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Using Fractal Iconography to Emulate Nature's Aesthetics

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Abstract: *This year's cover artists are members of a team of physicists and psychologists who create human-centered designs based on psychology experiments that investigate the positive impacts of viewing fractal patterns. These positive impacts include reduced physiological stress levels and enhanced cognitive skills. Here, the team explores the concept of "fractal iconography" as an approach to employing computers to generate naturalistic art. Adopting this approach, three forms of fractal patterning* ("*fractal icons"*) *are combined in a variety of ways to generate the rich complexity of nature's scenery. These composite fractals are remarkably effective at conveying nature's aesthetic power.*

Key Words: Fractals, iconography, human-centered design, stress reduction.

Mandelbrot's book *The Fractal Geometry of Nature* (Mandelbrot, 1982) built on Galileo Galilei's broader observation that "The book of nature is written in the language of mathematics" (Galilei & Finocchiaro, 2008). Although Mandelbrot invented the term "fractal," he was not the first to study the way their patterns repeat at difference size scales. Various mathematicians had been studying them for more than a century before the term was introduced. A striking theme in this historical development is that artistic creations of fractals frequently pre-dated their conscious mathematical discovery. Von Koch's famous fractal curve from 1904 serves as a demonstration. Its repetition of triangles was first used around 300 B.C.E. to illustrate waves in Hellenic friezes, and then again in the 12th century in the pulpit of Italy's Ravello Cathedral. Similarly, triangles within Cosmati mosaics from the 13th century created a fractal shape that became celebrated in mathematics as the Sierpinski Triangle 7 centuries later.

Many artistic fractals serve as symbolic representations of nature's fractals rather than precise replicas. Their recurring patterns at increasingly fine scales are often exact copies of each other and, as such, make no effort to incorporate the random variations that generate nature's statistical fractals. Nor do their patterns repeat across many size scales. Nevertheless, these limited-range, exact fractals are strikingly effective at capturing the essence of nature's beauty.

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Examples can be found across many centuries and many continents (Taylor, 2021): The *Book of Kells* (circa 800 C.E.), India's *Jain Dilwara Temple* (1031 C.E.), the *Ryoan-ji Rock Garden* in Japan (15th century), Leonardo da Vinci's *The Deluge* (1500), Katsushika Hokusai's *Great Wave* (1833), Salvador Dali's *Visage of War* (1940) and Mauk Escher's *Circle Limit III* (1959) are notable examples from previous eras.

In March 1980, Mandelbrot became the first mathematician to use a computer to visualize a fractal pattern on a computer monitor. Although crude by today's standards, this image launched an era in which computing power could be used by mathematicians and artists to generate fractals much more sophisticated than the artistic forerunners listed above. Whether employed for a poster or for the backdrop to a movie, computers can now replicate the visual appearance of nature's scenery with an impressive precision. Yet, there's something appealing about the simple, symbolic representations used by the artists from the pre-computer age. Is it possible for the two approaches to meet halfway, and by doing so celebrate nature's beauty without resorting to merely copying it? This question inspired the concept of "fractal iconography."

The term "iconography" is derived from two Greek words. Combining "eikon" (image) with "graphe" (writing), image-writing employs images to tell a story. In our case, we use simple fractal images as visual words and assemble them into a visual language that tells nature's story. More specifically, we focus on three forms of abstract fractal pattern and combine them into a "fractal composite" that represents a natural scene. This composite is the half-way state of our aims. Obviously abstract, the individual fractal icons are symbolic representations of nature. However, they are surprisingly impactful when combined.

This artistic journey towards fractal iconography was accompanied by a parallel scientific journey. Our psychology experiments gravitated towards employing mathematical methods to generate statistical fractals (Taylor, 2021; Taylor et al., 2018). Rather than using images of natural scenes, these abstract mathematical forms allow us to trace their positive aesthetic qualities to their underlying geometry rather than to superficial associations with nature. We also studied them in monochrome to rule out the influence of color. In essence, we removed other aesthetic factors so that we could concentrate purely on people's responses to their basic fractal form. Despite this aesthetic distillation, our experiments through the years have revealed a remarkable set of behavioral responses.

Central to these studies, fractal dimension D charts the visual complexity generated by the repeating patterns (Fairbanks & Taylor, 2021) – with mid-complexity patterns delivering peak performances from viewers (Taylor, 2021). Figure 1 shows some examples of these performances – the ability to detect fractal patterns (Spehar et al., 2015), the ability to discriminate between patterns with differing D values (Spehar et al., 2015), the ability of avatars to navigate successfully though virtual fractal scenes (Juliani, Bies, Boydston, Taylor, & Sereno, 2016) and, most significantly, their aesthetic appeal (Taylor, Spehar, Van

Donkelaar, & Hagerhall, 2011). Strikingly, aesthetic preference for mid-*D* fractals is displayed by observers as young as 3 years old (Robles, Liaw, Taylor, Baldwin, & Sereno, 2020).

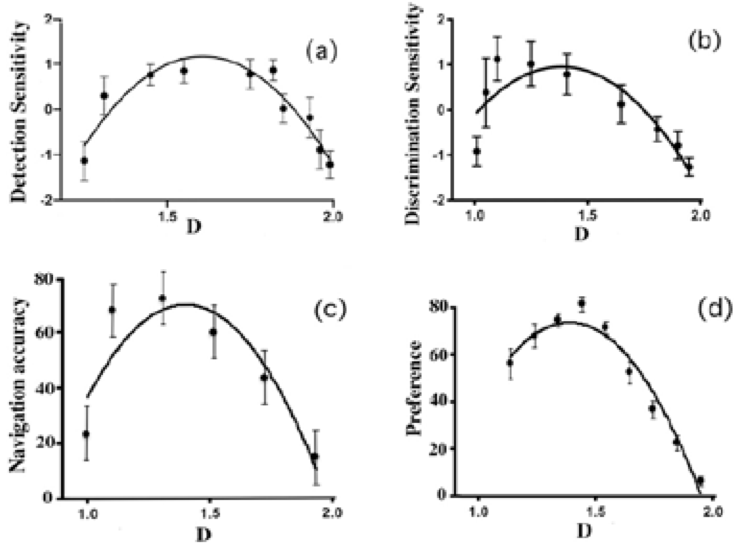

Fig. 1. Performance tasks: detection (a), discrimination (b), navigation (c), and preference ratings (d) plotted against the fractal's *D* value. Refer to Taylor (2021) for details of the measurements and the *y*-axis scales.

Taken together, these experiments inform the fractal fluency hypothesis – that evolutionary exposure to mid-*D* fractals (which are prevalent in natural scenery) has led to enhanced processing of these fractals, which in turn creates an associated aesthetic quality. Throughout our scientific studies of fractal fluency, we were intrigued by the fact that the relatively simple abstract images used in our experiments delivered such powerful results in light of the distillation of aesthetics described above. Would behavioral responses become amplified if we took these simple fractal icons and combined them into a fractal composite that resembled more realistic natural scenes? If so, which *D* values should be used for each of the icons and how should they be arranged? And what if we added color? These questions inspired our scientific journey to fractal iconography and now drive our current psychology experiments.

We employ three forms of statistical fractals that serve as our icons. The generation processes for two of the icons are related, as demonstrated in Fig. 2 (based on Spehar, Walker & Taylor, 2016). The grayscale image shown in the top square is generated either by Fourier spectrum or midpoint displacement methods (Bies et al., 2016; Fairbanks & Taylor, 2021). Its luminance variations across the horizontal plane follow a power law behavior that generates the scale invariance of fractal patterning. These luminance values are then converted into height variations (white being the highest) to generate the fractal terrain shown below the grayscale square. If we take a horizontal slice through the terrain at a particular height and then shade regions above this height as white and those below as black, we generate the pattern of clusters shown in the horizontal square to the right. We refer to these fractal icons as "fractal cluster" icons. If we use the analogous procedure for vertical slices, we generate the "fractal line" icons shown in the vertical square.

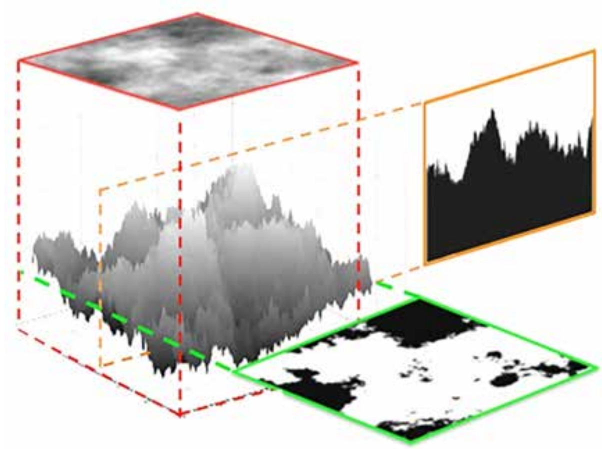

Fig. 2. Schematic showing the relationship between the fractal cluster and fractal line patterns.

Adopting this generation process, the exponent of the power law is inversely related to *D*, with the consequence that higher *D* patterns have larger contributions from their fine scale structure than the equivalent low *D* patterns (Bies et al., 2016). This spatial frequency content influences the perceived complexity of the pattern (Taylor, 2021). In Fig. 3, we show an example of a fractal cluster pattern with varying *D* values. Clearly, the perceived complexity ramps up as *D* increases across the range from 1.1 to 1.9.

Figure 4 shows some examples of fractal lines. In this case, we have used the same $D = 1.1$ value for the 3 images but generated them using different random variations (we refer to this as using different random seeds). These patterns are therefore different random versions of a fractal line icon capturing the same visual complexity.

Figure 5 shows our method for generating the third fractal icon, which we refer to as "fractal branch" icons. We start this process with the traditional H-Tree fractal, which repeats an H pattern exactly at different scales (Smith et al., 2021). For the case shown, there are 3 levels of repetition. The figure also demonstrates the role of *D,* which controls the rate of shrinkage of the branch lengths as we move to increasingly fine iterations of the pattern. This shrinkage follows a power law to generate the fractal scale invariance, with higher D patterns shrinking at a slower rate. Note also that we shrink the branch width with each iteration.

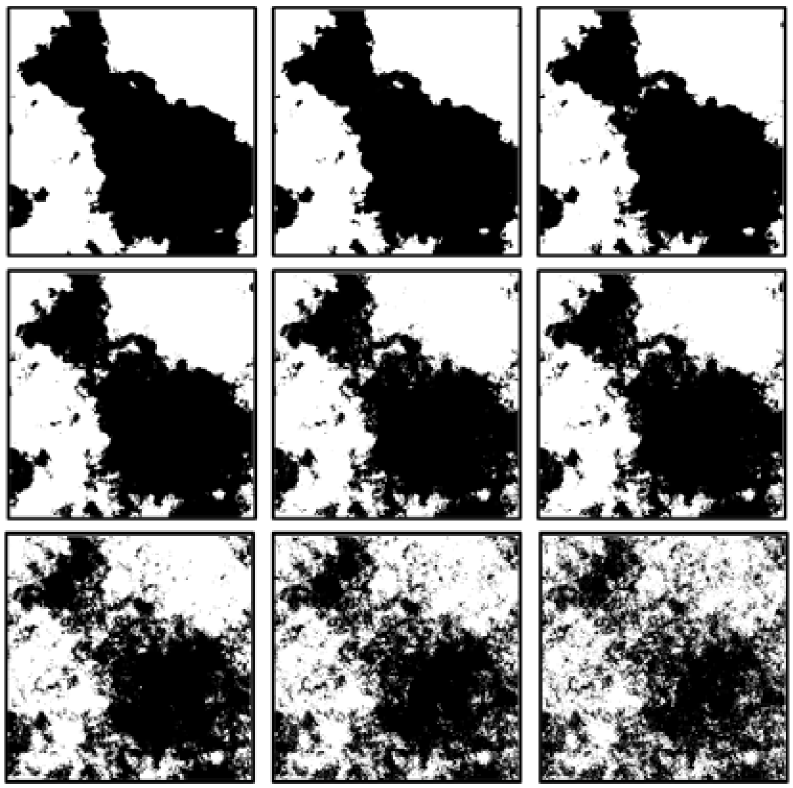

Fig. 3. Examples of a fractal cluster with D values ranging from 1.1 to 1.9.

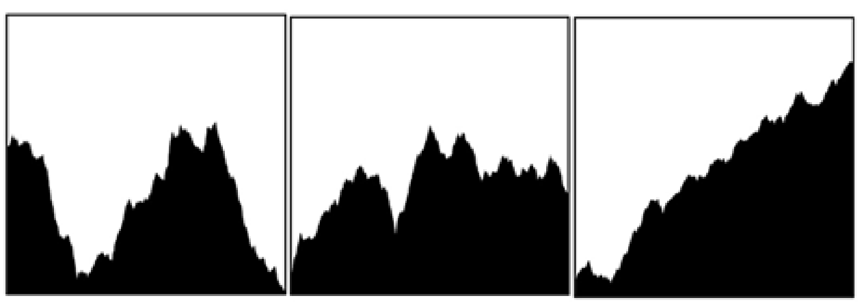

Fig. 4. Examples of a fractal lines with D = 1.1 generated using different random seeds.

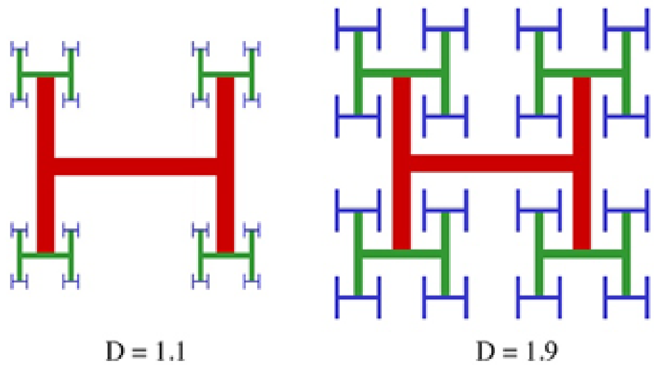

Fig. 5. Schematics showing a comparison between low *D* (left) and high *D* (right) H-Trees.

As shown in Fig. 6, we can vary the branch forking angle j and branch weaving angle q in addition to the branch length *L*. For the exact H-Tree, these branch angles are set at $j = 90^{o}$ and $q = 0^{o}$. Another form of the exact fractal branch pattern, shown in Fig. 6 (middle image), has been generated using $j = 45^{o}$ and $q = 0^{o}$. To convert these exact patterns into statistical versions for our branching fractal icons, we randomly select j and q values from a Gaussian distribution of angles, the standard deviation of which can be tuned (Fig. 6, right image) (Smith et al., 2021).

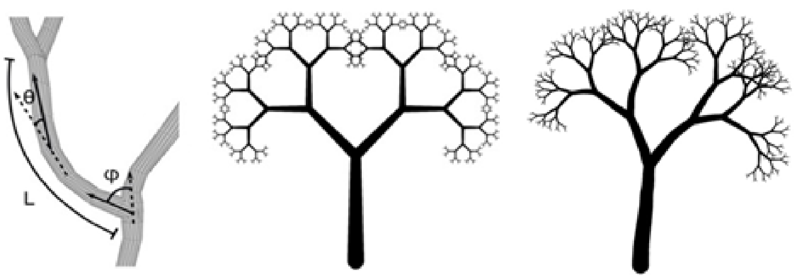

Fig. 6. Schematic representation showing branching length *L*, along with the weaving angle q and forking angle j for fractal branch icons (left image). The middle image shows an exact fractal branch pattern generated using $j = 45^{o}$ and $q = 0^{o}$. The right image shows a statistical fractal branch pattern generated by introducing randomness into the distributions of the j and q values.

These three fractal icons – fractal clusters, lines, and branches – can now be used as a visual toolbox for assembling composite fractals that resemble natural scenes. Within this toolbox, example roles include fractal clusters as clouds (Fig. 7, top left image), fractal lines as mountain profiles (Fig. 7, top right image), and fractal branches as trees (Fig. 7, bottom left image). Figure 7 (bottom right image)

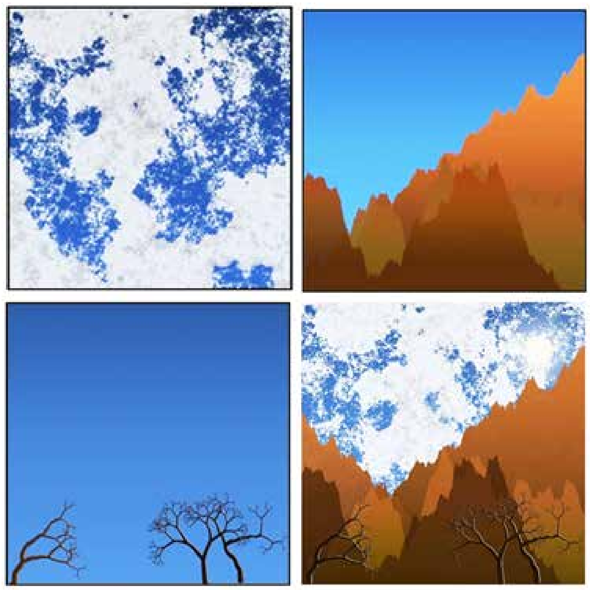

Fig. 7. Examples of fractal clusters (top left), fractal lines (top right), fractal branches (bottom left) and their composite (bottom right).

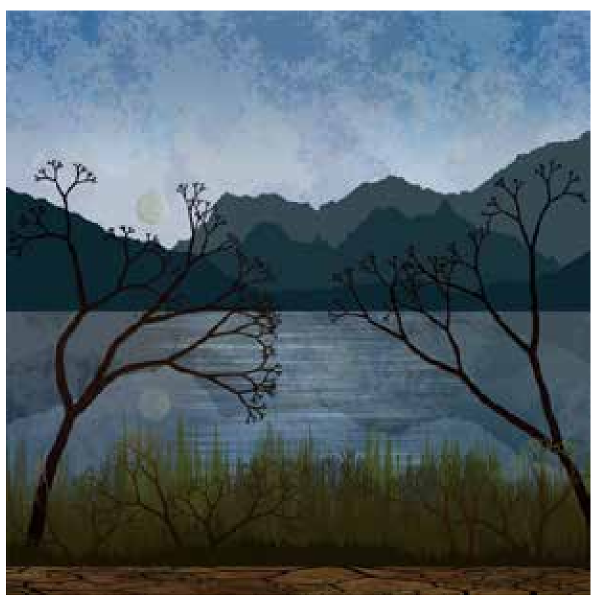

Fig. 8. Fractal iconography used to symbolize a natural scene.

is a composite fractal created from the combination of the three icons. Another example composite fractal is shown in Fig. 8. This composite uses fractal clusters to represent clouds along with textures on the moon surface. Fractal lines are used to represent mountains, water ripples, and grass. Fractal branches are used to represent trees, plants and cracks in the mud.

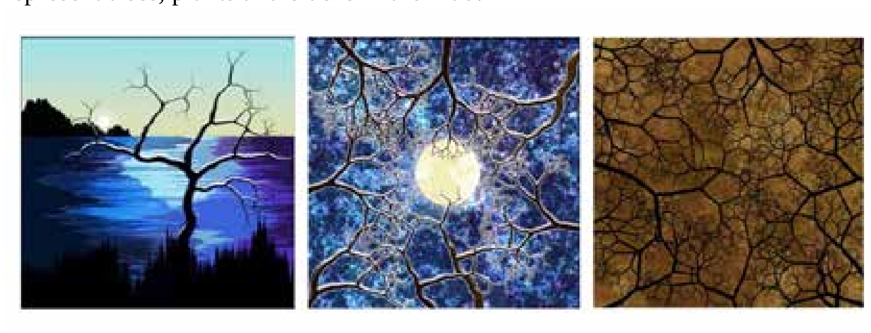

Fig. 9. Further examples of fractal composites.

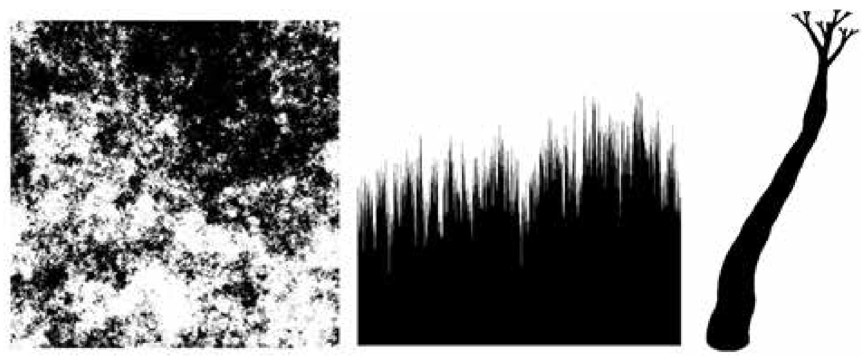

Fig. 10. Examples of using fractal icons to create unnatural images. The left image is a fractal cluster generated using D = 1.9. The middle image is a fractal line generated using D= 1.9. The right image is a fractal branch generated using D~ 1.

Further examples of composite fractals are shown in Fig. 9. In the left image, note how fractal lines have been used to symbolize ripples on the water, fractal clusters symbolize moon craters in the middle image, and branch fractals symbolize mud cracks in the right image.

Although our main aim is to use each of the three icon types to capture the aesthetics of typical scenes in nature, the icon parameters can be tuned to generate unnatural forms. Figure 10 shows some examples generated using D values that are much higher (left, middle) or lower (right) than the mid-D values found in typical scenes.

In this essay, we have described three fractal icons that can be combined to create artistic scenes that celebrate nature's beauty without resorting to merely copying it. Our examples of fractal art build on centuries of artistic forerunners, commencing in 300 B.C.E. with Hellenic friezes. Figure 11 emphasizes the "half-way" state achieved with fractal iconography by comparing it to previous examples of fractal cover art appearing previously in this journal. The cover art from 2005 featured photographs of fractal objects such as clouds (Taylor, 2005), while the cover art from 2020 featured purely abstract fractal images (Smith et al., 2020; Robles et al., 2021).

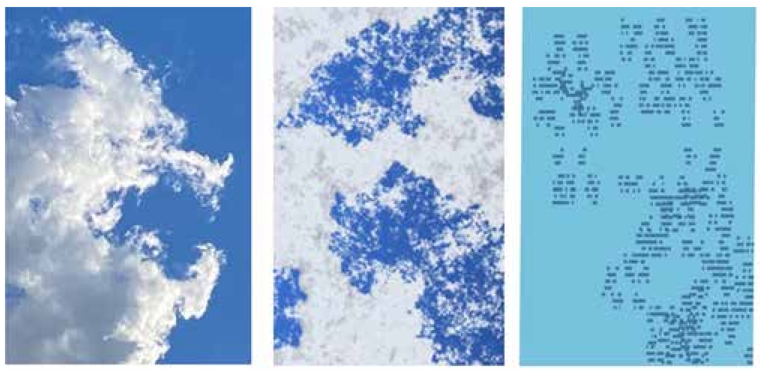

Fig. 11. A comparison of real clouds (left), cloud iconography (middle), and abstract clouds (right).

All three approaches to fractal art can be used to address the biophilia movement's call to incorporate natural images within the built environment (Wilson, 1984). This movement is gaining extra urgency with the recent prediction that mid-*D* fractals, so prevalent in our evolutionary history, might well disappear in the future due to the impact of climate change (York & Taylor, 2022). Whether or not this turns out to be the case, incorporating fractals into the built environment is a novel and highly effective approach to stress-reduction (Taylor, 2021). Recent studies indicate that the *D* values of the fractals will have to be tuned to allow for the complexity presented by the artificial environment (Abboushi, Elzeyadi, Taylor, & Sereno, 2019). Simply taking a photograph of a natural object such as a cloud and hanging it on a wall will be insufficient to induce the positive responses in the observer. The advantage of the middle and right images of Fig. 11 is that this fine-tuning can be achieved within the image generation process. Which of these two approaches – fractal iconography or fractal abstraction - is the most effective will likely depend on the environmental characteristics of the building along with the tasks being undertaken by the occupants. Returning to Galileo's declaration "The book of nature is written in the language of mathematics," in both cases the answer will lie with the mathematics of fractals.

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