generated using the above principles, each with an overall *D* value of 1.6. The three designs (Smith et al., 2020) differed in the number of repeating levels within the tree, the shapes chosen to build the tree, and also the extent to which the tree size was set relative to the flight trajectory. Here we focus on the design which used the trees shown in Figure 3.2 and which set all the trees to be the same size (irrespective of flight size).

Previous research demonstrates that visual complexity is a key component in the visual impact of fractals. Compared to the simplicity of Euclidean shapes, the fractal repetition of

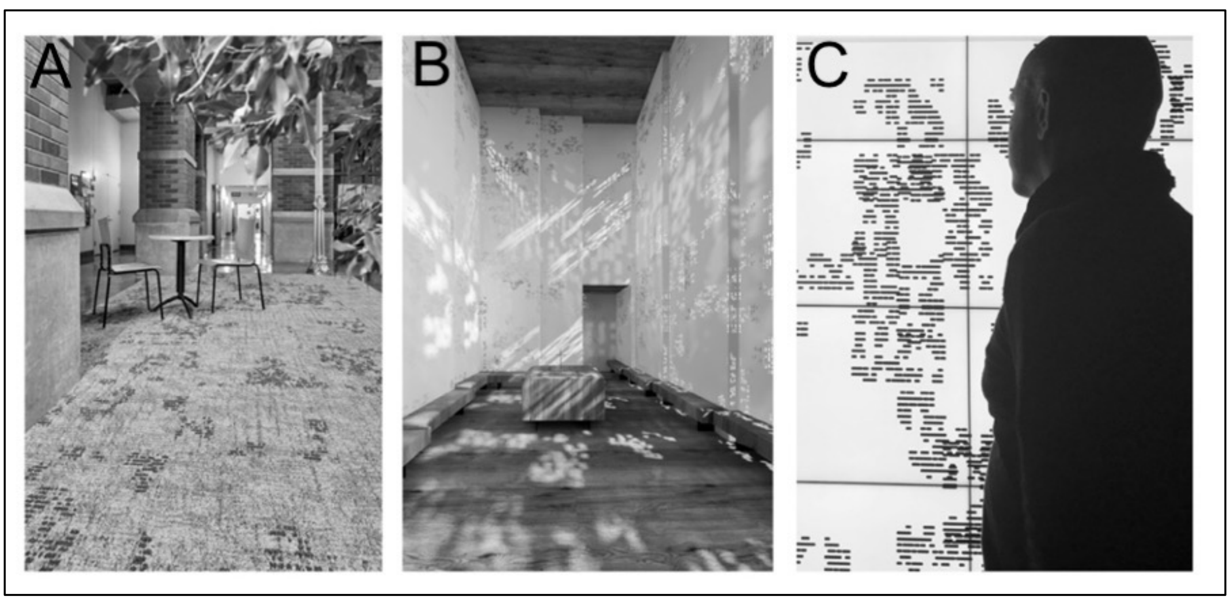

Figure 3.4. Installations. The fractal pattern of Figure 3.3 employed as a floor design at the University of Oregon, United States **(A)**, as wall patterns in the Fractal Chapel in the State Hospital in Graz, Austria **(B)**, and as a design for computer screen-savers **(C)**.

patterns at different scales results in fractal shapes that are inherently complex. The current series of studies expands upon typical measurement of fractal preference or complexity to address broader perceptual judgments (including ratings of complexity, engagement, preference, refreshment, and relaxation) of these “global forest” patterns and their respective local “tree-seed” patterns that are currently installed in multiple settings with the potential to promote viewer wellbeing (see Figure 3.4 for example installations). Figure 3.4 highlights an important key to success – the development of versatile designs that form the basis of multiple applications, in this case as carpet patterns for a university environment (in the *Mohawk* collaboration), as wall patterns used to disperse light throughout a chapel (in a collaboration with *INNOCAD Architecture*), and as computer screen savers (the latter are being made available for free personal use). The choice to use fractal patterns generated with design elements in mind, as opposed to images directly recruited from nature, serves to provide greater versatility in pattern design and application such that the base natural fractal pattern can be repeatedly varied to accommodate changing space requirements as well as adapting varying aesthetic design elements.

We will investigate these varied responses to global forest patterns of differing complexity by conducting studies in two laboratories (one at the University of Oregon in the United States [Experiment 1A] and the other at the University of New South Wales in Australia [Experiment 1B]) using slightly different rating scales as a test of the robustness of these effects. The use of both unipolar and bipolar rating scales is employed to ensure that our measurements are both sensitive enough to detect differences in psychological effects related to the fractal design patterns and generalizable across different measurement conditions. It is hypothesized that both of our rating scales will be able to identify consistent variations in the psychological effects of the various fractal design patterns, thus providing evidence of robust response patterns across measurement types. The goal of these studies is to establish an empirical basis for the optimal selection of fractal designs to meet varying psychological and aesthetic needs of a space (see Roe et al., 2020, for another example of this approach) by explicitly identifying whether general fractal preferences extend to more complex man-made fractal patterns and additional dimensions of psychological judgments. Finally, our results from subgroup analyses will guide the selection of specific fractal designs that balance various pattern factors (including *D*-value and arrangement) in order to benefit the most occupants possible without negatively impacting subgroups.

Experiment 1- Perception of Fractal "Global Forest" Patterns

We first examined the role of physical complexity and pattern arrangement in determining perceived complexity, engagement, preference, refreshment, and relaxation in 'global forest' fractal patterns. Experiment 1A used a series of unipolar slider tasks while Experiment 1B used a series of bipolar slider tasks.

Experiment 1A-Perception of Fractal "Global Forest" Patterns With Unipolar Ratings

Materials and Methods

Stimuli

We used the pattern's fractal dimension *D* to quantify visual intricacy. For the tree-seed patterns, the *D*-value dictates the rate of shrinkage of the patterns between repetition levels (Figures 3.2E–H). Similarly, the fractal flights follow a power law distribution with an exponent related to *D* that adjusts the relative sizes of the flights. In each case, high *D* results in a slower rate of shrinkage between the coarse and fine features. Lying on a scale between 1 and 2, higher *D*-value patterns feature larger contributions of fine scale patterns and thus appear to be rich in intricate detail. The *D*-values of the fractal forests were set by inputting the appropriate scaling parameters when generating the fractal trajectories and tree-seeds, and then a box-counting technique (Fairbanks & Taylor, 2011) was used to analyze the completed forest pattern to confirm that it scales according to the target *D*-value. This technique covers the pattern with a mesh of boxes and counts the boxes that are occupied by the pattern. By repeating the count for different box sizes, the pattern characteristics can be assessed at multiple size scales and confirmed to be scale invariant.

Fractal scaling was confirmed from the minimum pattern size of 0.2 inches (0.5 cm) up to 24 inches (61 cm). The box- counting method cannot confirm fractal scaling at scales larger than 24 inches due to a limited number of boxes at these scales (Fairbanks and Taylor, 2011). However, based on the fractal input parameters, it is expected that fractal scaling continues beyond the confirmed range. We note that even this restricted range of confirmed fractal scaling exceeds the magnification factor for typical physical fractals, for which the coarsest pattern is 25 times larger than the smallest (Avnir et al., 1998). Crucially, this factor of 25 was used for the stimuli used in most of the previous research that revealed the positive observation effects (Taylor et al., 2017, 2018). The scaling ranges of our designs therefore exceed those known to induce the positive effects.

Figure 3.5A–D shows examples of the 'forest' stimuli used in Experiment 1 with *D*-values of 1.2 (A), 1.4 (B), 1.6 (C), and 1.8 (D). The left side of each panel shows the original patterns while the right side shows the randomized version simulating the random pattern of ‘carpet squares’ installation in a space. Figure 3.5E shows example tree-seed stimuli of different *D*-values (1.2, 1.4, 1.6, and 1.8) that appear within the global forest stimuli.

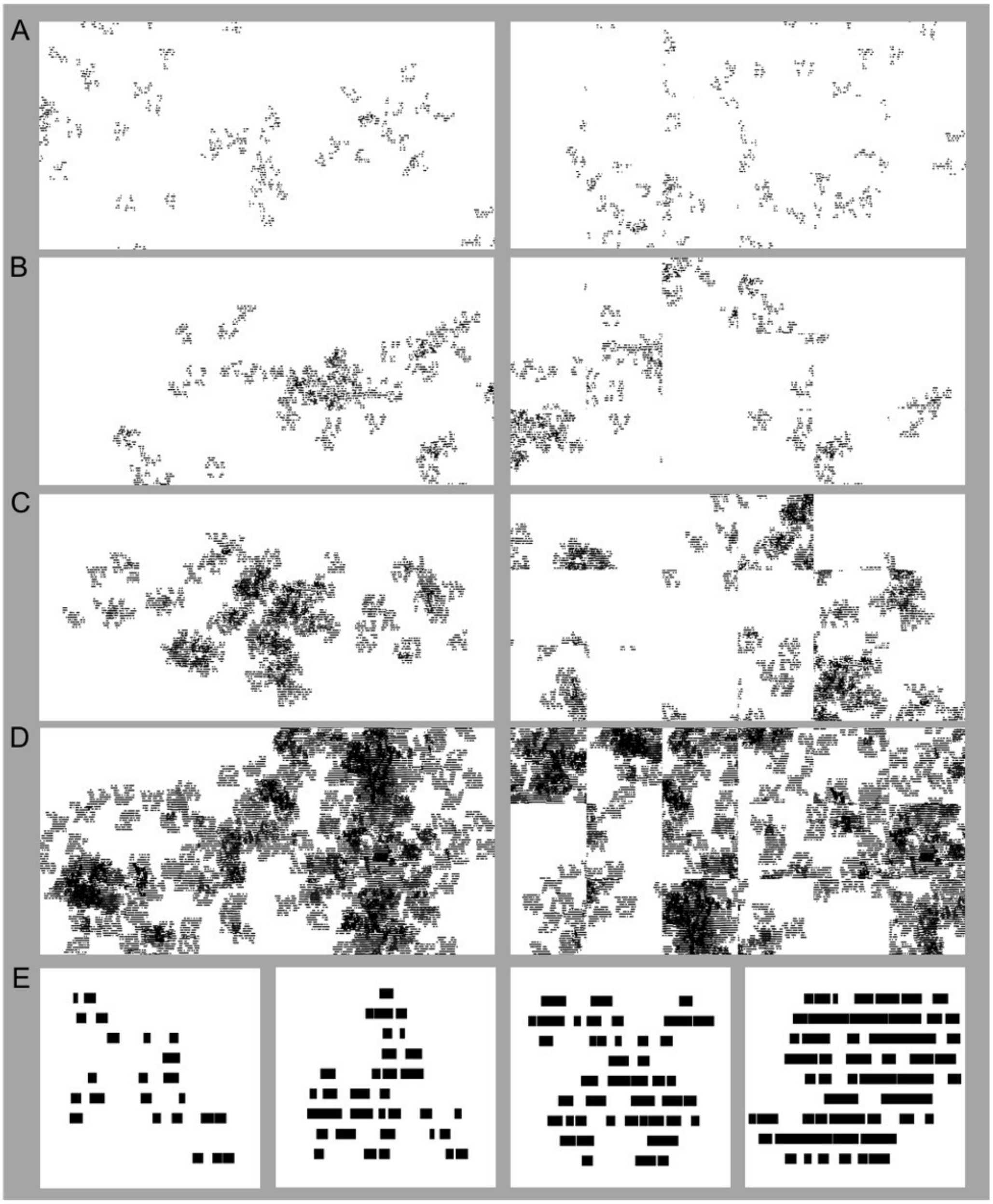

Figure 3.5. Example stimuli used in the experiments. Fractal ‘forest’ stimuli used in Experiment 1 of differing *D*-values where $D = 1.2$ **(A)**, 1.4 **(B)**, 1.6 **(C)**, and 1.8 **(D)**. On the left side of each panel **(A-D)** are images of the original forest pattern. On the right stimuli used in Experiment 1 of differing *D*-values where $D = 1.2$ **(A)**, 1.4 **(B)**, 1.6 **(C)**, and 1.8 **(D)**. On the right side of **(A-D)** are images of randomized versions of the original forest patterns, where the same forest has been divided into tiles and the tiles randomized. Fractal ‘tree’ stimuli used in Experiment 2 **(E)** of *D*-values 1.2, 1.4, 1.6, and 1.8 from the left to the right side of the panel.

Participants

To address how the addition of global fractal order may impact the perceptual judgments of fractal patterns, 78 participants comprised of undergraduate Psychology students from the University of Oregon were recruited for the current study through the SONA participant pool system (66 females, age ranging between 18 and 30 years old, mean age 20 years old). Informed consent was acquired following a protocol approved by the Institutional Review Board at the University of Oregon and all participants received class credit for their participation.

Visual Displays

This study was generated in PsychoPy3 (Peirce et al., 2019) and used the online research study platform of Pavlovia and was completed on participants' personal computers with program stimuli scaled to the individual computer's respective full- screen dimensions.

Design and procedure

Participants viewed the "global forest" fractal patterns presented in five randomized blocks, with each block consisting of a singular judgment type (complexity, engaging, preference, refreshing, or relaxing). Each block's stimulus set consisted of 5 unique patterns ranging across 4 levels of complexity or *D*-value (1.2, 1.4, 1.6, and 1.8) and varying in arrangement (non-randomized or randomized) giving rise to 40 trials per block and 200 total stimulus-related trials across the experiment. A slider response task was used to self-report ratings for each fractal pattern. Before each block, participants were instructed to make a single randomly ordered judgment (complexity, preference, engaging, refreshing, or relaxing) for each stimulus presented in that block. Specifically, they were asked to answer one of 5 questions for each block: "How _______ is the image?" with one of 5 different words placed in the blank (complex, engaging, preferable, refreshing, relaxing). They were told to indicate their rating of each given pattern on a slider ranging between 0 and 1 located below the image, with the "0" end of the slider indicating "not at all" and the "1" end of the slider indicating "completely." They were asked to use the full range of the slider and to click on the slider to indicate their rating. Periodically, an attention check trial appeared in which participants were instructed to select either "0" or "1." The images remained on the screen until participants selected their rating. Upon completion of the experiment, participants completed a demographic questionnaire and were debriefed according to the protocol approved by the Institutional Review Board at the University of Oregon.

Results

Data from 78 adult participants (between 18 and 33 years old) were retained from the 130 adults who participated in the experiment. Data were excluded due to: (a) failure to complete the study (6 participants), (b) failure of greater than 3 attention checks (24 participants), or (c) recording the same rating for greater than four consecutive trials. If the same rating was recorded for more than 4 consecutive trials, the entire block of ratings was excluded. Furthermore, if all blocks for a given judgment type were removed, then the participant was excluded (22 participants).

Fractal judgment task

A 3-way repeated measures 4 × 5 × 2 ANOVA [*D*-value (1.2, 1.4, 1.6, and 1.8) × Judgment (complexity, engaging, preference, refreshing, and relaxing) × Arrangement (randomized, non- randomized)] was performed using IBM SPSS Statistics for Macintosh (Version 25.0) on rating data for the fractal patterns (recorded as the location selected on a rating response slider), with *D*-value, Judgment, and Arrangement as within-subjects variables Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [$\chi^2(5) = 160.41$,

$p < 0.001$**], the interaction between D-value and Arrangement [$\chi^2(5) = 37.92$, $p < 0.001$* *], D-value and Judgment [χ^2 $(77) = 510.44$, $p < 0.001$* *], as well as the three-way interaction between D-value, Arrangement, and Judgment [$\chi^2(77) = 134.45$, $p < 0.001$* *]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.408$, 0.679, 0.365, and 0.672, respectively). Indicated with a double asterisk for significance of $p <$ 0.001 and single asterisk for significance of $p < 0.05$, a significant main effect of D-value [$F(1.22, 61.2) = 23.84$, $p < 0.001$**, 95% CI [0.15, 0.23], $\eta p^2 = 0.32$] and Arrangement emerged [$F(1, 50) = 19.67$, $p < 0.001$* * , 95% CI [0.09, 0.45], $\eta p\ ^2 = 0.28$]. Additional significant interactions were detected between D-value and Judgment [$F(4.38, 219.07) = 55.42$, $p < 0.001$** , 95% CI [0.43, 0.59], $\eta p^2 = 0.53$], D-value and Arrangement [$F(2.04, 101.86) = 11.37$, $p <$ 0.001* * , 95% CI [0.06, 0.31], $\eta p\ ^2 = 0.19$], Arrangement and Judgment [$F(3.47,173.45) = 2.15$, $p = 0.04$*, 95% CI [0.0, 0.1], $\eta p^2 = 0.09$], as well as D-value, Arrangement, and Judgment [$F(8.06, 403.14) = 1.86$, $p = 0.02$*, 95% CI [0.0, 0.06], $\eta p^2 = 0.33$]. For illustrative purposes we plot the 3 significant interactions (Figure 3.6). For the D-value and Judgment interaction, some judgments had ratings that increased in value with D (complexity, engagement, and preference), while others were relatively flat (refreshing) or decreased (relaxing) (Figure 3.6A). For the D-value and Arrangement interaction, ratings were slightly higher for non-randomized fractal patterns with mid-range D-values (Figure 3.6B). Finally, for the Judgment and Arrangement interaction, the amount of difference between the non-randomized and randomized versions of the patterns varied across judgment type (Figure 3.6C). The 3-way interaction indicates that the Dimension by Arrangement interaction varies across Judgment-type. This can be seen more clearly in Figure 3.7. Below we present a series of planned analyses exploring the interaction

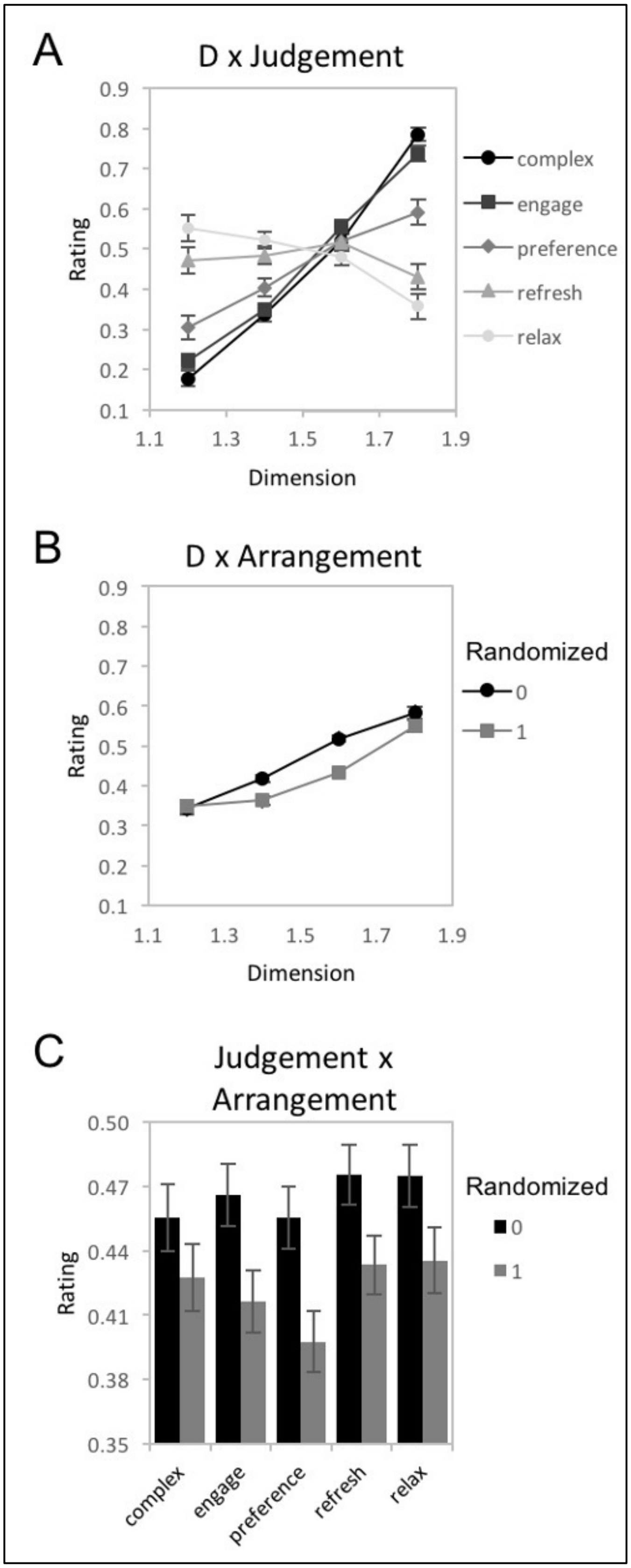

Figure 3.6. Experiment 1A results for "global forest" fractal patterns using a unipolar rating scale. Results show significant 2-way interactions among the experiment's 3 factors: fractal dimension (*D*), stimulus pattern arrangement ("0" for non-randomized and "1" for randomized), and judgment type (complex, engaging, preferred, refreshing, and relaxing). Participant rating (on a scale from 0 to 1) is plotted as a function of **(A)** *D*-value and different judgment conditions, **(B)** *D*-value and different pattern arrangements, and **(C)** judgment and randomization conditions (error bars represent standard error).

between D-value and pattern Arrangement for different Judgment types in more detail using ANOVAs, paired t-tests (Table 3.1), and a 2-step cluster analysis to determine if subgroups could better explain perceptual trends.

Complexity

A 2-way 4 × 2 repeated-measures ANOVA [D-value (1.2, 1.4, 1.6, and 1.8) × Arrangement (randomized, non-randomized)] was completed to examine the impact of D-value and Arrangement on pattern complexity judgments (Figure 3.7A). Assumptions of the violation of sphericity were indicated by Mauchly's test for D-value [χ^2 (5) = 123.06, $p < 0.001$* *] and the interaction between D-value and Arrangement [χ^2 (5) = 15.66, $p = 0.01$*], thus degrees of freedom were corrected using Greenhouse- Geisser estimates of sphericity ($\varepsilon = 0.512$ and 0.87, respectively). A significant main effect of D-value [$F(1.54, 118.21) = 343.44$, $p < 0.001$* * , 95% CI [0.76, 0.85], $\eta p^2 = 0.82$], Arrangement [$F(1,77) = 10.63$, $p = 0.002$*, 95% CI [0.02, 0.26], $\eta p^2 = 0.12$], and interaction between D-value and pattern arrangement [$F(2.6,200.94) = 2.99$, $p =$ 0.04*, 95% CI [0.0, 0.07], $\eta p^2 = 0.04$] were identified. Average complexity ratings (collapsed over pattern arrangement type) ranged from a low of 0.18 ($SD = 0.18$) for D=1.2 to a high of 0.77(SD=0.15) for D=1.8, indicating that participants perceived greater complexity for patterns with higher D-values. Paired samples t-tests revealed significant differences in perceived complexity between all pairs of D-values (Table 3.1). When comparing non-random and random pattern arrangements, significant differences exist for the mid-range D-values: $D = 1.4$ [$t(77) =$ 3.79, $p < 0.001$**, 95% CI [0.02, 0.08], $d = 0.32$] and $D = 1.6$ [$t(77) = 2.31$, $p =$ 02*, 95% CI [0.01, 0.07], $d = 0.28$]. The interaction between D-value and Arrangement indicates that the ratings differed across arrangement type depending on D-value, with slightly higher ratings for non-randomized compared to randomized fractal patterns with mid-range D-values.

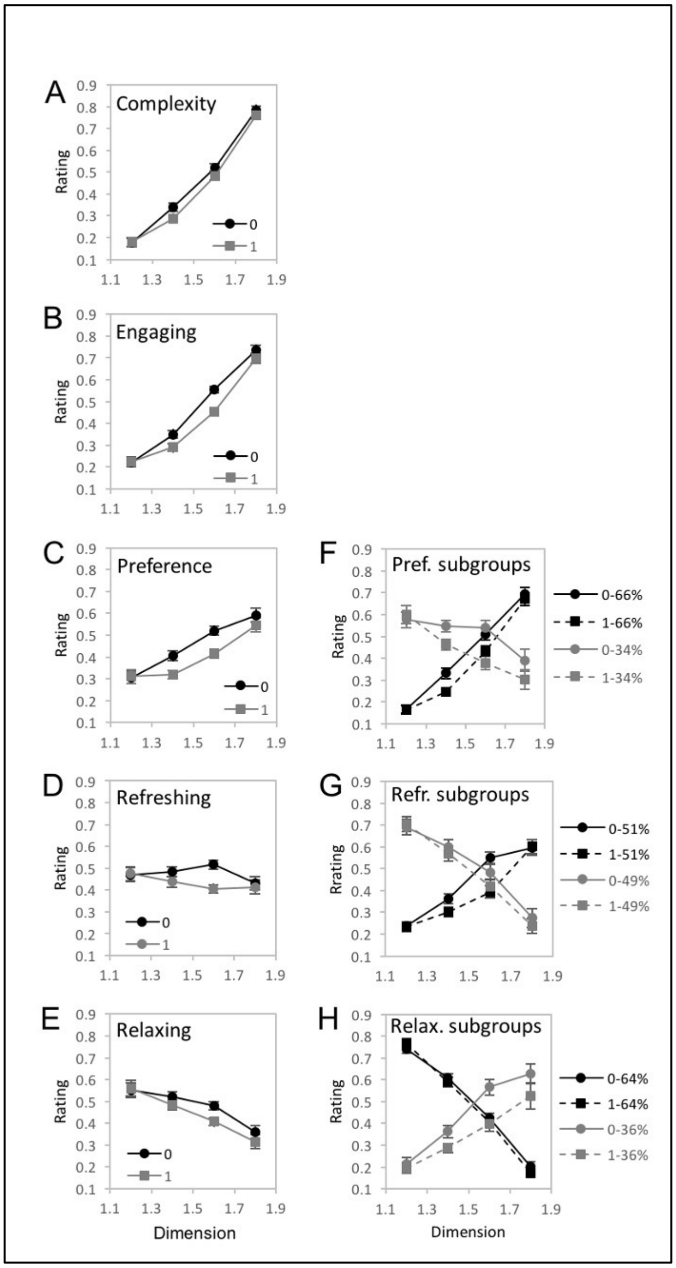

Figure 3.7. Experiment 1A results for "global forest" fractal patterns for 5 different judgment conditions (how complex, engaging, preferred, refreshing, and relaxing). **(A–E)** shows plots of mean ratings as a function of fractal dimension (*D*) and 2 pattern arrangements (not randomized "0," randomized "1") for the different judgment conditions (error bars represent standard error). **(F–H)** shows plots of mean ratings as a function of fractal dimension (*D*) and 2 pattern arrangements (not randomized "0," randomized "1") for each subpopulation identified with cluster analysis (error bars represent standard error).

To determine whether the observed trends could be due to a combination of responses from subgroups of participants, we performed a two-step cluster analysis similar to that used by Bies et al. (2016) and described in more detail in Noru˘sis (2012). We performed a hierarchical cluster analysis using Ward's method to separate individuals into groups using their complexity ratings for each level of *D*. Since the resultant agglomeration matrix did not indicate a multiple cluster solution, we did not follow up with a *k*-means clustering analysis.

Engaging

A 2-way 4 × 2 repeated-measures ANOVA [*D*-value (1.2, 1.4, 1.6, and 1.8) × Arrangement (randomized, non-randomized)] was completed to examine the impact of *D*-value and Arrangement on pattern engagement (Figure 3.7B). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [χ^2 (5) = 114.57, $p < 0.001$* *], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.521). A significant main effect of *D*-value [$F(1.56, 114.01) = 194.5$, $p < 0.001$* * , 95% *CI* [0.63, 0.78], $\eta p^2 = 0.73$], Arrangement [$F(1,73) = 19.69$, $p < 0.001$**, 95% *CI* [0.07, 0.36], ηp^2 = 0.21], and significant interaction between *D*-value and Arrangement [$F(2.71,198.09) = 9.58$, p = 0.04*, 95% *CI* [04, 0.19], $\eta p^2 = 0.12$] were identified. Collapsed over pattern arrangement, the mean engagement ratings ranged from a low of 0.22 (*SD*=0.17) for *D*=1.2 to a high of 0.72 (*SD*=0.19) for *D*=1.8, suggesting that participants were more engaged when viewing the higher *D*-value patterns. Paired samples *t*-tests revealed significant differences in perceived engagement for all pairs of *D*-values (Table 3.1). Comparing the non-random and random arrangements for different *D*-values, significant differences exist for the mid-range *D*-values: *D* = 1.4 [$t(73) = -4.12$, $p < 0.001$**, 95% *CI* [−0.09, −0.04], $d = 0.44$] and *D* = 1.6 [$t(73) = -4.95$, $p < 0.001$**, 95% *CI* [−0.14, −0.06], $d = 0.73$]. Again, the interaction between *D*-value and Arrangement indicates that the ratings differed across arrangement type depending on *D*-value, with slightly higher ratings for non-randomized compared to randomized fractal patterns with mid-range *D*-values. A cluster analyses did not indicate a multiple cluster solution.

Table 3.1: Experiment 1A- Paired Samples t-Tests across D-value and Judgement

	Complex	Engaging	Preference	Refreshing	Relaxing
D=1.2 vs D=1.4	t=-14.31** (d=.76)	t=-8.19** (d=.66)	t=-3.31* (d=.23)	t=.71 (d=.37)	t=3.57** (d=.24)
D=1.2 vs D=1.6	t=-23.26** (d=2.17)	t=-15.79* (d=1.7)	t=-6.12** (d=.75)	t=.42 (d=.05)	t=3.88** (d=.51)
D=1.2 vs D=1.8	t=-28.47** (d=3.56)	t=-20.56** (d=2.77)	t=-6.86** (d=1.02)	t=1.24 (d=.19)	t=5.16** (d=.79)
D=1.4 vs D=1.6	t=-16.51** (d=1.23)	t=-14.68** (d=1.2)	t=-6.04** (d=.63)	t=.01 (d=.0)	t=3.17* (d=.34)
D=1.4 vs D=1.8	t=-24.42** (d=2.97)	t=-20.5** (d=2.4)	t=-6.76** (d=1.2)	t=1.25 (d=.17)	t=5.07** (d=.69)
D=1.6 vs D=1.8	t=-18.38** (d=1.8)	t=-13.98** (d=1.25)	t=--5.03** (d=.59)	t=1.91 (d=.17)	t=5.48** (d=.45)

** indicates significance of p < 0.05*
*** indicates significance of p < 0.001*

Preference

A 2-way 4 × 2 repeated-measures ANOVA [*D*-value (1.2, 1.4, 1.6, and 1.8) × Arrangement (randomized, non-randomized)] was completed to examine the impact of *D*-value and Arrangement on pattern preference (Figure 3.7C). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [χ^2 (5) = 159.69, $p < 0.001$**] and the interaction between *D*- value and Arrangement [χ^2 (5) = 23.54, $p < 0.001$**], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.445 and 0.795, respectively). A significant main effect of *D*-value [$F(1.33,89.38) = 23.27$, $p < 0.001$**, 95% *CI* [0.11, 0.39], $\eta p^2 = 0.26$], Arrangement [$F(1,67) = 18$, $p < 0.001$**, 95% *CI* [0.06, 0.37], $\eta p^2 = 0.21$], and interaction between *D*-value and Arrangement were identified [$F(2.39,159.84) = 6.25$, $p = 0.001$*, 95% *CI* [0.01, 0.17], $\eta p^2 = 0.09$]. Collapsed over pattern arrangement, average ratings of preference ranged from a low of 0.31(*SD*=0.25) for *D*=1.2 to a high of 0.57(*SD*=0.26) for $D = 1.8$, indicating that participants' preference for global forest fractals increases with pattern complexity. Paired samples *t*-tests revealed significant differences in preference for all pairs of *D*-values (Table 3.1). Comparing non-random and random arrangements, significant differences exist for the mid-range *D*-values: $D = 1.4$ [$t(67) = 5.40$, $p < 0.001$**, 95% *CI* [0.05, 0.11], $d = 0.47$] and $D = 1.6$ [$t(67) = 4.45$, $p < 0.001$**, 95% *CI* [0.06, 0.15], $d = 0.65$].

A 2-step cluster analysis identified and separated individuals into 2 subgroups (Figure 3.7F). We investigated whether there was an interaction between cluster-membership, *D*-value, and arrangement by performing a mixed ANOVA with 4 levels of *D*, 2 levels of arrangement, and 2 groups. Mauchly's test indicated a violation of the assumptions of sphericity for *D*-value [χ^2 (5) = 58.05, $p < 0.001$* *] and the interaction between *D*-value and arrangement [χ^2 (5) = 21.95 $p = 0.001$*]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.676$ and 0.805, respectively). A significant main effect of *D*-value [$F(2.03,133.78) = 16.01$, $p < 0.001$**, 95% *CI* [0.08, 0.3], $\eta p^2 = 0.2$] and Arrangement emerged in the analysis [$F(1,66) = 18.88$, $p < 0.001$**, 95% *CI* [0.07, 0.38], $\eta p^2 = 0.22$], as well as a significant interaction between *D*-value and Cluster groups [$F(2.03,133.78) = 105.22$, $p < 0.001$**, 95% *CI* [0.51, 0.68], $\eta p^2 = 0.62$] as well as *D*-value and Arrangement [$F(2.41,159.32) = 7.12$, $p < 0.001$**, 95% *CI* [0.02, 0.18], $\eta p^2 = 1.0$]. The first cluster accounts for 66% of the sample and is most reflective of the overall perceptual trend with preference ratings increasing with higher *D*-value. The second cluster includes the remaining 34% of the sample and demonstrates an opposing trend with preference peaking with lower *D*-value and decreasing with added complexity. Although, on average, preference is highest for $D = 1.8$ (Figure 3.7C), the subgroup analysis shows that the D-value with the greatest agreement in preference amongst individuals in the different subgroups is $D = 1.6$ (Figure 3.7F).

Refreshing

A 2-way 4 × 2 repeated-measures ANOVA [D-value (1.2, 1.4, 1.6, and 1.8) × Arrangement (randomized, non-randomized)] was completed to examine the impact of D-value and Arrangement on perceived pattern refreshment (Figure 3.7D). A violation of the assumption of sphericity was indicated by Mauchly's test for D-value [χ^2 (5) = 213.96, $p < 0.001$* *], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.399$). Both the main effect of pattern Arrangement [$F(1,71) = 11.66$, $p = 0.001$*, 95% *CI* [0.02, 0.29], $\eta p^2 = 0.14$] and interaction between D-value and Arrangement were significant [$F(2.72,193.37) = 7.95$, $p < 0.001$**, 95% *CI* [0.03, 0.18], $\eta p^2 = 0.1$], but not D-value itself [$F(1.2,84.89) = 0.77$, $p = 0.41$, 95% *CI* [0.0, 0.09] $\eta p^2 = 0.01$]. Between non-random and random arrangements, significant differences exist for the mid- range D-values: $D = 1.4$ [$t(71) = 2.79$, $p = 0.01$*, 95% *CI* [0.01, 0.08], $d = 0.2$] and $D = 1.6$ [$t(71) = 4.54$, $p < 0.001$**, 95% *CI* [0.06, 0.16], $d = 0.67$].

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern refreshment (Figure 3.7G). We investigated whether there was an interaction between cluster-membership, D-value, and arrangement by performing a mixed ANOVA with 4 levels of D, 2 levels of arrangement, and 2 groups. Mauchly's test indicated a violation of the assumptions of sphericity for D-value [$\chi^2(5) = 73.86$, $p < 0.001$* *] and interaction between D-value and Arrangement [χ^2 (5) = 11.49, $p = 0.04$*]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.580$ and 0.893, respectively). Whereas the main effect of D-value was not significant [$F(1.74,121.72) = 1.49$, p

= 0.23, 95% *CI* [0.0, 0.09], $\eta p^2 = 0.02$], a significant main effect of Arrangement emerged in the analysis [$F(1,70) = 11.85$, $p = 0.001$*, 95% *CI* [0.03, 0.29], $\eta p^2 = 0.15$], as well as a significant interaction between *D*-value and Cluster membership [$F(1.74,121.72) = 143.09$, $p < 0.001$**, 95% *CI* [0.57, 0.73], $\eta p^2 = 0.67$] and between *D*-value and Arrangement [$F(2.68,187.57) = 8.32$, $p < 0.001$**, 95% *CI* [0.03, 0.18], $\eta p^2 = 0.11$]. The first cluster encompassed 51% of participants and produces a trend that increases with *D*-value. The second cluster contains the remaining 49% of participants and, in a steeper fashion, decreases with additional *D*-value. Although these represent opposing trends in judgments of refreshment, the *D*-value with the greatest agreement in refreshment ratings amongst individuals across subgroups is $D = 1.6$ (Figure 3.7G).

Relaxing

A 2-way 4 × 2 repeated-measures ANOVA [*D*-value (1.2, 1.4, 1.6, and 1.8) × Arrangement (randomized, non-randomized)] was completed to examine the impact of *D*-value and Arrangement on perceptions of pattern relaxation (Figure 3.7E). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [χ^2 (5) = 239.32 $p <$ 0.001* *], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.388$). A significant main effect of *D*-value [$F(1.16,79.11) = 11.9$, $p < 0.001$**, 95% CI [0.03, 0.29], $\eta p^2 = 0.15$] and Arrangement [$F(1,68) = 8.19$, $p = 0.01$*, 95% CI [0.01, 0.25], $\eta p^2 = 0.11$], and interaction between *D*-value and pattern arrangement were identified [$F(2.74,186.02) = 4.7$, $p = 0.01$* 95% CI [0.01, 0.13], $\eta p^2 = 0.01$]. Collapsed over pattern arrangement, average ratings of pattern relaxation ranged from a low of 0.34 (SD = 0.27) for D = 1.8 to a high of 0.56 (SD = 0.29) for D = 1.2, suggesting that participants perceived patterns as less relaxing with increasing *D*-value. Paired samples *t*-tests revealed significant differences in perceived relaxation between *D*-values (see Table 3.1). Comparing non-random and random arrangements, significant differences exist for the mid- to high- D patterns: D = 1.4 [$t(68) = 2.22$, $p < 0.001$**, 95% CI [0.0, 0.07], $d = 0.21$], $D = 1.6$ [$t(68) = 3.15$, $p = 002$*, 95% CI [0.03, 0.12], $d = 0.5$], and $D = 1.8$ [$t(68) = 2.18$, $p = 0.03$*, 95% CI [0.0, 0.1], $d = 0.22$].

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern relaxation. Mauchly's test indicated a violation of the assumptions of sphericity for *D*-value [$\chi^2(5) = 93.78$, $p < 0.001$**]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.554$). A significant main effect of *D*-value [$F(1.66,111.27) = 7.28$, $p = 0.002$*, 95% *CI* [0.01, 0.2], $\eta p^2 = 0.1$] and Arrangement [$F(1,67) = 13.86$, $p < 0.001$**, 95% *CI* [0.04, 0.33], $\eta p^2 = 0.17$] were identified, as well as significant interactions between *D*-value and Clusters [$F(1.66,111.27) = 168.83$, $p < 0.001$**, 95% *CI* [0.62, 0.77], $\eta p^2 = 0.72$], Arrangement and Cluster membership [$F(1,67) = 8.81$, $p = 0.004$*, 95% *CI* [0.01, 0.26], $\eta p^2 = 0.12$], and *D*-value and Arrangement [$F(2.72,181.88) = 5.79$, $p = 0.001$*, 95% *CI* [0.01, 0.15], $\eta p^2 = 0.08$]. The first cluster encompassed 64% of participants and produces a trend in which ratings of pattern relaxation steeply decrease with higher *D*-values. Conversely, the second cluster contains the remaining 36% of participants and increases with additional *D*-value. Similar to subgroup behavior for preference and refreshment ratings which also showed opposing trends in judgments, the *D*-value with the greatest agreement in relaxation ratings amongst individuals across subgroups is $D = 1.6$ (Figure 3.7H).

Discussion

Experiment 1A explored broad psychological effects of fractal patterns used in installations of multiple mediums including carpets, wall patterns, and screensavers. Overall, we find that perceptions of fractal pattern complexity, engagement, and preference, increase with greater *D*-value, perception of pattern refreshment is unchanging across *D*-value, and perception of relaxation decreases with *D*-value. For some judgments, the observed overall trends can be explained by the subgroup patterns of responses. We found 2 subgroups for preference, refreshment, and relaxation judgments with opposing trends. The overall trend for preference was positive, with increasing rating values with increasing *D*-value, because the largest subgroup trend was positive; the trend for refreshing was flat because the 2 subgroups were equivalent in size; and, finally, the overall trend for relaxation was negative (decreasing with *D*-value) because the largest subgroup trend was negative. Interestingly, the *D*-value with the greatest agreement amongst individuals for the preference, refreshing, and relaxing judgments was $D = 1.6$.

Experiment 1B-Perception of Fractal "Global Forest" Patterns With Bipolar Ratings

Materials and Methods

Stimuli

The current experiment used the same stimuli as described in Experiment 1A.

Participants

81 participants (69 females), comprised of undergraduate Psychology students from the UNSW Sydney volunteered to participate in the current study through the SONA participant pool system in exchange for course credit. The mean age of participants was 20.42 years (ranging between 18 and 47 years). All study protocols, including obtaining Informed Consent were approved by the UNSW Human Research Advisory Panel (Reference ID: HREAP-C 2349).

Visual displays

The study was generated with Inquisit (by Milliseconds) software and run via the Inquisit Web Platform. The participants completed the study on their personal computers with program stimuli scaled to the individual computer's respective full- screen dimensions.

Design and procedure

Like in the Experiment 1A, participants viewed the "global forest" fractal patterns presented in separate randomized blocks, with each block consisting of a singular judgment type (complexity, engaging, preference, refreshing, or relaxing). Each block's stimulus set consisted of 4 unique patterns ranging across eight levels of complexity or *D*-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) and varying in arrangement (non-randomized or randomized) giving rise to 64 trials per block and 320 total stimulus-related trials across the experiment. Instead of a slider-type response, we used five, Lickert-type, bipolar scales with values ranging from 1 to 7. The scales used were simple-complex; dislike (1) -like (7); indifferent (1) – engaged (7); relaxed (1) – tense (7); tired (1) – refreshed (7). [BS1] Participants indicated their response by pressing a number corresponding to their evaluation of a given pattern. Before each block, participants were introduced to a scale that will be used in that block, with the scale remaining visible on all trials. Upon completion of the experiment, participants completed a demographic questionnaire and were debriefed according to the protocol approved by the UNSW Human Research Ethics Advisory Panel C.

Results

Data from 75 adult participants were analyzed with 6 participants excluded due to a failure to complete the study (4 participants), or technical error with data recording (2 participants).

Fractal judgment task

A 3-way 8 × 5 × 2 repeated-measures ANOVA [*D*-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) × Judgment (complexity, engaging, liking, refreshing, and tense) × Arrangement (randomized vs. non-randomized)] was performed using IBM SPSS Statistics for Macintosh (Version 25.0) on rating data for the fractal patterns (recorded as location selected on a rating response slider). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [$\chi^2(27) = 638.83$, $p < 0.001$**], Judgment [$\chi^2(9) = 39.25$, $p < 0.001$**], the interaction between *D*-value and Arrangement [$\chi^2(27) = 63.65$, $p < 0.001$**], *D*-value and Judgment [$\chi^2(405) = 2571.82$, $p < 0.001$**], Judgment and Arrangement [$\chi^2(9) = 64.32$, $p < 0.001$**], as well as the three- way interaction between *D*-value, Arrangement, and Judgment [$\chi^2(405) = 647.13$, $p < 0.001$**]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.205, 0.789, 0.749, 0.121, 0.692, and 0.542, respectively). Indicated with a double asterisk for significance of $p < 0.001$ and single asterisk for statistical significance of $p < 0.05$, a significant main effect of *D*-value [$F(1.44,106.27) = 153.44$, $p < 0.001$**, 95% *CI* [0.57, 0.74], $\eta p^2 = 0.68$] and Arrangement emerged [$F(1,74) = 31.44$, $p < 0.001$**, 95% *CI* [0.3, 0.44], $\eta p^2 = 0.3$]. Additional significant interactions were found between *D*-value and Judgment [$F(3.38,249.96) = 32.35$, $p < 0.001$**, 95% *CI* [0.21, 0.38], $\eta p^2 = 0.3$], *D*-value and Arrangement [$F(5.25, 388.12) = 4.95$, $p < 0.001$**, 95% *CI* [0.02, 0.10], $\eta p^2 = 0.06$], Arrangement and Judgment [$F(2.78,204.98) = 9.59$, $p < 0.001$**, 95% *CI* [0.04, 0.09], $\eta p^2 = 0.12$], as well as *D*-value, Arrangement, and Judgment [$F(15.18,1123.58) = 2.75$, $p < 0.001$**, 95% *CI* [0.01, 0.05], $\eta p^2 = 0.04$]. For illustrative purposes we plot the 3 significant interactions (Figure 3.8). For the *D*-value and Judgment interaction, most judgments had ratings that increased in value with D (complexity, engagement, like, and tense), while one was relatively flat (refreshing) (Figure 3.8A). For the D-value and Arrangement interaction, ratings were increasingly higher for non-randomized compared to randomized fractal patterns as D-values increased (Figure 3.8B). Finally, for the Judgment and Arrangement interaction, the amount of difference between the non-randomized and randomized versions of the patterns varied across judgment type (Figure 3.8C). The 3-way interaction indicates that the Dimension by Arrangement interaction varies across Judgment-type. This can be seen more clearly in Figure 3.9. Similar to the previous studies, a series of planned comparisons explored the locus of the significant interaction between D-value and Judgment through ANOVAs, paired t-tests (Table 3.2), and a 2-step cluster analyses to determine if subgroups of participant responses could better explain perceptual trend data.

Simple-complex

A 2-way 8 × 2 repeated-measures ANOVA [D-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) × Arrangement (randomized vs. non- randomized)] was completed to examine the impact of D-value and Arrangement on pattern complexity judgments (Figure 3.9A). Assumptions of the violation of sphericity were indicated by Mauchly's test for D-value [χ^2 (27) = 521.02, $p < .001$ **] and interaction between D-value and Arrangement [$\chi^2(27) = 76.63$, $p < 0.001$**], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.232$ and 0.764, respectively). A significant main effect of D-value was identified [$F(1.62,119.95) = 204.35$, $p < 0.001$**, 95% CI [0.65, 0.79], $\eta p^2 = 0.73$], however, no significant effect of Arrangement [$F(1,74) = 0.89$, $p = 0.35$, 95% CI [0, 0.1], $\eta p^2 = 0.01$], nor interaction between D-value and pattern arrangement [$F(5.35,395.78) = 0.79$, $p = 0.56$, 95% CI [0, 0.02], $\eta p^2 = 0.01$]

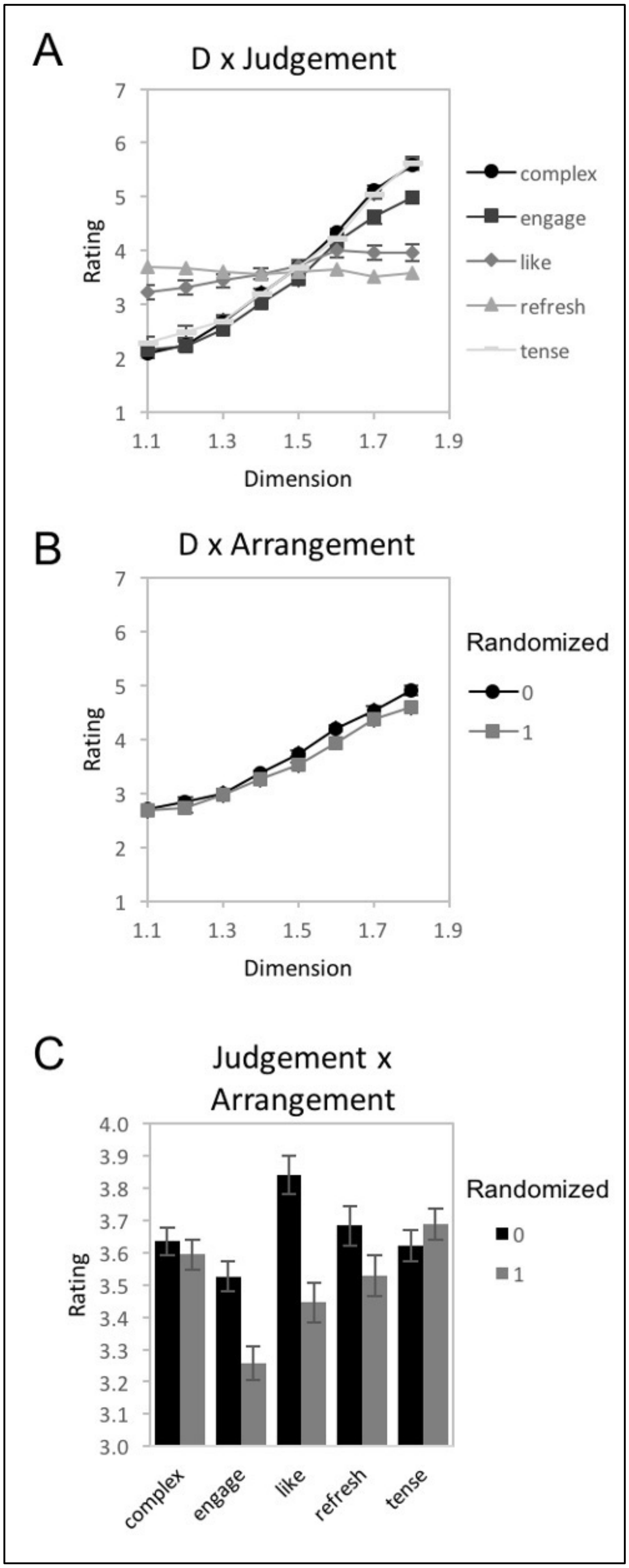

Figure 3.8. Experiment 1B. Results for "global forest" fractal patterns using a bipolar rating scale. Results show significant 2-way interactions among the experiment's 3 factors: fractal dimension (*D*), stimulus pattern arrangement ("0" for non-randomized and "1" for randomized), and judgment type (complex, engaging, liking, refreshing, and tense). Participant rating (on a scale from 1 to 10) is plotted as a function of **(A)** *D*-value and different judgment conditions, **(B)** *D*-value and different pattern arrangements, and **(C)** judgment and randomization conditions (error bars represent standard error).

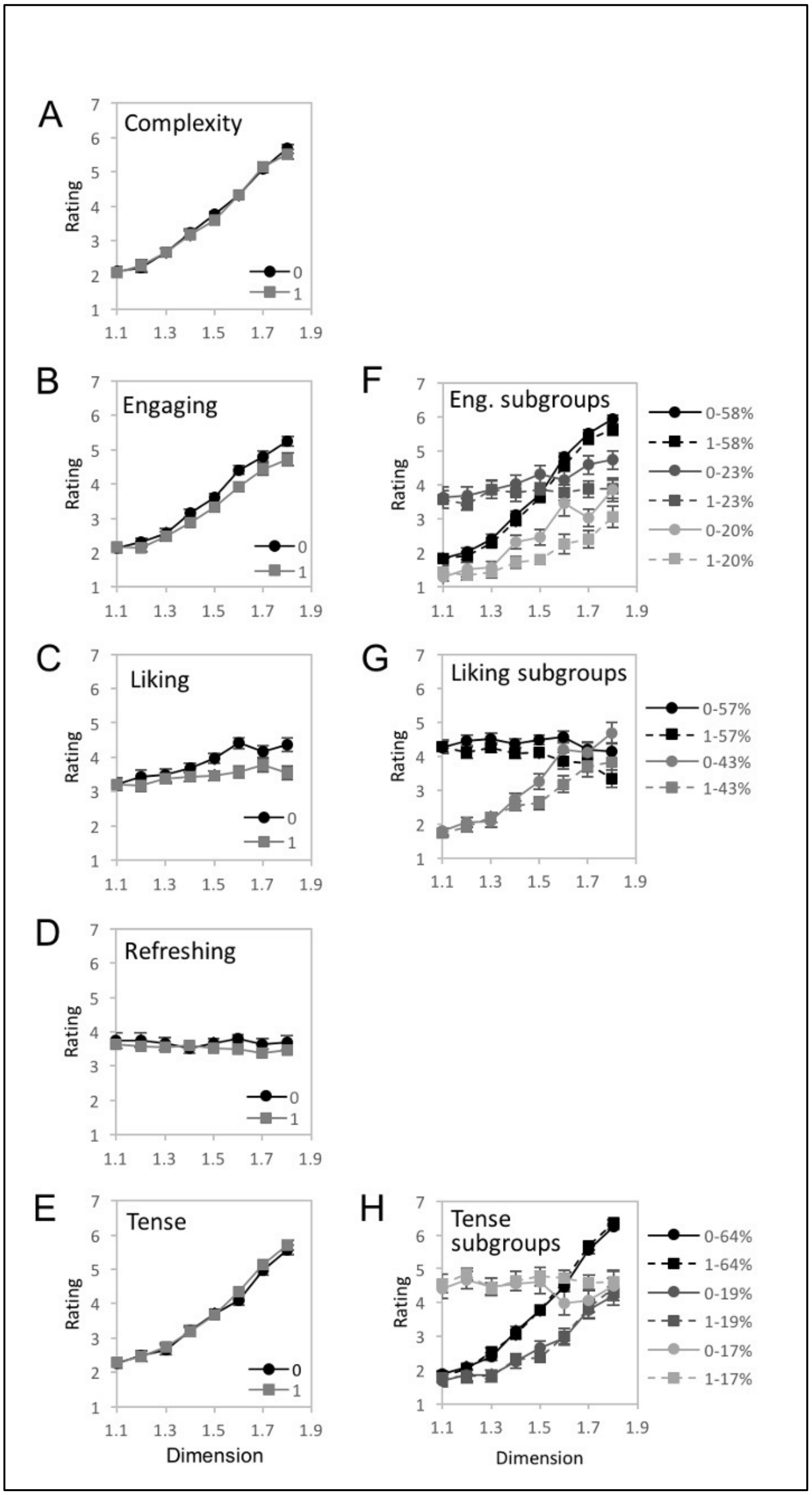

Figure 3.9. Experiment 1B results for "global forest" fractal patterns for 5 different judgment conditions (complex, engaging, liking, refreshing, and tense). **(A–E)** shows plots of mean ratings as a function of fractal dimension (*D*) and 2 pattern arrangements (not randomized "0," randomized "1") for the different judgment conditions (error bars represent standard error). **(F–H)** shows plots of mean ratings as a function of fractal dimension (*D*) and 2 pattern arrangements (not randomized "0," randomized "1") for each subpopulation identified with cluster analysis (error bars represent standard error).

Table 3.2: Experiment 1B- Paired Samples t-Tests across D-value and Judgement

	Simple-Complex	Indifferent-Engaging	Dislike-Like	Tired-Refreshing	Relaxing-Tense
D=1.1 vs D=1.2	t=-3.43* (d=1.3)	t=-1.93** (d=.93)	t=-1.35 (d=.17)	t=.39 (d=.01)	t=-3.95** (d=.15)
D=1.1 vs D=1.3	t=-10.05** (d=.51)	t=-16.01** (d=.32)	t=-3.03* (d=1.42)	t=.99 (d=.04)	t=-6.63** (d=.34)
D=1.1 vs D=1.4	t=-14.18** (d=1.02)	t=-10.61** (d=.8)	t=-3.51* (d=.25)	t=1.10 (d=.08)	t=-11.23** (d=.78)
D=1.1 vs D=1.5	t=-18.17** (d=1.51)	t=-13.01** (d=1.1)	t=-4.32** (d=.36)	t=.58 (d=.06)	t=-12.84** (d=1.18)
D=1.1 vs D=1.6	t=-19.81** (d=2.09)	t=-14.87** (d=1.7)	t=-4.82** (d=.52)	t=.19 (d=.08)	t=-14.55** (d=1.61)
D=1.1 vs D=1.7	t=-21.02** (d=2.61)	t=-16.62** (d=1.9)	t=-4.05** (d=.47)	t=.72 (d=.10)	t=-17.25** (d=2.25)
D=1.1 vs D=1.8	t=-24.54** (d=3.03)	t=-17.54** (d=2.14)	t=-3.48** (d=.44)	t=.38 (d=.06)	t=-18.89** (d=2.61)
D=1.2 vs D=1.3	t=-6.51** (d=.35)	t=-4.72** (d=1.15)	t=-1.71 (d=.08)	t=.78 (d=.03)	t=-3.52* (d=.17)
D=1.2 vs D=1.4	t=-11.02** (d=.83)	t=-11.13** (d=1.71)	t=-2.75* (d=.18)	t=1.04 (d=.06)	t=-9.41** (d=.61)
D=1.2 vs D=1.5	t=-15.53** (d=1.28)	t=-13.45** (d=2.06)	t=-3.69** (d=.3)	t=.46 (d=.04)	t=-12.04** (d=1.0)
D=1.2 vs D=1.6	t=-16.89** (d=1.83)	t=-15.58** (d=2.55)	t=-4.51** (d=.47)	t=.08 (d=.01)	t=-13.53** (d=1.43)
D=1.2 vs D=1.7	t=-18.69** (d=2.36)	t=-17.18** (d=1.68)	t=-3.65** (d=.42)	t=.67 (d=.09)	t=-16.21** (d=2.07)
D=1.2 vs D=1.8	t=-21.79** (d=2.75)	t=-18.29** (d=2.9)	t=--3.19* (d=.39)	t=.31 (d=.04)	t=-18.15** (d=2.43)
D=1.3 vs D=1.4	t=-7.79** (d=.52)	t=-7.0** (d=.45)	t=-1.4 (d=.10)	t=.57 (d=.03)	t=-7.62** (d=.46)
D=1.3 vs D=1.5	t=-14.22* (d=1.01)	t=-11.16** (d=.82)	t=-2.83* (d=.21)	t=.06 (d=.01)	t=-11.44** (d=.89)
D=1.3 vs D=1.6	t=-16.31** (d=1.61)	t=-13.35** (d=1.37)	t=-3.75** (d=.39)	t=-.37 (d=.03)	t=-14.24** (d=1.35)

Table 3.2. (continued)

	Simple-Complex	Indifferent-Engaging	Dislike-Like	Tired-Refreshing	Relaxing-Tense
D=1.3 vs D=1.6	t=-16.31** (d=1.61)	t=-13.35** (d=1.37)	t=-3.75** (d=.39)	t=-.37 (d=.03)	t=-14.24** (d=1.35)
D=1.3 vs D=1.7	t=-19.33** (d=2.19)	t=-15.86** (d=1.61)	t=-3.06* (d=.34)	t=.48 (d=.33)	t=-17.24** (d=2.03)
D=1.3 vs D=1.8	t=-22.58** (d=2.51)	t=-16.61** (d=1.84)	t=-2.64* (d=.32)	t=.11 (d=.02)	t=-19.23** (d=2.42)
D=1.4 vs D=1.5	t=-7.38** (d=.49)	t=-6.59** (d=.41)	t=-2.01 (d=.13)	t=-.50 (d=.02)	t=-6.49** (d=.45)
D=1.4 vs D=1.6	t=-12.26** (d=1.4)	t=-11.68** (d=1.01)	t=-3.79** (d=.33)	t=-.78 (d=.08)	t=-10.29** (d=.92)
D=1.4 vs D=1.7	t=-16.81** (d=1.77)	t=-13.51** (d=1.28)	t=-2.78* (d=.28)	t=.30 (d=.04)	t=-14.57** (d=1.63)
D=1.4 vs D=1.8	t=-20.82** (d=2.21)	t=-15.08** (d=1.54)	t=-2.32* (d=.26)	t=-.11 (d=.01)	t=-17.68** (d=2.04)
D=1.5 vs D=1.6	t=-8.49** (d=.67)	t=-8.47** (d=.61)	t=-2.64* (d=.21)	t=-.59 (d=.05)	t=-6.11** (d=.47)
D=1.5 vs D=1.7	t=-14.74** (d=.67)	t=-12.28** (d=.91)	t=-1.95 (d=.17)	t=.74 (d=.07)	t=-13.35** (d=1.18)
D=1.5 vs D=1.8	t=-19.12** (d=1.83)	t=-13.59** (d=1.67)	t=-1.58 (d=.18)	t=.13 (d=.01)	t=-17.27** (d=1.61)
D=1.6 vs D=1.7	t=-10.34** (d=.75)	t=-5.87** (d=.35)	t=.38 (d=.02)	t=1.69 (d=.11)	t=-10.3** (d=.73)
D=1.6 vs D=1.8	t=-17.44** (d=1.2)	t=-9.82** (d=.6)	t=.33 (d=.02)	t=.57 (d=.05)	t=-15.23** (d=1.18)
D=1.7 vs D=1.8	t=-7.99** (d=.41)	t=-5.86** (d=.25)	t=.04 (d=.0)	t=-.90 (d=.04)	t=-9.9** (d=.47)

** indicates significance of p < 0.05*
*** indicates significance of p < 0.001*

were identified. Average complexity ratings (collapsed over pattern arrangement type) ranged from a low of 2.09 (SD = 1.16) for $D = 1.1$ to a high of 5.60 (SD = 1.16) for $D = 1.8$, indicating that participants perceive greater complexity for patterns with higher *D*-values. Paired samples *t*-tests revealed significant differences in perceived refreshment between all pairs of *D*-values (Table 3.2). A cluster analysis did not indicate a multiple cluster solution.

Indifferent-engaging

A 2-way 8 × 2 repeated-measures ANOVA [*D*-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) × Arrangement (randomized vs. non-randomized)] was completed to examine the impact of *D*- value and Arrangement on pattern engagement (Figure 3.9B). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [$\chi^2(27) = 443.38$, $p < 0.001$**] and interaction of *D*-value and Arrangement [$\chi^2(27) = 88.06$, $p < 0.001$**], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.260$ and 0.661, respectively). A significant main effect of *D*-value [$F(1.82,134.71) = 131.39$, $p < 0.001$**, 95% *CI* [0.54, 0.71], $\eta p^2 = 0.64$], Arrangement [$F(1,74) = 16.98$, $p < 0.001$**, 95% *CI* [0.05, 0.33], $\eta p^2 = 0.19$], and interaction between *D*-value and pattern arrangement were identified [$F(4.63,342.64) = 3.8$, $p = 0.003$*, 95% *CI* [0.01, 0.09], $\eta p^2 = 0.05$]. Collapsed over pattern arrangement, the mean engagement ratings ranged from a low of 2.15 ($SD = 1.15$) for $D = 1.1$ to a high of 4.98 ($SD = 1.48$) for $D = 1.8$, suggesting that participants were more engaged when viewing the higher *D*-value patterns. Paired samples *t*-tests revealed significant differences in perceived engagement for all pairs of *D*-values (Table 3.2). Comparing the non-random and random arrangements for different *D*-values, significant differences exist for the mid- to high-range *D*-values: $D = 1.4$ [$t(74) = 3.1$, $p = 0.003$*, 95% *CI* [0.1, 0.45], $d = 0.26$], $D = 1.5$ [$t(74) =$

2.68, p = 01*, 95% CI [0.07, 0.48], d = 0.26], D = 1.6 [t(74) = 3.16, p = 0.002*, 95% CI [0.18, 0.78], d = 0.4], D = 1.7 [t(74) = 3.05, p = 0.003*, 95% CI [0.13, 0.62], d = 0.27], and D = 1.8 [t(74) = 3.77, p < 0.001**, 95% CI [0.25, 0.8], d = 0.36]. The interaction between D-value and Arrangement indicates that the ratings differed across arrangement type depending on D-value, with increasingly higher ratings for non-randomized compared to randomized fractal patterns as D-values increased.

A 2-step cluster analysis identified and separated individuals into 3 subgroups (Figure 3.9F). Mauchly's test indicated a violation of the assumptions of sphericity for D-value [$\chi^2(27)$ = 214.33, p < 0.001**] and the interaction between D-value and Arrangement [$\chi^2(27)$ = 82.31, p < 0.001**]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.446 and 0.673, respectively). A significant main effect of D-value [F(3.12,224.58) = 116.01 p < 0.001**, 95% CI [0.54, 0.67], ηp^2 = 0.62], and Arrangement emerged in the analysis [F(1,72) = 22.75, p < 0.001**, 95% CI [0.09, 0.39], ηp^2 = 0.24], as well as significant interactions between D-value and Clusters [F(6.24,224.58) = 31.25, p < 0.001**, 95% CI [0.36, 0.53], ηp^2 = 0.47] and D-value and Arrangement [F(4.71,339.19) = 5.37, p < 0.001**, 95% CI [0.02, 0.12], ηp^2 = 0.07]. All three clusters of engagement ratings increase with D-value, but with different rates of incline.

Dislike-like

A 2-way 8 × 2 repeated-measures ANOVA [D-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) × Arrangement (randomized vs. non-randomized)] was completed to examine the impact of D-value and Arrangement on pattern preference (Figure 3.9C). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [χ^2 (27) = 534, $p < 0.001$**] and the interaction between *D*-value and Arrangement [χ^2(27) = 108.05, $p < 0.001$**], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.232 and 0.608, respectively). A significant main effect of *D*-value [F(1.63,120.26) = 6.71, $p = 0.003$*, 95% *CI* [0.01, 0.18], $\eta p^2 = 0.08$], Arrangement [F(1,74) = 19.74, $p < 0.001$**, 95% *CI* [0.07, 0.36], $\eta p^2 = 0.21$], and the interaction between *D*-value and pattern arrangement [F(4.26,314.93) = 6.05, $p < 0.001$**, 95% *CI* [0.02, 0.13], $\eta p^2 = 0.08$] were identified. Collapsed over pattern arrangement, average ratings of preference ranged from a low of 3.21(*SD*=1.6) for *D*=1.1 to a high of 4.0 (*SD* = 1.45) for *D* = 1.6, indicating that participants' preference for global forest fractals increases with pattern complexity. Paired samples *t*-tests revealed significant differences in preference between *D*-values (see Table 3.2). Comparing non-random and random arrangements, significant differences exist for *D* = 1.2 [t(74) = 2.66, $p = 0.01$*, 95% *CI* [0.07, 0.47], $d = 0.17$], *D* = 1.5 [t(74) = 4.25, $p < 0.001$**, 95% *CI* [0.26, 0.72], $d = 0.4$], *D* = 1.6 [t(74) = 3.93, $p < 0.001$**, 95% *CI* [0.41, 1.26], $d = 0.55$], *D* = 1.7 [t(74) = 2.38, $p = 0.02$*, 95% *CI* [0.07, 0.75], $d = 0.25$], and *D* = 1.8 [t(74) = 4.14, $p < 0.001$**, 95% *CI* [0.43, 1.21], $d = 0.47$]. The interaction between *D*-value and Arrangement indicates that the ratings differed across arrangement type depending on *D*-value, with generally increasingly higher ratings for non-randomized compared to randomized fractal patterns as *D*-values increased.

Two subgroups were identified in ratings of pattern liking with the two-step cluster analysis (Figure 3.9G). Mauchly's test indicated a violation of the assumptions of sphericity for *D*-value [χ^2 (27) = 397.62, $p < 0.001$**] and interaction between *D*-value and Arrangement [χ^2(27) = 109.84, $p < 0.001$**]. Therefore, degrees of freedom were corrected using Greenhouse-

Geisser estimates of sphericity ($\varepsilon = 0.286$ and 0.603, respectively). A significant main effect of *D*-value [$F(2.0,146.05) = 14.31$, $p < 0.001$**, 95% CI [0.06, 0.26], $\eta p^2 = 0.16$] and Arrangement [$F(1,73) = 19.12$, $p < 0.001$**, 95% CI [0.06, 0.36], $\eta p^2 = 0.21$], as well as interactions between *D*-value and Clusters [$F(2.0,146.05) = 28.72$, $p < 0.001$**, 95% CI [0.16, 0.38], $\eta p^2 = 0.29$] as well as Arrangement and Clusters were identified [$F(4.22,308.32) = 6.33$, $p < 0.001$**, 95% CI [0.02, 0.18], $\eta p^2 = 0.08$]. Cluster 1, comprising 57% of the sample, shows similar ratings of pattern liking for low and moderate patterns then decreases with higher *D*-values. However, Cluster 2, comprising 43% of participants, demonstrates an increasing liking of the patterns with increasing *D*-value.

Tired-refreshing

A 2-way 8 × 2 repeated-measures ANOVA [*D*-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) × Arrangement (randomized vs non- randomized)] was completed to examine the impact of *D*-value and Arrangement on perceived pattern refreshment (Figure 3.9D). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [χ^2 (27) = 853.96, $p <$ 0.001* *] and the interaction between *D*-value and Arrangement [$\chi^2(27) = 46.53$, $p = 0.01$*], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.174 and 0.847, respectively). The only significant effect was for Arrangement [$F(1,74)$ = 15.97, $p < 0.001$**, 95% *CI* [0.05, 0.32], $\eta p^2 = 0.18$]. Ratings for non-randomized patterns (M = 3.68, SD = 1.53) were slightly higher than randomized patterns (M = 3.53, SD = 1.57). No significant main effect of *D*-value [$F(1.22,90.04) = 0.14$, $p = 0.75$, 95% *CI* [0, 0.05], ηp^2 = 0.002], or interaction between *D*-value and pattern arrangement [$F(5.93,438.61) = 1.54$, $p = 0.16$, 95% *CI* [0, 0.04], $\eta p^2 = 0.02$] were found. Between non-random and random arrangements significant differences exist for $D = 1.2$ [$t(74) = 2.22$, $p = 0.03$*, 95% *CI* [0.02, 0.36], $d = 0.1$], $D = 1.6$ [$t(74) = 2.86$, $p = 0.01$*, 95% *CI* [0.09, 0.52], $d = 0.27$] and $D = 1.7$ [$t(74) = 2.63$, $p = 01$*, 95% *CI* [0.07, 0.47], $d = 0.18$]. No subgroups were found amongst participant ratings of fractal pattern refreshment.

Relaxing-tense

A 2-way 8 × 2 repeated-measures ANOVA [*D*-value (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8) × Arrangement (randomized vs. non-randomized)] was completed to examine the impact of *D*-value and Arrangement on perceptions of patterns tension (non-relaxing quality) (Figure 3.9E). A violation of the assumption of sphericity was indicated by Mauchly's test for *D*-value [$\chi^2(27) = 560.25$, $p < 0.001$**] and interaction between *D*-value and Arrangement [$\chi^2(27) = 52.99$, $p = 0.002$*], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.218$ and 0.842, respectively). A sole significant main effect of *D*-value was identified [$F(1.53,113.17) = 140.86$, $p < 0.001$** , 95% *CI* [0.05, 0.32], $\eta p^2 = 0.66$]. Thus no main effect of Arrangement [$F(1,74) = 2.01$, $p = 0.16$, 95% *CI* [0, 0.05], $\eta p^2 = 0.03$] or significant interaction between *D*-value and pattern Arrangement were found [$F(5.89,436.1) = 1.38$, $p = 0.22$, 95% *CI* [0, 0.04], $\eta p^2 = 0.02$]. Average ratings of pattern relaxation ranged from a low of 2.28 (*SD* = 1.29) for $D = 1.1$ to a high of 5.63 (*SD* = 1.28) for $D = 1.8$, suggesting that participants perceived patterns as more tense with increasing *D*-value. Paired samples *t*-tests revealed significant differences in perceived relaxation for all pairs of *D*-values (Table 3.2).

Three subgroups of participant perceptions of tension/relaxation were identified through two step cluster analysis (Figure 3.9H). Mauchly's test indicated a violation of the assumptions of sphericity for *D*-value [$\chi^2(27) = 259.97$, $p < 0.001$**] and interaction between *D*-value and

Arrangement [χ^2 (27) = 52.56 p = 0.002*]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.367 and 0.839, respectively). A significant main effect of *D*-value [$F(2.57,185.17) = 101.1$ $p < 0.001$**, 95% *CI* [0.49, 0.65], $\eta_p^2 = 0.58$] and interaction between *D*-value and Clusters [$F(5.14,185.17) = 41.63$, $p < 0.001$**, 95% *CI* [0.42, 0.6], $\eta_p^2 = 0.54$] emerged in the analysis. Cluster 1 containing 64% of participants as well as cluster 2 containing 19% of participants both produced a perceptual trend in which ratings of tension increased with pattern complexity. Cluster 3 containing the remaining 17% of the sample, produces a flat trend in ratings of pattern tension/relaxation.

Overall, we find that bipolar ratings of fractal 'global-forest' pattern complexity, preference, and engagement increase with additional *D*-value, whereas ratings of relaxation decrease with additional *D*-value. Perceptions of pattern refreshment are impacted by participant membership to contradictory rating trends, producing greater variance in ratings thus a flatter trend in relaxation ratings.

Discussion

Experiment 1B expands our investigation of psychological effects of these installed patterns but incorporates a different population of viewers and bipolar rating design. In this iteration of the perceptual rating task, participants are still recruited from a college population but from a different continent in the opposing global hemisphere (Australia) with a very different natural landscape. The rating task is also altered such that participants are instructed to rate their perception of images on a larger sliding scale between two opposing descriptors. Even with a new population and expanded study design results are highly similar to Experiment 1A. Similar to Experiment 1A, complexity, engaging, and preference ratings of 'global-forest' patterns all increase with increasing *D*-value; perceptions of pattern relaxation (taken as the reversed rating of ‘tense’ for this experiment) decrease with *D*-value; and refreshment did not change with *D*-value.

Experiment 2- Perception of Fractal “Tree-Seed” Patterns

Materials and Methods

Stimuli

Experiment 2 isolates the local components of the ‘global- forest’ patterns. These local ‘tree-seed’ patterns represent a local fractal pattern composed of rectangular ‘seeds’ with locations determined by the generated flightpath (see the description of the generation method in the Introduction and Experiment 1A). The stimuli consisted of a total of 20 patterns, with 5 examples each of 4 *D*-values (D = 1.2, 1.4, 1.6, and 1.8). Figure 3.5E shows an example pattern from each *D*-value.

Participants

To identify the locus of these perceptual trends, 39 participants comprised of undergraduate Psychology students from the University of Oregon were recruited for the current study through the SONA participant pool system (22 females, age ranging between 18 and 29 years old, mean age 20 years old). Informed consent was acquired following a protocol approved by the Institutional Review Board at the University of Oregon and all participants received class credit for their participation.

Design and Procedure

Participants viewed a series of fractal “tree-seed” patterns presented in five randomized blocks. Each block’s stimulus set consisted of 5 unique patterns ranging across 4 levels of complexity or D-value (D = 1.2, 1.4, 1.6, and 1.8). A slider response task was used to self-report ratings for each fractal pattern, resulting in 20 trials per block. Each block consisted of a singular judgment type (complexity, engaging, preference, refreshing, or relaxing).

Before each block, participants were instructed to make a single randomly ordered judgment (complexity, preference, engaging, refreshing, or relaxing) for each stimulus presented in that block. Specifically, they were asked to answer one of 5 questions for each block: "How _______ is the image?" with one of 5 different words placed in the blank (complex, engaging, preferable, refreshing, relaxing). They were told to indicate their rating of each given pattern on a slider ranging between 0 and 1 located below the image, with the "0" end of the slider indicating "not at all" and the "1" end of the slider indicating "completely." They were asked to use the full range of the slider and to click on the slider to indicate their rating. Periodically, an attention check trial appeared in which participants were instructed to select either "0" or "1." The images remained on the screen until participants selected their rating. Upon completion of the experiment, participants completed a demographic questionnaire and were debriefed according to the protocols approved by the Institutional Review Board at the University of Oregon.

Results

Data from 39 adult participants (between 18 and 29 years old) were retained from the 60 adults who participated in the experiment. Data were excluded due to: (a) failure to complete the study, (b) failure of greater than 3 attention checks, or (c) recording the same rating for greater than four consecutive trials.

Fractal Judgment Task

A 2-way repeated-measures 4 × 5 ANOVA [*D*-value (1.2, 1.4, 1.6, and 1.8) × Judgment (complexity, engaging, preference, refreshing, relaxing)] was performed using IBM SPSS Statistics for Macintosh (Version 25.0) on rating data for the fractal patterns (recorded as location selected on a rating response slider). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [χ^2 (5) = 59.58, $p < 0.001$**], and Judgment [χ^2 (9) = 25.24, $p = 0.003$*], and the interaction of *D*-value and Judgment [χ^2 (77) = 216.75, $p < p <$ 0.001**]. Therefore, degrees of freedom were corrected using Greenhouse- Geisser estimates of sphericity (ε = 0.525, 0.732, and 0.463, respectively). Indicated by a double asterisk for significance of $p < 0.001$ and single asterisk for significance of $p < 0.05$, significant main effects of *D*-value [$F(1.58, 59.88) = 12.64$, $p < 0.001$**, 95% *CI* [0.07, 0.4], $\eta p^2 = 0.25$] and Judgment [$F(2.93, 111.29) = 5.55$, $p = 0.002$*, 95% *CI* [0.02, 0.23], $\eta p^2 = 0.13$], as well as an interaction between *D*-value and Judgment emerged [$F(5.56, 211.26) = 17.88$, $p < 0.001$**, 95% *CI* [0.21, 0.4], $\eta p^2 = 0.32$]. For the *D*-value and Judgment interaction, some judgments had ratings that increased in value with *D* (complexity, engagement, preference), while others were relatively flat or slightly decreasing (refreshing, relaxing) (Figure 3.10). Similar to the prior experiments, a series of planned comparisons explored the locus of the significant interaction between *D*-value and Judgment using ANOVAs, paired *t*-tests (Table 3.3), as well as a 2-step clustering analysis to determine if subgroups could further explain perceptual trends.

Complexity

A one-way repeated measures ANOVA was completed on the effects of *D*-value on ratings of pattern complexity (Figure 3.11A). Mauchly's test indicated a violation of the assumptions of sphericity for *D*-value [$\chi^2(5)$= 28.03, $p < 0.001$**], thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.659$). A significant main effect of *D*-value [$F(1.98, 75.08) = 107.58$, $p < 0.001$* * , 95% *CI* [0.63, 0.8], $\eta_p{}^2 = 0.74$] was detected. Average complexity ratings ranged from a low of 0.29 (*SD*=0.15) for *D*=1.2 to a high of 0.74(*SD*=0.13) for *D*=1.8, indicating that participants perceive greater complexity with the presence of higher *D*-value. Paired samples *t*-tests revealed significant differences in perceived complexity between all pairs of *D*-values (Table 3.3). A 2-step clustering analysis identified no significant subgroups for pattern complexity.

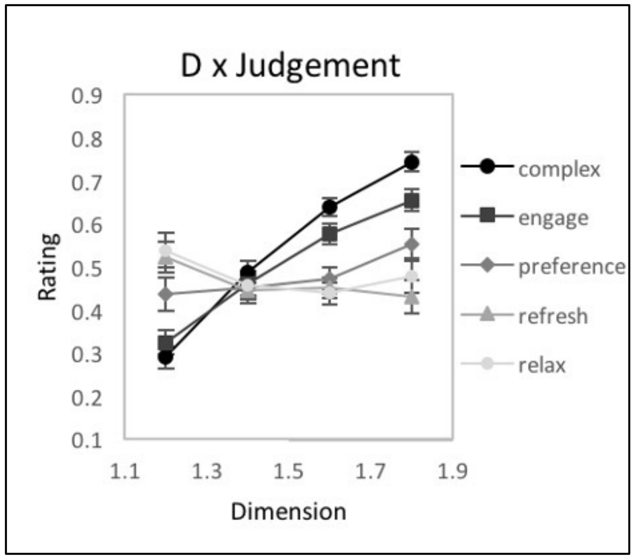

Figure 3.10. Experiment 2 results for 'tree-seed' fractal patterns using a unipolar rating scale. Results show a significant interaction between fractal dimension (*D*) and judgment type (complex, engaging, preferred, refreshing, and relaxing). Participant rating (on a scale from 0 to 1) is plotted as a function of *D*-value for the different judgment conditions.

Engaging

A one-way repeated measures ANOVA was completed on the effects of *D*-value on ratings of pattern engagement (Figure 3.11B). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [χ^2 (5) = 28.01, $p < 0.001$**], thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.660$). A significant main effect of *D*-value exists for ratings of pattern engagement [$F(1.98, 75.24) = 33.07$, $p < 0.001$**, 95% *CI* [0.29, 0.58], $\eta_p{}^2 = 0.47$]. Average engagement ratings ranged from a low of 0.32 (*SD* = 0.18) for *D* = 1.2 to a high of 0.65 (*SD* = 0.16) for *D* = 1.8, suggesting that patterns are perceived as more engaging with the introduction of higher *D*-values. Paired samples *t*-tests revealed

Table 3.3: Experiment 2- Paired Samples t-Tests across D-value and Judgement

	Complex	Engaging	Preference	Refreshing	Relaxing
D=1.2 vs D=1.4	t=-10.01** (d=1.29)	t=-4.49** (d=.8)	t=-.36 (d=.05)	t=2.11* (d=.33)	t=2.13* (d=.38)
D=1.2 vs D=1.6	t=-11.69** (d=2.35)	t=-6.02** (d=1.61)	t=-.71 (d=.15)	t=1.42 (d=.37)	t=1.98 (d=.53)
D=1.2 vs D=1.8	t=-13.39** (d=3.21)	t=-7.33** (d=1.94)	t=-1.77 (d=.49)	t=1.36 (d=.39)	t=.90 (d=.29)
D=1.4 vs D=1.6	t=-6.30** (d=1.03)	t=-3.67** (d=.77)	t=-.71 (d=.12)	t=-.20 (d=.0)	t=.66 (d=.13)
D=1.4 vs D=1.8	t=-8.41** (d=1.71)	t=-5.38** (d=1.15)	t=-2.17* (d=.51)	t=.27 (d=.09)	t=-.42 (d=.05)
D=1.6 vs D=1.8	t=-5.22** (d=.77)	t=-3.45** (d=.47)	t=-2.47* (d=.44)	t=.60 (d=.10)	t=-1.37 (d=.15)

* *indicates significance of p < 0.05*
** *indicates significance of p < 0.001*

significant differences in perceived engagement between all pairs of *D*-values (Table 3.3). No clusters were found amongst the participant ratings of pattern engagement.

Preference

A one-way repeated measures ANOVA was completed on the effects of *D*-value on ratings of pattern preference (Figure 3.11C). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [χ^2 (5) = 42.16, $p < 0.001$* *]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.586$). No significant main effect of *D*-value was identified [$F(1.58, 66.76) = 2.54$, $p = 0.09$, 95% CI [0,

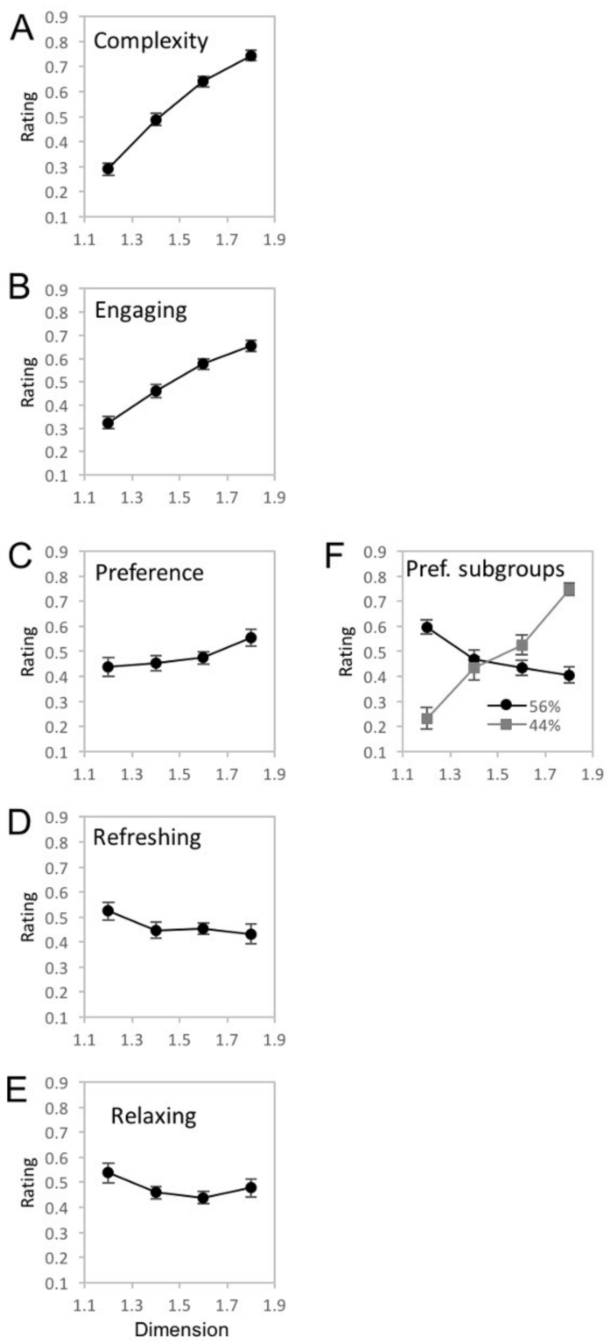

Figure 3.11. Experiment 2 results for 'tree-seed' fractal patterns for 5 different judgment conditions (how complex, engaging, preferred, refreshing, and relaxing). **(A–E)** shows plots of mean ratings as a function of fractal dimension (*D*) for the different judgment conditions (error bars represent standard error). **(F)** shows a plot of the mean ratings as a function of fractal dimension (*D*) for each subpopulation identified with cluster analysis (error bars represent standard error).

0.18], $\eta_p^2 = 0.06$]. Paired samples *t*-tests did reveal significant differences in preference between *D*-values (see Table 3.3) indicating a trend of higher preference ratings for patterns with higher *D*-values, at least among *D*-values of 1.4, 1.6, and 1.8.

Two subgroups emerged in the 2-step cluster analysis (Figure 3.11F). Mauchly's test indicated a violation of the assumptions of sphericity for *D*-value [$\chi^2(5) = 11.89$, $p = 0.04$*]. Therefore, degrees of freedom were corrected using Greenhouse- Geisser estimates of sphericity ($\varepsilon = 0.861$). Both a significant main effect of *D*-value [$F(2.58, 95.58) = 9.29$, $p < 0.001$**, 95% *CI* [0.06, 0.32], $\eta p^2 = 0.2$], and significant interaction between *D*-value and sub-groups [$F(2.58, 95.58) = 42.07$, $p < 0.001$**, 95% *CI* [0.38, 0.62], $\eta p^2 = 0.53$] emerged. Cluster 1 comprised 56% of the sample and represents a trend of fractal preference peaking at the lowest *D*-value and decreasing with added complexity. Conversely, cluster 2 which accounts for the remaining 44% of the sample, represents an opposing trend with fractal preference increasing steeply with *D*-value and peaking at the highest complexity.

Refreshing

A one-way repeated measures ANOVA was completed on the effects of *D*-value on ratings of pattern refreshment (Figure 3.11D). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [$\chi^2 (5) = 54.02$, $p < 0.001$* *]. Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.554$). No significant main effect of *D*-value was identified in the data [$F(1.66, 63.11) = 1.49$, $p = 0.24$, 95% *CI* [0, 0.15], $\eta p^2 = 0.04$]. Paired samples *t*-tests revealed one significant difference in perceived refreshment between $D = 1.2$ and $D = 1.4$ (see Table 3.3). No subgroup clusters were identified in the data.

Relaxing

A one-way repeated measures ANOVA was completed on the effects of *D*-value on ratings of pattern relaxation (Figure 3.11E). Mauchly's test indicated a violation of the assumption of sphericity for *D*-value [$\chi^2(5) = 64.07$, $p < 0.001$**]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.489$). No significant main effect of *D*-value was identified in the data [$F(1.47, 55.72) = 1.82$, $p = 0.18$, 95% *CI* [0, 0.18], $\eta_p^2 = 0.05$]. Paired samples *t*-tests revealed a sole significant difference in perceived relaxation between $D = 1.2$ and $D = 1.4$ (see Table 3.3). No additional clusters are found amongst the participant ratings of pattern relaxation.

Discussion

Experiment 2 maintains the same methodological structure and perceptual decisions as Experiment 1A but replaces the 'global-forest' pattern with fractal 'tree-seed' patterns. Similar to Experiment 1, judgments of complexity and engagement increase with *D*-value and there is a trend for higher preference ratings for patterns with higher *D*-values and 2 subgroups with opposing responses for preference for pattern complexity. The smaller sample size in Experiment 2 may have affected the strength of the overall positive trend. Also similar to Experiment 1, judgments for refreshing are similar across *D*-value. However, unlike Experiment 1, judgments of relaxing remain the same, rather than decrease, with *D*-value.

General Discussion

Evaluations of Euclidean human-made space can be altered by integrating the aesthetics of nature (Taylor et al., 2005; Hagerhall et al., 2015). Increased time spent amongst unnatural Euclidean structures is associated with higher rates of visual strain, headaches, and overall stress resulting from additional effort exerted by the visual system to process more artificial patterns (Hagerhall et al., 2008; O'Hare & Hibbard, 2011; Penacchio & Wilkins, 2015; Le et al., 2017; Ogawa & Motoyoshi, 2020). Fractal patterns have the opportunity to combat these negative effects of unnatural environments by introducing easy to visually process natural patterns that can alter the occupants' experience of a space. Previous research has shown that preference for statistically generated fractal patterns peaks at low-moderate fractal dimension ("*D*-value"), a level of complexity that is prevalent in nature. In contrast, preference for exact fractals peaks at higher *D*-values due to the increased order introduced by their exact repetition (Bies et al., 2016). In order to maximize the possible positive effects of a composite fractal design that may provide greater flexibility to be used in installations that vary in media, location, and artistic style, the current set of studies explores a novel range of perceptual responses to fractal designs that expands beyond typical measurements of viewer preference in order to categorize trends in fractal perception for individual and group profiles taken from a more expansive sample of observers.

Across 3 experiments that vary in stimulus pattern composition, participant population, and rating scale we find similar trends in fractal perception. Experiment 1 used 'global-forest' fractal designs to demonstrate that ratings of pattern complexity, engagement, and preference increase with fractal complexity or *D*-value. In contrast, perception of pattern refreshment stays constant across *D*-value while perception of relaxation decreases with increasing *D*-value. Experiment 2 investigates the contribution of the local 'tree-seed' patterns to ratings of the "global-forest" designs. By replicating Experiment 1A using images of individual 'tree-seed' patterns that feature in the global design, we are able to get a measure of the contribution of the local patterns to the ratings of the overall composite design. Results demonstrate that most of the trends in participant ratings remain consistent with those of the overall fractal installation design. Specifically, perceptions of pattern complexity and engagement, and to a certain extent preference, all increase with increasing *D*-value. Also similar are judgments for refreshing which in all experiments are similar across *D*-value. However, unlike Experiment 1, judgments of relaxing remain the same, rather than decrease, with *D*-value. These results suggest that the local patterns contribute to the perception of the global design. Thus, across this set of studies, robust perceptions of fractal patterns remain consistent across countries, methodology, and to a certain extent, pattern design. The use of unipolar and bipolar scales between Experiments 1A and 1B show similar overall trends for the 'global-forest' fractal designs.

Across both studies subgroupings have a significant impact on overall trends, supporting previous findings of individual differences in preference for fractal complexity (Bies et al., 2016; Spehar et al., 2016; Street et al., 2016). Opposing subgroup trends are found for perceptual ratings of preference, refreshing, and relaxing. The opposing nature of these subgroups can serve to inform industrial design choices when selecting fractal patterns for installation by taking into consideration the *D*-value with the greatest agreement amongst individuals for the various judgments, thus benefiting the majority of occupants without negatively affecting the experience of subgroups of occupants. Specifically, if the goal is to optimize the engagement, preference, refreshment, and relaxation qualities of the fractal design across participants, then a pattern with mid-high *D*-value would provide this optimal balance, since these patterns have the greatest agreement among individual participant ratings for preference, engagement and refreshment while maintaining mid- range relaxing effects that become much lower for patterns with the highest *D*-values. More generally, our results highlight the potential of fractals for human-centered design - the choice of *D* value might ultimately depend on both the occupants and the functionality of the space (e.g., classrooms might be different from hospitals).

Both studies also demonstrate an effect of pattern randomization, whereby ratings of engagement, preference, refreshing, and relaxing qualities are slightly higher for non-randomized compared to randomized patterns. Fortunately, for many of the installations (e.g., carpets and projected light patterns) the visibility of the edges defining the randomly positioned tiles is much less apparent in the installations than in the randomized patterns presented here.

Lastly, the similarity between findings of Study 1A and 1B are not impacted by the geographical location of participants. Our findings suggest that perceptions of fractal patterns are not altered by the diverse natural environments where participants reside. This result supports the finding that preference for fractal complexity forms early in human development (sometime prior to three years of age) and is not further altered by life experience in western participants (Robles et al., 2020). Although this study recruits from a broader group of participants, our findings are still limited due to the overarching homogeneity in “WEIRD” participant samples. However, the addition of variation in geographical location and composition of cultural subgroupings suggests that these consistent perceptions of fractal patterns are experienced by broader populations around the global, thus encouraging further studies addressing fractal perceptions in more diverse samples. Taken as a whole, findings from Experiment 1 lends support to possible universality of fractal pattern perception, despite variability in testing methods, individual differences driving rating subgroups, and samples coming from experience with two different natural landscapes.

The “global-forest” patterns with $D = 1.6$ have already been installed into humanmade spaces in hopes of reducing occupant stress while increasing the aesthetic experience of the space. For patterns to successfully decrease stress levels, they must elicit lower physiological arousal and provide a restorative effect for attention (Hagerhall et al., 2015). Relaxation and refreshment coincide with lower levels of arousal whereas engagement requires elevated levels of arousal. For installations to be effective without altering the overall aesthetics of the space, patterns must balance desirable levels of preference and engagement with relaxing and refreshing qualities. Unlike the fractal preference for natural statistical fractals (Spehar et al., 2016), preference for the current fractal patterns increase with increasing *D*-value more similar to fractal patterns that repeat in an exact manner (Bies et al., 2016). This result may be due to a number of factors including: (1) an increased preference for patterns with higher element density that is present in the higher *D*-value patterns; (2) the introduction of Euclidean structure and exact repetition found in the repeating rows of the 'tree-seed' patterns; and (3) the visibility of the square-shaped seed pattern that is used to grow the fractal 'tree-seed' patterns. For a biophilic installation to have the greatest stress reducing effect, the fractal design would be required to possess a mid-high *D*-value which would maintain elevated pattern preference, but not suffer from the steepest decline in pattern relaxation that occurs at the highest *D*-values. The fractal patterns employed in the installations shown in Figure 3.4 all have these optimal mid-high *D*-values.

Future studies will further explore the ways in which these fractal designs impact occupants' perceptions by expanding our studies to assess the extent to which our findings apply to broader populations of participants, additional changes in pattern design (including different local components, global flight-path arrangements, and global design), and can be directly identified with changes in physiological and verbal measures of stress and arousal. Further replications will be conducted utilizing Virtual Reality (VR) to assess responses to these patterns installed in 3-dimensional architectural spaces in order to more directly manipulate participant experience and measure changes in psychological effects in an immersive environment. By balancing perceptual factors, patterns can be produced and installed to maximize aesthetic experiences of particular spaces. The collaboration of design, physics, psychology, and technology provides a vital opportunity to test for and determine visual patterns that produce optimal perceptual responses and experiences in occupants of human-made structures. By selecting fractal patterns with *D*-values that are appropriate for particular built environments and mediums, instillations of these natural patterns have the opportunity to decrease eye- strain, headache rates, and stress (O'Hare & Hibbard, 2011; Penacchio & Wilkins, 2015; Le et al., 2017) in a large percentage of viewers (Bies et al., 2016; Street et al., 2016; Pyankova et al., 2019) while potentially increasing the aesthetic experience of the space.

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CHAPTER IV

BRINGING NATURE INDOORS: CHARACTERIZING THE UNIQUE CONTRIBUTION OF FRACTAL STRUCTURE AND THE EFFECTS OF EUCLIDEAN CONTEXT ON PERCEPTION OF FRACTAL PATTERNS

From Robles, K. E., Gonzales-Hess, N., Taylor, R. P., & Sereno, M. E. (2023). Bringing nature indoors: Characterizing the unique contribution of fractal structure and the effects of Euclidean context on perception of fractal patterns. *Frontiers in Psychology*. (Manuscript under revision).

The positive impact of bringing nature indoors reaches far beyond the aesthetic benefits of adding a plant to an office windowsill (Berman et al., 2008; Korpela et al., 2017). Fractals embody the self-similar pattern repetition found throughout nature (Mandelbrot, 1982; Taylor, 2021) and have been harnessed to improve occupant wellbeing (Smith et al., 2020; Taylor & Sprott, 2008). Exemplified by research supporting fractal fluency theory (Taylor & Spehar, 2016; Taylor et al., 2018) the visual system is tuned to more efficiently process fractal patterns of low-moderate complexity which are prevalent through nature (Spehar et al., 2003; Taylor et al., 2018; Hagerhall et al., 2008). This processing fluency supports perceptions of high aesthetic quality (Friedenberg et al., 2021) as well as peaks in task performance (Juliani et al., 2016; Spehar et al., 2015; Burtan et al., 2021; Taylor et al., 2017; Ferreira et al., 2012). In the same manner in which exposure to nature encourages positive psychological states (Ulrich, 1981; Ulrich et al., 1991; Kellert, 1993; Kaplan & Kaplan, 1982; Kaplan & Kaplan, 1989; Hagerhall et al., 2015) incorporation of fractal patterns into visual surroundings supports the biophilic hypothesis of a fundamental human need for connection to nature (Wilson, 1984).

Across a robust body of research (Spehar et al., 2003; Bies et al., 2016; Robles et al., 2020) as well as prevalence in artistic works (Taylor et al., 1999; Graham & Field, 2008; Graham & Redies, 2010; Taylor et al., 2018; Vienkgham & Spehar, 2018; Taylor, 2003; Taylor et al., 2007), fractal arrangements have demonstrated a high aesthetic quality. Judgments of fractal preference closely follow variations in perceived pattern complexity, with those possessing exact repetition and symmetry encouraging a greater tolerance for objective complexity than those that repeat in a statistical manner more common throughout the natural world (Taylor et al., 2005; Hagerhall et al., 2015; Taylor et al., 2011; Bies et al., 2016; Taylor & Sprott, 2008; Robles et al., 2020). Objective pattern intricacy results from variations in the relative coarse-to-fine pattern structure determined by internal pattern factors such as variations in recursion (number of repetitions across scales) and complexity of fractal dimension "*D*-value" (the rate of pattern shrinkage between repetitions to quantify the ratio of fine structure), perceived pattern complexity also constrains broader pattern judgments (Robles et al., 2021; Abboushi et al., 2019). Selection of optimal fractal features expands beyond observed improvements to aesthetic experiences of a given object, to facilitate viewer cognition and performance on a wide span of tasks (Juliani et al., 2016; Abboushi et al., 2019; Taylor et al., 2018; Roe et al., 2020; Spehar & Stevanov, 2021).

In stark contrast to the statistical configuration of nature embodied by fractals, humanmade spaces are composed of Euclidean arrangements which require further energy to sufficiently process (Taylor, 2006; Hagerhall et al., 2008; Le et al., 2017). Alongside diminished aesthetic experiences (for review see Brielmann et al., 2022) greater time spent inside artificial environments coincides with negative health effects including visual strain, headaches, and general increases in feelings of stress (Pennacchio & Wikins, 2015; O'Hare & Hibbord, 2011; Ogawa & Motoyoshi, 2020). In recent years interior design has sought to inject more naturalistic elements into interior space to improve occupant experiences (Smith et al., 2020; Korpela et al., 2017). Specifically, fractal installations have been manufactured to explicitly address the problems of an overabundance of unnatural spatial frequencies in occupant space by providing an opportunity to help mitigate the negative effects of Euclidean environments without compromising the utility of a given structure (Smith et al., 2020; Roe et al., 2020; Taylor & Sprott, 2008). The benefit of bringing natural design indoors can be maximized through conscientious selection of fractal configurations that balance aesthetic and perceptual properties of the pattern along with the confining factors of the space.

The current study investigates the influence of pattern structure on observer experiences, specifically how internal composition (with the presence or absence of fractal organization) and external context (with the presence or absence of surrounding Euclidean configuration) alter well-established trends in fractal perception (Robles et al., 2021; Abboushi et al., 2019). In the first ever study to compare ratings of fractal images to corresponding statistically matched nonfractal patterns, unipolar ratings are collected across a broad range of experiential measurements to isolate the impact of fractal structure on predictable viewer experience. The goal of this series of experiments is to establish an empirical basis for guiding optimal installment of fractal-based designs to maximize pattern effectiveness in eliciting various psychological experiences of a space. Moreover, results from subgroup analyses will inform calculated selection of designs that balance various internal pattern factors (including complexity and arrangement) as well as surrounding structure in order to accommodate occupants with contradictory preferences.

Experiment 1 – Isolating the impact of fractal structure on pattern perception

Materials and Methods

Stimuli:

In order to isolate the unique influence of fractal structure, participants were presented with both fractal and matched non-fractal images. All stimuli are first generated as fractal images and then systematically altered to produce non-fractal matches. Fractal patterns are initially generated in a graphic user interface (GUI) using midpoint displacement produce a series of 5 black-white fractal images per unique seed pattern (*D*-value of 1.1, 1.3, 1.5, 1.7, 1.9) (**Figure 4.1A**). The non-fractal control stimuli were created by generating normally distributed white noise, which was then Fourier transformed and band-pass filtered to match the average region size of a given fractal stimulus (**Figure 4.2**). The control stimuli are matched to the 5 levels of fractal dimension in two ways: 1) by equating mean region size (mean number of contiguous white or black pixels >3 pixels in a given fractal stimulus; "Average" control; see **Figure 4.1B**), and 2) by capturing larger scale structure by matching the upper mean (the mean of all above-average region sizes) in a given fractal image; "Large" scale control; see **Figure 4.1C**). This procedure generates control stimuli with similar levels of intricacy to their fractal matches, but without their fractal characteristics.

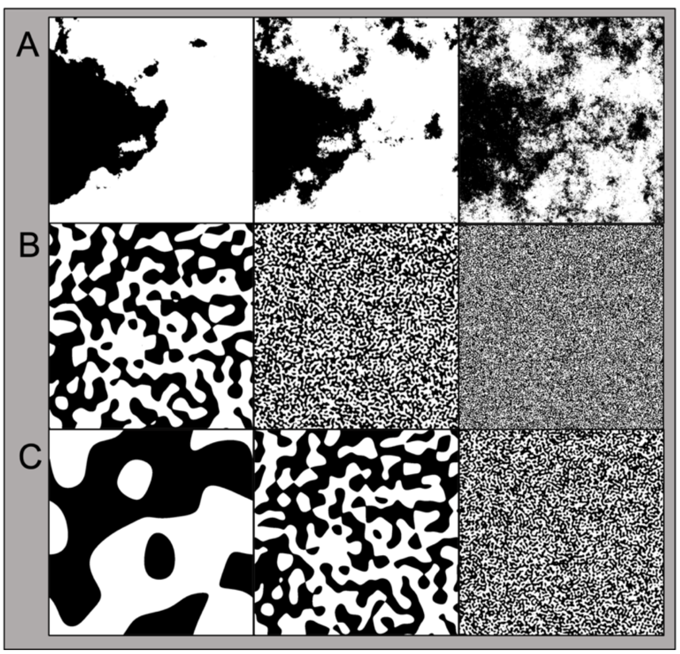

Figure 4.1. Examples of the three stimulus patterns generated by the same seed pattern and ranging from low (left column) to high intricacy (right column). (**A**) Fractals: fractal patterns with a fractal dimension (*D*) = 1.1, 1.5, and 1.9. (**B**) Average-nonfractals: non-fractal patterns with region sizes averaged to match the average region size of the original fractal pattern. (**C**) Large-nonfractals: non-fractal patterns with region sizes averaged to match the large-scale region size of the original fractal pattern.

Participants:

To quantify the unique impact of

underlying fractal structure on observer perceptions, 110 undergraduate Psychology students from the University of Oregon were recruited for the current study through the SONA participant pool system (69 females, age ranging between 18-32 years old, mean age 21 years old). Prior to participation, informed consent was acquired following a protocol approved by the Institutional Review Board at the University of Oregon and demographic information was collected. All participants were compensated with class credit.

Visual Displays:

Experiment 1 was generated in PsychoPy3 (Peirce et al., 2019). Participants were seated approximately 70cm from a computer with 27-inch monitor with screen resolution of 2,560 X 1440 pixels and 60Hz refresh rate. Thus, stimuli size was roughly 720 x 720 pixels or 13.8 degrees of visual angle across.

Design and Procedure:

Participants completed 18 randomized blocks of self-report slider judgments, with each block consisting of one pattern type (fractal, basic non-fractal, upper non-fractal) and a singular judgment type (complexity, appeal, naturalness, interest, relaxing, exciting). Each block's stimulus set consisted of 4 unique patterns ranging across 5 levels of intricacy (equal or matched to a *D*-value 1.1, 1.3, 1.5, 1.7, 1.9) giving rise to 20 trials per block and 360 total stimulus-related trials across the experiment. At the start of each block, participants were instructed to make a single randomly ordered judgment for each stimulus presented in that block. Specifically, they were asked to answer one of 6 questions for each block: "How _______ is the image?" with one of 6 different words placed in the blank (complex, appealing, natural, interesting, relaxing,

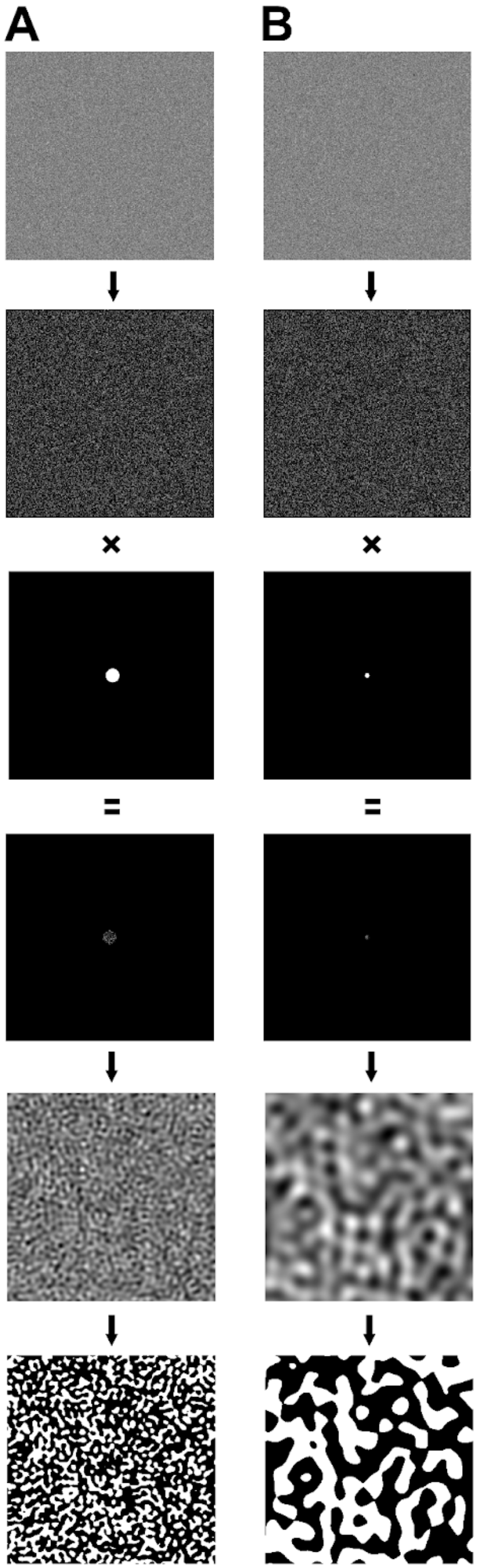

Figure 4.2. Two examples of the control stimulus generation process. A field of normally distributed white noise is generated, then processed using a Fast Fourier Transform to yield the frequency domain. The resulting frequency information was then multiplied with a circular filter to eliminate some amount of high frequency information. The product was then inverse Fast Fourier Transformed to yield the final noise pattern, which was then thresholded to produce a black and white image. (**A**) shows a wide filter, which results in a large range of frequencies in the final image, (**B**) employs a tighter filter, which eliminates higher frequencies and produces a final pattern with lower frequency information. The algorithm used to generate control stimuli systematically manipulated filter size to produce controls that closely matched the average region size of a given fractal stimulus.

exciting). Participants rated each pattern by clicking on a slider located beneath the image ranging between 0-1, with the "0" end of the slider indicating "not at all" and the "1" end of the slider indicating "completely." They were instructed to use the full range of the slider and stimuli remained on the screen until a response was recorded. Upon completion of the experiment, participants were debriefed according to the protocol approved by the Institutional Review Board at the University of Oregon.

Results

Data from 94 participants were retained from the 110 individuals who participated in the experiment. Data were excluded due to 1) failure to complete the study (3 participants), 2) failure to follow directions (8 participants), or 3) in greater than 3 blocks, a participant made 4 or more consecutive ratings that were within a thousandth of a degree of one another (5 participants).

Pattern Judgment Task:

A 3-way repeated-measures 3x5x6 ANOVA (Pattern-Type (fractal, Average-nonfractal, Large-nonfractal) x Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Judgment (complexity, appeal, naturalness, interest, relaxing, exciting)) was performed using IBM SPSS Statistics for Macintosh, (Version 28.0) on rating data for the black-white patterns (recorded as location selected on a rating response slider). Mauchly's test indicated a violation of the assumption of sphericity for Pattern-type ($\chi^2(2)=21.69$, $p<.001$**), Intricacy ($\chi^2(9)=415.06$, $p<.001$**), Judgment ($\chi^2(14)=45.21$, $p<.001$**), as well as the interactions between Pattern-type and Intricacy ($\chi^2(35)=562.39$, $p<.001$**), Intricacy and Judgment ($\chi^2(209)=1723.43$, $p<.001$**), Pattern-type and Judgment ($\chi^2(54)=135.04$, $p<.001$**), and the three-way interaction among Pattern-type, Intricacy, and Judgment ($\chi^2(819)=2282.14$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.826, .343, .832,

.338, .258, .756, and .348 respectively).

Indicated with a double asterisk for significance of p<.001 and a single asterisk for significance of p<.05, were significant main effects of Intricacy ($F(1.37,127.63)=17.77$, p<.001**, 95% *CI* [.06,.27], $\eta_p^2=.16$), Pattern-type ($F(1.65,153.72)=3.78$, p<.001**, 95% *CI* [0,.31], $\eta_p^2=.25$), and Judgment ($F(4.16,387.07)=19.67$, p<.001**, 95% *CI* [.10,.53], $\eta_p^2=.41$). Additional significant interactions were detected between Intricacy and Judgment ($F(5.15,479.28)=158.30$, p<.001**, 95% *CI* [.58,.67], $\eta_p^2=.63$), Intricacy and Pattern-type ($F(2.71,251.69)=11.37$, p<.001**, 95% *CI* [.04,.18], $\eta_p^2=.10$), Pattern-type and Judgment ($F(7.56,703.03)=65.43$, p<.001**, 95% *CI* [.36,.46], $\eta_p^2=.41$), as well as Intricacy, Pattern-type, and Judgment ($F(13.92,1294.3)=15.56$, p<.001**, 95% *CI* [.10,.17], $\eta_p^2=.14$). For the Intricacy and Judgment interaction, some judgments had ratings that decreased with additional intricacy

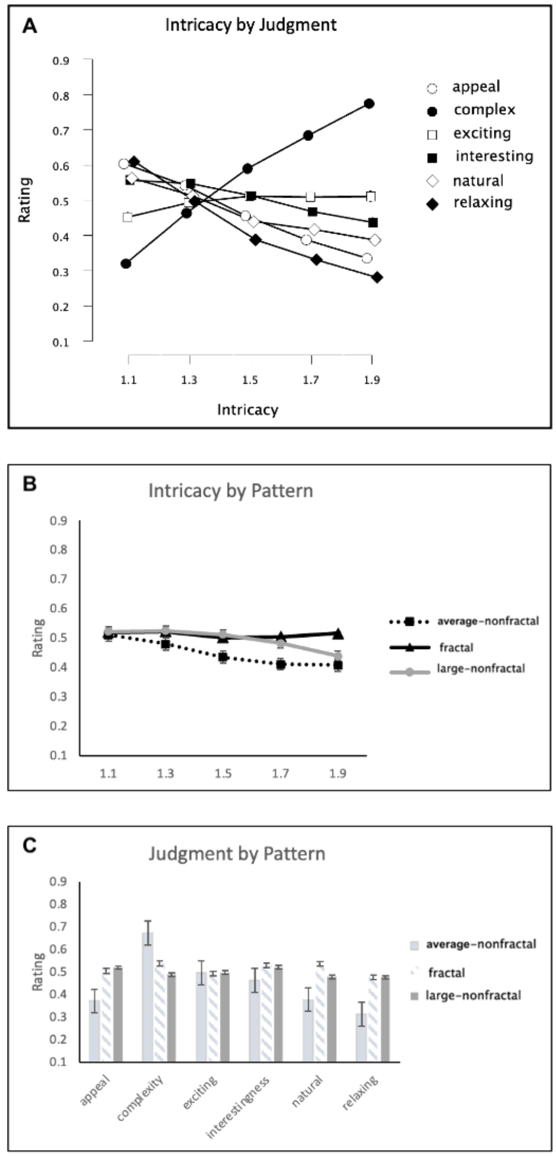

Figure 4.3. Experiment 1 results for the 3 pattern-types using a unipolar rating scale. Results show significant interactions among the experiment's 3 factors: intricacy, pattern type (fractal, Average-nonfractal, Large-nonfractal), and judgment type (appeal, complexity, exciting, interestingness, engaging, relaxing). Participant rating (on a scale from 0-1) is plotted as a function of **(A)** intricacy and different judgment conditions, **(B)** intricacy and different pattern type, and **(C)** judgment and pattern type.

(appeal, interesting, natural, relaxing), while others were relatively flat (exciting) or increased (complexity) (**Figure 4.3A**). For the Pattern-type and Intricacy interaction, ratings for the fractal, large non-fractal, and original non-fractal patterns were either relatively flat, decreased at the highest level of intricacy, or decreased across levels of intricacy, respectively (**Figure 4.3B**). Finally, for the Judgment by Pattern Type interaction, the differences in ratings among the 3 pattern types varied across judgment type (**Figure 4.3C**). The 3-way interaction indicates that the Pattern-type by Intricacy interaction varied across Judgment-type, seen more clearly in **Figure 4.4** (leftmost column of graphs). A series of planned ANOVA's and t-tests follow to better explore the interaction between pattern Intricacy and Type across various Judgments and whether these perceptual trends can be better explained by subgroups determined by a 2-step cluster analysis.

Appeal: A 2-way 5x3 repeated-measures ANOVA (Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Pattern-type (fractal, Average-nonfractal, Large-nonfractal,)) was completed to examine the impact of Intricacy and Pattern-type on ratings of image appeal (**Figure 4.4A**). A violation of the assumption of sphericity was indicated by Mauchly's test for Pattern-type ($\chi^2(2)=25.28$, $p<.001$**), Intricacy ($\chi^2(9)=238.57$, $p<.001$**), and the interaction between Pattern-type and Intricacy ($\chi^2(35)=394.10$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.806$, .420 and .443 respectively). There were significant main effects of Pattern-type ($F(1.63,149.97)=63.64$, $p<.001$**, 95% *CI* [.29,.50], $\eta_p^2=.41$) and Intricacy ($F(1.68,156.39)=113.65$, $p<.001$**, 95% *CI* [.45,.62], $\eta_p^2=.55$), and a significant interaction between Pattern-type and Intricacy ($F(3.54,329.46)=16.48$, $p<.001$**, 95% *CI* [.08,.21], $\eta_p^2=.15$). Collapsed over pattern-type, average ratings of appeal ranged from a high of .60 (*SD*=.18) for the least intricate patterns to a low of .33 (*SD*=.19) for the most intricate patterns indicating that appeal decreases with additional pattern intricacy. Collapsed over intricacy, average ratings of appeal were significantly higher for Large-nonfractal

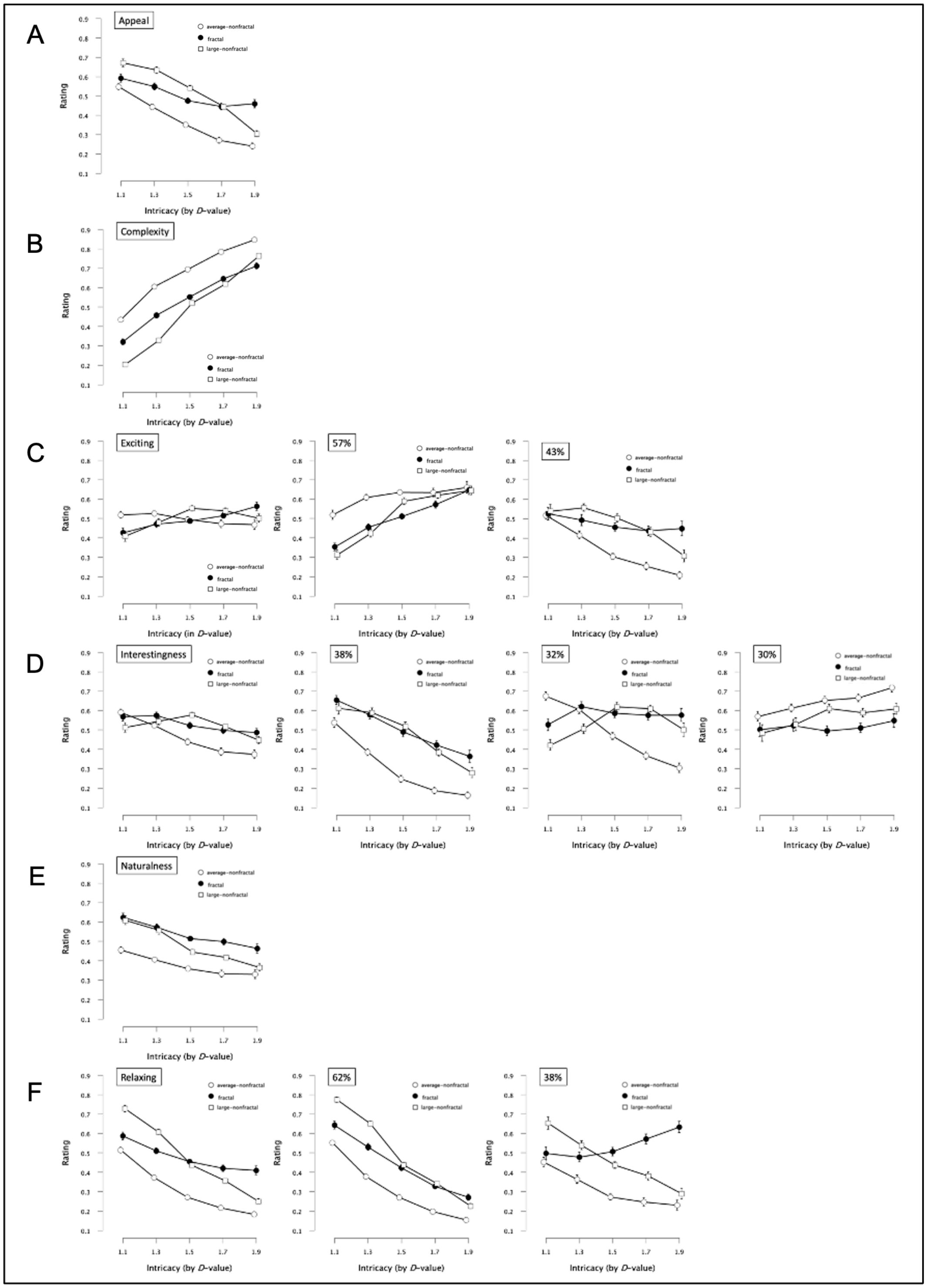

Figure 4.4. Experiment 1 results for the 3 patterns across 5 different judgment conditions (appeal, complexity, exciting, interestingness, engaging, relaxing). **(A-F left images)** Show plots of mean ratings as a function of pattern intricacy (displayed as corresponding fractal dimension "*D*-value") and pattern type (fractal, Average-nonfractal, Large-nonfractal) for the different judgment conditions (error bars represent standard error of the mean). **(A-F middle and right images)** Show plots of mean ratings as a function of intricacy and pattern type for each subpopulation identified with cluster analysis (error bars represent standard error of the mean).

(*M*=.52; *SD*=.08) and fractal (*M*=.50; *SD*=.12) patterns compared to Average-nonfractal patterns (*M*=.37; *SD*=.12): Average-nonfractals and fractals [*t*(93)=-7.69, *p*<.001**, 95% *CI* [-.17,-.10], *d*=.79]; Average-nonfractals and Large-nonfractals [*t*(93)=-13.31, *p*<.001**, 95% *CI* [-.17,-.13], *d*=1.37]. These results indicate an overall preference for the fractal and Large-nonfractal patterns, both of which contain large-scale structure. The interaction between Pattern-type and Intricacy demonstrates decreasing ratings of appeal across intricacy for both the non-fractal patterns but a decrease then leveling off of ratings across intricacy for the fractal patterns.

There were significant differences among the ratings of appeal across the three pattern types for individual levels of intricacy: ***D*=1.1** between Average-nonfractals and Large-nonfractals [*t*(93)=-5.70, *p*<.001**, 95% *CI* [-.17,-.08], *d*=.59] as well as fractals and Large-nonfractals [*t*(93)=-3.40, *p*=.001*, 95% *CI* [-.13,-.03], *d*=.35]; ***D*=1.3** between Average-nonfractals and fractals [*t*(93)=-4.05, *p*<.001**, 95% *CI* [-.16,-.05], *d*=.42], Average-nonfractals and Large-nonfractals [*t*(93)=-8.33, *p*<.001**, 95% *CI* [-.24,-.14], *d*=.86], and fractals and Large-nonfractals [*t*(93)=-4.34, *p*<.001**, 95% *CI* [-.12,-.05], *d*=.45]; ***D*=1.5** between Average-nonfractals and fractals [*t*(93)=-5.76, *p*<.001**, 95% *CI* [-.17,-.08], *d*=.59], Average-nonfractals and Large-nonfractals [*t*(93)=-12.71, *p*<.001**, 95% *CI* [-.22,-.16], *d*=1.31], and fractals and Large-nonfractals [*t*(93)=-2.96, *p*=.004*, 95% *CI* [-.11,-.02], *d*=.31]; ***D*=1.7** between Average-nonfractals and fractals [*t*(93)=-7.26, *p*<.001**, 95% *CI* [-.22,-.13], *d*=.99] and Average-nonfractals and Large-nonfractals [*t*(93)=-9.65, *p*<.001**, 95% *CI* [-.21,-.14], *d*=.99**]; *D*=1.9** between Average-nonfractals and fractals [*t*(93)=-8.61, *p*<.001**, 95% *CI* [-.27,-.17], *d*=.89], Average-nonfractals and Large-nonfractals [*t*(93)=-4.31, *p*<.001**, 95% *CI* [-.09,-.03], *d*=.44], and fractals and Large-nonfractals [*t*(93)=6.17, *p*<.001**, 95% *CI* [.11,.21], *d*=.64]) (see **Table 4.1** for complete information).

Table 4.1: Experiment 1- Paired Samples t-Tests between patterns across Intricacy and Judgment

Appeal					
	1.1	1.3	1.5	1.7	1.9
Average nonfractal - Fractal	$t = -1.597$ $p = .11$	$t = -4.054$ $p < .001$**	$t = -5.763$ $p < .001$**	$t = -7.264$ $p < .001$**	$t = -8.606$ $p < .001$**
Average nonfractal – Large nonfractal	$t = -5.699$ $p < .001$**	$t = -8.333$ $p < .001$**	$t = -12.709$ $p < .001$**	$t = -9.645$ $p < .001$**	$t = -4.319$ $p < .001$**
Fractal – Large nonfractal	$t = -3.398$ $p < .001$**	$t = -4.343$ $p < .001$**	$t = -2.959$ $p = .004$*	$t = -7.264$ $p < .001$**	$t = 6.173$ $p < .001$**
Complex					
	1.1	1.3	1.5	1.7	1.9
Average nonfractal - Fractal	$t = 6.499$ $p < .001$**	$t = 8.582$ $p < .001$**	$t = 10.137$ $p < .001$**	$t = 9.168$ $p < .001$**	$t = 8.638$ $p < .001$**
Average nonfractal – Large nonfractal	$t = 19.198$ $p < .001$**	$t = -3.361$ $p < .001$**	$t = 12.820$ $p < .001$**	$t = 12.692$ $p < .001$**	$t = 7.557$ $p < .001$**
Fractal – Large nonfractal	$t = 8.102$ $p < .001$**	$t = -10.454$ $p < .001$**	$t = 2.150$ $p = .03$*	$t = 1.564$ $p = .12$	$t = -3.119$ $p = .002$*
Exciting					
	1.1	1.3	1.5	1.7	1.9
Average nonfractal - Fractal	$t = 3.369$ $p < .001$**	$t = 2.186$ $p = .03$*	$t = 0.326$ $p = .75$	$t = -1.702$ $p = .09$	$t = -3.035$ $p = .003$*
Average nonfractal – Large nonfractal	$t = 4.202$ $p < .001$**	$t = 1.926$ $p = .06$	$t = -2.722$ $p = .01$*	$t = -2.785$ $p = .01$*	$t = -1.427$ $p = .16$
Fractal – Large nonfractal	$t = 0.710$ $p = .48$	$t = -0.409$ $p = .68$	$t = -3.129$ $p = .002$*	$t = -1.154$ $p = .25$	$t = 2.225$ $p = .03$*

Table 4.1. (continued)					
			Interesting		
	1.1	1.3	1.5	1.7	1.9
Average nonfractal - Fractal	$t = 0.861$ $p = .39$	$t = -2.235$ $p = .03$*	$t = -3.327$ $p < .001$**	$t = -4.530$ $p < .001$**	$t = -3.933$ $p < .001$**
Average nonfractal – Large nonfractal	$t = 2.955$ $p = .004$*	$t = -0.863$ $p = .39$	$t = -6.501$ $p < .001$**	$t = -6.283$ $p < .001$**	$t = -3.403$ $p < .001$**
Fractal – Large nonfractal	$t = 2.409$ $p = .02$*	$t = 1.336$ $p = .19$	$t = -2.577$ $p = .01$*	$t = -0.977$ $p = .33$	$t = 1.567$ $p = .12$
			Natural		
	1.1	1.3	1.5	1.7	1.9
Average nonfractal - Fractal	$t = -6.675$ $p < .001$**	$t = -7.801$ $p < .001$**	$t = -7.908$ $p < .001$**	$t = -6.637$ $p < .001$**	$t = -3.942$ $p < .001$**
Average nonfractal – Large nonfractal	$t = -8.193$ $p < .001$**	$t = -6.847$ $p < .001$**	$t = -4.424$ $p < .001$**	$t = -4.428$ $p < .001$**	$t = -2.133$ $p = .04$*
Fractal – Large nonfractal	$t = 0.591$ $p = .56$	$t = -6.847$ $p < .001$**	$t = 3.641$ $p < .001$**	$t = 4.076$ $p < .001$**	$t = 3.267$ $p = .002$*
			Relaxing		
	1.1	1.3	1.5	1.7	1.9
Average nonfractal - Fractal	$t = -3.364$ $p < .001$**	$t = -6.619$ $p < .001$**	$t = -10.337$ $p < .001$**	$t = -9.572$ $p < .001$**	$t = -8.991$ $p < .001$**
Average nonfractal – Large nonfractal	$t = -11.514$ $p < .001$**	$t = -13.837$ $p < .001$**	$t = -11.013$ $p < .001$**	$t = -9.145$ $p < .001$**	$t = -5.337$ $p < .001$**
Fractal – Large nonfractal	$t = -6.216$ $p < .001$**	$t = -5.151$ $p < .001$**	$t = 0.936$ $p = .035$*	$t = 3.182$ $p = .002$*	$t = 6.085$ $p < .001$**

* indicating significance of $p<.05$, ** indicating significance $p<.001$.

To account for possible effects of participant subgroups driving the overall observed trends, a two-step cluster analysis was performed (see Robles et al., 2021). In accordance with and described in Norušis (2012) hierarchical cluster analyses were first completed using Ward's method to separate individuals into groups using their appeal ratings for each level of pattern intricacy. The resulting agglomeration matrix did not indicate a multiple cluster solution, thus not prompting a follow up *k*-means clustering analysis.

Complexity: A 2-way 5x3 repeated-measures ANOVA (Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Pattern-type (fractal, Average-nonfractal, Large-nonfractal)) was completed to examine the impact of Intricacy and Pattern-type on pattern complexity judgments (**Figure 4.4B)**. Assumptions of the violation of sphericity were indicated by Mauchly's test for Intricacy ($\chi^2(9)=185.69$, $p<.001$**), Pattern-type ($\chi^2(2)=6.46$, $p=.04$*), and the interaction between Intricacy and Pattern-type ($\chi^2(35)=238.83$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.472$, .936 and .511 respectively). A significant main effect of Intricacy ($F(1.89,175.41)=983.37$, $p<.001$**, 95% *CI* [.89,.93], $\eta_p^2=.91$), Pattern-type ($F(1.87,174.19)=183.63$, $p<.001$**, 95% *CI* [.58,.72], $\eta_p^2=.66$), and interaction between Intricacy and Pattern-type ($F(4.09,380.12)=25.88$, $p<.001$**, 95% *CI* [.14,.28], $\eta_p^2=.22$) were identified. Average complexity ratings (collapsed over Pattern-type) ranged from .32 (*SD*=.27) for the least intricate patterns to .77 (*SD*=.11) for the most intricate patterns, indicating that participant perception of complexity increased with greater amount of visual intricacy. Average complexity ratings (collapsed over Intricacy) were highest for Average-nonfractal (*M*=.67; *SD*=.07), middling for fractal (*M*=.54; *SD*=.08), and lowest for Large-nonfractal (*M*=.49; *SD*=.08) patterns, indicating highest overall perceived complexity for the original-non-fractal patterns, lowest perceived complexity for the Large-nonfractal patterns, with fractal patterns in the middle. The significant differences among the ratings of complexity across the three pattern types were as follows: between Average-nonfractals and fractals [$t(93)=12.43$, $p<.001$**, 95% *CI* [.11,.16], $d=1.28$], Average-nonfractals and Large-nonfractals [$t(93)=21.40$, $p<.001$**, 95% *CI* [.17,.20], $d=2.21$], and fractals and Large-nonfractals [$t(93)=4.83$, $p<.001$**, 95% *CI* [.03,.07], $d=.50$]. The interaction between Pattern-type and Intricacy demonstrates a similar increase in ratings of complexity across intricacy for Average-nonfractal and fractal patterns but a steeper increase across intricacy for the Large-nonfractal patterns.

There were significant differences among the ratings of complexity across the three pattern types for individual levels of intricacy: ***D*=1.1** between Average-nonfractals and fractals [$t(93)=6.50$, $p<.001$**, 95% *CI* [.08,.15], $d=.67$], Average-nonfractals and Large-nonfractals [$t(93)=19.20$, $p<.001$**, 95% *CI* [.21,.25], $d=1.97$] as well as fractals and Large-nonfractals [$t(93)=8.10$, $p<.001$**, 95% *CI* [.09,.15], $d=.84$]; ***D*=1.3** between Average-nonfractals and fractals [$t(93)=8.94$, $p<.001$**, 95% *CI* [.11,.18], $d=.93$], Average-nonfractals and Large-nonfractals [$t(93)=21.88$, $p<.001$**, 95% *CI* [.25,.30], $d=2.25$], and fractals and Large-nonfractals [$t(93)=8.58$, $p<.001$**, 95% *CI* [.10,.16], $d=.88$]; ***D*=1.5** between Average-nonfractals and fractals [$t(93)=10.14$, $p<.001$**, 95% *CI* [.11,.17], $d=1.04$], Average-nonfractals and Large-nonfractals [$t(93)=12.82$, $p<.001$**, 95% *CI* [.15,.20], $d=1.32$], and fractals and Large-nonfractals [$t(93)=2.15$, $p=.03$*, 95% *CI* [.00,.06], $d=.21$]; ***D*=1.7** between Average-nonfractals and fractals [$t(93)=9.17$, $p<.001$**, 95% *CI* [.11,.17], $d=.95$] and Average-nonfractals and Large-nonfractals [$t(93)=12.69$, $p<.001$**, 95% *CI* [.14,.19], $d=1.31$]; ***D*=1.9** between Average-nonfractals and fractals [$t(93)=8.64$, $p<.001$**, 95% *CI* [.10,.17], $d=.89$], Average-nonfractals and Large-nonfractals [$t(93)=7.56$, $p<.001$**, 95% *CI* [.06,.10], $d=.78$], and fractals and Large-nonfractals [$t(93)=-3.12$, $p<.001$**, 95% *CI* [-.09,-.02], $d=.32$]) (*Table 4.1*). Cluster analyses did not indicate a multiple cluster solution.

Exciting: A 2-way 5x3 repeated-measures ANOVA (Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Pattern-type (fractal, Average-nonfractal, Large-nonfractal)) was completed to examine the impact of Intricacy and Pattern-type on ratings of pattern excitement (**Figure 4.4C**). A violation of the assumption of sphericity was indicated by Mauchly's test for Intricacy ($\chi^2(9)=442.0$, $p<.001$**), Pattern-type ($\chi^2(2)=6.67$, $p=.04$*), as well as the interaction between these factors ($\chi^2(35)=515.16$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.312$, .935, and .391 respectively). A significant main effect of Intricacy ($F(1.28,119.41)=3.921$, $p=.04$*, 95% *CI* [0,.12], $\eta_p^2=.04$) and interaction between Intricacy and Pattern-type ($F(3.13,290.98)=10.96$, $p<.001$**, 95% *CI* [04,.17], $\eta_p^2=.11$) were identified. Collapsed over Pattern-type, the mean excitement ratings ranged from a low of .45 (*SD*=.20) for the least intricate patterns to a high of .52 (*SD*=.15) with moderate-high intricacy. The interaction between Pattern-type and Intricacy demonstrates different trends for the different pattern types, with an increase in ratings of excitement across intricacy for the fractal patterns, an increase then leveling off of ratings for the large nonfractal patterns, and flat or slightly decreasing ratings for the original nonfractal patterns.

There were significant differences among the ratings of excitement across the three pattern types for individual levels of intricacy: ***D*=1.1** between Average-nonfractals and fractals [$t(93)=3.37$, $p=.001$*, 95% *CI* [.04,.15], $d=.35$] and Average-nonfractals and Large-nonfractals [$t(93)=4.20$, $p<.001$**, 95% *CI* [.06,.16], $d=.43$]; ***D*=1.3** between Average-nonfractals and fractals [$t(93)=2.19$, $p=.03$*, 95% *CI* [.01,.10], $d=.23$]; ***D*=1.5** between Average-nonfractals and Large-nonfractals [$t(93)=-2.72$, $p=.008$*, 95% *CI* [-.10,-.02], $d=.28$], and fractals and Large-nonfractals [$t(93)=-3.13$, $p=.002$*, 95% *CI* [-.11,-.02], $d=.32$]; ***D*=1.7** between Average-nonfractals and Large-nonfractals [$t(93)=-2.79$, $p=.006$*, 95% *CI* [-.11,-.02], $d=.29$]; ***D*=1.9** between Average-nonfractals and fractals [$t(93)=-3.04$, $p=.003$*, 95% *CI* [-.16,-.03], $d=.42$] and fractals and Large-nonfractals [$t(93)=2.23$, $p=.03$*, 95% *CI* [.01,.12], $d=.23$]) (*Table 4.1*).

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern excitement (**Figure 4.4C**). To test whether the trends found above varied by subgroup, we performed a mixed ANOVA with 5 levels of pattern Intricacy, 3 levels of Pattern-type, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=260.38$, $p<.001$**), Pattern-type ($\chi^2(2)=7.94$, $p=.02$*), and the interaction between Intricacy and Pattern-type ($\chi^2(35)=514.25$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.412$, .923 and .386 respectively). The main effect of Intricacy ($F(1.65,151.66)=2.66$, $p=.08$, 95% *CI* [0,.09], $\eta_p^2=.03$) and Pattern-type ($F(1.85,169.82)=.91$, $p=.40$, 95% *CI* [0,.05], $\eta_p^2=.01$) were not significant, but significant interactions were identified between Intricacy and Pattern-type ($F(3.09,284.14)=11.15$, $p<.001$**, 95% *CI* [.04,.17], $\eta_p^2=.11$), Pattern-type and Cluster membership ($F(1.85,169.82)=47.59$, $p<.001$**, 95% *CI* [.23,.44], $\eta_p^2=.34$, Intricacy and Cluster membership ($F(1.65,151.66)=101.61$, $p<.001$**, 95% *CI* [.42,.60], $\eta_p^2=.53$) as well as a three-way interaction among Intricacy, Pattern-type, and Cluster membership ($F(3.09,284.14)=3.26$, $p=.02$*, 95% *CI* [0,.08], $\eta_p^2=.03$). The larger cluster contains 57% of participants and demonstrates increases in excitement ratings with additional pattern intricacy. The smaller cluster encompasses 43% of participants and produces a trend in excitement ratings that decreases with additional intricacy, steeply for non-fractal patterns and subtly for fractal patterns. Although these represent opposing trends in judgments of excitement, each group is exemplified by a convergence of peak excitement ratings, respectively at either the lowest or highest levels of pattern intricacy. In addition, the Average-nonfractal patterns show the highest and lowest levels of excitement in the larger and smaller subgroups, respectively.

Interesting: A 2-way 5x3 repeated-measures ANOVA (Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Pattern-type (fractal, Average-nonfractal, Large-nonfractal)) examined the impact of Intricacy and Pattern-Type on perceived pattern interest (**Figure 4.4D**). A violation of the assumption of sphericity was indicated by Mauchly's test for Intricacy ($\chi^2(9)=307.43$, $p<.001$**), Pattern-type ($\chi^2(2)=11.67$, $p=.003$*), as well as the interaction between these two factors ($\chi^2(35)=341.30$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.408$, .894, and .500 respectively). There were significant main effects for Intricacy ($F(1.63,151.61)=20.36$, $p<.001$**, 95% *CI* [.08,.28], $\eta_p^2=.18$) and Pattern-type ($F(1.79,166.20)=10.06$, $p<.001$**, 95% *CI* [.03,.18], $\eta_p^2=.10$), and an interaction between Intricacy and Pattern-type ($F(4,372.16)=11.67$, $p<.001$**, 95% *CI* [.05,.17], $\eta_p^2=.11$). Collapsed over Pattern-type, the mean ratings of interest ranged from a high of .56 (*SD*=.55) for the least intricate patterns to a low of .44 (*SD*=.23) for the most intricate patterns, suggesting that participants interest decreases with additional pattern intricacy. Average interest ratings (collapsed over Intricacy) were highest for fractal (*M*=.53; *SD*=.10) and Large-nonfractal (*M*=.52; *SD*=.10), and lowest for Average-nonfractal (*M*=.46; *SD*=.16), indicating greater overall interest for fractal and Large-nonfractal patterns compared to Average-nonfractal patterns: Average-nonfractals and fractals [$t(93)=-3.59$, $p<.001$**, 95% *CI* [-.10,-.03], $d=.37$]; Average-nonfractals and Large-nonfractals [$t(93)=-3.88$, $p<.001$**, 95% *CI* [-.09,-.03], $d=.40$]. The interaction between Pattern-type and Intricacy demonstrates a decrease in interestingness for fractal and Average-nonfractal patterns, with a steeper decrease for the Average-nonfractal patterns, as well as an increase up to mid-intricacy patterns then a decrease for higher intricacy patterns for the Large-nonfractal patterns.

There were significant differences among the ratings of interestingness across the three pattern types for individual levels of intricacy: ***D*=1.1** between Average-nonfractals and Large-nonfractals [$t(93)=3.00$, $p=.004$*, 95% *CI* [.03,.13], $d=.30$] as well as fractals and Large-nonfractals [$t(93)=2.41$, $p=.02$*, 95% *CI* [.01,.10], $d=.25$]; ***D*=1.3** between Average-nonfractals and fractals [$t(93)=-2.24$, $p=.03$*, 95% *CI* [-.10,-.01], $d=.23$]; ***D*=1.5** between Average-nonfractals and fractals [$t(93)=-3.33$, $p=.001$*, 95% *CI* [-.13,-.03], $d=.34$], Average-nonfractals and Large-nonfractals [$t(93)=-6.50$, $p<.001$**, 95% *CI* [-.18,-.10], $d=.67$], and fractals and Large-nonfractals [$t(93)=-2.58$, $p=.01$*, 95% *CI* [-.10,-.01], $d=.27$]; ***D*=1.7** between Average-nonfractals and fractals [$t(93)=-4.53$, $p<.001$**, 95% *CI* [-.16,-.06], $d=.47$] and Average-nonfractals and Large-nonfractals [$t(93)=-6.23$, $p<.001$**, 95% *CI* [-.17,-.09], $d=.65$]; ***D*=1.9** between Average-nonfractals and fractals [$t(93)=-3.93$, $p<.001$**, 95% *CI* [-.17,-.06], $d=.41$] and Average-nonfractals and Large-nonfractals [$t(93)=-3.40$, $p<.001$**, 95% *CI* [-.12,-.03], $d=.35$] (*Table 4.1*).

A 2-step cluster analysis identified and separated individuals into three distinct subgroups with respect to ratings of pattern interest (**Figure 4.4D**). We performed a mixed ANOVA with 5 levels of pattern Intricacy, 3 levels of Pattern-type, and 3 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=183.16$, $p<.001$**), Pattern-type ($\chi^2(2)=13.05$, $p=.001$*), and the interaction between Intricacy and Pattern-type ($\chi^2(35)=268.46$, $p<.001$**), thus correcting degrees of freedom with Greenhouse-Geisser estimates of sphericity ($\varepsilon=.546$, .881 and .564 respectively). Both main effects of Intricacy ($F(2.18,198.72)=25.932$, $p<.001$**, 95% *CI* [.12,.31], $\eta_p^2=.22$) and Pattern-type ($F(1.76,160.36)=10.88$, $p=.40$, 95% *CI*

[.03,.20], η_p^2=.11) were significant, as well as interactions between Intricacy and Pattern-type ($F(4.51,410.56)=13.60$, $p<.001$**, 95% *CI* [.07,.18], η_p^2=.13), Pattern-type and Cluster membership ($F(3.52,160.36)=32.29$, $p<.001$**, 95% *CI* [.29,.50], η_p^2=.42, Intricacy and Cluster membership ($F(4.37,198.72)=35.46$, $p<.001$**, 95% *CI* [.33,.51], η_p^2=.44), and a three-way interaction among Intricacy, Pattern-type, and Cluster membership ($F(9.02,410.56)=9.17$, $p<.001$**, 95% *CI* [.09,.22], η_p^2=.17). The first cluster encompassed 38% of participants and produces a trend in which ratings decrease with additional intricacy; conversely the third cluster contained 30% of participants and a trend in which ratings increase with additional pattern intricacy. In addition, the Average-nonfractal patterns show the lowest and highest levels of interest in the largest and smallest subgroups, respectively. The second cluster was comprised of 32% of participants and represented a general decrease in interest for Average-nonfractal patterns with additional intricacy, similar to the largest subgroup, alongside higher ratings for the other two pattern types at higher levels of intricacy (intricacy levels 1.5 and 1.7 for Average-nonfractal patterns and 1.3-1.9 for fractal patterns).

Natural: A 2-way 5x3 repeated-measures ANOVA (Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Pattern-type (fractal, Average-nonfractal, Large-nonfractal)) assessed the impact of Intricacy and Pattern-type on perceived pattern naturalness (**Figure 4.4E**). Mauchly's test indicated a violation of the assumption of sphericity for Intricacy ($\chi^2(9)=405.23$, $p<.001$**) and the interaction between Intricacy and Pattern-type ($\chi^2(35)=498.31$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.329 and .302 respectively). There were significant main effects of pattern Intricacy ($F(1.31,122.25)=36.43$, $p<.001$**, 95% *CI* [.15,.40], η_p^2=.28) and Pattern-type ($F(2,186)=61.73$, $p<.001$**, 95% *CI* [.29,.48], η_p^2=.40), and a significant interaction between these factors

($F(2.42,224.87)=3.46$, $p=.03$*, 95% *CI* [0,.45], $\eta_p^2=.04$). Collapsed over Pattern-type, the mean ratings of naturalness decreased with additional pattern intricacy from a mean of .56 (*SD*=.19) for the least intricate patterns to a mean of .39 (*SD*=.23) for most intricate patterns, suggesting that participants' perception of naturalness decreases with additional pattern intricacy. Average naturalness ratings (collapsed over Intricacy) were highest for fractal (*M*=.54; *SD*=.09), middling for Large-nonfractal (*M*=.48; *SD*=.10), and lowest for Average-nonfractal (*M*=.38; *SD*=.14), indicating the greatest, middling, and least overall perception of naturalness for fractal, Large-nonfractal, and Average-nonfractal patterns, respectively. The significant differences among the ratings of naturalness across the three pattern types were as follows: between Average-nonfractals and fractals [$t(93)=-9.85$, $p<.001$**, 95% *CI* [-.19,-.13], $d=1.02$], Average-nonfractals and Large-nonfractals [$t(93)=-7.21$, $p<.001$**, 95% *CI* [-.13,-.07], $d=.74$], and fractals and Large-nonfractals [$t(93)=4.35$, $p<.001$**, 95% *CI* [.03,.08], $d=.45$]. The interaction between Pattern-type and Intricacy demonstrates a similar decrease in perceived naturalness for fractal and Average-nonfractal patterns, with overall higher ratings of naturalness for the fractal patterns, as well as a steeper decrease in ratings for the Large-nonfractal patterns.

There were significant differences among the ratings of naturalness across the three pattern types for individual levels of intricacy: ***D*=1.1** between Average-nonfractals and fractals [$t(93)=-6.68$, $p<.001$**, 95% *CI* [-.22,-.12], $d=.69$] and Average-nonfractals and Large-nonfractals [$t(93)=-8.19$, $p<.001$**, 95% *CI* [-.19,-.12], $d=.84$]; ***D*=1.3** between Average-nonfractals and fractals [$t(93)=-7.80$, $p<.001$**, 95% *CI* [-.21,-.12], $d=.80$] and Average-nonfractals and Large-nonfractals [$t(93)=-6.85$, $p<.001$**, 95% *CI* [-.19,-.11], $d=.67$]; ***D*=1.5** between Average-nonfractals and fractals [$t(93)=-7.91$, $p<.001$**, 95% *CI* [-.19,-.12], $d=.82$], Average-nonfractals and Large-nonfractals [$t(93)=-4.42$, $p<.001$**, 95% *CI* [-.12,-.07], $d=.45$], and fractals and Large-nonfractals [$t(93)=3.64$, $p<.001$**, 95% *CI* [.03,.11], $d=.37$]; ***D*=1.7** between Average-nonfractals and fractals [$t(93)=-6.64$, $p<.001$**, 95% *CI* [-.21,-.12], $d=.68$], Average-nonfractals and Large-nonfractals [$t(93)=-4.43$, $p<.001$**, 95% *CI* [-.12,-.05], $d=.46$], and fractals and Large-nonfractals [$t(93)=4.08$, $p<.001$**, 95% *CI* [.04,.12], $d=.42$]; ***D*=1.9** between Average-nonfractals and fractals [$t(93)=-3.94$, $p<.001$**, 95% *CI* [-.20,-.07], $d=.41$], Average-nonfractals and Large-nonfractals [$t(93)=-2.13$, $p=.04$*, 95% *CI* [-.07,0], $d=.22$], and fractals and Large-nonfractals [$t(93)=3.27$, $p=.002$*, 95% *CI* [.04,.16], $d=.34$]) (*Table 4.1*). No significant subgroups were identified for participant ratings of pattern naturalness.

Relaxing: A 2-way 5x3 repeated-measures ANOVA (Intricacy (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Pattern-type (fractal, Average-nonfractal, Large-nonfractal)) assessed the impact of Intricacy and Pattern-type on perceived relaxation (**Figure 4.4F**). Mauchly's test indicated a violation of the assumption of sphericity for Intricacy ($\chi^2(9)=320.05$, $p<.001$**), Pattern-type ($\chi^2(2)=21.91$, $p<.001$**), and interaction between these effects ($\chi^2(35)=347.04$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.356$, .825, and .446 respectively). There were significant main effects of pattern Intricacy ($F(1.43,132.49)=207.80$, $p<.001$**, 95% *CI* [.60,.75], $\eta_p^2=.69$) and Pattern-type ($F(1.65,153.48)=108.21$, $p<.001$**, 95% *CI* [.48,.65], $\eta_p^2=.54$) as well as an interaction between these factors ($F(3.56,331.48)=26.94$, $p<.001$**, 95% *CI* [.14,.29], $\eta_p^2=.23$). Collapsed across Pattern-type, average ratings of pattern relaxation ranged from a high of .61 ($SD=.16$) for the simplest patterns to a low of .28 ($SD=.16$) for the highest intricacy patterns, suggesting that participants perceived patterns as less relaxing with increasing intricacy. Collapsed over intricacy, average ratings of relaxation were higher for fractal ($M=.48$; $SD=.11$) and Large-nonfractal ($M=.48$; $SD=.09$) patterns compared to Average-nonfractal patterns ($M=.31$; $SD=.09$), indicating an overall greater relaxation response for the fractal and Large-nonfractal patterns, both of which contain large-scale structure: Average-nonfractals and fractals [$t(93)=-11.28$, $p<.001$**, 95% *CI* [-.19,-.14], $d=1.16$]; Average-nonfractals and Large-nonfractals [$t(93)=-17.23$, $p<.001$**, 95% *CI* [-.18,-.15], $d=1.78$]. The interaction between Pattern-type and Intricacy demonstrates decreasing ratings of relaxation across intricacy for both the non-fractal patterns but a decrease then leveling off of ratings across intricacy for the fractal patterns.

There were significant differences among the ratings of relaxation across the three pattern types for individual levels of intricacy: ***D*=1.1** between Average-nonfractals and fractals [$t(93)=-3.36$, $p=.001$*, 95% *CI* [-.12,-.03], $d=.35$], Average-nonfractals and Large-nonfractals [$t(93)=-11.51$, $p<.001$**, 95% *CI* [-.25,-.18], $d=1.19$], and fractals and Large-nonfractals [$t(93)=-6.22$, $p<.001$**, 95% *CI* [-.18,-.10], $d=.64$]; ***D*=1.3** between Average-nonfractals and fractals [$t(93)=-6.62$, $p<.001$**, 95% *CI* [-.18,-.10], $d=.68$], Average-nonfractals and Large-nonfractals [$t(93)=-13.84$, $p<.001$**, 95% *CI* [-.27,-.20], $d=1.42$], and fractals and Large-nonfractals [$t(93)=-5.15$, $p<.001$**, 95% *CI* [-.13,-.06], $d=.53$]; ***D*=1.5** between Average-nonfractals and fractals [$t(93)=-10.34$, $p<.001$**, 95% *CI* [-.22,-.15], $d=1.07$] and Average-nonfractals and Large-nonfractals [$t(93)=-11.01$, $p<.001$**, 95% *CI* [-.20,-.14], $d=1.14$]; ***D*=1.7** between Average-nonfractals and fractals [$t(93)=-9.57$, $p<.001$**, 95% *CI* [-.25,-.16], $d=.99$], Average-nonfractals and Large-nonfractals [$t(93)=-9.15$, $p<.001$**, 95% *CI* [-.17,-.11], $d=.95$], and fractals and Large-nonfractals [$t(93)=3.18$, $p=.002$*, 95% *CI* [.02,.10], $d=.33$]; ***D*=1.9** between Average-nonfractals and fractals [$t(93)=-8.99$, $p<.001$**, 95% *CI* [-.28,-.18], $d=.93$], Average-nonfractals and Large-nonfractals [$t(93)=-5.34$, $p<.001$**, 95% *CI* [-.09,-.04], $d=.55$], and fractals and Large-nonfractals [$t(93)=6.09$, $p<.001$**, 95% *CI* [.11,.21], $d=.63$]) (*Table 4.1*).

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern relaxation. We performed a mixed ANOVA with 5 levels of pattern Intricacy, 3 levels of Pattern-type, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=192.34$, $p< .001$**), Pattern-type ($\chi^2(2)=17.04$, $p< .001$**), and the interaction between these factors ($\chi^2(35)=287.06$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.459, .854, and .516 respectively). There were significant main effects for Intricacy ($F(1.84,168.94)=271.89$, $p<.001$**, 95% *CI* [.68,.79], $\eta_p^2=.75$) and Pattern-type ($F(1.71,157.16)=122.57$, $p<.001$**, 95% *CI* [.47,.64], $\eta_p^2=.57$), as well as significant interactions between Intricacy and Pattern-type ($F(4.13,379.78)=35.28$, $p<.001$**, 95% *CI* [.20,.34], $\eta_p^2=.28$), Intricacy and Clusters ($F(1.84,168.94)=68.06$, $p<.001$**, 95% *CI* [.31,.51], $\eta_p^2=.43$), Pattern-type and Cluster membership ($F(1.71,157.16)=13.71$, $p<.001$**, 95% *CI* [.04,.22], $\eta_p^2=.13$), and a three-way interaction between Intricacy, Pattern-type, and Clusters ($F(4.13,379.78)=11.99$, $p<.001$**, 95% *CI* [.06,.17], $\eta_p^2=.12$). The largest cluster encompassed 62% of participants whereas the smaller cluster contained the remaining 38% of individuals. Across both clusters, perceptions of relaxation swiftly decrease with additional intricacy for Average-nonfractal and Large-nonfractal patterns. The difference between these clusters is driven by contradictory trends in relaxation ratings for fractal stimuli, with participants in the smaller cluster perceiving higher intricacy fractals as more relaxing whereas those in the larger cluster rate lower intricacy fractals as more relaxing (**Figure 4.4F**).

Discussion

Experiment 1 explored how a variety of psychological effects are altered by variation in underlying pattern structure. Overall, results indicate that with regards to increasing pattern intricacy, viewer perceptions of pattern complexity increase, whereas perceptions of pattern appeal, interestingness, naturalness, and relaxation decrease. Furthermore, perceptions of pattern excitement remain more moderate regardless of pattern intricacy. With regard to complexity, the highest overall perceived complexity was for the original-non-fractal patterns, the middle was for the fractal patterns, and the lowest was for the Large-nonfractal patterns. For the naturalness judgments, the highest overall perceived naturalness was for the fractal patterns, the middle was for the Large-nonfractal patterns, and the lowest was for the original-non-fractal patterns. In addition, there were overall higher ratings of appeal, relaxation, and interestingness for fractal and Large-nonfractal compared to the matched Average-nonfractal patterns. For appeal and relaxation judgments, Large-nonfractal compared to fractal patterns show a steeper drop off in ratings across levels of intricacy. For interesting judgments, peak ratings for Large-nonfractal patterns are for the mid-level of intricacy, ratings for fractal patterns are relatively flat, and ratings for original-non fractals decrease with intricacy. These results show a distinctive pattern of perceptual responses to the 3 pattern types.

Viewer ratings of pattern excitement and relaxation were shown to be more completely explained through the comparison of 2 subgroups present in the data. The larger subgroups demonstrated lower ratings for relaxation and higher ratings of excitement with the presence of additional pattern intricacy. The smaller subgroups demonstrate decreasing ratings across intricacy for both non-fractal patterns but a decrease then leveling off of excitement ratings and a flat then increasing relaxation rating across intricacy for the fractal patterns. Ratings of pattern interestingness were more completely explained through the comparison of 3 subgroups. The largest group demonstrates decreasing ratings with additional intricacy, the smallest subgroup demonstrates the opposite trend, and the middle subgroup demonstrates a more complicated trend in responses. Comprising just over a third of viewers, this group demonstrates an agreement with the largest subgroups' assessment of Average-nonfractal patterns (i.e., decreasing ratings across levels of intricacy), but shows relaxation ratings peaking with moderate-to-high levels of intricacy for the Large-nonfractal and fractal patterns. Presented fractal trends in complexity, naturalness, and relaxation ratings reinforce previously established findings (Robles et al., 2021), however, ratings of fractal appeal noticeable deviate from prior findings (Bies et al., 2016; Abboushi et al., 2019; Robles et al., 2020; Robles et al., 2021) by peaking with lowest pattern intricacy and decreasing steadily through moderate-high complexity at which point appeal ratings increase for highest complexity. This deviation is suspected to be a product of context effects created through the mixed presentation of the three pattern types, such that the overall discrepancy between in pattern complexity between fractal and nonfractal patterns shifts perceptual tolerance towards the simplest patterns.

Experiment 2 – Impact of the incorporation of Euclidean structure on fractal pattern perception

Materials and Methods

Stimuli:

To understand how the integration of Euclidean surroundings alters trends in fractal perception, Experiment 2 utilizes a new series of fractal images generated in the same manner as described in Experiment 1. Viewer ratings are compared across trials with stimuli presented in isolation on the computer screen or trials where stimuli are surrounded by a frame composed of one large outer square connected to the pattern through lines connecting the corners of the fractal pattern and the frame (**Figure 4.5**). Stimuli consisted of a total of 40 patterns, with 8 examples each of 5 *D*-values (*D*=1.1, 1.3, 1.5, 1.7. 1.9).

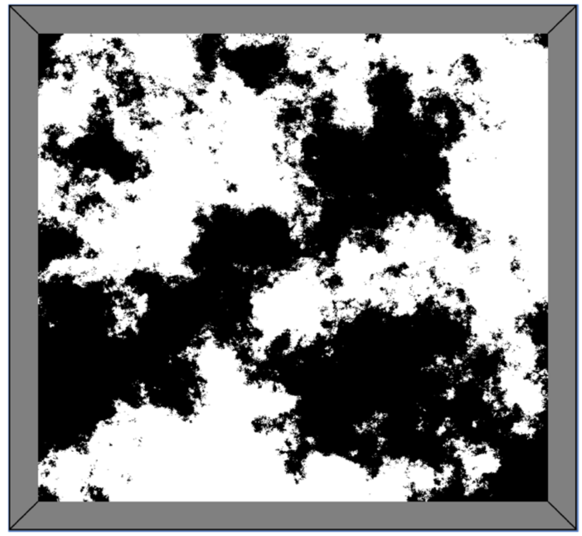

Figure 4.5. Experiment 2 stimulus presented with simple Euclidean surrounding structure reminiscent of a frame or wall of an interior humanmade space.

Participants:

To identify unique changes in perceptual trends due to combining fractal and Euclidean structure, 60 participants were recruited via Prolific (http://www.prolific.co/), [November, 2022] with the majority of participants (26) residing in the United Kingdom (32 females, age ranging between 18-75 years old, mean age 35 years old). Informed consent was acquired following a protocol approved by the Institutional Review Board at the University of Oregon and all participants were compensated with $10 for their time.

Visual Displays:

Experiment 2 was also programmed in PsychoPy3 but presented using the online research study platform of Pavlovia (Peirce et al., 2019). Participants completed the experiment using their personal computers with program stimuli scaled to the individual computer's respective full-screen dimensions.

Design and Procedure:

Similar to the procedure in Experiment 1, participants rated fractal patterns on 6 different factors (complex, appealing, natural, interesting, relaxing, exciting). Experiment 2 consisted of 12 randomized rating blocks with 20 fractal images ranging in intricacy (*D*= 1.1, 1.3, 1.5, 1.7, 1.9), for a total of 40 unique images. Half of the blocks contained fractal images surrounded with a Euclidean frame and the remaining blocks presented images in isolation. Each block consisted of a singular judgment type and an on-screen slider located beneath each image was used to record self-report ratings for each pattern. The rating task was completed in the manner as described in Experiment 1.

Results

Data from 40 participants were retained from the 60 individuals who participated in the experiment. Data were excluded due to a) failure to complete the study (8), b) failure to follow instructions (8), or c) if in at least 3 blocks participants recorded the same rating for greater than four consecutive trials (4).

Pattern Rating Task:

Similar to Experiment1, a 3-way repeated-measures 2x5x6 ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (*D*-values of 1.1, 1.3, 1.5, 1.7, 1.9) x Judgment (complexity, exciting, appeal, interesting, natural, relaxing)) was performed on rating data for the fractal patterns. Mauchly's test indicated a violation of the assumption of sphericity for Intricacy ($\chi^2(9)=225.58$, $p< .001$**), Judgment ($\chi^2(14)=47.17$, $p<.001$**), the interactions between Context and Intricacy ($\chi^2(9)=61.41$, $p<.001$**), Intricacy and Judgment ($\chi^2(209)=858.36$, $p<.001$**), Context and Judgment ($\chi^2(14)=29.39$, $p<.001$**), and the three-way interaction between Context, Intricacy, and Judgment ($\chi^2(209)=426.35$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.295, .612, .510, .213, .750, and .420 respectively). Indicated by a double asterisk for significance of $p<.001$ and single asterisk for significance of $p<.05$, are a significant main effect of Judgment ($F(3.06,119.43)=9.29$, $p<.001$**, 95% *CI* [.07,.30], $\eta_p^2=.19$) and a significant interaction between Intricacy and

Judgment (F(4.27,166.50)=38.24, p<.001**, 95% CI [.38,.57], η_p^2=.50). Coinciding with findings from Experiment1, the Intricacy and Judgment interaction is demonstrated through ratings that decreased in the presence of additional intricacy (appeal, interesting, natural, relaxing), while others were relatively flat (exciting) or increased (complexity) (**Figure 4.6)**. A series of planned ANOVA's and t-tests follow to determine whether observed perceptual trends can be better explained by subgroups determined by a 2-step cluster analysis.

Appeal: A 2-way 2x5 repeated-measures ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (D-values of 1.1, 1.3, 1.5, 1.7, 1.9)) was completed to examine the impact of surrounding context and pattern intricacy on ratings of image appeal (**Figure 4.7A**). A violation of the assumption of sphericity was indicated by Mauchly's test for Intricacy (χ^2(9)=209.34, p<.001**) and the interaction between Context and Intricacy (χ^2(9)=63.53, p<.001**), thus correcting degrees of freedom using Greenhouse-Geisser estimates of sphericity (ε=.295 and .518 respectively). A significant main effect was identified for Intricacy (F(1.18,46)=8.74, p=.003*, 95% CI [.02,.36], η_p^2=.18). Average ratings of appeal ranged from a high of .55 (SD=.24) for the least intricate patterns to a low of .36 (SD=.27) for the most intricate patterns suggesting that appeal decreases with additional pattern intricacy. Paired sample t-tests revealed no significant differences in appeal between patterns that vary in surrounding context.

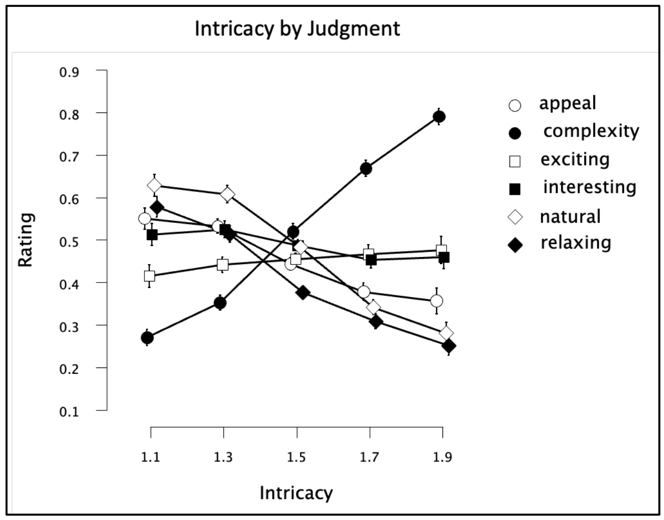

Figure 4.6. Experiment 2 results for unipolar ratings of fractal patterns varying in surrounding context. Results show a significant interaction among two of the experiment's factors: pattern intricacy (presented in fractal dimension "D-value") and judgment type (appeal, complexity, exciting, interestingness, naturalness, relaxing). Participant rating (on a scale from 0-1) is plotted as a function of D-value and different judgment conditions.

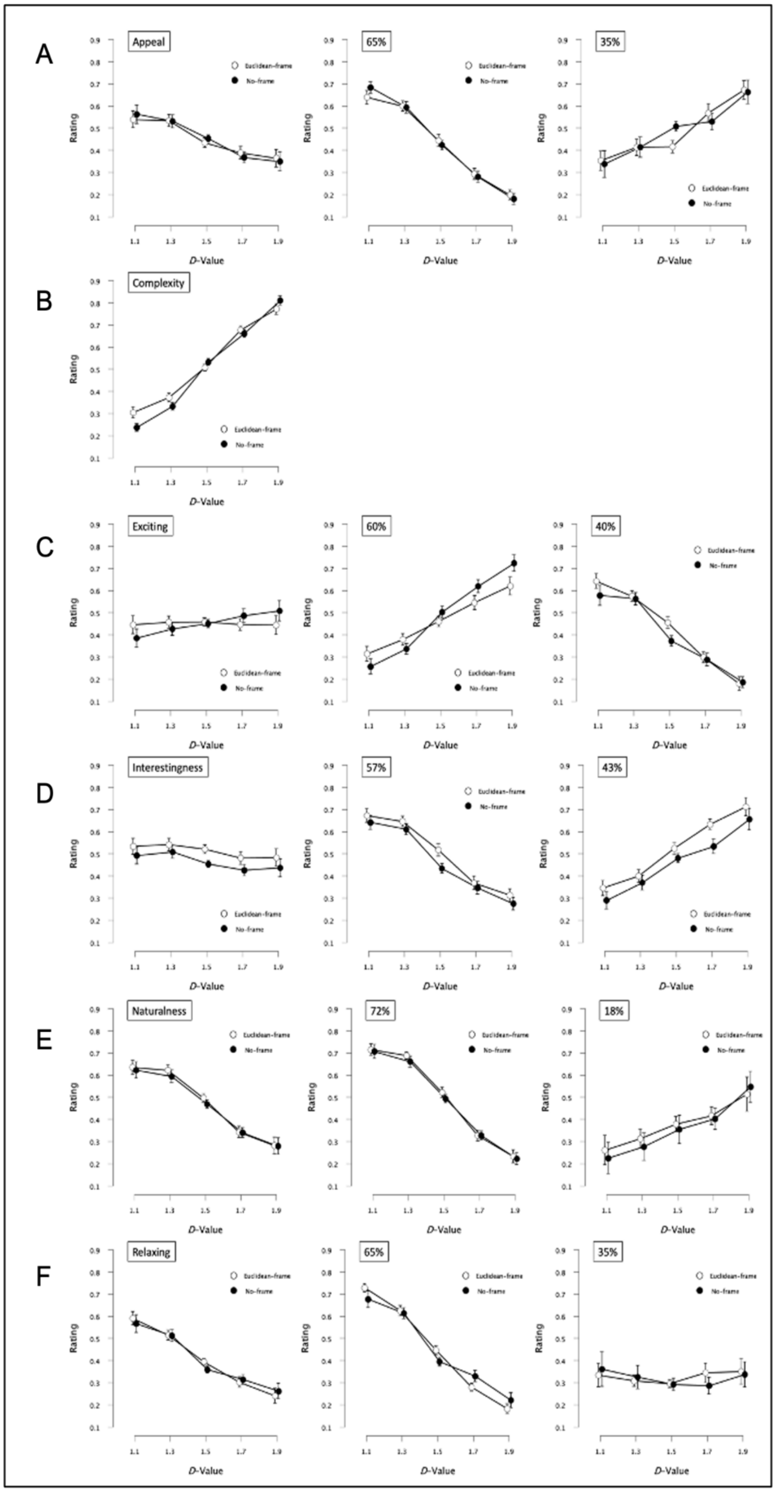

Figure 4.5. Experiment 2 results for fractal patterns with variation in surrounding context (Euclidean-frame, no-frame) for 6 different judgment conditions (appeal, complexity, exciting, interestingness, naturalness, relaxing). **(A-F left images)** Show plots of mean ratings as a function of fractal dimension (*D*-value) and 2 context conditions (Euclidean-frame, no-frame) for the different judgment conditions (error bars represent standard error of the mean). **(A-F middle and right images)** Show plots of mean ratings as a function of fractal dimension (*D*-value) and 2 context conditions (Euclidean-frame, no-frame) for each subpopulation identified with cluster analysis (error bars represent standard error of the mean).

In accordance with the subgroup analysis used in Experiment1, a two-step cluster analysis was performed to determine the impact of possible subgroups on overall trends (first using hierarchical cluster analyses with Ward's method to separate individuals into groups then follow up with *k*-means clustering analysis for the number of indicated groups). This 2-step clustering method indicated the presence of two clusters in the data. We performed a mixed ANOVA with 5 levels of pattern Intricacy, 2 levels of Context, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=89.53$, $p<.001$**) and the interaction between Intricacy and Context ($\chi^2(9)=64.19$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.418$ and .499 respectively). Despite the main effect of context not being significant ($F(1,38)=.01$, $p=.93$, 95% *CI* [0,.01], $\eta_p^2=.00$), Intricacy ($F(1.67,63.48)=5.54$, $p=.009$*, 95% *CI* [.01,.27], $\eta_p^2=.13$) and the interaction between Intricacy and Subgroup ($F(1.67,63.48)=84.15$, $p<.001$**, 95% *CI* [.55,.76], $\eta_p^2=.69$) were significant. The larger subgroup (65% of participants) demonstrates ratings that steeply decrease with additional pattern intricacy, while smaller subgroup (35% of participants) produces a trend in ratings that increase with increasing intricacy. These findings support previous individual differences research identifying opposing trends in judgments of pattern appeal (Robles et al., 2021; Spehar et al., 2016; Street et al., 2016).

Complexity: A 2-way 2x5 repeated-measures ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (*D*-values of 1.1, 1.3, 1.5, 1.7, 1.9)) was completed to examine the impact of surrounding Context and pattern Intricacy on complexity judgments (**Figure 4.7B)**. Assumptions of the violation of sphericity were indicated by Mauchly's test for Intricacy ($\chi^2(9)=65.71$, $p<.001$**) and the interaction between Intricacy and Context ($\chi^2(9)=79.83$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.522$ and

.452 respectively). The only significant effect was identified for Intricacy (F(2.09,81.45)=226.48, p<.001**, 95% *CI* [.79,.89], η_p^2=.85). Average complexity ratings ranged from .27 (*SD*=.14) for the least intricate patterns to .83 (*SD*=.15) for the most intricate patterns, indicating that perceptions of complexity increased with greater amount of visual intricacy. Paired samples *t*-tests revealed significant differences in perceived complexity between patterns at a *D*-value=1.1[t(39)=2.51, p=.02*, 95% *CI* [.01,.12], d=.37] (*Table 4.2*), with patterns that are surrounded by a Euclidean frame being rated as more complex (*M*=.30, *SD*=.15) than those without (*M*=.24, *SD*=.13). Cluster analyses did not indicate a multiple cluster solution.

Table 4.2: Experiment 2- Paired Samples t-Tests between patterns across Intricacy and Judgment

	1.1	1.3	1.5	1.7	1.9
Appeal: Euclidean frame – no frame	*t* = -.73 *p* = .47	*t* = .11 *p* = .91	*t* = -.60 *p* = .55	*t* = .74 *p* = .46	*t* = .62 *p* = .54
Complex: Euclidean frame – no frame	*t* = 2.35 *p* = .02*	*t* = 1.68 *p* = .10	*t* = =1.22 *p* = .23	*t* = .62 *p* = .54	*t* = -1.24 *p* = .22
Exciting: Euclidean frame – no frame	*t* = 1.99 *p* = .05	*t* = 1.32 *p* = .19	*t* = .29 *p* = .78	*t* = -1.33 *p* = .19	*t* = -2.03 *p* = .05
Interesting: Euclidean frame – no frame	*t* = 1.59 *p* = .12	*t* = 1.32 *p* = .20	*t* = 2.51 *p* = .02*	*t* = 1.97 *p* = .06	*t* = 1.54 *p* = .13
Natural: Euclidean frame – no frame	*t* = .55 *p* = .58	*t* = 1.18 *p* = .25	*t* = .97 *p* = .34	*t* = .13 *p* = .89	*t* = .12 *p* = .91
Relaxing: Euclidean frame – no frame	*t* = .81 *p* = .42	*t* = .08 *p* = .93	*t* = 1.77 *p* = .08	*t* = -.50 *p* = .62	*t* = -1.0 *p* = .33

* indicating significance of *p<.05*, ** indicating significance *p<.001*.

Exciting: A 2-way 2x5 repeated-measures ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (*D*-values of 1.1, 1.3, 1.5, 1.7, 1.9)) was completed to examine the impact of Context and Intricacy on ratings of pattern excitement (**Figure 4.7C**). A violation of the assumption of sphericity was indicated by Mauchly's test for Intricacy ($\chi^2(9)=195.39$, $p<.001$) and the interaction between Intricacy and Context ($\chi^2(9)=85.67$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.308$ and .437 respectively). No significant main effects were identified (Intricacy ($F(1.23,48.07)=.57$, $p=.57$, 95% *CI* [0,.13], $\eta_p^2=.01$); Context (1,39)=.01, $p=.77$, 95% *CI* [0,.01], $\eta_p^2=.01$). Paired samples *t*-tests revealed no significant differences in perceived excitement for patterns with or without surrounding context (*Table 4.2*).

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern excitement (**Figure 4.7C**). A mixed ANOVA was performed with 5 levels of pattern Intricacy, 2 levels of Context, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=67.62$, $p<.001$**) and the interaction between Intricacy and Pattern-type ($\chi^2(9)=84.43$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon= .524$ and .435 respectively). The main effects of Intricacy ($F(2.10,79.59)=.57$, $p=.57$, 95% *CI* [0,.08], $\eta_p^2=.02$) and Context ($F(1,38)=.09$, $p=.77$, 95% *CI* [0,.09], $\eta_p^2=.00$) were not significant. The only significant interaction was identified between Intricacy and Subgroup ($F(2.10,79.59)=93.12$, $p<.001$**, 95% *CI* [.59,.77], $\eta_p^2=.71$). The remaining interactions (Intricacy and Context ($F(1.74,66.11)=2.94$, $p=.07$, 95% *CI* [0,.20], $\eta_p^2=.07$), Context and Subgroup ($F(1,38)=3.51$, $p=.07$, 95% *CI* [0,.27], $\eta_p^2=.09$), Intricacy, Context, and Subgroup ($F(1.74,66.11)=1.44$, $p=.24$, 95% *CI* [0,.14], $\eta_p^2=.04$)) were not significant. The larger subgroup (60% of participants) produced an increasing trend in ratings with additional pattern intricacy, whereas conversely, the smaller subgroup (40% of participants) produced a decreasing trend with additional intricacy.

Interesting: A 2-way 2x5 repeated-measures ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (*D*-values of 1.1, 1.3, 1.5, 1.7, 1.9)) examined the impact of Intricacy and Context on perceived pattern interest (**Figure 4.7D**). A violation of the assumption of sphericity was indicated by Mauchly's test for Intricacy ($\chi^2(9)=217.02$, $p<.001$**) and the interaction between Context and Intricacy ($\chi^2(9)=34.41$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.297$ and .645 respectively). The sole significant effect was found for Context ($F(1,39)=10.64$, $p=.002$*, 95% *CI* [.03,.41], $\eta_p^2=.21$). There were no significant effects for Intricacy ($F(1.12,46.33)=1.15$, $p=.30$, 95% *CI* [0,.16], $\eta_p^2=.03$) or the interaction between Intricacy and Context ($F(2.58,100.68)=.27$, $p=.82$, 95% *CI* [0,.04], $\eta_p^2=.01$). Paired sample *t*-tests revealed a significant difference in perceived excitement for patterns that varied in context and possessed a *D*-value=1.5 [$t(39)=2.51$, $p=.02$*, 95% *CI* [.01,.12], $d=.40$] (*Table 4.2*). Overall, patterns surrounded by additional Euclidean context were rated more interesting than those without.

A 2-step cluster analysis identified and separated individuals into two distinct subgroups with respect to ratings of pattern interest (**Figure 4.7D**). We performed a mixed ANOVA with 5 levels of pattern Intricacy, 3 levels of Context, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=94.51$, $p<.001$**) and the interaction between Intricacy and Pattern-type ($\chi^2(9)=34.83$, $p<.001$**), thus correcting degrees of freedom with Greenhouse-Geisser estimates of sphericity ($\varepsilon=.435$ and .635 respectively). The main effect of Context ($F(1,38)=10.66$, $p=.002$*, 95% *CI* [.03,.42], $\eta_p^2=.22$) and interaction between Intricacy and Subgroup ($F(1.74,66.18)=82.19$, $p<.001$**, 95% *CI* [.54,.76], $\eta_p^2=.68$)

were significant. However Intricacy (F(1.74,66.18)=.58, p=.54, 95% CI [0,.10], η_p^2=.02) and interactions between Intricacy and Context (F(2.54,96.45)=.25, p=.83, 95% CI [0,.04], η_p^2=.01), Context and Subgroup (F(1,38)=.23, p=.63, 95% CI [0,.13], η_p^2=.01) and three-way interaction between Intricacy, Context, and Subgroup (F(2.54,96.45)=.69, p=.54, 95% CI [0,.08], η_p^2=.02) were not. The larger subgroup (57% of participants) demonstrates a general decrease in interest for patterns of additional intricacy whereas the smaller subgroup (43% of participants) produces a trend that linearly increases with additional intricacy.

Natural: A 2-way 2x5 repeated-measures ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (D-values of 1.1, 1.3, 1.5, 1.7, 1.9)) assessed the impact of Intricacy and Context on perceived pattern naturalness (**Figure 4.6E**). Mauchly's test indicated a violation of the assumption of sphericity for Intricacy (χ^2(9)=160.51, p<.001**) and the interaction between Intricacy and Context (χ^2(9)=20.34, p<.001**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.326 and .804 respectively). The main effect of pattern Intricacy (F(11.01,50.90)=33.36, p<.001**, 95% CI [.77,.89], η_p^2=.46) was significant, whereas Context (F(1,39)=.94, p=.34, 95% CI [0,.17], η_p^2=.02) and the interaction between Intricacy and Context (F(3.22,125.49)=.32, p=.83, 95% CI [0,.04], η_p^2=.01) were not. Overall trends demonstrate decreased perceptions of naturalness for patterns of greater intricacy with average ratings of .63 (SD=.25) for patterns with D-value=1.1 and .28 (SD=.22) for D-value=1.9, with no significant differences between patterns varying in Context at the 5 levels of intricacy.

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern naturalness. We performed a mixed ANOVA with 5 levels of pattern Intricacy, 3 levels of Context, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy (χ^2(9)=85.38, p<.001**) and the interaction of Intricacy and Context ($\chi^2(9)=19.82$, $p<.001$**). Thus, correcting degrees of freedom using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.433$ and .804 respectively). The main effect of Intricacy ($F(1.73,65.85)=4.71$, $p=.02$*, 95% *CI* [0,.25], $\eta_p^2=.11$) and the interaction of Intricacy and Subgroup ($F(1.73,65.85)=41.40$, $p<.001$**, 95% *CI* [.34,.63], $\eta_p^2=.52$) were found to be significant while Context ($F(1,38)=.54$, $p=.47$, 95% *CI* [0,.15], $\eta_p^2=.01$), interactions between Intricacy and Context ($F(3.22,122.23)=.34$, $p=.81$, 95% *CI* [0,.04], $\eta_p^2=.01$), Context and Subgroup ($F(1,38)=0$, $p=.99$, 95% *CI* [0,0], $\eta_p^2=.00$), and Intricacy, Context, and Subgroup ($F(3.22,122.23)=.22$, $p=.89$, 95% *CI* [0,.03], $\eta_p^2=.01$) were not significant. Ratings from the large subgroup (72% of individuals) indicated a steep decrease in perceptions of pattern naturalness with additional intricacy, whereas those of the small subgroup (18% of participants) indicated a more subtle increase in perceptions of pattern naturalness with additional intricacy.

Relaxing: A 2-way 2x5 repeated-measures ANOVA (Context (Euclidean-frame, no-frame) x Intricacy (*D*-values of 1.1, 1.3, 1.5, 1.7, 1.9)) addressed the impact of Intricacy and Context on perceived pattern relaxation (**Figure 4.7F**). Mauchly's test indicated a violation of the assumption of sphericity for Intricacy ($\chi^2(9)=146.61$, $p<.001$**), Pattern-type ($\chi^2(2)=21.91$, $p<.001$**), and interaction between these effects ($\chi^2(9)=36.76$, $p<.001$**), thus degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.343$ and .653 respectively). The only significant effect identified was that of pattern Intricacy ($F(1.37,53.48)=27.66$, $p<.001$**, 95% *CI* [.21,.56], $\eta_p^2=.42$). Effects of Context ($F(1,39)=.23$, $p=.63$, 95% *CI* [0,.12], $\eta_p^2=.01$) and the interaction between Intricacy and Context ($F(2.61,101.93)=1.01$, $p=.26$, 95% *CI* [0,.09], $\eta_p^2=.03$) were not significant, (see *Table 4.2*). Collapsed across Context, average ratings of pattern relaxation ranged from a high of .58 (*SD*=.24) for patterns with a *D*-value=1.1 to a low of .25 (*SD*=.21) with patterns possessing a *D*-

value=1.9, suggesting that participants perceived patterns as less relaxing with increasing intricacy.

A 2-step cluster analysis identified and separated individuals into two subgroups with respect to ratings of pattern relaxation. We performed a mixed ANOVA with 5 levels of pattern Intricacy, 3 levels of Context, and 2 Subgroups. Mauchly's test indicated a violation of the assumptions of sphericity for Intricacy ($\chi^2(9)=97.31$, $p<.001$**) and the interaction of Intricacy and Context ($\chi^2(9)=36.31$, $p<.001$**). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.413$ and .655 respectively). Significant effects were identified for Intricacy ($F(1.65,62.81)=23.52$, $p<.001$**, 95% *CI* [.19,.52], $\eta_p^2=.38$) and the interaction between Intricacy and Subgroup ($F(1.65,62.81)=22.48$, $p<.001$**, 95% *CI* [.18,.51], $\eta_p^2=.37$). The effects of Context ($F(1,38)=.22$ $p=.64$, 95% *CI* [0,.13], $\eta_p^2=.01$), and interactions between Intricacy and Context ($F(2.61,99.61)=.43$, $p=.70$, 95% *CI* [0,.63], $\eta_p^2=.01$), Context and Context, and Subgroup ($F(2.61,99.61)=2.70$, $p=.06$, 95% *CI* [0,.16], $\eta_p^2=.07$) were not significant. The difference between the subgroups is driven by contradictory response patterns in relaxation ratings for fractal patterns, with participants in the larger subgroup (65% of participants) perceiving lower intricacy fractals as highly relaxing, with ratings of relaxation steeply decreasing with the presence of additional intricacy. In contrast, those in the smaller subgroup (35% of participants) remain more moderate in their ratings of pattern relaxation across pattern intricacy (**Figure 4.7F**).

Discussion

Experiment 2 maintains the same methodological structure and perceptual decisions as described in Experiment 1 but employs only fractal patterns either presented alone or in the presence of a surrounding Euclidean frame (referred to as Euclidean context). In alignment with findings from Experiment 1, judgments of complexity increased with additional *D*-value whereas ratings of appeal, naturalness, and relaxation decreased. Similarly, perceptions of pattern interest and excitement remained more moderate regardless of pattern intricacy with interest and excitement showing slightly negative or positive relationships with *D*-value, respectively. Overall, perceptual judgments of patterns were not shown to vary based on the presence of surrounding context. There were 2 subgroups in all judgment conditions aside from pattern complexity. In 4 judgments (pattern appeal, excitement, interestingness, and naturalness) the smaller subgroup trend is in the opposite direction of that of the larger subgroup, while for ratings of pattern relaxation the smaller subgroup deviates from the overall trend with moderate ratings of relaxation across all levels of complexity.

General Discussion

Since modern society's shift away from the previously agrarian lifestyle, humans have begun spending the majority of their time indoors resulting in a new series of health consequences propelled by the additional exertion of energy required to process non-natural spatial frequencies (O'Hare & Hibbord, 2011; Ogawa & Motoyoshi, 2020; Hagerhall et al., 2008, Pennacchio & Wikins, 2015; Le et al., 2017). In an effort to minimize the higher rates of visual strain, headaches, and general stress associated with Euclidean surroundings, research has sought to integrate natural arrangements into human-made spaces through the inclusion of fractal displays (Taylor & Sprott, 2008; Abboushi et al., 2019; Smith et al., 2020; Robles et al., 2021). Driven by the apparent ease with which the visual system is able to process these patterns (Taylor et al., 2018; Taylor & Spehar, 2016; Hagerhall et al., 2008), introduction of fractal designs into already existing structures can alter viewer perceptions of the space without impacting the function of the space as a whole (Hagerhall et al., 2015; Taylor et al., 2005). To better inform selection of effective installments, it is critical to understand how pattern characteristics alter viewer perception both in isolation and in non-natural spaces.

Across two experiments, the current study serves as the first research to isolate the unique contribution of fractal structure on visual perception as a whole and provides findings as to how these perceptions act in the presence of the simplest prototypical Euclidean context. Both studies demonstrate similar trends in viewer experience of visual patterns despite variations in intricacy, underlying structure, and context. Experiment 1 used 3 different types of stimuli (fractal, Average-nonfractal, Large-nonfractal) to demonstrate how variations in pattern structure produces shifts in viewer perception driven by the pattern's intricacy. Perceptions of pattern complexity provide insight into driving factors behind the 5 additional judgments. Although two patterns shared a lack of fractal structure and statistical intricacy, they are viewed as significantly different in complexity, with the Average-nonfractal pattern being perceived as the most complex at every level of generated intricacy compared to the Large-nonfractal pattern being typically seen as lowest in complexity, and fractal patterns falling somewhere between. The mixed presentation of these patterns, which are broadly different in complexity, likely factors into the remaining observed trends. Akin to how the presence of symmetry and exactness of pattern repetition found in "exact" fractal patterns can increase a viewer's tolerance of pattern intricacy (Robles et al., 2020; Bies et al., 2016), the presence of overwhelming complexity in Average-nonfractals has the capability to cement viewer inclination towards simplicity.

The results from Experiment 1 suggest that overall 1) there are greater positive responses (higher ratings of appeal, relaxation, and interestingness) to fractal compared to size-matched non-fractal control stimuli (i.e., the Average-nonfractal patterns), 2) these positive responses occur when large-scale structure is present (i.e., for fractal and Large-nonfractal patterns), and 3) removing fractal structure while retaining mean size information (Average-nonfractal patterns) not only increases the perception of complexity but simultaneously reduces the perceived naturalness of the patterns. The finding of generally positive responses to fractal and Large-nonfractal patterns points to the important role of large-scale structure that is present in both of these pattern types. There are also interesting differences in perceptual responses between these pattern types. The fractal compared to the Large-nonfractal patterns are perceived as both more complex and more natural. Interest peaks at lower levels of intricacy for the fractal patterns and mid-level intricacy for the Large-nonfractal patterns, while excitement peaks at the highest levels of intricacy for the fractal patterns and mid-level intricacy for the Large-nonfractal patterns. Finally, perceived pattern appeal and relaxation for the Large-nonfractal compared to fractal patterns starts higher, but drops off more rapidly with increasing intricacy. Fractals are perceived as distinctly different than nonfractal arrangements, exemplified in ratings of higher intricacy patterns where fractals are consistently associated with greater appeal, naturalness, relaxation, and excitement than even Large-nonfractal arrangements despite similarities in perceived complexity and interestingness. These differences among the perceptions of fractal and matched non-fractal patterns provide strong evidence for human sensitivity to fractal structure that characterizes natural objects and environments.

Whereas Experiment 1 serves to establish the role of complexity and pattern structure to predictions of viewer experience, Experiment 2 functions to apply these considerations more directly to the fundamental task of incorporating fractal patterns into Euclidean space (i.e., the built environment). Although fractal patterns may produce stable trends when presented in isolation on a screen with the monitor bezel serving as the only image boundary, it is imperative to confirm their expected effects when they are embedded in contrasting unnatural human-made design. By comparing fractal perceptions with and without the incorporation of a rudimentary Euclidean context (i.e., a Euclidean frame), results reinforce the perceptual trends established in Experiment 1 irrespective of the inclusion of Euclidean context. Specifically, perceptions of pattern appeal, interestingness, naturalness, and relaxation decrease with increasing *D*-value, while ratings of complexity increase, and those of interest remain more moderate across all levels of intricacy. Driven by the imposed pattern boundary created by the Euclidean frame, the effects of nonfractal structure produce experiences of greater interest, and unchanging judgments of excitement across intricacy compared to context-free fractals in which ratings of excitement increase with increases in intricacy. Thus, despite robust perceptions of patterns across perturbations of structure and surrounding context, selection of optimal patterns for occupant wellbeing must account for the interaction of general pattern complexity with regards to its intended environment.

Viewer subgroupings have a significant impact on overall trends, further substantiating previous findings of individual differences in preference for fractal intricacy (Robles et al., 2021; Bies et al., 2016; Spehar et al. 2016; Street, 2016). Opposing subpopulation trends are found for all perceptual ratings aside from complexity which serves to inform design choices by emphasizing the consideration of perceived installment intricacy (quantified with *D*-value in the case of fractal patterns) to align with the highest rates of desired experience for the greatest number of viewers.

Lastly, the similarity of the general trends reported between the two studies highlights the seemingly universal nature of fractal perception. While not immense, the expansion in participant age, ethnicity, national origin, natural surroundings, as well as presentation format (in lab or on-line survey) did not seem to impact shared perceptions. This result suggests that perceptions of fractal patterns are unlikely to be altered by experiences of more diverse biomes and thus promotes the application of natural patterns in a broad range of locations. Although this study recruits from both a convenient population as well as a broader group of cultures and countries, our findings are still limited due to an overarching homogeneity of “WEIRD” participant samples. Holistically, findings from Experiment 1 emphasizes the significance of pattern complexity and structure on fractal perception whereas Experiment 2 reinforces the importance of considering Gestalt aspects of complexity when incorporating fractal patterns into surrounding occupant space. The current study serves to provide a foundational understanding of how pattern structure impacts integration with built environments and encourages future work to explore how responses to fractal structure interact with more prominent Euclidean context (through more extended 2D displays, extension to 3D using Virtual Reality technology, as well as with physical installations) and can be optimized for specific categories of locations and products to maximize occupant benefit.

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CHAPTER V

MEMORY FOR THE FOREST AND THE TREES: THE IMPACT OF FRACTAL STRUCTURE ON MEMORY

From Robles, K. E., Gonzales-Hess, N., Taylor, R. P., & Sereno, M. E. (2023). Memory for the forest and the trees: The impact of fractal structure on memory. *Journal of Experimental Psychology: Human Perception and Performance*. (Manuscript under revision).

Even with brief presentations, viewer memory for natural scenes and objects is highly accurate (Shepard, 1967; Standing et al., 1970; Standing, 1973, Konkel et al., 2010). Global image features (Olivia & Torralba, 2006) and environmental regularity present in stimuli are readily processed by the visual system to enable holistic scene comprehension and ease of later recall (Greene & Olivia, 2009). Scene memory is further facilitated by successful encoding of discrete visual features in a meaningful and deep manner, suggesting that visual working memory for realistic environments relies more heavily upon higher-level processing as opposed to solely the encoding of low-level features (Brady & Stormer, 2022). Memory performance is shown to be hindered with additional overlap in shared conceptual and visual features (Huebner & Gegenfurtner, 2012), specifically resulting in increased occurrence of false memories when tested on image parts (Dechterenko & Lukavsky, 2022). Unlike meaningful realistic natural scenes, stimuli which are more ambiguous or "meaningless" additionally lack the benefit of clear semantic labeling and thus results in poorer viewer recall performance overall (Hegde & Kersten, 2010). Visual long-term memory (VLTM) for whole items as well as memory for local visual properties are severely hindered when semantic information is removed from target objects (Shoval et al., 2022). Furthermore, even changes in surrounding spatial frequencies have the ability to impact accurate pattern perception of adjacent targets and impede memory accuracy across various trials (Huang & Sekuler, 2010).

Fractal patterns are composed of natural arrangements that repeat across rough-to-fine scaling (Mandelbrot,1982). Natural fractal patterns repeat their base "seed" configuration across scales in a statistical manner which introduces a seemingly random appearance to the pattern (Taylor et al., 2005; Taylor & Sprott, 2008; Taylor et al., 2011; Hagerhall et al., 2015) in comparison to exact fractals which repeat exactly across scale and often possess symmetry (Bies et al., 2016; Robles et al., 2020). Overlapping composite fractal arrangements combine to form the natural structures and landscapes most commonly viewed around the world (Mandelbrot, 1982; Spehar et al., 2003; Taylor et al., 2018; Hagerhall et al., 2008). Despite the seemingly arbitrary quality of whole fractal patterns, local features often elicit pareidolia (Rogowitz & Voss, 1990; Rezaei et al., 2020; Taylor et al., 2017b) for natural items. Object naming is found to be greater when fractals possess low-to-moderate complexity and coincide with heightened perceptions of aesthetic appeal (Spehar et al., 2003). Furthermore, the discrete objects identified within fractal displays provide semantic labeling for these otherwise meaningless patterns.

Fractal Fluency Theory proposes that the self-similar arrangement of fractal patterns allows for more effortless processing since the visual system can extrapolate the comprehension of local regions to the global pattern without further energy (Falk & Balling, 2010; Taylor et al., 2018; Hagerhall et al., 2008). Beyond increased aesthetic appeal and pareidolia, natural fractal organization has been found to support broader cognitive effects, impacting both psychological states as well as performance (Juliani et al., 2016; Taylor et al., 2018; Abboushi et al., 2019; Roe et al., 2020; Spehar & Stevanov, 2021). Specifically, exposure to low-to-moderate complexity fractal patterns has been shown to have restorative effects on viewer attention encouraging greater time spent on cognitively taxing procedures (Hagerhall et al., 2015) and improvements in landscape comprehension for navigational abilities (Juliani et al., 2016, Ferreria et al., 2012).

Increased ease of fractal processing may allow for these patterns to be sufficiently understood without exhausting limited working memory capacity, enabling these resources to be allocated to other cognitive tasks thus coinciding with improved memory abilities.

The current study examines the influence of pattern structure on observer memory, and specifically answers if memory performance can be added to the list of cognitive abilities explained by Fractal Fluency Theory (Taylor & Spehar, 2016; Taylor et al., 2018). Recognition and source memory are probed across variations in internal pattern factors (pattern complexity and underlying structure) to quantify the unique impact of statistical configuration on pattern distinctiveness. This series of experiments seeks to define the unique effects of fractal arrangement on general pattern memorability. Moreover, results will further the understanding of how seemingly random images are processed by the visual system in an effortless manner that allows efficient general pattern comprehension without de-emphasizing the differentiating features that make each pattern unique.

Experiment 1 – Recognition memory for global fractal patterns

Materials and Methods

Stimuli:

Experiment 1 utilized stimuli consisting of fractal patterns and matched non-fractal counterparts to determine how underlying pattern structure alters memory performance for visual patterns. Fractal images are initially generated using the midpoint displacement method to produce a series of unique black-white fractal patterns (see Bies et al., 2016 for generation specifics). These images are generated with varying pattern complexities or "*D*-values" ranging from simple to complex (1.1, 1.3, 1.5, 1.7, 1.9) (**Figure 5.1A, left to right**). For every fractal pattern the average region size is calculated. The non-fractal control stimuli were created by generating normally distributed white noise, which was then Fourier transformed and band-pass filtered to match the average region size of a given fractal stimulus. The control stimuli are matched to the 5 levels of fractal dimension in 2 ways: 1) by equating mean region size (mean # of contiguous white or black pixels >3 pixels in a given fractal stimulus; "Average" control; see **Figure 5.1B**), and 2) by capturing larger scale structure by matching the upper mean (the mean of all above-average region sizes in a given image; "Large" scale control; see **Figure 5.1C**). These procedures transform the original fractal images into two distinct sets of stimuli matched for complexity and general quality of pattern arrangement but lacking fundamental fractal structure.

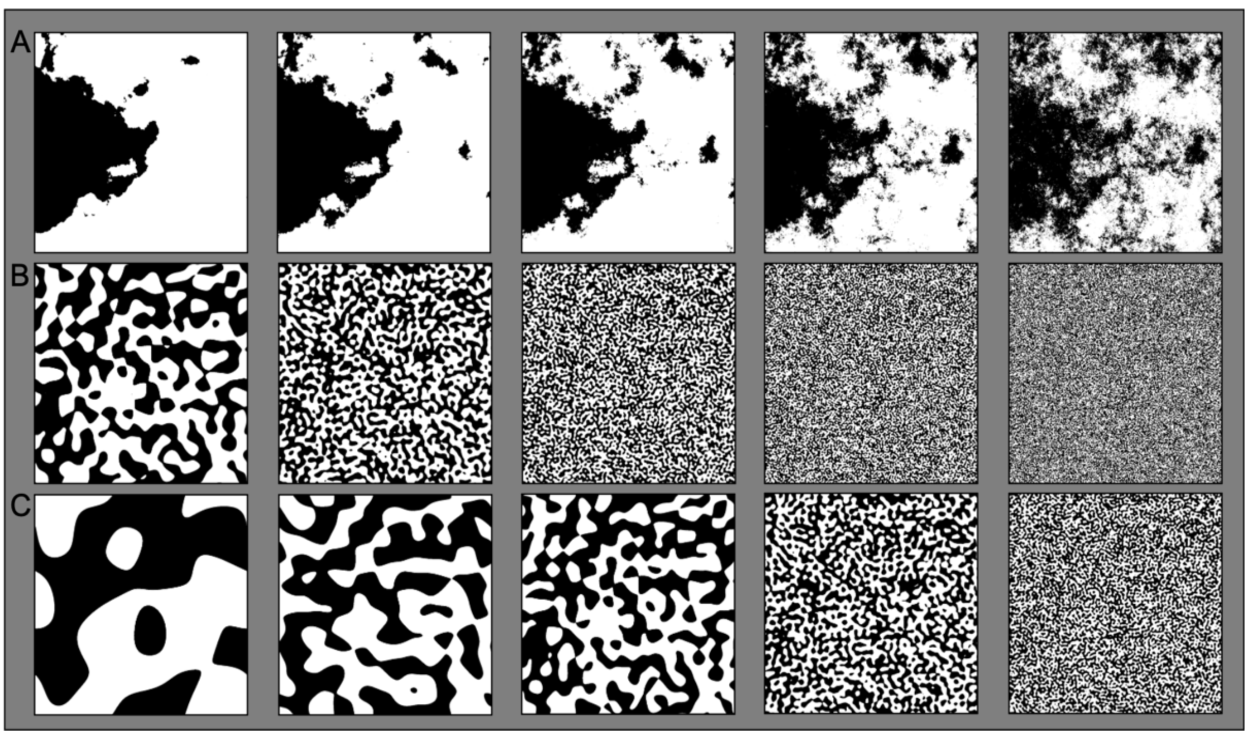

Figure 5.1. Example stimuli used in the Experiments. From left to right, stimuli statistically vary across 5 levels of visual complexity from simplest (far left) to most complex (far right). (**A**) Fractals: fractal patterns with a fractal dimension (D) = 1.1, 1.3, 1.5, 1.7, and 1.9. (**B**) Average-nonfractals: non-fractal patterns with region sizes averaged to match the average region size of the original fractal pattern. (**C**) Large-nonfractals: non-fractal patterns with region sizes averaged to match the large-scale region size of the original fractal pattern.

Participants:

To assess how underlying pattern structure and arrangement impacts memory performance, 90 undergraduate Psychology students (69 females, age ranging between 18-32 years old, mean age 23 years old) were recruited from the University of Oregon through the SONA participant pool system. Prior to participation, informed consent was acquired following a protocol approved by the Institutional Review Board at the University of Oregon and demographic information was collected. All participants were compensated with class credit for their involvement.

***Visual Displays*:**

Experiment 1 was generated in PsychoPy3 (Peirce et al., 2019) and presented on a 2013 iMac computer with 27-inch monitor (screen resolution of 2,560 X 1440 pixels and 60Hz refresh rate). Participants were seated roughly 28 inches from the screen; thus viewing stimuli as approximately 13.8 degrees of visual angle across (720 x 720 pixels).

Design and Procedure:

Participants completed a memory task three times, each consisting of an encoding block followed by a recognition test. In the encoding block participants were instructed to memorize a series of images shown in the center of the screen for 5 seconds with each item preceded by a fixation cross. Stimuli in each encoding block consisted of one stimulus type (fractal, original non-fractal averaged, large non-fractal large region averaged) with patterns ranging across 5 levels of complexity (matched to a D-value 1.1, 1.3, 1.5, 1.7, 1.9) giving rise to 20 unique patterns per block (20 unique seeds, 4 per D-value). This block was immediately followed by a memory test requiring participants to decide whether a presented image was considered “old” (present in the previous encoding block) or "new" (absent from the previous encoding block). Across 20 recall trials participants were instructed to press the "z" key for "old" images and the "m" key for "new images", both of which were labeled on the keyboard to ensure participants understood instructions. Recall trials lasted until participants pressed one of the two keys, and order of stimuli presentation was randomized. Within each block, participants were randomly presented with an attention check trial that instructed them to press a specific key to indicate they were fully attending to the task. Following the completion of the session, participants were debriefed according to protocol approved by the Institutional Review Board at the University of Oregon and compensated with class credit.

Transparency and Openness:

Sample size was predetermined by G*Power prior to data collection in 2022. Data exclusion criteria are listed at the start of the results section. Data and research materials are available at https://doi.org/10.7910/DVN/85ED7M. Data were analyzed using IBM SPSS Statistics for Macintosh (Version 29.0). This study's design and its analyses were not pre-registered.

Results

Data from 70 participants were retained from the 90 individuals who participated in the experiment. Data were excluded due to a) failure to complete the study (1), b) failure of 3 or more attention checks (6), or c) failure to follow instructions indicated by greater than 4 consecutive trials with the same response occurring in multiple blocks (13).

Pattern Recognition Task:

A 2-way 3x5 repeated measures ANOVA (Pattern-type (fractal, original-nonfractal, large-nonfractal) x Complexity (equal or matched to *D*-values of 1.1, 1.3, 1.5, 1.7, 1.9)) was performed using IBM SPSS Statistics for Macintosh (Version 29.0) on corrected recognition scores (hit rate – false alarm rate) from an image recognition test. Mauchly's test indicated a violation of the assumption of sphericity for the interaction between Pattern-type and Complexity ($\chi^2(35)=50.59$, $p<.043$*). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.847$). Pattern recognition is highest for fractal images ($M=57.43\%$, $SD=14.72\%$) compared to the average-nonfractal ($M=38.43\%$, $SD=16.07\%$) and large-nonfractal patterns ($M=49.36\%$, $SD=16.04\%$) (Figure 5.2A): fractals and average-nonfractals [$t(69)=7.55$, $p<.001$**, 95% *CI* [13.98,24.02], $d=.90$]; fractals and large-nonfractals [$t(69)=3.57$, $p<.001$**, 95% *CI* [3.56,12.58], $d=.43$], and average-nonfractals and large-nonfractals [$t(69)=-4.58$, $p<.001$**, 95% *CI* [-15.69,-6.17], $d=1.37$]. The interaction between pattern-type and complexity demonstrates that while recognition rates for non-fractal patterns steeply decrease across levels of complexity, rates for fractal patterns decrease then remain stable for the mid-to-highest levels of pattern complexity (see Figure 5.2C and Table 5.1). Specifically, *t*-Tests indicate that large-nonfractal patterns have greater accuracy than fractal and average-nonfractals at complexity level 1.1; there are no differences in accuracy among the patterns for complexity level 1.3; both fractals and large-nonfractals show higher accuracy than average-nonfractals for complexity level 1.5; and fractals have greater accuracy than both large- and average-nonfractals at complexity levels 1.7 and 1.9 (Table 5.1).

A regression model was created to predict average participant accuracy on recognition trials by including the effects of pattern factors (complexity and pattern type) as well as viewer factors (reaction times and rating confidence). Overall, this model significantly predicts individual recognition accuracy ($F(4,1045)=85.87$, $p<.001$**, 95% *CI* [.20,.29], $\eta_p^2=.25$), and accounts for 25% of variance in individual scores (*Table 5*.2). All pattern factors included in the

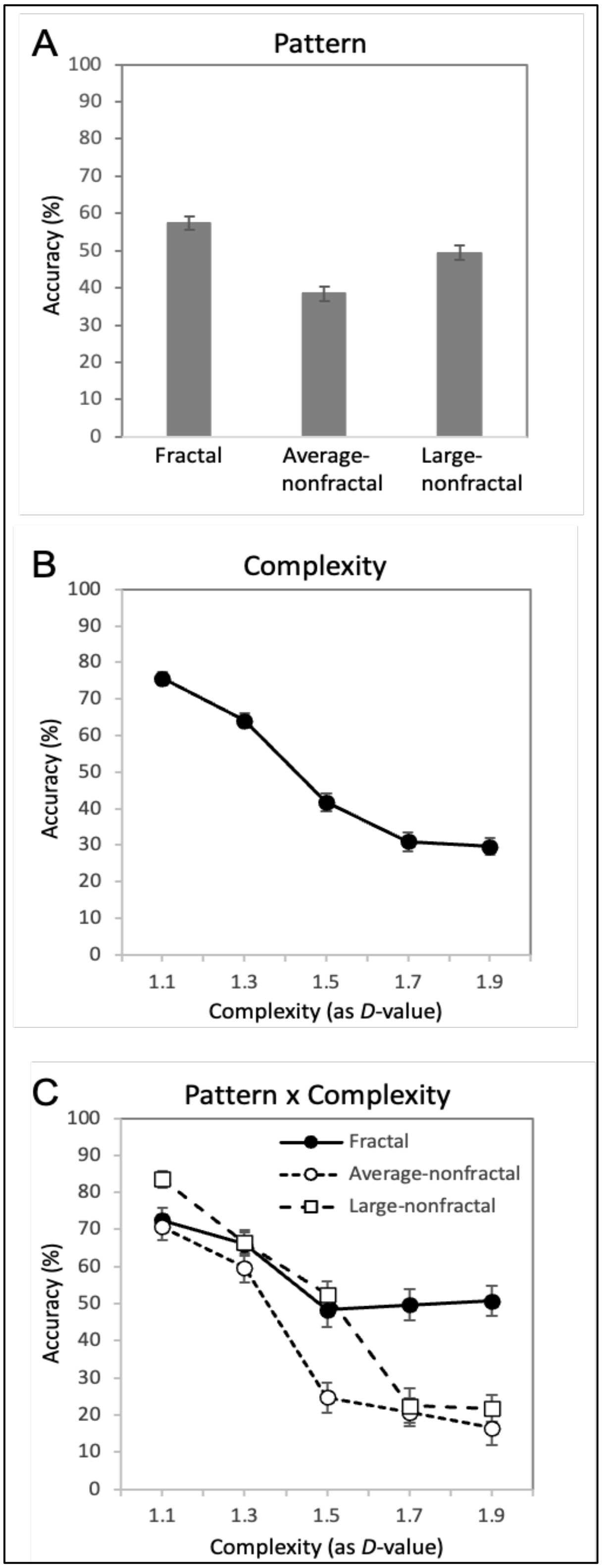

Figure 5.2. Experiment 1 results for pattern recognition. Results show significant main effects of pattern-type (fractal, average-nonfractal, large-nonfractal), pattern complexity (equal or matched to D=1.1, 1.3, 1.5, 1.7, 1.9) and a significant interaction between pattern complexity and pattern type. Participant accuracy (on a scale from 0-100%) is plotted as a function of **(A)** pattern type, **(B)** pattern complexity, and **(C)** pattern type and complexity. Error bars represent ±1 *SEM*.

model (Complexity (β=-61.06, p<.001**), Pattern type (β=5.14, p<.001**)) as well as viewer factors (Reaction time (β=2.45, p=.001**), Confidence (β=16.04, p<.017*)) serve as significant predictors of performance.

Table 5.1. Experiment 1 – Paired Samples t-Tests across the 3 pattern types for each *D*-value.

Paired Samples T-Test					
Measure 1		**Measure 2**	***t***	***df***	***p***
Fractal 1.1	-	Average-nonfractal 1.1	.431	69	.668
Fractal 1.1	-	Large-nonfractal 1.1	-2.842	69	.006*
Average-nonfractal 1.1	-	Large-nonfractal 1.1	-2.943	69	.004*
Fractal 1.3	-	Average-nonfractal1.3	1.299	69	.198
Fractal 1.3	-	Large-nonfractal 1.3	-.079	69	.937
Average-nonfractal 1.3	-	Large-nonfractal 1.3	-1.321	69	.191
Fractal 1.5	-	Average-nonfractal 1.5	3.876	69	< .001**
Fractal 1.5	-	Large-nonfractal 1.5	-.772	69	.443
Average-nonfractal 1.5	-	Large-nonfractal 1.5	-4.988	69	< .001**
Fractal 1.7	-	Average-nonfractal 1.7	5.265	69	< .001**
Fractal 1.7	-	Large-nonfractal 1.7	4.275	69	< .001**
Average-nonfractal 1.7	-	Large-nonfractal 1.7	-.320	69	.750
Fractal 1.9	-	Average-nonfractal 1.9	5.775	69	< .001**
Fractal 1.9	-	Large-nonfractal 1.9	5.265	69	< .001**
Average-nonfractal 1.9	-	Large-nonfractal 1.9	-.841	69	.403

Note: *p < .05; **p < .01.

Table 5.2. Experiment 1- Linear Regression

Outcome Variable	**Predictors**	**β**	***t***	***P***	***95% CI for* β**
Accuracy	Complexity	-61.06	-16.21	<.001**	(-68.45, -53.67)
	Pattern	5.14	4.04	<.001**	(2.64, 7.64)
	Reaction Time	2.45	5.35	<.001**	(1.55, 3.35)
	Confidence	16.04	2.40	.017*	(2.93, 29.15)

Note: N = 70; *p < .05; **p < .01.

Discussion

Experiment 1 investigated viewer recognition memory for visual black and white patterns. To determine the impact of image complexity and underlying pattern arrangement on memory performance, accuracy scores were compared across five levels of visual complexity and three pattern types. A regression analysis indicated that trial reaction times and rating of decision confidence positively coincide with viewer accuracy (Table 5.2). Overall, recognition memory was highest for fractal images, followed by large-nonfractal and average-nonfractal images (Figure 5.2A) and demonstrates an inverse relationship with image complexity (Figure 5.2B). Despite highest accuracy coinciding with large-nonfractal images of lowest complexity (equivalent to a fractal *D*-value of 1.1), accuracy for this category as well as the average-nonfractal condition steeply declined with increasing complexity (Figure 5.2C; Table 5.1). In contrast, recognition accuracy for fractal images remained less affected even at higher levels of visual complexity. Findings from Experiment 1 suggest that the self-similar nature of fractal patterns facilitates pattern recognition at mid-to-high levels of complexity. The slightly higher performance of large-nonfractal patterns at the lowest level of complexity underscores the importance of large-scale structure, also present in natural fractal patterns, for pattern recognition.

Experiment 2 – Spatial memory for local fractal patterns

Materials and Methods

Stimuli:

To probe how pattern structure impacts memory performance for local pattern elements, Experiment 2 employs a new series of fractal images generated in the same manner as described in Experiment 1. Participants are presented with three types of black-white patterns (fractal, non-fractal averaged, non-fractal large region averaged) at 5 levels of visual complexity (relating to *D*-values of 1.1, 1.3, 1.5, 1.7, and 1.9). In encoding trials participants view the entire image in the center of the screen for 5 seconds, whereas in recall trials participants are presented with a quadrant of this original image (either the top-left, top-right, bottom-left, or bottom-right)

(Figure 5.3). Stimuli consisted of a total of 120 patterns with 4 examples each pattern type presented per block, and each block consisting of one of 5 *D*-values (*D*=1.1, 1.3, 1.5, 1.7, 1.9).

Participants:

To identify unique changes in perceptual trends due to incorporating fractal and Euclidean structure, 80 participants were recruited via Prolific (www.prolific.co) [November, 2022] with the majority (42) of participants residing in the United Kingdom (45 females, age ranging between 18-75 years old, mean age 37 years old). Informed consent was acquired in accordance with protocol approved by the Institutional Review Board at the University of Oregon and all participants were compensated with $10 for their time.

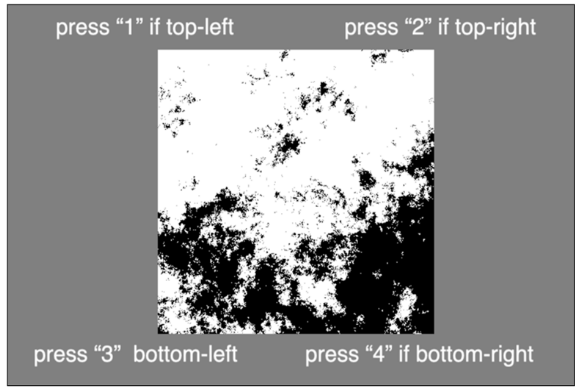

Figure 5.3. Example trial from Experiment 2. Using the same three types of patterns used presented in Experiment 1, Experiment 2 first displays a whole image for 5 seconds. Following a 1 second blank screen, a region of the initial pattern is displayed in the center of the screen and the viewer must indicate the source location of this test region (either the top-left, top-right, bottom-left, or bottom-right).

Visual Displays:

Experiment 2 was also programmed in PsychoPy3 but presented through the online research study platform of Pavlovia (Peirce et al., 2019). This experiment was completed on participants' personal computers with program stimuli being scaled to the individual computer's respective full-screen dimensions.

Design and Procedure:

Participants completed 10 randomized blocks in which they were tasked to memorize black and white images, each one presented for 5 seconds and then immediately followed by a recall task about the original location of a subsection of the overall pattern. Every block contained patterns with only one level of complexity equivalent to *D*-values of 1.1, 1.3, 1.5, 1.7, and 1.9, with each level of complexity encountered twice. The stimulus set within each block consisted of 12 items comprised of 4 unique seed patterns transformed into 3 types of patterns (fractal, average non-fractal, and large non-fractal). After memorizing the initial pattern for 5 seconds, the stimulus disappears and is followed 1 second later by a new stimulus in the middle of the screen that is comprised of a quadrant from the original pattern (either the top-left, top-right, bottom-left, or bottom-right region). Participants are instructed to indicate the original position of the test stimulus with a corresponding button press. The test stimulus remains on the screen until the participant makes their selection. Participants were randomly presented with an attention check per block in which they were instructed to press a specific key to indicate that they were giving the task their full attention. Upon completion of the experiment, participants were debriefed according to the protocols approved by the Institutional Review Board at the University of Oregon.

Transparency and Openness:

Similar to experiment 1, sample size for experiment 2 was predetermined by G*Power prior to data collection in 2022 and data exclusion criteria is listed at the start of the results section. Data and research materials are available at https://doi.org/10.7910/DVN/85ED7M, and all data were analyzed using IBM SPSS Statistics for Macintosh (Version 29.0). This study's design and its analyses were not-preregistered.

Results

Data from 50 participants were retained from the 80 individuals who participated in the experiment. Data were excluded due to a) failure to complete the study (7), b) failure of 3 or more attention checks (4), or c) failure to follow instructions (19) indicated by the same exact response being given for greater than 4 consecutive trials in more than 2 blocks.

Feature Source Memory Task:

Accuracy of the source task (recorded through key responses corresponding to one of the four possible source locations) was assessed through a 2-way repeated measures 5x3 ANOVA (Complexity represented by corresponding fractal dimension or "*D*-value" (1.1, 1.3, 1.5, 1.7, 1.9)) x Pattern (fractal, average-nonfractal, large-nonfractal). Mauchly's test indicated no violation of the assumption of sphericity for the two within-subjects variables or the interaction between variables. A significant main effect was detected for Complexity ($F(4,196)=16.74$, $p<.001$**, 95% *CI* [.14,.34], $\eta_p^2=.26$) and Pattern ($F(2,98)=32.08$, $p<.001$**, 95% *CI* [.24,.51], $\eta_p^2=.40$), and a significant interaction between these variables ($F(8,392)=2.44$, $p=.014$*, 95% *CI* [.00,.08], $\eta_p^2=.05$) (Figure 5.4). Feature source accuracy is highest for fractal images (*M*=66.1%, *SD*=10.39) compared to the average-nonfractal (*M*=51.45%, *SD*=12.57%) and large-nonfractal patterns (*M*=58.45%, *SD*=12.65%) (Figure 5.4A): fractals and average-nonfractals [$t(49)=7.66$, $p<.001$**, 95% *CI* [10.81,18.49], $d=1.08$]; fractals and large-nonfractals [$t(49)=3.81$, $p<.001$**, 95% *CI* [3.61,11.69], $d=.54$], and average-nonfractals and large-nonfractals [$t(49)=-4.58$, $p<.001$**, 95% *CI* [-10.08,-3.93], $d=.65$]. Overall accuracy decreases with additional pattern complexity from a mean of 63.92% (*SD*=12.01%) for the least complex patterns to 49.50% (*SD*=13.33%) for the most complex patterns (Figure 5.4B). The interaction between complexity and pattern type reveals that viewer accuracy steadily decreases for average-nonfractal patterns, peaks with moderate complexity for large-nonfractal patterns, and decreases with a slight dip at mid-range complexity for fractal patterns (Figure 5.4C). Specifically, t-Tests indicate that fractal patterns have greater accuracy than the matched average-nonfractal patterns at all levels of

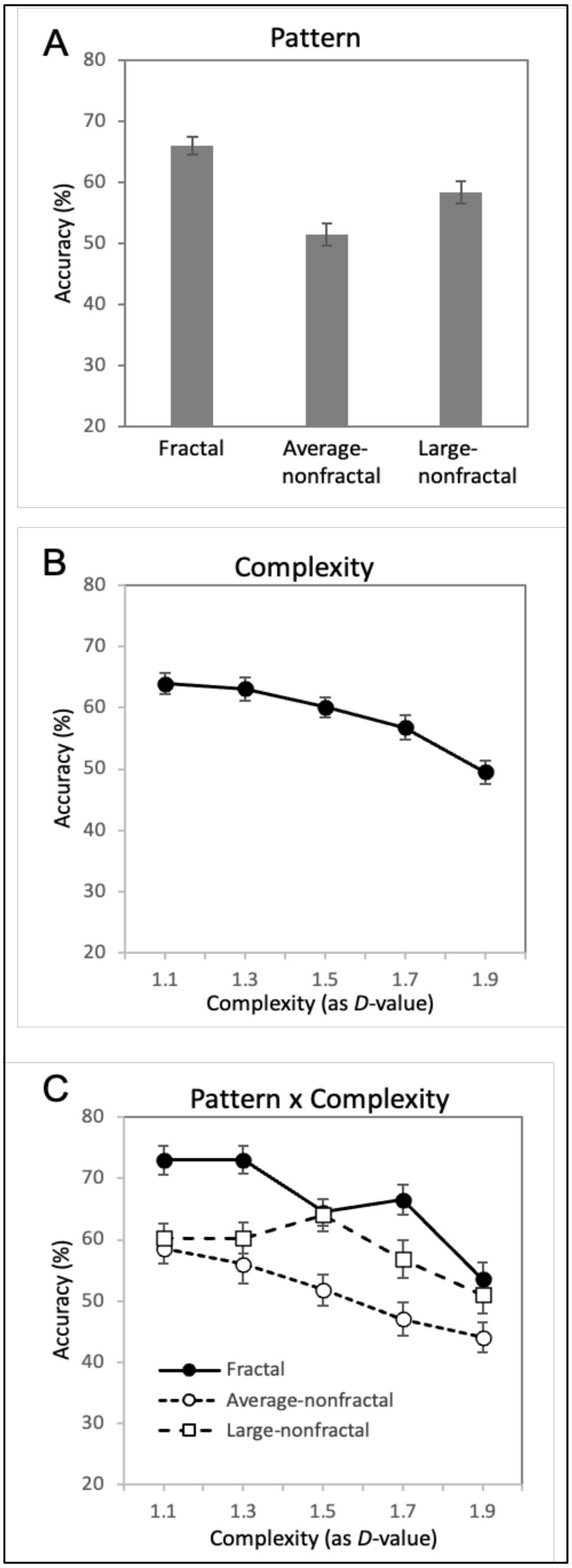

Figure 5.4. Experiment 2 results for source recognition memory. Results show significant main effects of pattern-type (fractal, average-nonfractal, large-nonfractal), pattern complexity (equal or matched to D=1.1, 1.3, 1.5, 1.7, 1.9) and a significant interaction between pattern complexity and pattern type. Participant accuracy (on a scale from 0-100%) is plotted as a function of **(A)** pattern type, **(B)** pattern complexity, and **(C)** pattern type and complexity. Error bars represent ±1 *SEM*.

complexity, and greater accuracy than the large-non fractals at the lowest (*D*=1.1 and 1.3) and mid-to-high (*D*=1.7) levels of complexity. Large-nonfractals have greater accuracy than the average-nonfractals at mid-to-high levels of complexity (see Table 5.3).

A linear regression analysis was carried out to quantify the impact of stimulus factors (complexity and pattern type) and viewer response factors (rating reaction time and viewer confidence) on source memory performance for pattern features (Table 5.4). Overall, this model significantly predicts individual source memory accuracy ($F(4,745)=23.21$, $p<.001$**, 95% *CI* [.07,.15], $\eta_p^2=.11$), and accounts for 11% of the variance in individual scores. Both pattern factors included in the model (Complexity ($\beta=-16.42$, $p<.001$**), Pattern type ($\beta=3.36$, $p<.001$**)) as well as viewer confidence ($\beta=3.82$, $p<.001$**) serve as significant predictors of performance.

Discussion

Experiment 2 further probes the impact of pattern complexity and arrangement on viewer memory abilities by assessing source memory for features found within the original stimulus patterns. Like Experiment 1, overall accuracy is higher for fractal stimuli compared to both sets of non-fractal control stimuli (Figure 5.4A) and decreases with additional pattern complexity (Figure 5.4B). Furthermore, source memory for fractal patterns remains higher than the size-matched average-nonfractal arrangements across all levels of pattern complexity and higher or equivalent to large-nonfractal arrangements across levels of pattern complexity (Figure 5.4C). The higher recognition accuracy for large-nonfractal compared to average-nonfractal patterns points to the importance of large-scale structure for source recognition memory. Viewer confidence ratings once again predict memory accuracy. However, viewer response time for deciding source location is not a significant predictor of judgment accuracy. Findings from

Experiment 2 suggest that the self-similar nature of fractal patterns is generally more distinctive than non-fractal images across image complexity, thus facilitating source memory.

Table 5.3. Experiment 2 – Paired Samples t-Tests across the 3 pattern types for each *D*-value.

Paired Samples T-Test					
Measure 1		**Measure 2**	***t***	***df***	***p***
Fractal 1.1	-	Average-nonfractal 1.1	5.101	49	< .001**
Fractal 1.1	-	Large-nonfractal 1.1	4.252	49	< .001**
Average-nonfractal 1.1	-	Large-nonfractal 1.1	-.590	49	.558
Fractal 1.3	-	Average-nonfractal1.3	4.864	49	< .001**
Fractal 1.3	-	Large-nonfractal 1.3	3.979	49	< .001**
Average-nonfractal 1.3	-	Large-nonfractal 1.3	-1.447	49	.154
Fractal 1.5	-	Average-nonfractal 1.5	4.056	49	< .001**
Fractal 1.5	-	Large-nonfractal 1.5	.149	49	.882
Average-nonfractal 1.5	-	Large-nonfractal 1.5	-4.175	49	< .001**
Fractal 1.7	-	Average-nonfractal 1.7	6.982	49	< .001**
Fractal 1.7	-	Large-nonfractal 1.7	2.673	49	.010*
Average-nonfractal 1.7	-	Large-nonfractal 1.7	-2.826	49	.007**
Fractal 1.9	-	Average-nonfractal 1.9	2.601	49	.012*
Fractal 1.9	-	Large-nonfractal 1.9	.661	49	.511
Average-nonfractal 1.9	-	Large-nonfractal 1.9	-2.124	49	.039*

Note: $*p < .05$; $**p < .01$.

Table 5.4. Experiment 2- Linear Regression

Outcome Variable	**Predictors**	**β**	***t***	***P***	***95% CI for* β**
Accuracy	Complexity	-16.42	-6.64	<.001**	(-21.27, -11.56)
	Pattern	3.36	3.94	<.001**	(1.69, 5.03)
	Reaction Time	.10	.30	.77	(-.58, .78)
	Confidence	3.82	5.00	<.001**	(2.31, 5.33)

Note: $N = 50$; $*p < .05$; $**p < .01$.

General Discussion

Coinciding with the greatest prevalence in nature (Mandelbrot, 1982; Spehar et al., 2003; Taylor et al., 2018; Hagerhall et al., 2008), low-to-moderate complexity fractal patterns seem to facilitate performance on a variety of cognitive tasks in viewers (Juliani et al., 2016; Taylor et al., 2018; Abboushi et al., 2019; Roe et al., 2020; Spehar and Stevanov, 2021). Along with increased aesthetic and naturalistic experiences (Robles et al., 2021; Hagerhall et al., 2015), performance peaking at this level of visual complexity lends support to Fractal Fluency theory's tenant that the self-similar structure of fractal patterns in this range of complexity is more efficiently processed by the visual system (Taylor & Spehar, 2016; Taylor et al., 2017a). Determining the extent to which Fractal Fluency Theory can apply to memory performance provides additional insight into how self-similar repetition impacts viewer processing.

Across two experiments, the current study serves to examine how memory accuracy varies with stimulus complexity and structure, particularly focusing on how patterns are processed holistically in a manner similar to scenes that allows for efficient global pattern comprehension without discounting the distinctiveness of local features unique to each image. Unlike previous measures of performance for fractal patterns, the experiments completed here not only examine performance across fractal complexity but also, for the first time, compare responses across fractal and matched non-fractal control stimuli in order to quantify the overall impact of fractal structure on performance. Despite measuring two separate forms of memory performance, both experiments demonstrate similar trends in viewer accuracy across pattern complexity and underlying fractal or non-fractal arrangement. Experiment 1 measured recognition memory for whole patterns that varied in both complexity and pattern type (fractal, average-nonfractal, large-nonfractal) to determine if pattern complexity and the presence of fractal structure alter the perceived distinctiveness of the entire image. At the lowest levels of complexity, pattern features are more distinct and thus more memorable. With increased complexity, the overall large-scale structure is still apparent in fractal patterns but lost in nonfractal patterns, thus masking the distinctive qualities of the individual non-fractal patterns resulting in lower memory performance. This maintenance of structure present across levels of complexity lends further support for fractal processing fluency being a driver of improved memory performance (Taylor & Spehar, 2016; Taylor et al., 2018).

Whereas Experiment 1 establishes the importance of visual complexity and pattern arrangement (fractal or non-fractal) on fundamental pattern comprehension and detection of pattern uniqueness, Experiment 2 probes how this relationship applies to memory for pattern features as opposed to entire images. Although fractal arrangement may facilitate comprehension of the entire pattern, determined by its large-scale structure, it is equally important to consider how this structure impacts distinctiveness of local features. Upon assessing source memory for pattern regions with and without fractal structure, results are found to reinforce the impact of visual complexity on overall pattern distinctiveness established in Experiment 1. The self-similar nature of fractal patterns is not found to limit feature memory. Specifically, source memory for fractal patterns remains higher than the size-matched average-nonfractal arrangements across all levels of pattern complexity and higher or equivalent to large-nonfractal arrangements across levels of pattern complexity. Surprisingly, source memory is significantly higher for fractal compared to both types of non-fractal patterns at the lowest levels of visual complexity, where pattern features are most distinct regardless of structure. Thus, the overall ease of pattern comprehension impacts memory for whole images as well as internal features.

The overlapping findings reported between the two studies lends further support to the applicability of Fractal Fluency Theory to broad cognitive performance. The proposed effortlessness of visual processing for fractals likely drives improved whole-pattern and feature comprehension resulting in improved memory for these compositions. These results have implications for our abilities to recognize patterns in natural scenes, which have abundant fractal structure. The current study's consistent results found between typical participant samples (a convenience sample of college students) from the first experiment as well as a more diverse range of participants and viewing conditions from the second experiment (broader participant age, ethnicity, natural surroundings, as well as survey experience) supports the robust nature of fractal perception, suggesting that improved cognitive performance associated with fractals can be applied to wider populations. Despite recruiting from both a convenience population as well as a broader group of cultures and countries, findings are currently limited due to the homogeneity of "WEIRD" participant samples. Holistically, findings from Experiment 1 emphasize how the success of whole pattern recognition is established by visual complexity moderating whole pattern distinctiveness whereas Experiment 2 reinforces the importance of pattern comprehension for accurate feature source memory. The current study serves to expand the consideration of Fractal Fluency effects to the field of memory and encourages future work to explore how the connection between fractal patterns and improved memory abilities can be applied to humanmade environments.

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CHAPTER VI

GENERAL DISCUSSION

The human visual system is adept at processing the self-similar patterns which organize the natural world (Mandelbrot, 1982; Falk & Balling, 2010; Taylor et al., 2021; Brielmann et al., 2022). Though this fractal processing fluency has been implicated in occurrences of highly aesthetic experiences (Viengkham & Spehar, 2018; Taylor et al., 2011; Taylor, 2003; Taylor et al., 2007; Rawls et al., 2021; Lukman et al., 2007; Graham & Field, 2008; Forsythe et al., 2017; Beauvois, 2007) and improved cognitive performance (Juliani et al., 2016; Burtan et al., 2021; Taylor et al., 2017; Ferreira et al., 2012) it is unclear whether these effects are present in a wider variety of contextual conditions. Variation in viewing conditions (Aboushi et al., 2019; Sereno et al, 2020) as well as viewer specific individual differences (Pyankova, 2019) have the capacity to categorically alter visual perception. Natural fractal patterns do not exist in isolation; requiring the visual system to accommodate adjacent nonnatural elements that require greater processing effort (Billington et al., 2008; Rezaei et al., 2020). Viewer experience is a derived from not only a culmination of local and global pattern features, but also familiarity with visual complexities (Roder et al., 2000) and the integration of surrounding contextual information (Billington et al., 2008). Thus, the present dissertation aimed to define how visual pattern perception is impacted by 1) viewer individual differences and the inclusion of 2) additional design elements, 3) fractal, and Euclidean structure. Subsequently applying findings to 4) probe how fractal pattern perception relates to visual memory.

Impact of Development and Individual Differences on Fractal Perception

Fractal structure is omnipresent in natural environments worldwide (Taylor et al., 2005;

Hagerhall et al., 2015; Taylor et al., 2011; Bies et al., 2016; Taylor & Sprott, 2008). Thus, the first goal of the dissertation was to address how perception of these unavoidable patterns is impacted by individual viewer variations. Chapter 2 first explored how years of fractal exposure related to degree of fractal preference. Prior studies have established a robust quadratic trend in fractal preference in which preference peaks with low-moderate complexity when patterns are statistically repeated across scale (Bies et al., 2016; Spehar et al., 2016; Street et al., 2016; Pyankova et al., 2019) and linear trend peaking with high complexity with exact repetition (Bies et al., 2016; Hagerhall et al., 2015; Friedenberg et al., 2021). However, these findings have only been observed in adult samples which possess decades of experience processing fractal patterns, inspiring this study to compare adult fractal preference to a sample with significantly less familiarity, children ranging from 3-10 years old. Furthermore, this study sought to explain whether common variations in perceptual tendencies were driving observed variations in fractal preferences. Findings from Chapter 2 suggest a shared general fractal preference that is established before 3 years of age and is unaffected by biological sex or perceptual bias. These findings are the first to compare fractal preference across fractal pattern type (exact and statistical) and a wide span of development and determine that preference for the most common natural spatial structure is uncoupled from years of experience interacting with fractals. Instead, fractal preference appears to be related to possibly more innate tuning of the human visual system, set to efficiently process patterns prevalent in nature (Spehar et al., 2003; Taylor et al., 2018; Hagerhall et al., 2008).

Pattern Perception with Integration of Additional Structure

The second goal of this dissertation was to test whether trends in fractal perception could withstand integration of additional pattern structure, including elements of aesthetic design. Prior research has demonstrated the potential of injecting natural spatial structure into artificial environments through fractal installation to mitigate occupant visual strain (Penacchio & Wilkins, 2015; O'Hare & Hibbard, 2011; Ogawa & Motoyoshi, 2020). However, for fractals to have a chance at improving occupant well-being, installations must be able to be broadly incorporated into already built spaces without limiting the function or aesthetics of a space. Thus to promote their practicality, fractal design needs to accommodate the Euclidean structural elements of its surroundings in addition to variation in artistic choices (Smith et al., 2020). Using nature inspired fractal designs already manufactured and installed as carpet products, Chapter 3 assesses the unique impact of Euclidean arrangement and local design elements across a wide set of viewer experiences. Through a series of empirical studies that span multiple countries and rating methodologies, findings demonstrate that fractal pattern complexity impacts viewer experience regardless of variations in pattern design. Furthermore, complexity appears to moderate experience by altering levels of viewer interest and physiological arousal. Importantly, Chapter 3 identified significant subgroups in perceptual trends, confirming prior research regarding consistent subpopulations (Street et al., 2016; Spehar et al., 2016; Bies et al., 2016) and emphasizing the importance of implementing fractal designs that can evoke a desired experience for the majority of occupants. Notably, robust conclusions from this chapter indicate that through control of local and global elements of fractal design, aesthetic modifications can be applied to the manufacturing and installation of versatile nature inspired designs that encourage tailored occupant experiences.

Unique Contribution of Fractal Arrangement within Euclidean Space

Building upon findings from Chapter 3, Chapter 4 further examines the utility of fractal design and impact of pattern integration on visual perception. This third goal of the dissertation was to explicitly determine the effect of blending Euclidean and fractal arrangements on perception and define the fundamental contribution of fractal structure to viewer perception. Incorporation of fractals into surrounding Euclidean space has been implemented in both small (Taylor & Sprott, 2008) and large installations (Abboushi et al., 2019; Roe et al., 2020), with results suggesting benefits to occupant mood. To validate prior findings that fractal statistics are the driving factor in viewer mood ratings and define how perception is altered by embedding fractal patterns into Euclidean space, Chapter 4 compared ratings of fractal and mathematically matched nonfractal patterns. This study is the first to use truly comparable nonfractal stimuli that maintain general arrangement, complexity, and local region size but remove basic fractal order. This chapter first determined differences in perceptual trends with and without fractal underlying structure, then directly reassessed the same perceptual judgments for fractals in the present of a surrounding Euclidean frame, producing a Euclidean boundary reminiscent of a prototypical surrounding room. Perceived pattern complexity is shown to serve as a main driving factor of visual experience in the majority of viewers regardless of structure, and consistent participant subgroups are detected that resemble those found in previous work (Street et al., 2016; Spehar et al., 2016; Bies et al., 2016), thus further confirming findings from Chapter 3. Interestingly, compared to nonfactal images, the presence of fractal structure produces on average more positive viewer judgments. When Euclidean structure encloses fractal images it establishes discrete pattern boundaries that impact viewer interest and excitement, while not altering remaining perceptions. Taken together these results support the general connection between viewing fractals and positive feelings and emphasize the importance of selecting patterns with perceived complexities that support the space's desired experience.

Relevance of Fractal Fluency Theory to Viewer Memory Performance

Whereas the first three goals of this dissertation serve to fill critical gaps in our understanding of how viewers perceive fractal designs and how fractal incorporation can optimize humanmade space, the final goal of this work is to connect perception to performance. Chapter 5 applies Fractal Fluency Theory to memory accuracy to test whether fractal statistics facilitates visual recognition. Fractal Fluency underlies findings of improved navigational performance (Juliani et al., 2016) and object identification (Spehar et al., 2003) coinciding with low-to-moderate fractal patterns, suggesting a likely connection between fractal comprehension and pattern memory. With a global structure reflecting the repetition of local elements across scaling, fractals evoke qualities of natural scenes. Despite the visual system's expertise in processing pattern regularities (Greene & Olivia, 2009) ambiguous forms often limit memory accuracy (Huebner & Gegenfurtner, 2012; Hegde & Kersten, 2010), creating a question as to how fractal patterns may influence memory performance. To determine how the visual system handles fractal arrangements, two experiments were conducted using fractal and matched nonfractal patterns. A recognition task was used to assess sensitivity for global patterns whereas a source recall task was employed to measure memory for local pattern elements. Global fractal arrangements were found to be more recognizable and possessed local features which were better encoded than their nonfractal counterparts. This relationship was particularly apparent at high levels of stimulus complexity, where pattern discrimination is most difficult. Together findings from this chapter further underscore the influence of perceived pattern complexity on visual processing and illuminate the ability of fractal organization to mitigate perceptual difficulties associated with ambiguous stimuli. Chapter 5 serves to explore how the visual system processes local and global fractal structure to aid pattern comprehension and points to possible underlying memory facilitation involved in the fractal task performance.

Broader Implications

The current dissertation furthers our understanding of how the visual system handles fractal structure and provides compelling evidence for the utility of fractal installments in humanmade spaces. Understanding how visual perception is altered by natural spatial structure is a notable yet rather under examined area of research. Thus far, studies have demonstrated a link between artificial environments and visual strain resulting in higher incidences of occupant stress (Penacchio & Wilkins, 2015; O'Hare & Hibbard, 2011; Ogawa & Motoyoshi, 2020). Fractals provide a versatile option for injecting natural order into already existing spaces (Smith et al., 2020; Roe et al., 2020; Abboushi et al., 2019; Taylor & Sprott, 2008). Understanding how fractal fluency influences perception will allow the successful prediction of viewer experiences across various settings, granting the opportunity to tailor a space to optimize its function while considering occupant needs. Recent research has even begun to probe the connection between fractal perception and enhanced cognitive performance (Juliani et al., 2016; Burtan et al., 2021; Taylor et al., 2017; Ferreira et al., 2012). The current dissertation adds to this literature by defining the impact of fractal statistics on viewer perception, and additionally probing its ubiquitous effects despite perturbations to pattern design. Findings from the current body of work emphasize the potential of fractal design to regulate occupant experience, encouraging future opportunities for direct assessment of fractal effects on viewer wellbeing and behavior.

Limitations & Future Directions

The dissertation explored how fractal patterns are fluently processed by the human visual system to impact perception. Familiarity with statistical complexities may contribute to differences in pattern comprehension (Hadad, 2018; Roder et al., 2000), and thus variations in perception. Although the current dissertation provides evidence that adult-like fractal perception is established by 3-years of age (Robles et al., 2020), the effects of earlier experience with fractals and visual complexities cannot be ruled out. Furthermore, findings from subsequent chapters also reaffirms the presence of perceptual subgroups in sampled populations found in previous fractal studies (Street et al., 2016; Spehar et al., 2016; Bies et al., 2016). The sometimes contradicting trends in viewer experiences cannot be explained by Fractal Fluency Theory, limiting the generalizability of findings despite its presence in only a smaller percentage of individuals, suggesting that these perceptual variations may better be explained by unexamined cultural factors (Hagerhall et al., 2018), sensitivity (Spehar et al., 2016; Spehar et al., 2015), or partiality towards a given complexity (Güçlütürk et al., 2016). The stability of subgroup trends underscores the importance for future studies to expand past the use of largely homogenous participant samples which overwhelmingly share the same W.E.I.R.D. demographics, in order to assess the true generalizability and utility of fractal biophilic design.

The present dissertation has shown the robust connection between controlled modifications to fractal patterns and viewer perception but stops just shy of observing a causal impact of fractal design on viewer perception. Generation of matched nonfractal images provides a major methodological improvement to the isolation of fractal effects, encouraging future generation of more precise nonfractal stimuli that match spatial frequencies and general shape of fractal regions in addition to region size. Although the current findings definitively support prior assertions that visual complexity (Bies et al., 2016; Hagerhall et al., 2016; Güçlütürk et al., 2016) and pattern composition (Aboushi et al., 2019; Sereno et al, 2020) are key factors driving visual experiences, it is critical to directly test the application of fractal exposure to manipulate viewer mood and behavior. This collection of findings serves to promote the next logical step of explicit assessment of viewer perception and performance prior to and following fractal exposure. Even once this key relationship is established numerous factors must still be investigated (including pattern size, location, medium, and duration of exposure) for implementation of fractal design to truly tailor occupant experiences whether they be in virtual reality or physical space. Despite the need for further exploration, this dissertation provides an optimistic outlook on the utility of fractal design to exploit natural visual tuning to promote well-being.

General Conclusion

The present dissertation serves as a major advancement in the study of fractals, particularly by expanding beyond typical fractal aesthetics research to demonstrate robust shared experiences of fractal patterns across varying contexts. Moreover, it is shown that viewer experience can be predicted by aspects of pattern composition. Crucially, this information can be directly applied to decisions of occupant centered design to facilitate the effectiveness of humanmade spaces. Combined, findings from this body of work further our fundamental understanding of how the visual system integrates target features as well as arrangements to facilitate pattern comprehension and emphasizes the vast potential of embracing fractal designs to optimize viewer experiences, performance, and wellbeing.

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