Chapter 45
Fractal Fluency: Processing of Fractal Stimuli Across Sight, Sound, and Touch

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Abstract People are continually exposed to the rich complexity generated by the repetition of fractal patterns at different size scales. Fractals are prevalent in natural scenery and also in patterns generated by artists and mathematicians. In this chapter, we will investigate the powerful significance of fractals for the human senses. In particular, we propose that fractals with mid-range complexity play a unique role in our visual experiences because the visual system has adapted to these prevalent natural patterns. This adaptation is evident at multiple stages of the visual system, ranging from data acquisition by the eye to processing of this data in the higher visual areas of the brain. Based on these results, we will discuss a fluency model in which the visual system processes mid-complexity fractals with relative ease. This fluency optimizes the observer's capabilities (such as enhanced attention and pattern recognition) and generates an aesthetic experience accompanied by a reduction in the observer's physiological stress levels. In addition to reviewing people's responses to viewing fractals, we will compare these responses to recent research focused on fractal sounds and fractal surface textures. We will extend our fractal fluency model to allow for stimuli across multiple senses.

Keywords Fractals · Complexity · Behavioral and physiological responses

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45.1 Introduction

What happens to your brain when you take a walk through nature's scenery? Our senses soak in the sights, sounds, and physical textures of nature, along with smells and perhaps even tastes. Each of our senses has evolved to detect variations in the natural environment for our brains to respond to. Interest in quantifying the positive impacts of experiencing nature gained momentum in the 1980s with the biophilia movement [1]. Biophilia – nature-loving – emphasizes the inherent need of humans to connect with nature. Whereas the primary goal of biophilia is to incorporate elements of nature into built environments, other complementary missions aim to maximize exposure to natural environments. For example, the Japanese traditional practice of Shinrin-yoku, or "forest bathing," continues to thrive.

Evolution has transformed the eye from its initial role as a simple motion detector to the remarkable system that we benefit from today. Vision is our dominant sense. The brain receives 2 billion pieces of information from our eyes every second, while it receives only 1 billion pieces from the rest of the body. Consequently, up to one-third of the brain's volume is dedicated to visual processing, compared to just 8% to touch and 3% to hearing. Under such data pressure, the visual system has developed efficient strategies for processing what we see. In this chapter, we will propose that this efficient processing results in anesthetic experience accompanied by positive impacts on our well-being.

Previous pioneering psychology experiments have demonstrated that exposure to nature's scenery induces significant stress reduction – even to the extent of accelerating patients' recovery from surgery [2–4]. Attention Restoration Theory (ART) has been proposed to help explain our inherent fascination with nature [5, 6]. ART declares that the "soft" attention induced by nature differs fundamentally from the "hard" attention required for unnatural tasks such as reading text. Consequently, this "effortless looking" restores depleted mental resources and prevents occupational burnout. Conversely, unnatural scenes strain the visual system and induce negative responses such as headaches and stress [7].

Although groundbreaking, these demonstrations of "biophilic" responses employed vague descriptions for nature's visual properties. More generally, although we all recognize that nature's beauty is profound, identifying the origin of this beauty is challenging. This is due in part to the multitude of factors that potentially contribute to beauty. Another major challenge arises from a historic lack of understanding of the underlying geometry of natural scenes. What do we see in the wispy edges of clouds, in the intricate branches of trees, and in the jagged peaks of a snowy mountain range? For many years, scientists assumed these images were a haphazard mess devoid of any pattern. However, the past 50 years have seen a remarkable revolution in the way scientists study nature's scenery, which has brought scientific inquiry and artistic views of nature closer together. Fractal patterns, named by Benoit Mandelbrot, lie at the heart of this revolution [8]. Dramatically referred to as "the fingerprint of life," their repetition of patterns across multiple scales forms the basic building blocks of many of nature's patterns, ranging from clouds, trees, and mountains through to our brains, blood vessels, and lungs. The visual complexity generated by their repeating patterns stands in sharp contrast to the relative smoothness of artificial shapes such as circles, triangles, and straight lines.

We will review psychology experiments conducted over the past two decades that suggest the aesthetic qualities of fractals might be triggering the powerful effects of biophilia. These experiments inform the "fractal fluency" model which states that human (and presumably animal) vision has become fluent in the visual language of fractals through evolutionary exposure. Accordingly, a cascade of subconscious processes places the observer in their visual "comfort zone," ushering in a neuro-aesthetic experience accompanied by a decrease in physiological stress.

Similar to the phenomenon of synesthesia, in which sensations are transferred between the senses, fractal fluency might extend to the other senses. Although receiving significantly less attention, we will compare people's responses to auditory and tactile fractals with those well charted in the visual realm. Ultimately, our goal is to identify whether there are emergent experiences induced by exposing multiple senses simultaneously, whereby the whole is much more than the sum of the parts. Returning to the walkthrough nature, we can replace "forest bathing" with "fractal bathing." While enjoying the views of trees, clouds, and rivers, the observer can also listen to fractal sounds ranging from bird songs to waterfalls and can reach out to experience the fractal textures of wood and rock surfaces.

In addition to investigating the fundamental science of human responses to nature's beauty, we will also consider strategies for transferring this knowledge to applications in the built environment. Biophilia's warning takes on more urgency with the predicted impacts of climate change [9]. In the future, humans might no longer be able to rely on the countryside to provide the fractal complexity that their senses have developed to expect and respond to throughout evolution. Fractal bathing in the sights, sounds, and textures of a forest could be reduced to a behavior of our past.

This possibility places an urgency on the need for fractal art, fractal music, and the tactile surfaces of fractal sculptures. Fractal creation is not new to humans; fractals have permeated cultures spanning across many centuries and continents, ranging from Hellenic friezes (300 B.C.E) [10] to Jackson Pollock's poured paintings (1940–50s) [11–14]. However, prior to Mandelbrot's labeling of fractals in the 1970s, these creations were intuitive. Similarly, although elements of auditory fractals have appeared in natural noises and music, it wasn't until the 1990s that Hugh McDowell (cellist in the Electric Light Orchestra) deliberately composed music using algorithms based on Mandelbrot's work [10]. Driven by technological advances, we now live in an era in which art–science collaborations can generate novel science-informed fractal patterns for the built environment. We will therefore close the chapter by discussing applications created by the Science Design Laboratory (SDL) based on the neuro-aesthetic principles described earlier in the chapter.

45.2 The Visual Complexity of Biophilic Fractals

We begin our discussions with visual fractals. In Fig. 45.1, we use a coastline to demonstrate their intrinsic visual properties. As shown in the left column, fractals can be divided into two categories – "exact" (top image) and "statistical" (bottom image). Whereas exact fractals are built by repeating a pattern at different magnifications, "statistical" fractals introduce randomness into their construction. This disrupts the precise repetition so that only the pattern's statistical qualities (e.g., density, roughness, and complexity) repeat. Consequently, statistical fractals simply look similar at different size scales. Whereas exact fractals display the cleanliness of artificial shapes, statistical fractals capture the "organic" signature of natural objects.

Statistical fractals are highly topical in the field of "bio-inspiration," in which scientists investigate the favorable functionality of natural systems and apply their findings to artificial systems. For example, the ability of fractal coastlines to

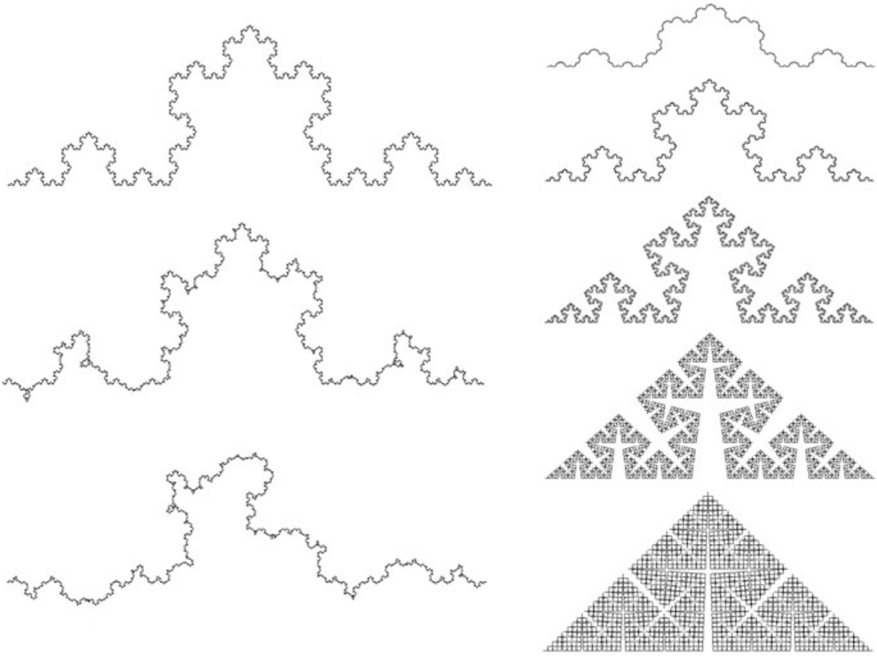


Fig. 45.1 Left column: A computer-generated coastline based on exact fractals (top) is morphed into a statistical fractal coastline (bottom) by introducing randomness. For the top fractal, all of the headlands point upward. For the bottom fractal, half point downward and the positions of the up and down headlands are randomized. Note the fractal dimension (*D*) value (1.24) is preserved for all 3 patterns (top, middle, and bottom). Right column: The effect of increasing *D* is shown for 5 exact coastlines. Each of the coastlines is built using the same coarse-scale pattern. Increasing the contributions of the fine-scale patterns causes the coastlines to occupy more of the 2-dimensional plane, thus raising their *D* values: 1.1 (top), 1.3, 1.5, 1.7, and 1.9 (bottom)

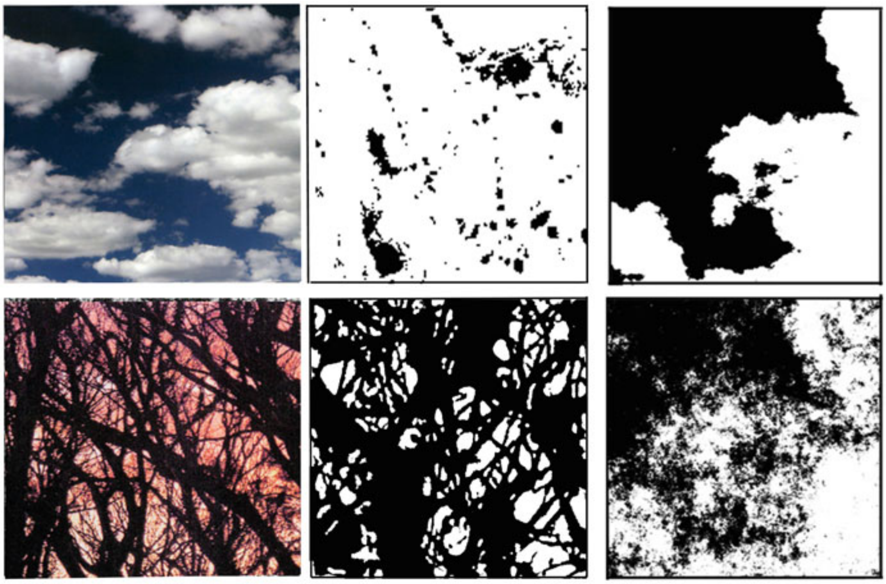


Fig. 45.2 Fractal complexity in nature, art, and mathematics. The left column shows clouds with $D = 1.3$ (top) and a forest with $D = 1.9$ (bottom). The middle column shows Jackson Pollock's *Untitled 1945* with $D = 1.1$ (top) and *Untitled 1950* with $D = 1.89$ (bottom). The right column shows computer-generated fractals with $D = 1.2$ (top) and $D = 1.8$ (bottom)

efficiently disperse wave energy has inspired fractal storm barriers. The ability of fractal tree canopies to efficiently collect sunlight has inspired fractal solar panels. The growing role of fractals in art suggests that the repeating patterns might serve another bio-inspired function beyond the scientific realm – an aesthetic quality.

To quantify the rich visual intricacy of the statistical fractals, we adopt a traditional mathematical measure to quantify the fractal image projected on the retina – fractal dimension D [8, 15]. This parameter describes how the patterns occurring at different magnifications combine to build the resulting fractal shape. For a smooth line (containing no fractal structure) D has a value of 1, while for a completely filled area (again containing no fractal structure) its value is 2. However, the repeating patterns of the fractal line cause the line to begin to occupy space. As a consequence, its D value lies between 1 and 2. When the contribution of the fine structure to the fractal mix is raised, the line increasingly fills in the 2-dimensional surface of the retina and the fractal's D value approaches 2. Figure 45.2 demonstrates how a statistical fractal's D value has a profound effect on the visual appearance of fractal patterns found in nature, art, and mathematics. Clearly, for fractals described by low D values, the small content of fine structure builds a very smooth sparse shape. However, for fractals with D values closer to 2, the larger amount of fine structure builds a shape full of intricate, detailed structure. More specifically, because the D value charts the ratio of fine to coarse structure, it is expected that *D* will serve as a convenient measure of the visual complexity generated by the repeating patterns. Behavioral research confirms that people's perception of complexity increases with *D* [16, 17].

Our initial investigations used three distinct categories of stimuli summarized in Fig. 45.2: natural fractals (using photographs of clouds, trees, mountains, etc.), artistic fractals (paintings generated by Jackson Pollock using his famous pouring technique), and mathematics (computer-generated images) [18]. Our more recent studies focus exclusively on computer-generated fractals due to their advantageous properties [19]. First, the *D* values of the images are known precisely because they are input parameters for the computer-generated process. Second, the greater control offered by computers allows the separation of different visual characteristics. For example, whereas density and *D* value are intrinsically linked in Pollock's paintings (as seen in Fig. 45.2, he raised the painting's *D* value by adding more paint which in turn inevitably raised the density [12]), these 2 parameters can be adjusted independently using computer-generated images. Thirdly, the images are purely abstract. Consequently, responses are not contaminated by associations with recognizable objects such as trees and clouds.

Figure 45.3a shows examples of our current stimuli, which are generated either by Fourier spectrum or midpoint displacement methods [15]. For the far left image,

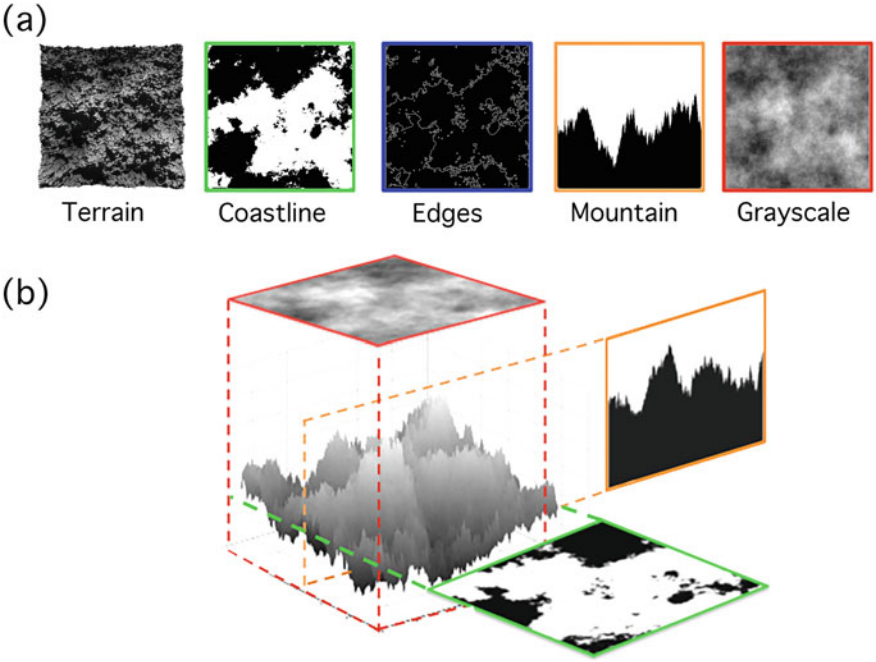


Fig. 45.3 (**a**) Computer-generated fractal stimuli. From left to right: terrains, coastlines, coastline edges, mountains, and grayscale patterns. (**b**) Schematic showing the relationship between the 5 types of fractal image

the computer has generated a geographical terrain (in this case viewed from above). The second image shows a horizontal slice taken through the terrain at a selected height. The terrain below this height is colored black, and all of the terrain above is colored white. Referred to as the coastline pattern (black being the water), this image is used to generate the third image by highlighting the coastline edges in white. The fourth image is created by taking a vertical slice through the terrain to create a mountain profile. Finally, the grayscale image is generated by looking down on the terrain from above and assigning grayscale values to the heights of the terrain (white being the highest). Taken together, these 5 families of fractals are powerful stimuli for examining people's responses because, although superficially quite different in appearance, they all possess identical scaling properties.

45.3 Fractal Fluency of Visual Fractals

The physical processes that form nature's fractals determine their D values. For example, wave erosion generates the low complexity ($D = 1.1$) of the Australian coastline, while ice erosion results in the high complexity ($D = 1.5$) of the Norwegian fiords. Significantly, although all D values in the range $1.1 < D < 1.9$ appear in natural scenes, the most prevalent fractals lie in the narrower range of 1.3–1.5. For example, many examples of clouds, trees, and mountains lie in this range. We therefore previously proposed a fluency model in which the human visual system has adapted to efficiently process the mid-complexity patterns of these prevalent $D = 1.3$–1.5 fractals [13]. We expect this adaptation to be evident at multiple levels of the visual system, ranging from data acquisition by the eye to processing of this data in the higher visual areas of the brain.

Our studies of fractal fluency commenced with the eye movement studies shown in Fig. 45.4 [13, 15]. The eye-tracking system (Fig. 45.4a) integrates infrared and visual camera techniques to determine the eye's gaze when looking at a pattern presented on the computer monitor. During the 60-s observation period, participants were instructed to memorize the pattern in order to induce "free viewing" activity. Figure 45.4b shows a section of the spatial pattern traced out by the eye's gaze as it moves across the monitor. As expected, the pattern is composed of long saccade trajectories as the eye jumps between the locations of interest and smaller micro-saccades that occur during the dwell periods. These periods of relative motionlessness can also be seen in the associated temporal trace of Fig. 45.4c. Details of the fractal measurement technique applied to the eye's spatial and temporal patterns are reported elsewhere [13, 15, 20, 21].

The results show that the saccade trajectories trace out fractal patterns with D values that are insensitive to the D value of the fractal pattern being observed: the saccade pattern is quantified by $D = 1.4$, even though the underlying pattern varied over a large range from 1.1 to 1.9. This mid-D saccade pattern was confirmed for viewing computer-generated, natural, and Pollock fractals. Furthermore, participants with Alzheimer disease, frontal and anterior temporal lobe degeneration,

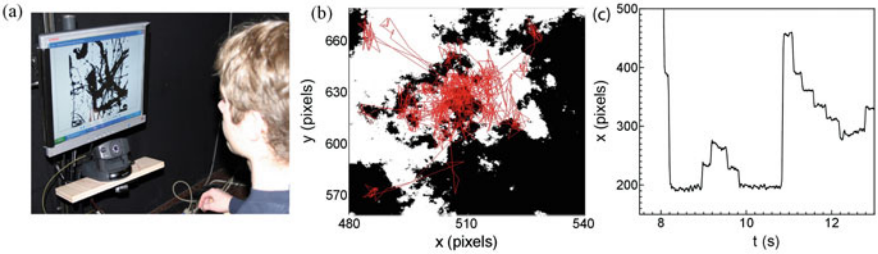


Fig. 45.4 (**a**) A photograph of the eye-tracking apparatus, (**b**) the spatial pattern of the eye tracks (red) plotted in the x (horizontal) and y (vertical) directions. The eye track (red) is overlaid on the observed fractal pattern (black and white), (**c**) the equivalent time series data which plots x versus time

and progressive supranuclear palsy all exhibited the same fractal gaze dynamics as healthy participants, indicating that it is fundamental to eye movement behavior and that it is not modified by processing in the higher levels of the visual system [21].

We propose that the purpose of the eye's search through fractal scenery is to confirm its fractal character (this ability to confirm that, for example, a forest features only fractal trees and no predators would promote survival). If the gaze is directed at just one location, the peripheral vision only has sufficient resolution to detect coarse patterns. Therefore, the gaze shifts position to allow the 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 fractal character. Why, though, does the eye adopt a fractal trajectory when performing this task? A possible answer can be found in the fractal motions of animals when they forage for food [22]. The short trajectories allow the animal to look for food in a small region and then to travel to neighboring regions and then onto regions even further away, allowing searches across multiple size scales. Significantly, such fractal motion has an 'enhanced diffusion' compared to the equivalent random movements of Brownian motion. The amount of space covered by the fractal search is therefore larger. This might explain why it is adopted for both animal searches for food and the eye's search for visual information [15]. The mid-D saccade is optimal for this fractal search because it matches the D values found in prevalent fractal scenery – the saccades then have the same amounts of coarse and fine structure as the observed stimulus, allowing the eye to shift through the visual information efficiently.

We expect that strategies for efficiently processing mid-D fractals will also be evident at higher levels in the visual system. In the 1990s, Field and others presented a neural model featuring virtual "pathways" used for processing scenic information in the visual cortex of the brain [23, 24]. Some pathways are dedicated to analyzing large structures in nature's environments and others to small structures. It was proposed that these pathways have evolved to accommodate our fractal view of nature as follows: the number of pathways dedicated to each structure size is proportional to the number of structures of that size appearing in the scene. In other words, the distribution of processing pathways matches the D values that dominate the viewed environment. In other early studies, Geake and Landini proposed that fractal processing utilizes images stored in memory [25]. Their experiments showed that people who displayed a superior ability to distinguish between fractals with different D values were found to also excel in mental tasks involving simultaneous synthesis (an ability to combine current perceptual information with data from long-term memory). Modern neurophysiological measurement techniques such as quantitative EEG (qEEG) and functional MRI (fMRI) now offer the potential for researchers to refine these preliminary ideas of how the brain processes fractal stimuli.

EEG is a well-established measure of cortical activity. While the alpha frequencies (9–12 Hz) indicate a wakefully relaxed state, the beta frequencies (18–24 Hz) are associated with external focus, attention, and an alert state [26]. Previous recordings by Ulrich and colleagues revealed that people are more wakefully relaxed during exposure to natural landscapes than to townscapes, and studies of wall art found that images with natural content have positive effects on anxiety and stress [2, 3]. In our studies, participants' responses were continuously monitored using a digital EEG recorder while they viewed fractal "mountain" stimuli (Fig. 45.3) with different D values [27]. The images were viewed for 1 minute each and interspaced by a neutral gray picture for 30 seconds. This exposure period was chosen to ensure that a relaxation effect in the participants could occur. Three regions of the brain – frontal, parietal, and temporal – were chosen because processes in these associational zones are known to be complementary [26]. The results showed that fractal images quantified by $D = 1.3$ induce the largest changes in participants' alpha and beta responses [27]. Intriguingly, these responses were dampened when the images were morphed from the statistical to exact versions (Fig.45.1), emphasizing the adaptation of processing fluency to nature's biophilic fractals [28, 29].

Our preliminary studies using the fMRI technique further indicate that mid-D fractals induce distinct responses when compared to those of low or high D equivalent images [30, 31]. Ongoing fMRI studies will consider the role of the parahippocampal region (which is known to be involved in memory retrieval and scene recognition) and the default-mode network (a large brain network associated with wakefully restful activities such as daydreaming and mind-wandering, and which features in modern versions of ART [32]).

45.4 Fractal Aesthetics and Stress Reduction

The fluency model predicts that the increased processing capabilities should result in enhanced performance of visual tasks when viewing mid-D fractals. Indeed, our behavioral studies demonstrate participants' heightened sensitivity to mid-D fractals [33]. Using grayscale fractal images displayed on a computer monitor (Fig. 45.3), the contrast in the patterns was gradually reduced until the monitor displayed uniform mean luminance. Participants were able to detect the mid-D

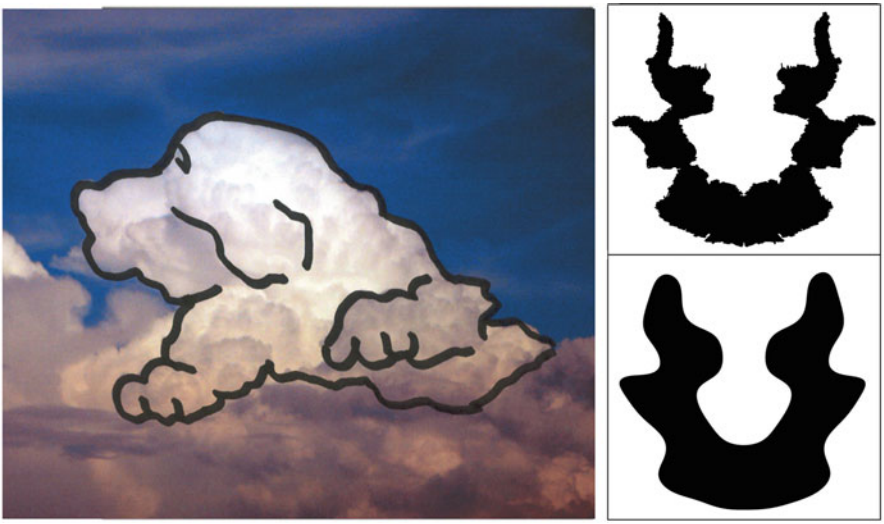


Fig. 45.5 Left: Fractal clouds are renowned for inducing perceived images (as an illustration, a perceived dog is drawn on the photograph of a cloud). Right: an example ink blot (top) which induces fewer percepts when its fractal edges are smoothed (bottom)

fractals for much lower contrast conditions than the low and high D fractals [32]. Similarly, participants displayed a superior ability to distinguish between fractals with different D values in the mid-D range [24, 25, 33]. The increased beta response in the qEEG studies suggests a heightened ability to concentrate when viewing mid-D range [27].

There is also anecdotal evidence to suggest that pattern recognition capabilities increase for mid-D fractals. We are all familiar with the percepts induced by cumulus clouds (Fig. 45.5). A possible explanation is that our pattern recognition processes are so enhanced by these $D = 1.3$ clouds that the visual system becomes "trigger happy," and consequently, we see patterns that aren't actually there. Our research confirms that mid-D fractals induce large numbers of percepts [34] and that they activate the visual cortex's object perception and recognition regions [29]. This is supported by our studies of Rorschach ink blots. Perception of shapes in the fractal blots peaks in the lower D range [35] and declines when the fractal structure is electronically removed from the blot images (Fig. 45.5).

Does fractal fluency create a unique aesthetic quality because we find them relatively easy to process and comprehend? Perhaps this "aesthetic resonance" for $D = 1.3$–1.5 fractals induces the state of relaxation indicated by the peak in alpha response in the qEEG studies. Our skin conductance measurements similarly demonstrated that mid-D fractals are stress-reducing [36]. The question of fractal aesthetics holds special significance for the field of experimental aesthetics. One of its early pioneers, George Birkhoff, introduced "aesthetic measure" in the 1930s – the idea that aesthetics could be linked to measurable mathematical properties of the observed images. Visual complexity was a central parameter in his proposals [37]. In 1993, we conducted the first aesthetics experiments on fractals, showing that 95% of observers preferred complex fractal images over simple Euclidean ones [38]. Soon after, Sprott employed computer-generated fractals to show that mid-*D* fractals were preferred over low and high *D* fractals [39].

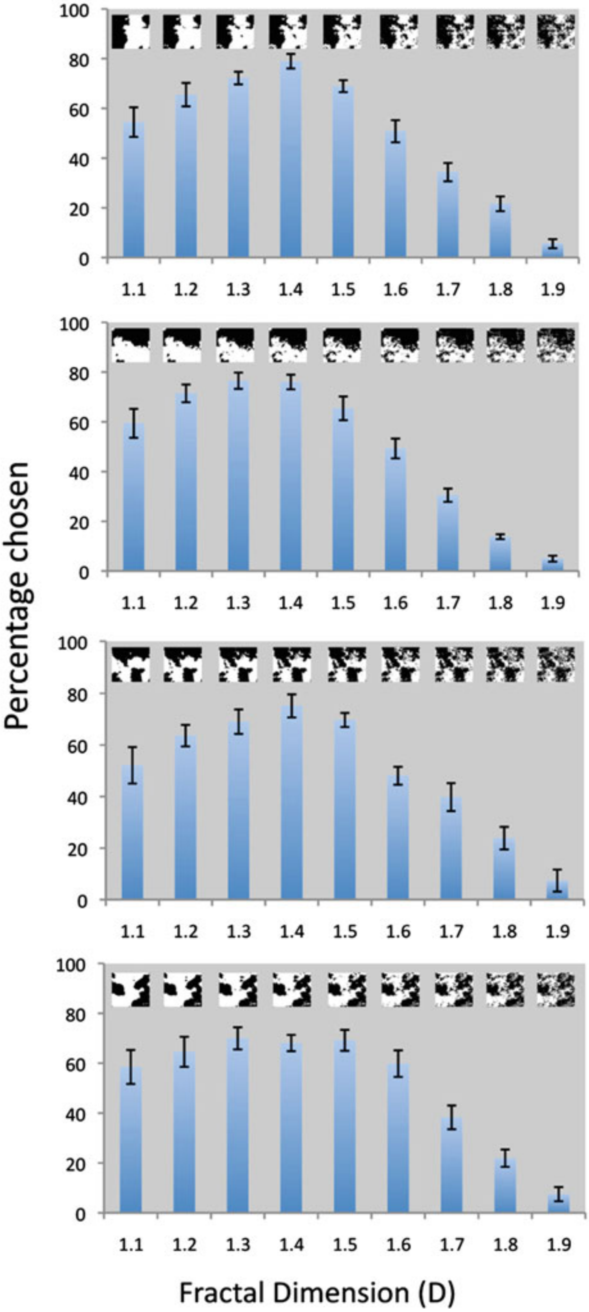
Over the past two decades, fractal aesthetics experiments performed by us and other groups on statistical fractals have shown that preference for mid-*D* fractals is "universal" rather than dependent on specific details of how the fractals are generated. Fractal aesthetics experiments also confirm that preference for mid-*D* complexity occurs for a wide variety of fractal image types, including fractal "composites" (natural scenes composed of multiple fractal objects) [40] and that this preference is already evident by the age of 2 [41]. Figure 45.6 shows example results for the coastline stimuli of Fig. 45.3 [13]. Preference was determined using a "forced choice" technique in which participants were shown a pair of images with different *D* values on a monitor and asked to choose the most visually appealing image. In these experiments, all of the images were paired in all possible combinations. The presentation order was fully randomized, and preference was quantified in terms of the proportion of times each image was chosen.

The panels are for four different "configurations" (i.e., different random arrangements of the fractal pattern). The peak preference shows remarkable consistency despite superficial variations in the 4 families of fractal. Figure 45.7 further emphasizes the "universality" of the preference for mid-complexity fractals by comparing 3 of the fractal types (coastline, edge, and grayscale images) shown in Fig. 45.3 [17]. Our experiments also find a direct correlation between the observer's enhanced capabilities (based on their abilities to detect and discriminate fractals) and preference [32].

In addition to these laboratory-based behavioral experiments, a computer server has been used to send screen savers to a large audience of 5000 people. New fractals were generated by an interactive process between the server and the audience, in which users voted electronically for the images they preferred [42]. In this way, the parameters generating the fractal screen savers evolved with time, much like a genome, to create the most aesthetically preferred fractals. The results re-enforced the preference for mid-*D* fractals found in the laboratory-based experiments. The majority of research into responses to visual fractals have presented the images on the 2-dimensional planes of computer monitors. Funded by NASA, the skin conduction relaxation studies were a rare exception when the images were presented to participants on the walls of a mock-up space laboratory [36]. We expect that the fractal fluency effects will be amplified in 3-dimensional environments. A recent virtual-reality experiment indicates that spatial awareness skills are heightened in fractal terrains. When participants were instructed to navigate an avatar to find an object randomly placed within a virtual landscape, accuracy and completion speeds peaked for the mid-complexity landscapes predicted by the fluency model [43].

Intriguingly, when fractal images are projected on the walls of a room rather than displayed on monitors, the preferred *D* shifts to slightly higher values (*D* ~ 1.6–1.7) [44]. The observer then sees the fractal surrounded by the blank surface of the

Fig. 45.6 Visual preference for computer-generated fractal patterns. For each of the 4 panels, *D* is plotted along the x-axis and the preference on a scale of 0–100 is plotted along the y-axis. This scale is based on the number of times an image is chosen as being the most preferred (see the main text for details). Each of the 4 panels uses a different fractal configuration to investigate preference. The fractal images are shown as insets in each panel



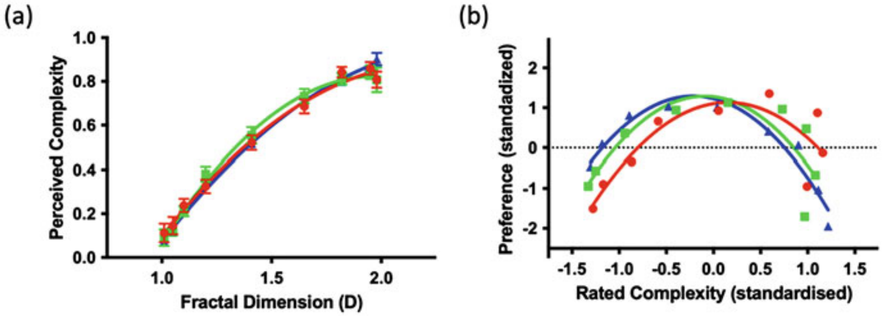


Fig. 45.7 (**a**) Perceived complexity plotted against fractal dimension for the coastline (green), edges (blue), and grayscale (red) images of Fig. 45.3. (**b**) Preference plotted against perceived complexity (both plotted on standardized scales)

wall. Introduction of Euclidean simplicity increases the tolerance for high fractal complexity. This experiment serves as a warning for future fractal studies aimed at biophilic applications. Because practical applications will embed fractals within artificial environments, we will need to adapt them (bio-inspiration) rather than simply copy them (biomimicry). For example, when sitting in a room surrounded by simple walls, the preferred *D* value will be higher than when the observer walks through a forest and is engulfed by other fractals. Experiments investigating the importance of matching city skylines to the backdrop of fractal mountains [45] further emphasize the importance of viewing context.

Clearly, as we shift from fundamental to applied research, the specifics of the individual spaces along with the needs of the individuals who occupy them will be crucial. Although the overall population prefers mid-*D* values, there are 3 subgroups that exhibit distinct preferences. As shown in Fig. 45.8, whereas the majority's preference peaks at mid-*D*, just under 25 percent of observers are instead "sharpies" (preferring high *D*) and a similar number are "smoothies" (preferring low *D*) [17]. One recent study proposed that genetic factors might influence the fractal aesthetics of individuals [46]. Furthermore, the art works of Willem De Kooning decreased in *D* value as he descended into Alzheimer's, highlighting the influence of neurological conditions on fractal fluency and therefore on fractal aesthetics [47]. It will also be intriguing to explore if there are underlying personality traits that characterize the smooth and sharpie subgroups. For example, it has been suggested that creative people might have a preference for higher *D* values [48]. Some studies show that urban versus rural living along with aging can shape fractal preference, indicating that adaptation during our lifetimes might also be a factor [49]. Consistent with this view, the *D* values of Jackson Pollock's paintings increased during his career, possibly as a result of adaptation [50–53]. Clearly, one fractal will not fit all when it comes to the aesthetics associated with fractal fluency!

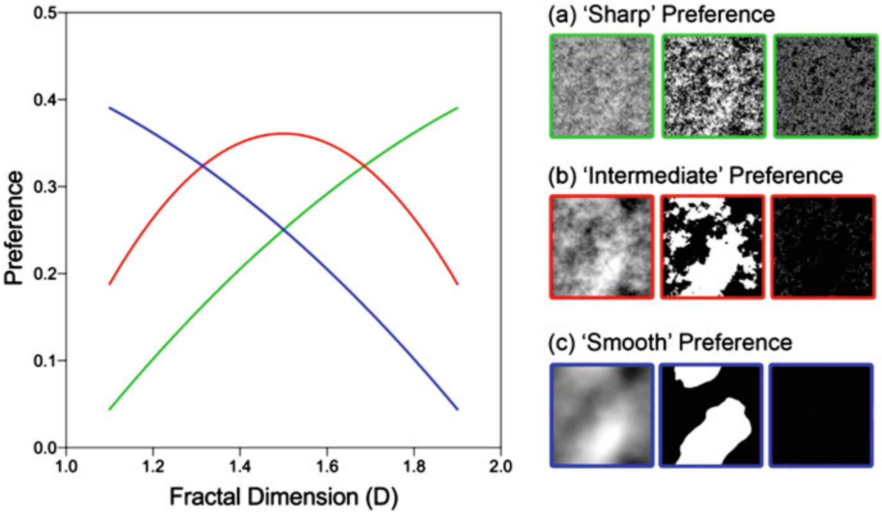


Fig. 45.8 Visual preference for computer-generated fractal patterns. Left. Preference dependencies on *D* for "smoothies" (blue), "intermediates" (red), and "sharpies" (green) [17]. Preference is quantified on a scale spanning 0–1 based on the number of times an image is chosen as being the most preferred. Right. Example preferred fractal images for (a) "sharpies," (b) "intermediates," and (c) "smoothies"

45.5 Beyond the Visual: Fractal Fluency in Touch and Sound?

The physicality of real-life, three-dimensional spaces presents opportunities to move beyond the visual sense. Inspired by the idea of synesthesia, it is possible that mid-complexity fractals might also hold special significance for tactile experiences. Three-dimensional printers now allow computer-generated patterns to be printed ("contour-crafted") as physical objects and artists such as Daniel Della-Bosca have used them to construct fractal sculptures [54]. In discussions with Della-Bosca, we pictured rooms incorporating fractal surfaces for passersby to touch. Mandelbrot had previously asked: "In order to understand geometric shapes, I believe you have to see them." Della-Bosca took this thought process one step further by asking "what happens if you touch them too?" [54].

Fractal surface textures have been used in previous studies of aesthetics to gauge perceived roughness [55] as well as their aesthetic value [17]. As expected, visual preference was found to be greatest for the mid-complexity surfaces. However, the surfaces in both studies were presented on a monitor and visually inspected as opposed to being touched. In our ongoing experiments, the terrains shown in Fig. 45.3 (left) are printed to investigate the visual and tactile impacts of these physical terrains [56]. As shown in Fig. 45.9, these fractal sculptures are printed onto the face of 10 by 10 by 1 cm hard, synthetic blocks. They are presented to participants on a

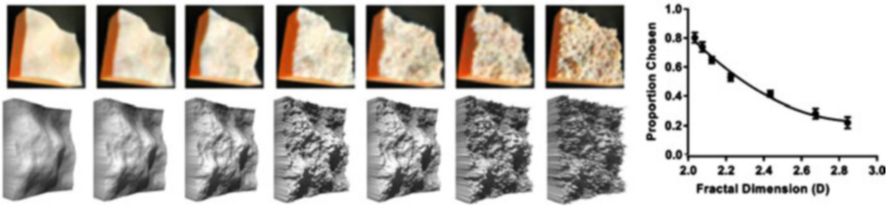


Fig. 45.9 Left: Computer-generated three-dimensional fractal images (bottom row) and their printed tactile surfaces (top row). The fractal dimensions of the tactile surfaces range from 2 (left) to 2.8 (right). Right graph: Preferences plotted as a function of fractal dimension for the sculptures. Preference is quantified on a scale spanning 0–1 based on the number of times a sculpture is chosen as being the most preferred

tabletop, and an adjustable occluder is used to hide the sculptures from view for the purely tactile experiences.

To discuss the dependence of participants' responses on D, we return to the discussions of the images in Figs. 45.1 and 45.2. Because these fractal patterns are embedded in a 2-dimensional plane, their D values lie below the $D = 2$ value associated with a fully filled (i.e., uniformly black) plane. This reasoning extends to the middle "coastline" and "mountain" images of Fig.45.3. Embedded in horizontal and vertical planes, respectively, they are described by a mid-complexity value of $D = 1.5$. However, the terrain's surface shown in Fig. 45.3(left) is not confined to a 2-dimensional plane – it spreads out into a volume and consequently has a raised dimensionality of $D = 2.5$ [57]. The physical sculptures of Fig.45.9 therefore all have physical fractal dimensions lying between 2 and 3, with a mid-complexity in these experiments corresponding to 2.5.

Backing up the fractal fluency experiments performed using images displayed on monitors, the purely visual inspections of the sculptures reveal a preference for mid-complexity D values. However, the tactile experiments reveal a preference for smoother surfaces closer in dimension to $D = 2$ (Fig. 45.9). Previous haptic studies have shown that roughness is a particularly important descriptor [58–61]. Consistent with our fractal surface study, ratings of everyday materials were found to have a negative relationship between perceptions of pleasantness and roughness [62].

However, this does not necessarily suggest that the visual and tactile domains have no common basis for how fractal statistics influence aesthetic perception. Indeed, it is possible that the range of complexity variations between the visual and tactile domains differs; in other words, the stimuli between the two sensory domains might not have been cross-modally matched. Notably, the low D tactile stimuli still maintain a slightly rough and irregular surface when touched even though they look smooth, leading to a more compressed range of variations in the tactile domain compared to the visual domain. Furthermore, it is worth noting that, although the majority of participants preferred to touch low D surfaces, a small proportion showed a greater preference for intermediate or for high D stimuli. This emphasizes that “smoothies,” “intermediates,” and “sharpies” play roles for both tactile and visual responses.

That all said, the differences in tactile and visual preferences might also be explained by extra factors influencing the tactile experience. If fractal fluency was the only factor, it would be predicted that the abundance of mid-D fractals would make them easier to detect and therefore be more preferred for both the visual and tactile realms. However, physical interactions with the surface present the potential for harm. The sharpness of mid-to-high D surfaces might therefore cause low D surfaces to dominate the aesthetics.

Real environments also offer the opportunity to move beyond static fractals to explore spatiotemporal qualities. Nature’s dynamic fractals include moving ripples of water, tree branches swaying the breeze, flickering flames, and clouds moving across the sky. These time variations in dynamic fractals might be expected to attract and maintain the observer’s attention to a higher degree than their static equivalents and might therefore boost the favorable fractal fluency effects. For example, the shifting sun could cast fractal shadows from trees across a room during the day and clouds could create extra variations on shorter timescales. This idea of projecting nature’s movements into rooms is central to the biophilia movement [63]. However, introducing time variations into the static images of Fig. 45.3 could also be employed to achieve a similar dynamic impact.

To consider the visual complexity of dynamic fractals in more detail, we return to the role of D in quantifying the spatial frequency content of fractal patterns. Employing Fig. 45.3 (right) as an example, when this grayscale image is decomposed into its component spatial frequencies using Fourier analysis, the intensity amplitudes follow a power law relationship $A \sim f^{-\alpha}$ as a function of spatial frequency f. This power law generates the scale invariance of the fractal’s repeating patterns, and its exponent α is inversely related to the pattern’s D value [57]. Studies of dynamic natural scenes have shown that this power law relationship not only holds for spatial frequencies but also extends to temporal frequencies. The measured temporalα value approximates to 1 [64–66], which translates mathematically to the mid-complexity of $D = 1.5$ for these stimuli [57]. Thus, whereas the physical terrains of Fig. 45.3(left) extend beyond the horizontal (x–y) plane along a third spatial (z) axis representing height, the dynamic fractals extend their fractality along an axis representing time. In other words, the observer now experiences fractal variations both when moving between locations in the spatial (x, y) pattern and also when positioned at one location and watching the pattern evolves with time.

Altering the temporal α (and therefore the temporal D) changes how much “energy” is found in certain temporal frequencies in the dynamic pattern. For example, as α approaches 0, energy is distributed equally across all temporal frequencies resulting in a large rate of change at all frequencies. As α increases, more energy is distributed to the lower frequencies, resulting in large rates of change at low frequencies and relatively smaller changes at high frequencies. This is most clearly perceptible in the speed that the pattern changes over time, with low α stimuli generating a fast-frequency effect similar to “flicker.”

For physical fractals in real environments, the spatial fractals influence their temporal fractal variations. Taking the mechanics of a tree as an example, longer branches will experience more inertia than shorter branches when subject to the same force of the wind. Thus, shorter branches will display faster temporal frequencies. In this way, the temporal D values will be determined by the structure's spatial D values along with driving factors from the surrounding environment such as the magnitude and direction of the wind's force. In contrast to this interdependence of the spatial and temporal D values for nature's fractals, an advantage of studying synthetic spatiotemporal fractals is that the two fractal dimensions (spatial and temporal) can be adjusted independently [64].

Billock et al. [64] investigated the ability of the visual system to tune to the fractal $A \sim f^{-\alpha}$ spectrum in both space and time and demonstrated visual sensitivity to the condition predominant in nature (i.e., approximately to $\alpha \sim 1$). In terms of aesthetics, Toet et al. [67] asked participants to label real-world natural temporal textures such as moving water in terms of pleasure. Although the study did not measure α values, the movie images were rated for spatial and temporal characteristics. Significantly, pleasure was found to be negatively correlated with speed (i.e., rate of change of the image). Our own recent investigations of the spatiotemporal fractals of Fig. 45.3 [68] also highlight that visual preference does not align with the visual system's sensitivity. While sensitivity is highest for intermediate modulation rates (temporal $\alpha \sim 1.25$, which is abundant in nature), consistent with fractal fluency expectations, the most preferred stimulus has high temporal values of $\alpha \sim 2.25$.

Figure 45.10a shows this preference for dynamic fractals when plotted against D. Figure 45.10b shows perceived complexity ratings in order to confirm that this rises with increasing D, consistent with the original studies performed on static spatial fractals [16, 17]. Thus, moving beyond static fractals by introducing dynamic experiences doesn't impact the perceived complexity generated by D (Fig. 45.10 confirms that this also holds when introducing tactile and, to be discussed later, auditory experiences). Having excluded changes to perceived complexity as a cause for the shift in preference to lower D values, one possible explanation relates to safety. While sensitivity is aligned with abundance through the fractal fluency effect, preference for temporal variations might be based on slower stimuli signaling safer and therefore more preferred environmental factors. This deviation of the aesthetic condition away from the fractal fluency D value due to additional safety factors is similar to that described earlier for tactile experiences.

Nature's dynamic fractals are rarely quiet. We are all familiar with the sounds of trickling water and tree branches creaking in the wind. Fractal sounds in nature even extend to bird songs. Given that nature's fractal sounds are generally regarded as pleasant, it is logical to expand fractal aesthetics studies to the auditory domain to include noises and, ultimately, music. Just as the spatial D values of nature's fractal structures influence their temporal fractal variations, they also influence the fractal noises they induce. Returning to the tree as an example, the fractal distribution of gap sizes between the branches will influence the temporal frequencies of the noise of the wind passing through them. Similarly, the D values of the fractal sculptures in Fig. 45.9 will influence the fractal noise generated by tricking water across their

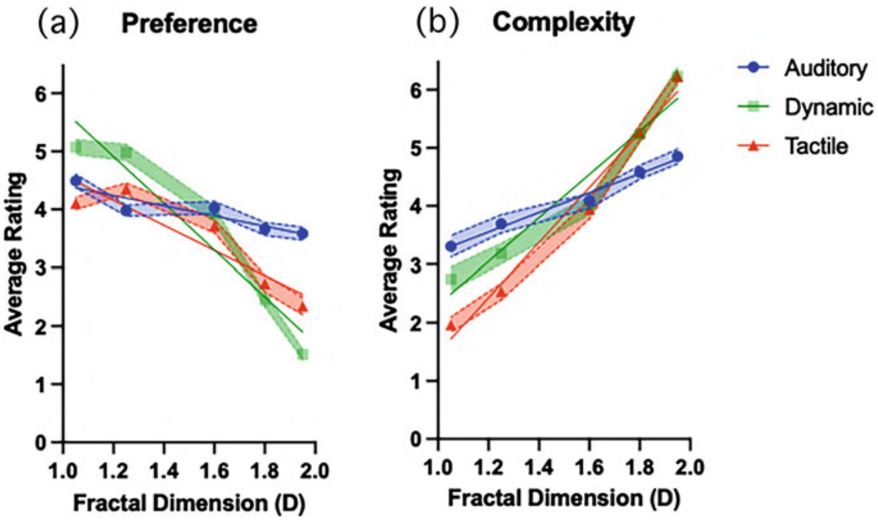


Fig. 45.10 Ratings of preference (**a**) and complexity (**b**) as a function of *D* for tactile, dynamic, and auditory fractals

surfaces. Fractal noises are labeled using an analogy with the color spectrum of light [15]. For example, white power laws with $\alpha = 0$ have equal power at all frequencies, equivalent to white light featuring contributions from all visible frequencies. Pink power laws have a higher α value, indicative of an increase in power at lower frequencies analogous to pink light.

Remarkably, fractal noises are not restricted to those generated by natural processes but can appear in artificial auditory experiences that are sufficiently complex to assume fractal variations [69]. A variety of music, sound, and talk show programs on the radio have been shown to have a fractal $1/f^{\alpha}$ frequency spectrum. Hour-long segments from various radio programs [70] including speech, classical music, and rock music sounds were found to have an average α value similar to that generated by natural scenes. However, the significance of fractal measures such as *D* remains unclear in terms of determining the aesthetics and perception of different genres of music. For example, some studies have found that various genres differ in their *D* value [71–73], while others have found no discernible consistencies in the role of fractal-scaling statistics at all [74].

In addition to these fractal spectral noise studies, there are many other ways to incorporate fractality into music. For example, fractal rhythms can be introduced through drumbeats. Other research has focused on employing $1/f^{\alpha}$ synthetic melodies [75] to examine fractal melodicity and preference. That is, when music is presented in its most basic form – a sequence of single notes of the same duration spaced equally to form a melody – does a $1/f^{\alpha}$ manipulation of this sequence alter its perceived aesthetic value? Applying this approach to simple melodic sequences (see, e.g., Fig. 45.11), investigations of α values ranging from approximately 0–2

Fig. 45.11 Examples of synthetic $1/f^{\alpha}$ melodies for α values of 0.25, 1.25, and 2.25

revealed a preference for the intermediate (equivalent to "natural") values [70, 75]. However, preference ratings from our own studies (Fig. 45.10) exhibit a preference for high α (i.e., low D) similar to that revealed for the tactile and dynamic fractal studies. This shift for the auditory realm might well be inherited from the dynamic realm (since low-frequency spatial motions are more likely to generate low temporal frequencies). Finally, we emphasize the preference variations for the "smoothie" and "sharpie" subpopulations should be expected for the auditory realm. Indeed, Güçlütürk and van Lier [76] measured participant liking ratings for 25 song excerpts from a variety of musical genres that had been previously rated for instrumental complexity. The analysis of preferences clustered the participants into 2 relatively equal-sized groups, where 1 group showed a preference for more complex songs and the other group showed a preference for more simple songs.

45.6 Fractal Applications

The Science Design Laboratory (SDL) was founded in 2017 to translate the science of fractal fluency into applications for indoor and outdoor architectural environments [77, 78]. Initial fractal designs focused on interior spatial patterns. Because floors occupy such a large part of our eye's visual field, an award-winning collection of carpet designs called Relaxing Floors was developed for the Mohawk Group, one of the world's largest carpet manufacturers [77]. As shown in Fig. 45.12, the eye's fractal trajectories provided the underlying layout for the carpet designs. A circular "seed" pattern was then inserted at the locations between trajectories, and its size was scaled according to the length of the preceding trajectory. Then each circle was replaced by a fractal pattern which could be varied between designs.

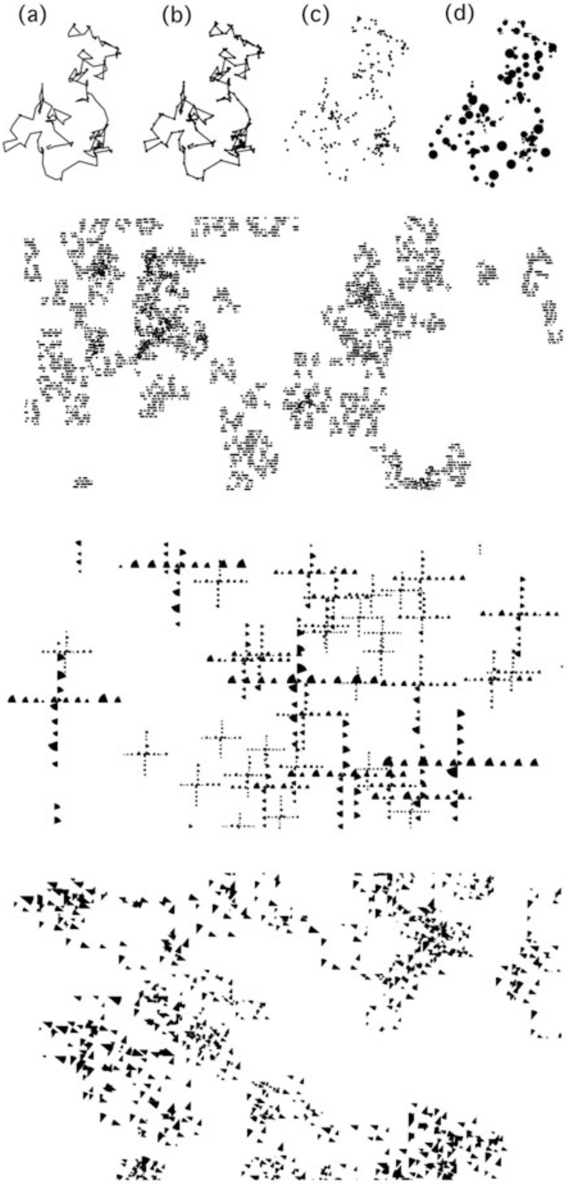


Fig. 45.12 Top: The pattern generation process for the Relaxing Floor designs. (a) The fractal pattern of the eye’s trajectories, (b) the fractal pattern when circular “seeds” are added to the locations between these trajectories, (c) the fractal pattern when the trajectories are removed, and (d) the fractal pattern when the sizes of the circles are scaled based on the length of the previous trajectory. Bottom: three complete carpet designs generated by replacing the circular patterns by three different fractal patterns. (Images courtesy of *Fractals Research* and *13&9 Design*)

The D value of the overall pattern generated by this process was informed by the $D = 1.6–1.7$ target range suggested by the aesthetics experiments that projected fractal images into rooms [44]. Behavioral studies performed on the Relaxing Floor patterns show this complexity to be very effective at balancing engagement, preference, refreshment, and relaxation qualities for a broad group of observers [79]. Specifically, these patterns have the greatest agreement across individuals in terms of their preference, engagement, and refreshment while also maintaining relaxing effects.

Emphasizing the versatility of statistical fractals, cutting the pattern into tiles and randomly re-arranging them did not disrupt the fractal character nor significantly shift their D values. This has important consequences because many carpets in large spaces ranging from airports to hotels are installed as tiles rather than as continuous carpets.

Figure 45.13 demonstrates a key strategy – development of versatile designs that can be used for multiple applications. In this case, the applications are carpet patterns (in the *Mohawk* collaboration), wall patterns used to disperse light throughout a chapel (in a collaboration with *INNOCAD Architecture*), computer screen savers (the latter are being made available for free personal use during the pandemic), and ceiling tiles (in collaboration with *Fact Design*). The ceiling tile application demonstrates a second key strategy – that patterns should, when possible, provide multiple functions. In this case, the patterns are embossed in the ceiling tiles, offering the potential to create an aesthetic impact coupled with the established noise-dampening capabilities of fractal surfaces. Inspired by this strategy of combining aesthetics with other favorable functions, a psychology-engineering project recently incorporated fractal aesthetics into solar panels [80].

Fractal window patterns offer further possibilities for multi-functionality [10, 81]. The fractal pattern can be used as a window shade to obscure an unattractive view, to provide shade, and to also cast dynamic fractal shadows across a room. For open windows, the shade can also generate a fractal breeze. In addition to the fractal variations in light, it can therefore provide analogous variations in heat and air currents for the room's occupants. The fractal designs are also being developed for outdoor surfaces. In addition to their visual and textural aesthetics, these surfaces offer the possibility of floor surfaces that reduce slipping (based on fractal shoe souls that have been patented because of their proposed superior traction). Interestingly, the basic pattern of Fig. 45.13 reminds many viewers of Morse Code patterns. With their sequences of dots and dashes, Morse Code can be both visual and sonic. Consequently, we are using computers to convert the visual stimuli of Fig. 45.13 into the auditory equivalents.

45.7 Conclusions

In this chapter, we have reviewed experiments that support the "fractal fluency" model which states that human senses have become fluent in the visual, sonic, and tactile language of fractals through evolutionary exposure. Reflecting the focus of previous research, most of our discussion centered on fractal fluency effects in the visual realm. In addition to biophilia's well-known effects, our own research of visual fractals has demonstrated increases in detection sensitivity, attention,

Fig. 45.13 The SDL fractal pattern of Figure 45.12 employed as (top left) a floor design at the University of Oregon, USA (image courtesy of *Fractals Research*, *13&9 Design,* and the *Mohawk Group*), (top right) as light patterns in the Fractal Chapel in the State Hospital in Graz, Austria (image courtesy of *Fractals Research*, *13&9 Design,* and *INNOCAD Architecture*), (bottom left) as a design for ceiling tiles, Linz, Austria (image courtesy of *Fractals Research*, *13&9 Design*, *INNOCAD Architecture, and FACT Design*), (bottom right) as a design for computer screen savers. (Image courtesy of *Fractals Research* and *13&9 Design*)

visual performance (e.g., pattern recognition and navigation), aesthetic appeal, and stress reduction. Consistent with fractal fluency, these effects peak at the mid-*D* complexity prevalent in natural scenery.

Extending the experiments to dynamic visual fractals and to tactile experiences reveals a more subtle dependence of responses to the *D* value of the fractal stimulus. Whereas sensitivity to the dynamic and tactile fractals peaks at the mid-*D* complexity expected from the fluency hypothesis, aesthetic preference peaks for lower complexity fractals. This might be explained by extra factors that influence fractal aesthetics in real-life physical environments. Whereas aesthetics aligns with detection in the visual realm, safety cues might drive the aesthetic appreciation away from this condition when physical interactions are involved. For example, in the

Fig. 45.14 Examples of high-*D* (top), mid-*D* (middle), and low-*D* (bottom) scenery

tactile realm, the potential harm from the sharp texture of high *D* surfaces might drive the aesthetics to lower *D* smooth surfaces. Similarly, the high frequencies of high *D* fractal noises might signal the approach of dangerous conditions such as storms and earthquakes.

Seasonal changes can induce small shifts in the *D* value of the visual fractals in some scenes. For example, as leaves detach from trees in the Fall, the fine-scale patterns of the exposed twigs raise the *D* values of the trees. Whether these small shifts contribute to seasonal mental disorders has not been investigated. Looking to the future, climate change might induce larger and more permanent shifts in *D*. As an example of the human impact on fractality, picture the mid-complexity scene of trees spread across a savannah (a landscape in which our ancestors evolved) (Fig. 45.14). If climate change reduces the trees to a barren desert, then the one-dimensional line of its horizon will shift the scene out of the

Fig. 45.15 A fractal atmosphere in which the room occupant is immersed in fractal floor patterns, fractal wall patterns, and fractal music. (Image courtesy of *Fractals Research*, *13&9 Design,* and the Mohawk Group)

aesthetic zone. Similarly, forests that become filled in with fine-scaled branches will shift to higher *D* and, again, out of the zone. Cloud patterns also contribute to the mid-complexity of scenery, and any increased likelihood of uniformly blue or gray skies will similarly cause a shift away from the aesthetic zone.

Even if we can evade climate change, modern life forces people away from nature's fractals and into urban scenery. We have therefore also considered strategies for transferring the fundamental science of fractal fluency to applications in the built environment. Imagine a future in which we immerse building occupants in a "fractal atmosphere" of visual, auditory, and tactile experiences – potentially inducing an emergent experience that we have all evolved to expect and appreciate (Fig. 45.15). Based on the examples presented in this chapter, we already have the potential to walk into a room in which the fractal ceilings dampen the noise, the fractal window shades provide an optimal breeze, fractal solar panels deliver efficient energy, and all of their patterns combine to create a stress-reducing visual environment analogous to the complex scenes of nature.

Finally, although we have concentrated on visual, sonic, and tactile fractals, it is interesting to note that fractals have consequences for smells and taste. For example, the fractal airflows induced by fractal window patterns will influence not only wind variations in the room but also the smells they carry. Fractal objects are also known for their large surface areas which might promote taste. We hope that this chapter highlights the diverse range of future opportunities for studying human responses to fractals across many senses and for applying these to provide positive environments for the occupant. Without a doubt, the fractal geometry of nature influences the fractal geometry of the brain and vice versa.

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