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Biophilic Fractals and the Visual Journey of Organic Screen-savers

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Abstract: *Computers have led to the remarkable popularity of mathematically-generated fractal patterns. Fractals have also assumed a rapidly expanding role as an art form. Due to their growing impact on cultures around the world and their prevalence in nature, fractals constitute a central feature of our daily visual experiences throughout our lives. This intimate association raises a crucial question – does exposure to fractals have a positive impact on our mental and physical condition? This question raises the opportunity for readers of this journal to have some visual fun. Each year a different nonlinear inspired artist is featured on the front cover of the journal. This year, Scott Draves's fractal art works continues this tradition. In May 2007, we selected twenty of Draves's artworks and invited readers to vote for their favorites from this selection. The most popular images will feature on the front covers this year. In this article, we discuss fractal aesthetics and Draves's remarkable images.*

Key Words: fractals, biophilia, aesthetics, screen-savers

On the 1st of March 1980, Benoit Mandelbrot first glimpsed what would become known as the *Mandelbrot Set*. In the intervening years, it has assumed iconic status, conquering the world's computer screens in the role of the ultimate screen-saver. It has also been called the ultimate computer virus, consuming not only all the computational resources but also the minds of a generation of computer hobbyists! The image seeped into society's consciousness to such an extent that it even appeared as a crop circle in 1991 – a sure sign of our embrace of this remarkable pattern! The first tentative examples of the *Mandelbrot Set* (Peitgen, Jurgens, & Saupe, 1992) look like faint and ethereal ghosts compared to the rich and intricate patterns that can be generated on today's laptops. It is often said that the computer is to fractal investigations what the telescope is to astronomy and the microscope is to biology. How, then, have fractal patterns evolved with the increasingly vast computing resources available to us?

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Electric Sheep are intriguing examples of the current sophistication of computer-generated fractal patterns, in terms of both the inventive methods used to create the images and also their visual appearance. Developed by computer programmer and artist Scott Draves, images called *Fractal Flames* are first generated by chaotic attractors, and then an algorithm expands the *Fractal Flames* into animations called *Electric Sheep* (named after Philip Dick's novel "Do Androids Dream of Electric Sheep?"). Draves's server (http://electricsheep.org/) sends the *Electric Sheep* to a large audience of computer users where the animations act as screen-savers. New sheep are generated by an interactive process between the server and the users, in which users vote electronically for the *Electric Sheep* they like while the screen-saver is running. In this way, Draves regards his images as evolving artificial life forms and the parameters that generate them as genomes. The manner in which the viewers' responses are encoded into the algorithms is discuused elsewhere (Draves, 2008).

Figure 1 shows monochrome images of *Fractal Sheep* that will feature on the covers of this journal. Draves describes the process that created them as follows: "It validates the premise of artificial life: that beauty and life can spring from iteration of simple mechanical rules. That you can get out more than what you put in. The intent of my work is to show that creation does not require control, and in fact, giving up control is the primary creative." (Draves, 2007). His statements are reminiscent of Mandelbrot's remarks about seeing the *Mandelbrot Set* for the first time: "I never had the feeling of invention. I never had the feeling that my imagination was rich enough to invent all these extraordinary things" (Clark & Lesmoir-Smith, 1994).

This description of discovery rather than invention is intriguing in light of the shared geometry that describes these artificial fractal patterns and the many prevalent natural forms, such as trees, clouds, rivers and mountains that they resemble and that are central to our daily visual experiences. Mandelbrot remembers: "When I first saw … [the features of the *Mandelbrot Set*] … I was the first person to see them … yet … I was finding features in it that I had seen somewhere, certainly in natural phenomena" (Clark & Lesmoir-Smith, 1994). Mathematician Ian Stewart further emphasized the connection to natural forms: "It is not easy to explain the *Mandelbrot Set* visually … [it] reminds us almost of anything you can see out in the real world, particularly living things, and so it has character that reminds us of a lot of things and yet it itself is unique and new." (Clark & Lesmoir-Smith, 1994). Draves's Sheep also appear 'natural.' He states: "The style is organic rather than geometric" and concludes that the primary purpose of the *Electric Sheep* "is simply to create beauty" (Draves, 2007).

This organic beauty is far from being a universal quality of fractal patterns. In particular, early versions of exact fractals (for which patterns repeat exactly at different magnifications) were labeled as 'pathological' because they lack visual connections to nature's scenery (Mandelbrot, 1982). Figure 2 shows a Koch curve as an example of how the exact repetition of patterns creates a

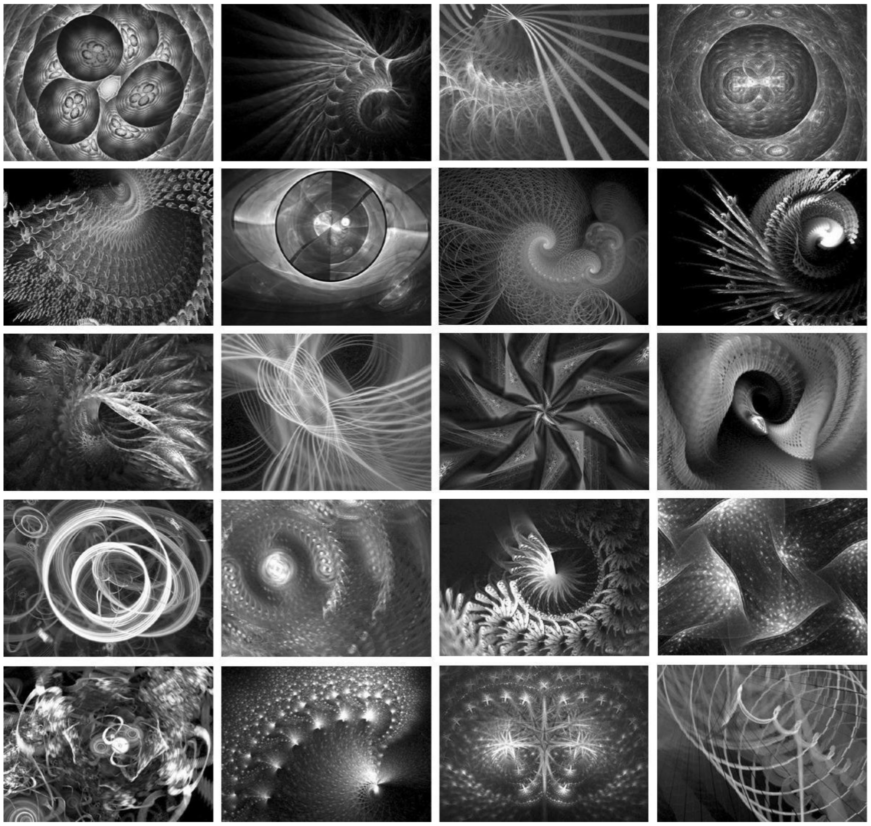


Fig. 1. The 20 *Electric Sheep* selected for the aesthetic voting experiment. The images are labeled 1 (top left) through to 20 (bottom right). See Table 1 for the votes received for each image.

cleanliness rarely found in natural forms. However, in the same figure we morph this exact fractal into a more natural-looking fractal by introducing random variations into the pattern (see the figure caption for details). These random variations preserve the fractal scaling properties while removing the artificial look of the exact Koch curve, allowing a radically different and more natural aesthetic value to emerge. Random fractals therefore represent a relatively simple mathematical method for generating 'natural-looking' fractal forms. In addition to randomness, introduction of another natural process – chaos – into the fractal generation is also effective. The nonlinear equations used to generate the *Mandelbrot Set* and *Electric Sheep* serve as examples. More generally, it is helpful to introduce the collective term 'biophilic fractal' to classify fractals that possess positive aesthetic qualities that are deeply routed in their natural appearance. As such, biophilic fractals are not defined by their specific method of construction but by their resulting organic visual aesthetic. They represent an amazing playground for aesthetic investigations: artificial patterns that capture important visual qualities of our natural environment.

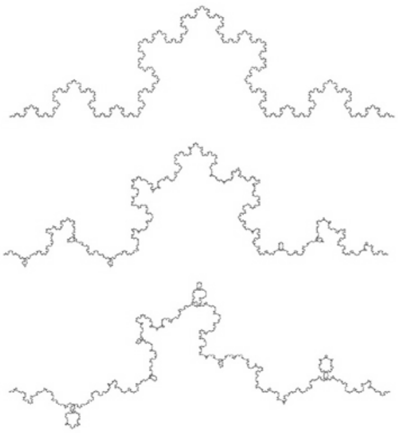


Fig. 2. Koch curves The top image shows a traditional Koch curve (D = 1.24). The probability p for a "spike" on the curve to be pointing up or down changes for the three curves. For the traditional Koch curve p = 0, corresponding to zero probability of having a spike pointing down. For the second image p = 0.25, so most of the spikes are pointing up. For the third curve, p = 0.5, corresponding to a 50% chance of pointing up or down. In each case, the spatial distribution of the up and down spikes is random.

Mandelbrot quickly emphasized the importance of the aesthetic power of fractals and the connection of mathematical fractals to their counterparts in art and nature (Mandelbrot, 1982). Peitgen and Richter's book "Beauty of Fractals" also used mathematical fractals to highlight their artistic importance (Peitgen & Richter, 1986). Nevertheless, the first visual experiments with fractals avoided aesthetics and concentrated on other perceived qualities. It was not until the mid-1990s that the authors of this article independently introduced experimental aesthetics to the arena of fractals. Whereas RPT used a chaotic pendulum to show that images generated by chaos were judged more aesthetically appealing than equivalent non-chaotic patterns (Taylor, 1998), JCS and colleagues used computer-generated (chaotic attractor) images to investigate the basic parameters that determine fractal aesthetics (Aks & Sprott, 1996; Sprott, 1992). JCS and colleagues investigated parameters that quantified the chaotic dynamics that generated the patterns (the Lyapunov exponent L) and the scaling behavior of the patterns (the fractal dimension D). RPT's subsequent experiments built on JCS's results by showing that the aesthetic preference for mid-range D values revealed for computer-generated fractals extended to natural (Hagerhall, Purcell,

& Taylor, 2004; Spehar, Clifford, Newell, & Taylor, 2003) and artistic fractals (Taylor, 2001). Taken together, the results of these surveys indicate that we can establish three ranges with respect to aesthetic preference for fractal dimension: 1.1-1.2 low preference, 1.3-1.5 high preference, 1.6-1.9 low preference.

Recent experiments by RPT and colleagues show that these perceptual preferences for mid-*D* fractals impact on the observer's physiological condition in a manner that might be used to reduce their physiological stress. For example, skin conductance measurements have shown that the observers' physiological response to stress is reduced when they view mid-*D* fractals (Taylor, 2006). More recent experiments have focused on the observers' brain activity to investigate how fractals affect their physiology. fMRI studies show that mid-*D* fractals activate distinctly different visual areas of the brain than high-*D* fractals (Watts & Taylor, 2007). Furthermore, EEG experiments show that alpha waves (a signature of being wakefully relaxed) are maximal for mid-*D* fractals (Hagerhall et al., 2007). The possibility that the visual appeal of mid-*D* fractals might be used to relax the viewer opens up many intriguing applications.

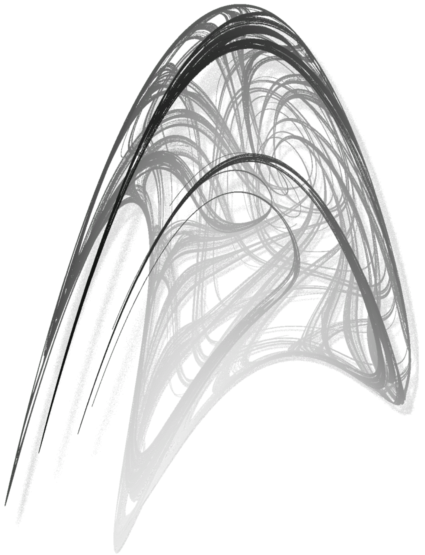


Fig. 3. An example of a fractal strange attractor using the equation $X_{n+1} = X_n^2 - 0.2X_n - 0.9X_{n-1} + 0.6X_{n-2}$. This image is from Sprott (2003).

These distinct responses can be applied, for example, to computer-generated screen-savers. JCS developed a "Fractal of the day" website (http://sprott.physics.wisc.edu/fractals.htm), in which the computer generates fractal patterns using chaotic attractors and iterated function systems, and then selects one image each day based in-part on the measured *D* value. This completely automated procedure generates a wealth of fractals designed to be aesthetically-appealing to humans. JCS's fractal images featured on the covers of this journal several years ago, and an example is shown in Fig. 3 (Sprott, 2004). Draves's *Electric Sheep* represent a logical progression because the process involves continuous human interaction.

Table 1. Results of the 'Vote for Your Favorite' Survey.

Rank	*Image*	*Points*	*Algorithmic Complexity*
1	18	207	0.857
2	7	197	0.435
3	13	130	0.688
4	10	102	0.345
5	19	96	0.509
6	5	85	0.989
7	8	80	0.542
8	3	79	0.341
9	15	79	0.244
10	11	72	0.647
11	16	68	0.070
12	12	65	0.158
13	17	62	1.000
14	1	53	0.852
15	6	52	0.056
16	2	50	0.000
17	20	24	0.413
18	9	20	0.634
19	4	18	0.601
20	14	9	0.425

In May 2007, the authors selected 20 of Draves's images and invited readers of this journal to vote for their favorites from this selection. The selected images are shown in Fig.1. Participants were asked to vote for their favorite three art works from the 20 images. For each participant, three points were assigned to their first choice, two points for their second choice, and one point for their third. A total of 258 people voted. The results are listed in Table 1 and show a remarkable agreement in preferences among the voters. The top 5 images will appear on the front covers of this journal during the coming year.

Although the primary aim of this survey project was to determine the most popular fractals images to be used on the front cover of the journal, the survey mirrored an earlier and more comprehensive aesthetic experiment conducted on the *Electric Sheep* by Draves and colleagues (Draves, Abraham, Viotti, Abraham, & Sprott, in press). Their results, which were based on 5000 participants recording their aesthetic preferences, reinforce the preference for mid-*D* fractals found earlier by JCS (Aks & Sprott, 1996; Sprott, 1992), RPT (Spehar et al., 2003; Hagerhall et al., 2004) and others (Abraham et al., in press). Given that the visual appearances of the *Electric Sheep* are evolving based on voter preferences, it will be fascinating to see if the results of this on-going project change with time.

Why is *D* so important in determining the visual appearance of fractals? *D* describes how the patterns occurring at different magnifications combine to build the resulting fractal shape (Gouyet, 1996). For Euclidean shapes, dimension is described by familiar integer values − for a smooth line (containing no fractal structure) *D* has a value of one, while for a completely filled area (again containing no fractal structure) its value is two. For the repeating patterns of a fractal line, *D* lies between one and two, and, as the complexity and richness of the repeating structure increases, its value moves closer to two. A traditional method for measuring *D* is the 'box-counting' method, in which the pattern is covered with a computer-generated mesh of identical squares (or 'boxes'). The number of squares, $N(L)$, that contain part of the pattern are counted, and this count is repeated as the size, L, of the squares in the mesh is reduced. $N(L)$ gives a measure of the space coverage of the pattern, and reducing the square size is equivalent to looking at this coverage at finer magnifications. For fractal behavior, $N(L)$ scales according to the power law relationship $N(L) \sim L^{-D}$, where $1 < D < 2$ (Gouyet, 1996).

This power law generates the scale-invariant properties that are central to fractal geometry. It also quantifies the crucial role played by *D* in determining the pattern's visual appearance. According to this equation, *D* corresponds to the gradient magnitude of a 'scaling plot' of log $N(L)$ versus log L. A high *D* value is therefore a signature of a large $N(L)$ value at small L and reflects the fact that many small boxes are being filled by fine structure. This can be seen, for example, for the two fractal patterns formed by repeating polygons shown in Fig. 4. The fine features play a more dominant 'space coverage' role for the high *D* pattern than for the low *D* pattern. Further examples can be found in (Mandelbrot, 1982). In particular, Fig. 165 is a striking demonstration of the relative contributions of fine and course structures for patterns with different D values. Whereas Fig. 4 concentrates on an exact fractal for clarity, the same effect occurs for the random fractals shown in Fig. 5. For fractals described by a low *D* value, the patterns observed at different magnifications repeat in a way that builds a relatively smooth-looking shape compared to the detailed structure of high *D* patterns. Perception experiments confirm that raising the *D* value of the fractal pattern increases its perceived roughness and complexity (Cutting & Garvin, 1987; Gilden, Schmuckler, & Clayton, 1993; Pentland, 1984). Clearly, *D* is a highly appropriate tool for quantifying fractal complexity. Traditional measures of visual patterns quantify complexity in terms of the ratio of fine structure to course structure. *D* goes further by quantifying the relative contributions of the fractal structure at all the intermediate magnifications between the course and fine scales.

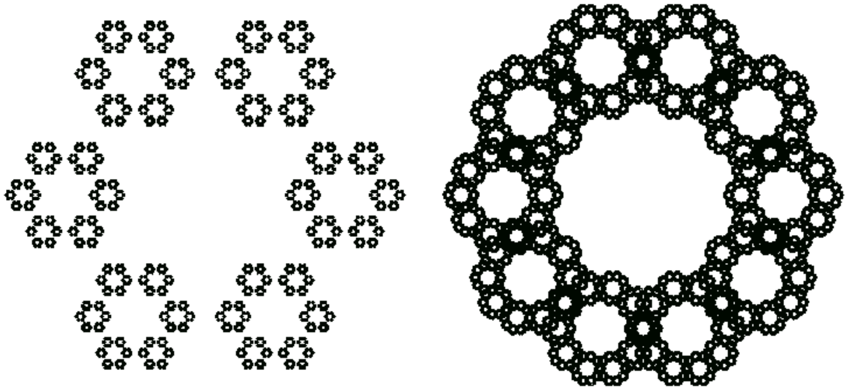
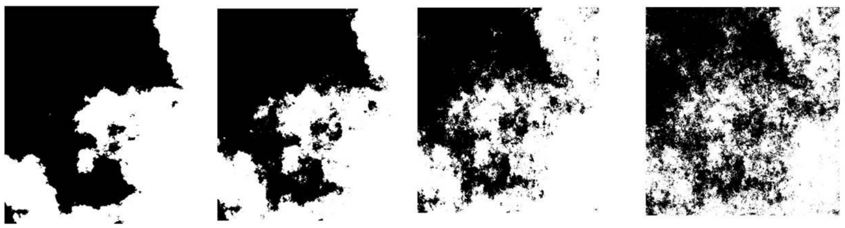


Fig. 4. A visual demonstration of the effect of increasing *D* for a fractal pattern: two fractal polygons with low (left) and high (right) *D* values.



D=1.2 D=1.4 D=1.6 D=1.8

Fig. 5. Fractal images generated using the mid-point displacement method. The fractal dimension increases from left to right: D = 1.2, 1.4, 1.6 and 1.8 (Note: all images have an identical density ratio of 50:50 for the black and white regions).

Given the key role of complexity in fractal patterns, it is informative to consider other ways of assessing visual complexity. ‘Algorithmic complexity’ is another example that lends itself to the task of quantifying fractals (Sprott, 2003). This concept is based on the size of the smallest computer program that can produce the pattern. Lempel and Ziv (1976) and others provided computer algorithms for compressing a time series and thereby estimating its complexity. Their algorithm is the basis for the compression technique used to produce gif files. This suggests a very simple and elegant way to determine the complexity of an image that is easy for anyone to employ – save the image in both bmp and gif format, and calculate the ratio of the two file sizes, perhaps after subtracting the size of the file headers (as determined from the file sizes for an image of a single pixel). The complexity of the image is then quantified on a scale from 0 (least complex) to 1 (most complex). These values are then linearly rescaled so that the image with the smallest complexity is 0 and the one with the largest complexity is 1 in order to provide a larger spread of values. Intriguingly, when we applied this procedure to the 20 *Electric Sheep* images in Fig. 1, we found no correlation between algorithmic complexity and the aesthetic ranking of the images (Table 1).

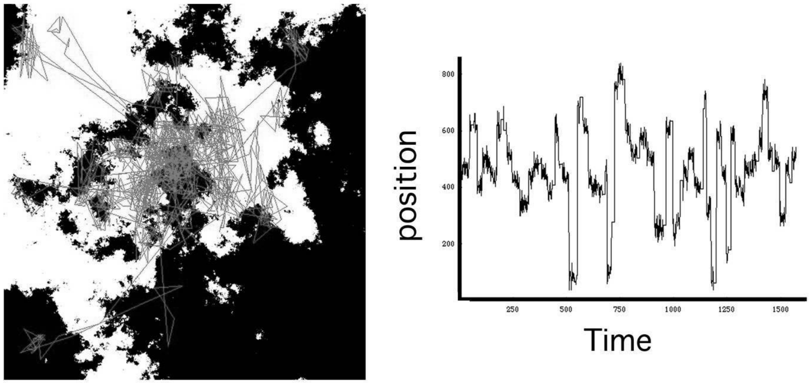


Fig. 6. (left) The gray lines represent the eye-trajectories in *x-y* space, superimposed on the black and white fractal image (*D* = 1.8) that was viewed by the observer for 30 seconds. (right) A graph of *x* versus time. (Taylor, Boydston & Van Donkelaar, 2006).

Although the survey study was preliminary in nature, it appears that the precise measure of complexity is important when considering fractal aesthetics. Whereas fractal dimension and algorithmic complexity use a computer to assess the complexity of the fractal pattern, an alternate approach is to investigate the complexity of the way we view the fractal pattern. As shown in Fig. 6 for an experiment conducted by RPT and colleagues (Taylor, Boydston & Van Donkelaar, 2006), infra-red cameras can be used to map out the eye-trajectories both spatially (in *x-y* space) and as a function of time (*x* or *y* versus *t*) while the observer looks at the pattern. Interestingly, previous experiments by Aks, Zelinsky and Sprott (2002) reveal that the time series follows a fractal power law when the eye views complicated (non-fractal) patterns in a search task. This emergence of fractal behavior in the eye physiology makes sense − fractal trajectories cover space more efficiently than Brownian trajectories and thus are ideal for visual searches. It will be intriguing to see if the eye motion responds in a similar manner when viewing the visual complexity of fractal patterns and, if this is the case, whether the *D* value of the eye motion matches that of the fractal pattern being observed.

The high aesthetic appeal of mid-*D* fractals and their intermediate complexity has triggered a number of intriguing theories. ‘Geometric’ theories link the aesthetic quality to the underlying geometric structure of the fractals. For example, combining the mid-range complexity of mid-*D* fractals with statistical variations (as we did in Fig. 2) might generate an appealing balance between predictability and unpredictability and between order and disorder. Based on this theory, the shared aesthetic quality of nature's scenery and random fractals generated using mathematics is, in part, captured by this geometric balance. An 'evolutionary' theory considers the appeal of mid-*D* complexity within the context of an evolutionary theory of aesthetics, in which a scene's attraction is related to survival instinct (Wise & Leigh-Hazzard, 2000). It has been speculated that observers prefer images with low *D* values because they mimic African savannah scenery. Our ancestors spent the bulk of their evolutionary history in this landscape, and its low visual complexity facilitates detection of predators. According to the 'evolutionary' theory, observers may have judged the high *D* images as too intricate and complicated, making it difficult to detect predators in the surrounding vegetation (Wise & Leigh-Hazzard, 2000). An alternative 'exposure' theory explains the aesthetics of biophilic fractals in terms of our appreciation of the familiar, since mid-*D* fractals are prevalent in our natural environment.

Although initial studies have concentrated mainly on *D*, we have only just begun to look for fractal measures that correlate with aesthetics. The appeal of images as rich and intricate as *Electric Sheep* will depend on the interplay of many visual parameters. In our search, we will also have to consider the many interesting visual tensions that are created by the integration of fractal and Euclidean geometries. Similar to nature's scenery, *Electric Sheep* throw an occasional circle, square and triangle into the organic mix of biophilic fractals. In fact, the collision between these distinct geometries is a common aspect of viewing fractal patterns. Whether we gaze out of a window onto nature's structures or stare at fractal screen-savers, we view the fractal shapes through a Euclidean outer frame.

This confinement also limits the number of magnifications that can be experienced by the viewer. Perception studies show that a magnification range of 25 is sufficient to set the aesthetic responses discussed above, a factor that matches the fractal scaling properties of typical natural objects such as trees (Spehar et al., 2003). Thus, although physical fractals are approximately scale-invariant over only a limited range of sizes, this limited courtship with mathematical fractals is sufficient to establish their aesthetic fractal character. We will never know if infinite mathematical patterns generate an enhanced aesthetic quality compared to their limited-range counterparts because the limited resolution of our visual system prevent us from seeing them; infinite fractals only exist as algorithms rather than as aesthetic images.

Finally, we move beyond static images and consider the dynamic visual experience of *Electric Sheep*. Time variations will be critical if we want to harness the positive effects of biophilic fractal patterns and expose people to them in their daily environments. For example, time-evolving images are more likely to maintain the viewer's gaze over time. Furthermore, they create an enhanced aesthetic quality compared to their static counterparts. Examples are abundant in natural scenery, including tree branches swaying in the wind and flames flickering over a fire. Figure 7 shows a static image of a flame to emphasize the different aesthetic quality compared to the dynamic view familiar to us all. Whereas the movement of the individual components captures and viewer's attention, the *D* values of the overall fractal pattern remains nearly constant over time and maintains its aesthetic appeal. Similar to the flames and trees, investigations of *Electric Sheep* show that the *D* values of individual images do not change significantly over the course of running the screen-saver (Draves et al., in press). *Electric Sheep* serve as a remarkable demonstration of the impact of dynamic fractal patterns.

Fig. 7. A photograph of a flame front (photograph by R. P. Taylor). The propagation fronts of flames are well-established fractals.

We conclude with a crucial question: why bother with biophilic screen-savers? Given the close relationship between these fractals and nature's patterns, why not experience their positive effects by simply looking through a window at a natural scene? After all, some of the most striking experiments of the biophilic movement are based on investigations where participants did just that! For example, Ulrich (1984) demonstrated that people recovered from major surgery far more quickly when placed in hospital rooms that had windows looking out on natural scenery. However, many high-stress situations occur where it is not possible to stare out at nature, particularly when located in the heart of a major city or in the depths of a large building, although video images of natural scenes could be used. It may eventually be possible, nonetheless, to produce fractals images that are even more effective at stress-reduction than natural scenes.

Research of biophilic fractals is still at an early stage of development, with many questions to explore. For example, it is not known whether positive physiological responses persist when the fractals are no longer observed, nor do we know the extent to which people become saturated by fractal stimuli. Nevertheless, the possibility of using biophilic fractal patterns to reduce people's physiological stress holds enormous potential since the U.S. currently spends $300 billion annually on stress-related illnesses. Using images to manipulate the public's emotions (even if in a positive manner) might set off alarms for some. Certainly, an Orwellian future where we all assemble to stare at a communal fractal for a strictly allotted period does not seem very appealing. For stress-reducing fractals to be applied effectively in the future, visual scientists will have to collaborate closely with visual artists and architects to formulate subtle visual strategies for incorporating fractals into our everyday environment. Meanwhile, visually-creative screen-savers such as *Fractal Sheep* are an obvious strategy for increasing people's exposure to these beautiful and potentially stress-reducing fractals.

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