Fractal Fluency: An Intimate Relationship Between the Brain and Processing of Fractal Stimuli

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Abstract

Humans are continually exposed to the rich visual complexity generated by the repetition of fractal patterns at different size scales. Fractals are prevalent in natural scenery and in patterns generated by artists and mathematicians. In this chapter, we will investigate the powerful significance of fractals for the human visual system. In particular, we propose that fractals with mid-range complexity (D = 1.3 - 1.5 measured on a scale between D = 1.1 for low complexity and D = 1.9 for high complexity) play a unique role in our visual experiences because the visual system has adapted to these prevalent natural patterns. This adaption 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. For example, eye-movement studies show that the eye traces out mid-D fractal trajectories that facilitate visual searches through fractal scenery. Furthermore, qEEG and preliminary fMRI investigations demonstrate that mid-D fractals induce distinctly different neuro-physiological responses than less prevalent fractals. Based on these results, we will discuss a fluency model in which the visual system processes mid-D 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 exploring the fundamental science of our visual system, the results have important practical consequences. For example, mid-D fractals have the potential to address stress-related illnesses.

Keywords: fractals, complexity, perception, stress-reduction, qEEG

Introduction: The Complexity of Biophilic Fractals

Fractal patterns are prevalent throughout nature. Examples include lightning, clouds, trees, rivers and mountains. Furthermore, they have permeated cultures spanning across many centuries and continents, ranging from Hellinic friezes (300 B.C.E) to Jackson Pollock's poured paintings (1950s) [1-2]. From the 1860s onward, their visual properties have also been explored by mathematicians. Consequently, fractals constitute a central component of our daily experiences. In Fig. 1, we use a coastline to demonstrate their intrinsic visual properties. As shown in the left column, fractals can be divided into 2 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, 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.

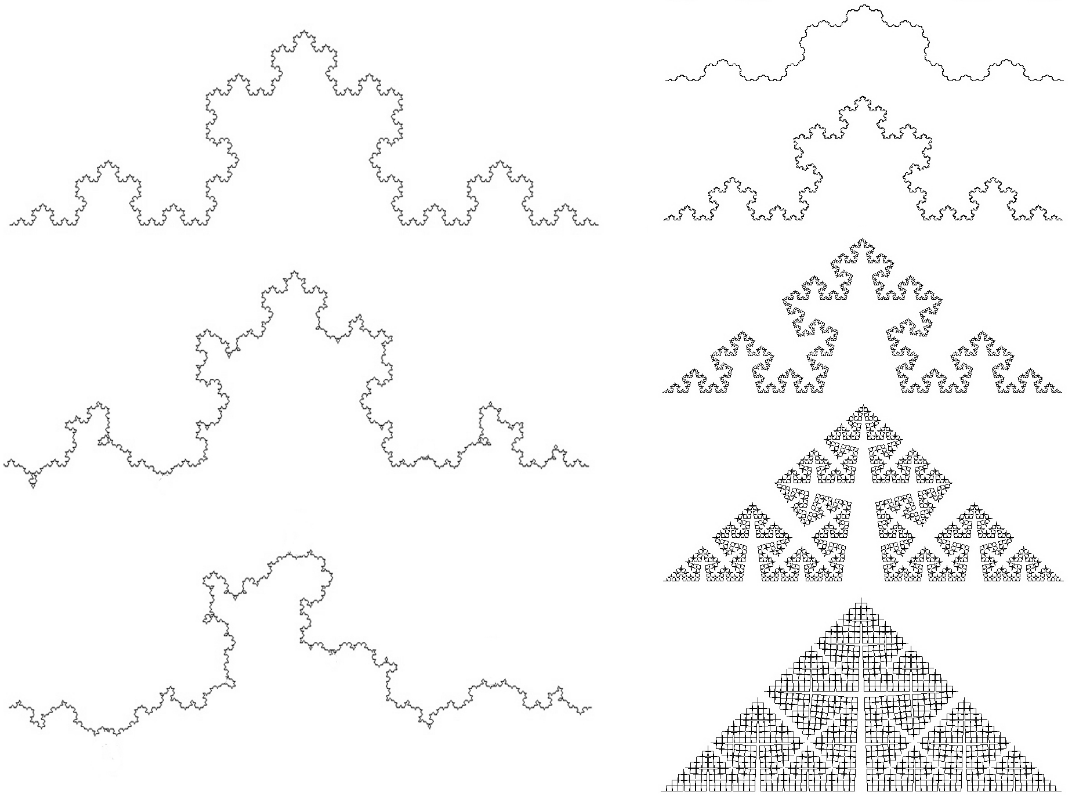

Fig. 1. Left column: A computer-generated coastline based on exact fractals (top) is morphed into a statistical fractal coastline (bottom) by introducing randomness. For the top fractal, all of the headlands point upward. For the bottom fractal, half point downward and the positions of the up and down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

Statistical fractals 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 efficiently disperse wave energy reduces erosion, inspiring fractal storm barriers. 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. Previous studies have shown that exposure to natural scenery can have dramatic, positive consequences for the observer [3-5]. In particular, Ulrich and colleagues showed that patients recover more rapidly from surgery in hospital rooms with windows overlooking nature. Although groundbreaking, these demonstrations of 'biophilic' (nature-loving) responses employed vague descriptions for nature's visual properties. Our research builds on these studies by testing a highly specific hypothesis – that the statistical fractals inherent in natural objects are inducing these remarkable effects [6].

To quantify the rich visual intricacy of the statistical fractals, we adopt a traditional measure employed by mathematicians – the pattern's fractal dimension D [7]. This parameter describes how the patterns occurring at different magnifications combine to build the resulting fractal shape. For a smooth line (containing no fractal structure) D has a value of 1, while for a completely filled area (again containing no fractal structure) its value is 2. However, the repeating patterns of the fractal line cause the line to begin to occupy space. As a consequence, its D value lies between 1 and 2. By increasing the amount of fine structure in the fractal mix of repeating patterns, the line spreads even further across the two-dimensional plane (see the right column of Fig. 1) and its D value therefore moves closer to 2. Figure 2 demonstrates how a 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 coarse to fine structure, it is expected that D will serve as a convenient measure of the visual complexity generated by the repeating patterns. Behavioral research by Cutting and Garvin confirms that the complexity perceived by observers does indeed increase with D [8].

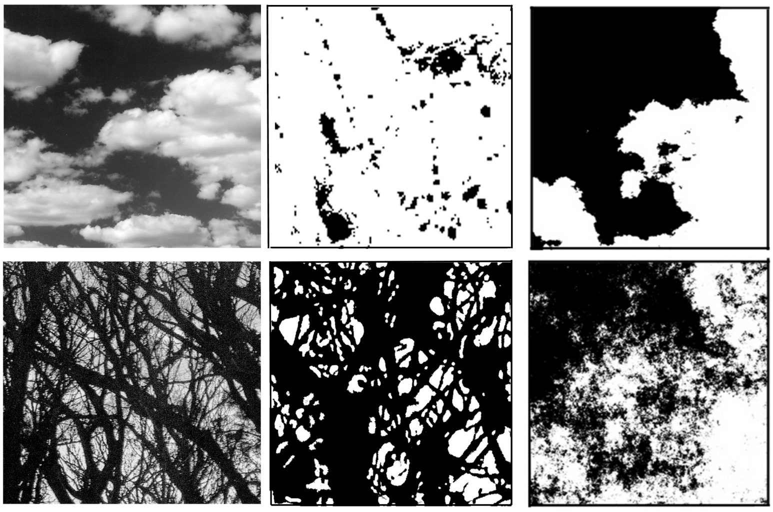

Fig. 2. Fractal complexity in nature, art and mathematics. The left column shows clouds with $D = 1.3$ (top) and a forest with $D = 1.9$ (bottom). The middle column shows Jackson Pollock's *Untitled 1945* with $D = 1.1$ (top) and *Untitled 1950* with $D = 1.89$ (bottom). The right column shows computer-generated fractals with $D = 1.2$ (top) and $D = 1.8$ (bottom).

Our initial investigations used 3 distinct categories of stimuli summarized in Fig. 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) [9]. Our current studies focus exclusively on computer-generated fractals due to their advantageous properties [10]. Firstly, the *D* values of the images are known precisely because they are input parameters for the computer-generation process. Secondly, the greater control offered by computers allows the separation of different visual characteristics. For example, whereas density and *D* are intrinsically linked in Pollock's paintings (as seen in Fig. 2, he raised the painting's *D* value by adding more paint which in turn inevitably raised the density [2]) 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 3 shows examples of our current stimuli, which are generated by Fourier spectrum or midpoint displacement methods [7]. For the far left image, the computer has generated a geographical terrain (in this case viewed from above) and this serves as the source to generate the other images. To obtain the second image, a horizontal slice is taken through the terrain at a selected height. Then all of 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 forth image is created by taking a vertical slice through the terrain to create a mountain profile. Finally, the grayscale image is generated by assigning grayscale values (on a scale from 0 to 255) to the heights of the terrain. 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.

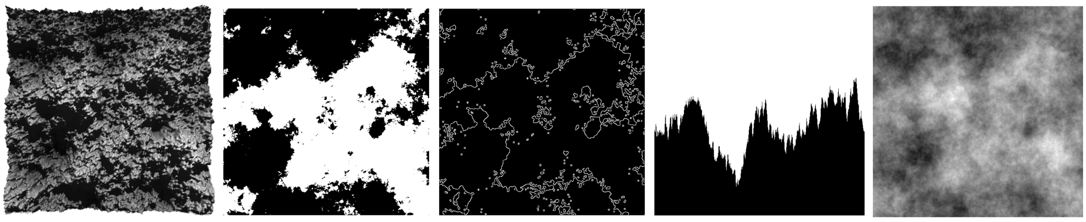

Fig. 3. Computer-generated fractal stimuli. From left to right: terrains, coastlines, edges, mountains, and grayscale patterns.

Fractal Fluency

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 between $1.1 < D < 1.9$ 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 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 [6]. We expect this adaption 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. Based on the phenomenon of synesthesia, in which sensations are transferred between the senses, it is possible that mid-complexity fractals might also hold special significance for tactile and audial experiences in addition to visual ones. This could be tested in the future using three-D printers to generate physical versions of the terrains shown in Fig. 3 and to use computers to convert visual stimuli into the sonic equivalents. This includes plans to convert the fractals in Pollock paintings into music and compare people's responses to these equivalent visual and sonic fractals.

Our studies of fractal fluency commenced with the eye-movement studies shown in Fig. 4 [6-7]. The eye-tracking system (Fig. 4a) integrates infra-red and visual camera techniques to determine the eye's gaze to an accuracy of 4 pixels when looking at a 1024 by 1024 pixel pattern presented on the computer monitor. During the 60s observation period, participants were instructed to memorize the pattern in order to induce 'free viewing' activity. Figure 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 motionless can also be seen in the associated temporal trace of Fig. 4c. Details of the fractal measurement technique applied to the eye's spatial and temporal patterns are reported elsewhere [6-7, 11-12]. 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, 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 [12].

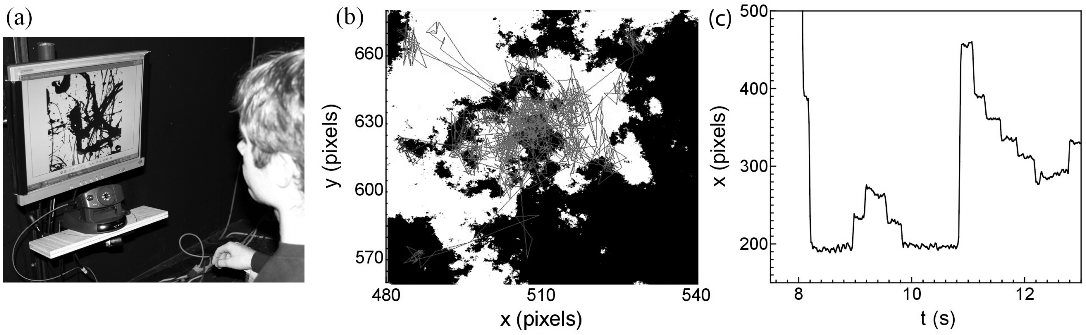

Fig. 4. (a) A photograph of the eye-tracking apparatus, (b) the spatial pattern of the eye tracks (light gray) plotted in the x (horizontal) and y (vertical) directions. The eye-track is overlaid on the observed fractal pattern (black and white), (c) the equivalent time series data which plots x versus time.

We propose that the purpose of the eye's search through fractal scenery is to confirm its fractal character (for example, the ability to confirm that 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 [13]. 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 motion 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 [7]. 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 sift 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 [14-15]. Some pathways are dedicated to analyzing large structures in nature's environment, others to small structures. He 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 [16]. 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 arousal. 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 [17]. 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 [4,5]. In our studies, participants' responses were continuously monitored using a digital EEG recorder while they viewed fractal 'mountain' stimuli (Fig. 3) with different *D* values [18]. The images were viewed for 1 minute each and interspaced by a neutral grey picture for 30 seconds. This exposure period was chosen to ensure that a relaxation effect in the subjects could occur. Three regions of the brain - frontal, parietal and temporal - were chosen because processes in these associational zones are known to be complementary [17]. The results showed that fractal images quantified by $D = 1.3$ induce the largest changes in participants' alpha and beta responses [18]. Intriguingly, these responses were dampened when the images were morphed from the statistical to exact versions (Fig.1), emphasizing the adaption of processing fluency to nature's biophilic fractals [19]. 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. Although requiring further study, they suggest that mid-*D* fractals preferentially activate specific regions such as the ventral visual stream (including the ventrolateral temporal cortex), the parahippocampal region and the dorsolateral parietal cortex [6].

Enhanced Performance and Fractal Aesthetics

The fluency model predicts that the increased processing capabilities should result in enhanced performances of visual tasks when viewing mid-*D* fractals. Indeed, our recent behavioural studies demonstrate participants' heightened sensitivity to mid-*D* fractals [20]. Using grayscale fractal images displayed on a computer monitor (Fig. 3), the contrast in the patterns was gradually reduced until the monitor displayed uniform mean luminance. Participants were able to detect the mid-*D* fractals for much lower contrast conditions than the low and high *D* fractals [20]. Similarly, participants displayed a superior ability to distinguish between fractals with different *D* values in the mid-*D* range [20]. The increased beta response in the qEEG studies suggests a heightened ability to concentrate when viewing mid-*D* range [18]. There is also anecdotal evidence to suggest that pattern recognition capabilities increase for mid-*D* fractals. We are all familiar with percepts induced by cumulus clouds (Fig. 5, top). 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.

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 earlier skin conductance measurements similarly demonstrated that mid-*D* fractals are stress-reducing [18, 21]. 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 measureable mathematical properties of the observed images. Visual complexity was a central parameter in his proposals [22]. In 1993, RPT conducted the first aesthetics experiments on fractals, showing that 95% of observers preferred complex fractal images over simple Euclidean ones [23]. Soon after, Sprott employed computer-generated fractals to show that mid-*D* fractals were preferred over low and high *D* fractals [24].

Over the past 2 decades, fractal aesthetics experiments performed by ourselves and other groups have shown that preference for mid-*D* fractals is universal rather than dependent on specific details of how the fractals are generated. We showed that preference for mid-*D* patterns occurred for fractals generated by mathematics, art and nature [9]. Whereas this experiment featured relatively simple natural images such as a tree or a cloud, this was soon broadened to include more complex natural scenes featuring many fractals [24]. Figure 5 shows example results for computer-generated stimuli [6]. The panels are for 4 different 'configurations' (i.e. the computer uses 4 different seed patterns). The peak preference shows remarkable consistency despite superficial variations in the 4 families of fractals. More recently, our experiments demonstrated a direct correlation between preference and the observer's enhanced capabilities (based on their abilities to detect and discriminate fractals) [20]. 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 [26]. 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.

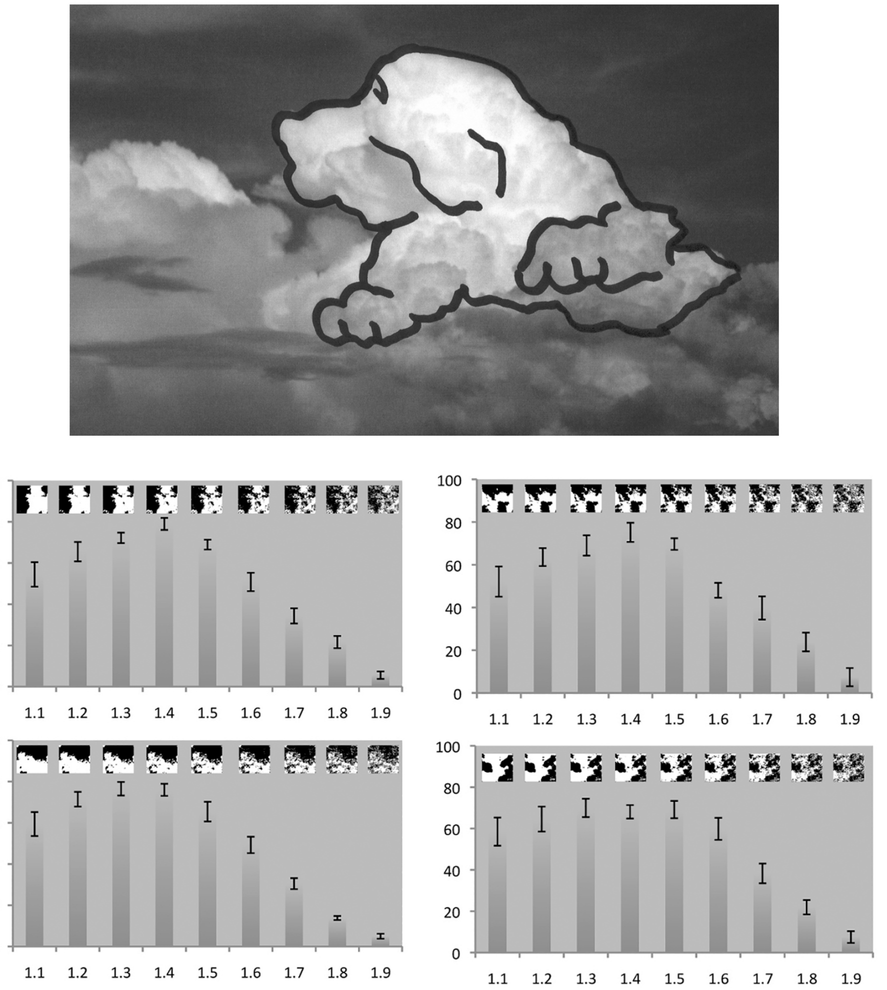

Fig. 5. Top: A perceived image of a dog drawn on a $D = 1.3$ cloud. Bottom: Visual preference for computer-generated fractal patterns. For each of the 4 panels, D is plotted along the x-axis and the preference on a scale 0-100 is plotted along the y-axis. Each of the 4 panels uses a different fractal configuration to investigate preference. The fractal images are shown as insets in each panel.

Conclusion: The Brave New World of Neuro-aesthetics

Behavioral experiments, coupled with qEEG and fMRI techniques, might initially appear to be highly unusual tools for judging art and aesthetics. The history of neuro-aesthetics can be viewed as an epic battle fought between scientists and art theorists since the days of Surrealism and Freudian psychology [27]. This deep clash between art and science is fuelled by a fundamental concern: to what extent is art appreciation driven by the automatic responses of human neurophysiology and biology versus the intellectual and emotional deliberations of the culture-influenced observer? Consider the neurophysiological responses to Pollock's paintings as an example. Can an appreciation of his paintings be likened to the way a frog continues to twitch when its head is cut off? Afterall, our results indicate that both are automatic responses. Such a comparison seems simplistic, but it does reflect the widespread fear of the "neurophysiology is destiny" approach to art. Equally, the "culture is destiny" supporters cannot distance art from neurophysiology. Pollock's colleague, Willem de

Kooning, serves as a dramatic example of how drastically his artistry changed as his Alzheimer's disease progressed. The reality of aesthetics will almost certainly prove to be "neurophysiology and culture are destiny." Its foundation is set by the observer's neurophysiology, which is then modified by intellectual and emotional deliberations.

The neuro-aesthetics debate is also fueled by Zeki's use of fMRI to catalog art based on the regions of the observer's brain that are activated [28]. Imagine taking Zeki's vision one step further - if we can identify the region that is activated when looking at a Pollock, then might we replace the original artwork with technology that allows us to stimulate this region directly? Though efficient, this radical and controversial approach would dishearten the art lovers who frequent galleries and museums. In reality, it is doubtful that we will ever master a technology sufficiently subtle to stimulate the same fMRI pattern that a Pollock painting does.

Despite these and similar concerns, the interplay between art and the brain will be crucial for our future understanding of humanity. Novel measurement technology is destined to play an increasing role. Our results follow a long tradition of experimental aesthetics and the use of modern tools for analyzing human response to art works. They provide a fascinating insight into the impact that art might have on the observer's perceptual, physiological, and neurological condition. Our studies have only started to probe the neurophysiological origin of fractal aesthetics. It might well turn out that there is a deep resonance between the observed fractal stimuli and the fractal properties of the brain. In addition to exploring the fundamental science of our visual system, our fractal studies have important practical consequences. Mid-*D* fractals have the potential to address stress-related illnesses, which currently cost countries such as the US over $300 billion annually.

Acknowledgments

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References

[1] Taylor RP, Micolich AP, & Jonas D. Fractal analysis of Pollock's drip paintings. Nature. 1999; 399: 422.

[2] Taylor RP, Guzman R, Martin TM, Hall G, Micolich AP, Jonas D, Scannell BC, Fairbanks MS, & Marlow CA. Authenticating Pollock paintings with fractal geometry. Pattern Recognition Letters. 2007; 28: 695 - 702.

[3] Ulrich RS & Simons RF. Recovery from stress during exposure to everyday outdoor environments. Proceedings of EDRA. 1986; 17: 115-122.

[4] Ulrich RS. Biophilia, biophobia and natural landscapes. In: The biophilia hypothesis. Washington DC: Island Press; 1993.

[5] Ulrich RS. Natural versus urban scenes: Some psychophysiological effects. Environment and Behavior. 1981; 13: 523-556.

[6] Taylor RP, Spehar B, von Donkelaar P & Hagerhall CM. Perceptual and physiological responses to Jackson Pollock's fractals. Frontiers in Human Neuroscience. 2011; 5: 1-13.

[7] Fairbanks MS & Taylor RP. Scaling analysis of spatial and temporal patterns: from the human eye to the foraging albatross. In: Non-linear Dynamical Analysis for the Behavioral Sciences Using Real Data. Boca Raton: Taylor and Francis Group; 2011.

[8] Cutting JE & Garvin JJ. Fractal curves and complexity. Perception & Psychophysics. 1987; 42: 365-370.

[9] Spehar B, Clifford C, Newell B, Taylor RP. Universal aesthetic of fractals. Chaos and Graphics. 2003; 37: 813-820.

[10] Spehar B & Taylor RP. Fractals in art and nature: why do we like them? SPIE Electronic Imaging. 2013; 865: 1-18.

[11] Moon P, Murday J, Raynor S, Schirillo J. Fairbanks MS, & Taylor RP. Fractal images induce fractal pupil dilations. The International Journal of Psychophysiology. 2014; 93: 316 - 321.

[12] Marlow CA, Viskontas IV, Matlin A, Boydston C, Boxer A, Taylor RP. Temporal structure of human gaze dynamics is invariant during free viewing. PLoS one. 2015; 10: e0139379.

[13] Viswanathan GM, Afanasyev V, Buldyrev SV, Murphy EJ, Prince PA & Stanley HE. Lévy flight search patterns of wandering albatrosses. Nature. 1996; 381: 413 - 415.

[14] Field DJ. & Brady N. Visual sensitivity, blur and the sources of variability in the amplitude spectra of natural scenes. Vision Research. 1997; 37: 3367-3383.

[15] Knill DC, Field D & Kersten D. Human discrimination of fractal images. Journal of the Optical Society of America. 1990; 77: 1113-1123.

[16] Geake J & Landini G. Individual differences in the perception of fractal curves. Fractals. 1997; 5: 129-143.

[17] Kolb B & Whishaw IQ. Fundamentals of Human Neuropsychology. New York: Worth Publishers; 2003.

[18] Hagerhall CM, Laike T, Taylor RP, Küller M, Küller R, & Martin TP. Investigation of EEG response to fractal patterns. Perception. 2008; 37: 1488-1494.

[19] Hagerhall CM, Laike T, Küller M, Marcheschi E, Boydston C & Taylor RP. Human Physiological Benefits of Viewing Nature: EEG Response to Exact and Statistical Fractal Patterns. The Journal of Nonlinear Dynamics, Psychology, and Life Sciences. 2015; 19: 1-12.

[20] Spehar B, Wong S, van de Klundert S, Lui J, Clifford CWG & Taylor RP. Beauty and the beholder: the role of visual sensitivity in visual preference. Frontiers in Human Neuroscience. 2015; 9: 1-12.

[21] Taylor RP. Reduction of physiological stress using fractal art and architecture. Leonardo. 2006; 39: 245 - 251.

[22] Birkhoff GD. Aesthetic Measure, Cambridge (U.S.A.): Harvard University Press; 1933.

[23] Taylor RP. Splashdown. New Scientist. 1998; 2144; 30-31.

[24] Aks D & Sprott J. Quantifying aesthetic preference for chaotic patterns. Empirical Studies of the Arts. 1996; 14: 1-16.

[25] Hagerhall CM, Purcell T & Taylor RP. Fractal dimension of landscape silhouette outlines as a predictor of landscape preference. Journal of Environmental Psychology. 2004; 24: 247-255.

[26] Taylor RP & Sprott JC. Biophilic fractals and the visual journey of organic Screen-savers. Journal of Non-linear Dynamics, Psychology and Life Sciences. 2008; 12: 117-129.

[27] Taylor RP. Across the cultural divide. Nature. 2010; 463: 431.

[28] Zeki S. Inner vision: An exploration of art and the brain. Oxford: Oxford University Press; 1999.