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Fractal Art and Architecture Reduce Physiological Stress

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ABSTRACT

Human beings are apparently tuned to prefer an environment that has the self-similar properties of a fractal. Furthermore, as different types of fractals are characterized by what is known as their “fractal dimension” D , we respond best to “mid-range” fractals where D is between 1.3 and 1.5. In such fractal environments, our body automatically dampens its response to stress induced by intensive tasks and reaction to external forces. This implies that particular fractal environments are healing, or at least buffer us from life’s stresses. The remarkable fact is that this response is independent of what the fractal designs around us actually look like: they can be either representational or abstract. Altogether, we have here the beginnings of a new way of interpreting how the visual environment affects our health.

Key words: fractals, biophilic design, healing environment, stress, ornament, cognitive resonance.

INTRODUCTION

The term "fractal" refers to "broken"; that is, fractal designs are not geometrically smooth or pure, but are defined by components on a hierarchy of different scales. Fractals can be either built with accumulated accretions (patterns of ordered heterogeneity, spikes, granulations, "hairiness"), or instead have gaps or holes (perforations, sieves, hierarchically-ordered spacings). In either case, fractal structures depart from smoothness and uniformity by breaking geometrical linearity. Their name, however, tends to emphasize the "jaggedness" aspect that is characteristic of only one group of fractals. Fractals could be curved: a cauliflower is composed of superimposed whorls of ever-decreasing sizes, so there is nothing "jagged" here.

A key property of fractals is their self-similarity, where a similar structure is apparent at increasing (or decreasing) magnifications. Each perfect fractal can be magnified repeatedly by a specific scaling ratio, and will appear the same every time. Among the few natural fractals that are obviously and remarkably self-similar are cauliflowers and the mammalian lung. In a mathematical fractal, scaling similarity shows for any number of successive magnifications while for natural fractals, the basic structure eventually changes: for example, successively magnifying the bronchial tree of a mammalian lung eventually gets down to the cellular level, which shows no branching structure (West, Deering 1995; West, Goldberger 1987). Many natural fractals such as plants and other biological structures tend to be only statistically self-similar. In that case, a magnified portion of the fractal will resemble but not be identical to the original.

Architects are increasingly interested in fractal patterns and shapes, and are beginning to use them in their designs. Applications tend to be restricted to fractal building plans and fractal decoration on façades. The fractal forms that have been built recently, however, contrast strikingly with traditional fractal architectural expressions such as the Gothic form language (Joye 2007). Even so, this trend moves away from the uncompromisingly "pure" forms favored by twentieth-century modernism, which insisted upon simple and empty geometrical shapes such as squares, rectangles, or regular curves such as semicircles or parabolas. Elementary pure solids and fractals represent opposite ends of the design spectrum: the former express reductionist design, while the latter express ordered complexity that is a result of mixing a hierarchy of linked scales. There is no reason why contemporary architects should not use fractals in their designs, but those should be more than just motifs.

We are commonly exposed to both natural and artificial fractals in our everyday experience. It turns out that much, if not all of natural structure is fractal. Natural forms exhibit complex geometrical structure on a hierarchy of scales, from the large to the small, going down to the microscopic scale. Artificial fractals have always been produced as part of traditional artifacts and buildings (Goldberger 1996). Computer-generated fractals are now common in our everyday environment because of our pervasive digital technology. They are generated by recursive algorithms, which create substructure on a frame on increasingly smaller scales, or build up a complex whole by progressively adding contributions that create the whole out of smaller components.

I am interested here in knowing how the human perception system responds to fractals. We can begin with the conjecture by Ary Goldberger (1996) that our mind somehow has an intrinsically fractal structure, and therefore more readily accepts fractal information (Mikiten *et al.* 2000). As a consequence of this anatomical trait — and this point is crucial to architecture and design — we tend to imagine fractal forms as the most “natural”. While this hypothesis is not yet proven, it does contradict the often-made claim by modernist architects that humans have a predilection for crude geometric forms. Indeed, it implies quite the opposite. Let us consider the experimental evidence on exactly what type of form makes human beings feel more comfortable, which should resolve this issue. Before doing so, it helps to remember that the modernist architects’ assertion favoring abstract geometric preferences predates this latest scientific evidence by many decades, but the architecture community never went back to re-examine the original claims.

EXCITEMENT VERSUS STRESS

This paper argues that fractal images reduce stress in the workplace and living environment, and digs deeper into results that certain fractals are better than others in accomplishing this task. Experimental evidence suggests that there is an optimal fractal dimension required to reduce stress, and that being exposed to plain non-fractal shapes increases a person’s stress levels. These results explain why we naturally prefer fractal images in our environment, and consequently, why humankind has produced intrinsically fractal traditional art, artifacts, and architecture. We know that we enjoy the complex patterns of woodland scenes, which are shown to be fractal. Going beyond simple enjoyment, people consider exposure to natural scenery to be restorative: it is good for our health.

In architecture, the stark modernist interiors that came of age with Adolf Loos and later with the Bauhaus have been very unsuccessful in eliciting the type of universal and visceral attraction and sense of comfort that more traditional interior environments accomplish, as witnessed by what the majority of the population chooses as their living interiors. People like to bring objects such as photographs, plants, dolls, and *objets d’art* into their living space and workplace. This practice has been condemned by a rather narrow design élite that continues to support the old minimalist design ideology against overwhelming evidence of what makes people most comfortable.

The research that provides a scientific basis for these general societal preferences would suggest that plain, empty shapes have no place in architecture; at least in architecture that has to be used by human beings (industrial buildings being a separate case altogether). Is it then the purpose of architecture to reduce stress? This is an open question that raises important issues, as some contemporary architects make it a point to induce stress in the user. Here it is necessary to distinguish between excitement that has a positive physiological effect, and stress that has the opposite negative effect on the human organism. Positive excitement is elicited by euphoria; the emotion of love; inspiration through traditional art, music, and dance; religious ecstasy; transcendental and mystical experience; sexual attraction, etc., whereas stress from negative excitement comes from physical threats (the fight-or-flight response); war; panic situations; horror and intensely violent real-world experiences and films; and prolonged exposure to environmental conditions or pollutants that wear a person out. Both groups of environmental factors disturb homeostasis (an equilibrium condition in the body), yet one is nourishing while the other is harmful (Selye 1974).

I believe that architecture that is adapted to human physiology is nourishing because it generates positive feelings through positive cognitive response to symmetries and fractal structures (Salingaros 2003). An artificial environment with those measurable qualities provides a better quality of life (Salingaros 2012). By contrast, stressful environments with the opposite characteristics induce anxiety and depressive behavior, and ultimately pathology in their users and residents.

PHYSIOLOGICAL RESPONSE TO FRACTALS

Visual perception studies reveal human preferences for fractal landscapes and structures. I review material here from Richard Taylor and James Wise (Taylor 2006; Wise, Rosenberg 1986; Wise, Taylor 2002). They found that people feel more comfortable with fractal images showing nature, over non-fractal images such as non-fractal abstract art. The first point to emphasize is that those research studies used physiological measures and did not depend upon responses giving the subject's preference, because that could be, and usually is, influenced by learned biases. Instead, the body's automatic responses were rated by measuring skin conductance. It is known in the medical profession that raised skin conductance (electro-dermal response) correlates very well with increased bodily stress. Therefore, the skin conductance will peak in a stress-inducing environment, and will be reduced in a low-stress environment.

The results from a 1986 study carried out by NASA (Wise, Rosenberg 1986) strongly indicated that persons respond positively to natural scenes (either real scenes, or visual images of them), whereas they respond negatively to non-fractal abstract shapes. Subjects had to perform three types of challenging mental tasks: arithmetic, logical problem solving, and creative thinking while exposed to four different 1m x 2m images. Ordinarily, such tasks induce a degree of physiological stress, so that it was possible to measure the effect of the image on the body state while performing these tasks. The skin conduction measurements in the three different environments were compared with the same tasks performed in a control setting, which featured a pure white panel of the same dimensions. The results are as follows: the abstract non-fractal artwork *increased* the stress by 13% as compared to the control situation, whereas the two natural scenes *decreased* the stress by 3% and 44% as compared to the control (Taylor 2006).

A second interesting point emerges from further analyzing the data. The two natural scenes used in this experiment had a markedly different effect on reducing stress in the subject. The first image, showing a dense forest scene (top of Figure 1), lowered the stress somewhat, but the second image, showing a savannah landscape of isolated trees (middle of Figure 1), lowered stress considerably. The researchers concluded that, for some unexplained reason, persons react far more positively to a specific type of natural scenery. It's not just a question of having more nature, because the forest scene has a higher density of plants. This finding is nevertheless consistent with the biophilia hypothesis (Kellert *et al.* 2008), where humans feel most comfortable in environments that reproduce the mathematical qualities of ancestral human evolutionary environments. It is believed that we evolved in a savannah rather than in a forest. Thus a savannah landscape should (and does) provide the most positive response. The difference in the two natural scenes is one of fractal dimension (a mathematical measure of the fractal's internal scaling, which is described below) hence it is possible to pinpoint with some accuracy our innate biophilic fractal preferences.

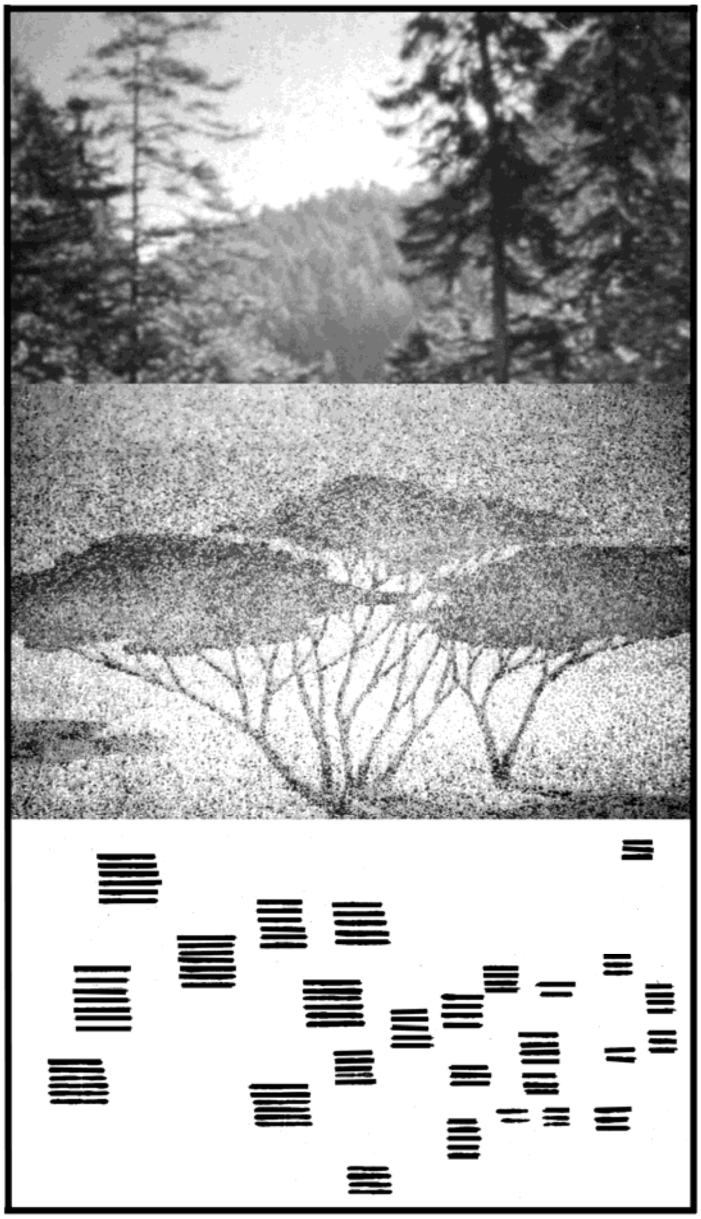

Figure 1. A photograph of a forest (top), an artistic rendition of a landscape (middle), painted lines (bottom). © Richard P. Taylor, used with permission.

There is yet a third result that comes out of these experiments. The forest scene used in the results referred to above is a photograph. It happened that the savannah landscape scene is not a photograph, but a rather stylized drawing of a savannah landscape. This reveals that our response is triggered by fractal properties much more than by an accurate representation. As such, the importance of the scenes in creating their physiological response relies squarely upon their mathematical content, and not in some intrinsic or mysterious vitalistic qualities of the natural scenes themselves. This result makes possible a remarkable simplification of what is at first a very puzzling effect.

In this interpretation of what is responsible for the physiological effects of fractals on human beings, I agree with my former student Yannick Joye, who attributes the mechanism to the mathematical and not the biological content of the environment (Joye 2007). Only this assumption explains why we respond in a positive manner to artificial fractals and, coincidentally, why humankind has produced fractal designs on artifacts and buildings for millennia (Goldberger 1996).

ANOTHER INTERPRETATION OF THE STRESS REDUCTION EFFECT

I wish to present an alternative interpretation using the same data reviewed above and draw a new conclusion. By taking the savannah landscape scene — our presumed ancestral evolutionary environment — as a fixed baseline, we can list the increasing stress conditions caused by the different experimental environments. I will use the control situation (plain white panel) as just another of the elements, giving it equal importance.

(*i*) Savannah landscape: minimal environmental stress
(*ii*) Dense forest scene: slight increase of environmental stress
(*iii*) Minimalist colorless environment: significant increase of stress
(*iv*) Abstract non-fractal design: further increase of stress

Ordering the experimental environments in this way demonstrates clearly that minimalist design is neither preferred, nor particularly good for us as far as dampening our physiological response to stress. It increases stress over our innate baseline fractal preference. When we abandon minimalism in design and create complex but non-fractal artificial environments, we actually increase our stress ever further. I'm aware that this is a disconcerting statement to designers, artists, and architects, yet it is supported by incontrovertible experimental data.

Working with Judith Heerwagen for the Herman Miller Furniture Company, Wise did a later variant of his original NASA experiment (Heerwagen, Wise 2000). In this case, cognitive measures were used. The study used standard workstation cubicles of three different varieties, identical except for the pattern on the fabric covering their visible surface. One variety had a digital image of a savannah landscape, another variety was plain grey, and the other variety was covered with a geometrical pattern. Subjects sat in these workstations for half a day while performing a series of creative problem-solving tasks. A positive correlation was found between the scores on creative problem-solving tests and the natural-image workstation. Please note that since the work is proprietary, few details are available for publication.

WE NOTICE FRACTAL EDGES AND CONTOURS

It is instructive to explain how the fractal dimensions are computed for the images shown in Figure 1, above. In general, the eye forms a two-dimensional image of a three-dimensional complex of objects. Ordinarily, it focuses attention on contrasting edges in this image: a definite line, outline, border, edge where two contrasting regions meet, etc. We know that the eye scans an image by following its regions of highest contrast, called the "scan path" (Salingaros 2003; Yarbus 1967). Impressions of scenes are therefore determined for us by the fractal character (or not) of dominant contrasting lines within them, called fractal contours. For buildings, these dominant lines could be the roofline or skyline, borders, edges, articulated or otherwise ornamental lines, etc. The fractal dimension D (explained below) is then computed for these dominant lines, with the numbers expected to lie between 1 and 2.

Figure 2. A fractal edge defined by the repeating patterns of the Borobodur Temple, Java. © Richard P. Taylor, used with permission.

These experiments with fractals confirm that the presence of dominant lines in our environment affects our physiological state: this effect, though subconscious, is significant. Furthermore, the effect is beneficial when such environments have a fractal property, and specifically, when they correspond to a "mid-range" fractal. People have been creating fractal art and architecture since the beginnings of humankind and civilization, which is verified by undertaking a survey of traditional art, artefacts, and architectural ornamentation produced ever since the first humans (Eglash 1999; Washburn and Crowe 1988). This enormous effort, concomitant with the rise of humanity and culture, may now be interpreted as the natural attempt to create stress-reducing environments using sensory feedback. This conjecture explains a great deal of anthropology and history, until we come to the 20th Century, when Art and Architecture began to diverge drastically from traditional models.

THE FRACTAL DIMENSION

Allow me to provide some background on what the fractal dimension D represents. A smooth line (either straight or curved) has $D = 1$, whereas an area fills in a two-dimensional region and has $D = 2$. However, an infinitely crinkled, meandering, and convoluted line will fill a little into its adjoining area and will have D somewhere between 1 and 2. An example of this type of fractal line is the von Koch Snowflake, with $D = 1.26$ (which is amply documented on the World-Wide Web). A mathematical object that has dimension approximately halfway between a line and an area, i.e. that has fractal dimension around 1.5, is called a "mid-range" fractal. The more convoluted and meandering a fractal line, the closer its fractal dimension will approach 2, at which point it ceases to be a line because it fills in all the area.

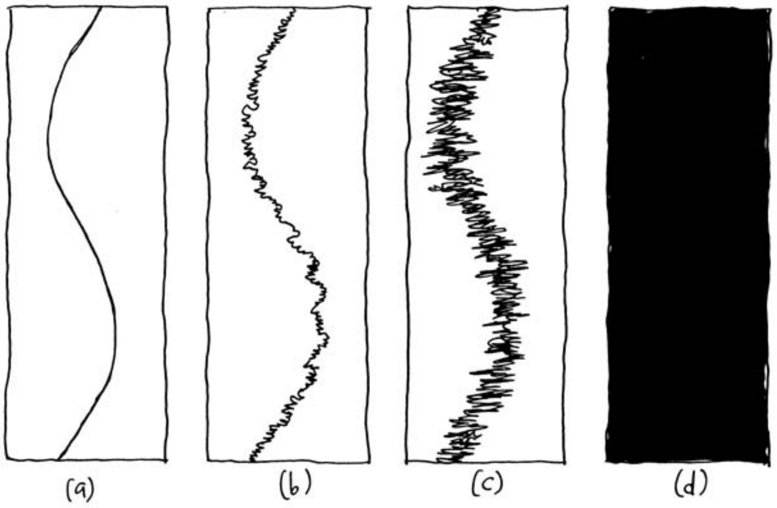

Figure 3. Fractal lines of increasing dimension, until they become an area: (a) D = 1 (not fractal), (b) D = 1.2, (c) D = 1.7, (d) D = 2 (not fractal). Actually, these are drawings and not accurate fractals. Figures by Nikos Salingaros.

We can also arrive at a "mid-range" fractal in quite a different manner. Starting from a filled-in plane with $D = 2$ we begin to punch holes into it, perforating it with smaller and smaller holes. If we do this in a regular hierarchical manner, we are reducing its dimension and eventually create a "mid-range" fractal with D somewhere between 1 and 2. But this object arises in a very different manner from a crinkly line: it is a sieve and did not begin as a line at all, yet it could have comparable fractal dimension to a fractal line. The triangular Sierpinski gasket, with $D = 1.58$, is an example of such a fractal (again, see the World-Wide Web for a description).

Let us go back to the visuals used in the NASA experiment. Each of the straight parallel lines grouped in sets of three to seven (bottom of Figure 1) has dimension $D = 1$, and is not fractal. The lines being grouped together may form a visually interesting pattern, but do not contribute to any fractal structure. The groups themselves are arranged randomly without any type of scaling symmetry that might generate a fractal.

TAYLOR'S ANALYSIS BASED UPON THE FRACTAL DIMENSION OF DOMINANT LINES

An analysis by Taylor using a great variety of fractal lines having different fractal dimension D reveals that human beings do indeed have a preference for a specific type of fractal (Taylor 2006). It turns out that we have a stress-reducing experience with D around 1.4, i.e. for a specific “mid-range” fractal. These measurements are very approximate, yet they serve to establish a clear peak for human physiological response to fractal lines observed in scenery.

This finding helps to explain the curious and unexpected result of the original NASA experiment (Wise, Rosenberg 1986; Wise, Taylor 2002). The forest scene (top of Figure 1), which turned out to have a mildly positive effect, has dominant lines with fractal dimension $D = 1.6$, whereas the savannah landscape scene (middle of Figure 1), with a strongly positive effect, has lines with fractal dimension $D = 1.4$. According to this and other experiments, human beings do have an enhanced response to fractal images characterized by lines with fractal dimension nearer a preferred value of $D = 1.4$. Therefore, it should be no surprise that the subjects in the above experiment responded better to the savannah landscape scene.

Further distinct experiments by Taylor and his associates reveal a preferred value for the fractal dimension of edge lines with $D = 1.3$ (Hagerhall *et al.* 2008). Subject responses were evaluated this time by using Quantitative Electroencephalography (qEEG) to measure the alpha waves of cerebral cortical activity. Fractal edges having four mid-range fractal dimensions from $D = 1.1$ to 1.7 were generated by computer. (The figures were supposed to mimic fractal horizons that resemble the silhouette of the Borobodur temple shown in Figure 2, but are not nearly as attractive). By measuring the intensity of the alpha waves in the subjects, a peak preference for $D = 1.3$ was detected from among the different figures they were exposed to. Since high alpha-wave activity is known to be associated with a relaxed state, this finding is consistent with the hypothesis that such fractal edges are the most restorative and relaxing (Hagerhall *et al.* 2008).

A SQUARE GASKET AND THE RELAXING EFFECTS OF NEEDLEWORK

I will now construct a square fractal gasket, a variant of the triangular Sierpinski gasket, and compute its fractal dimension. This exercise shows that, starting from an area, one can construct a “mid-range” fractal that is no different from a fractal line. We begin with a filled-in square of side L, and divide it into 9 smaller squares with sides $L/3$ (Figure 4). Repeat this procedure with each of the newly-defined squares, which eventually leads to the more line-like pattern shown below in its third iteration (Figure 5).

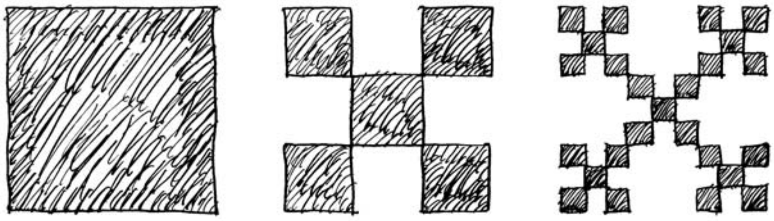

Figure 4. Construction of a square fractal gasket with scaling factor equal to 3, by successively removing smaller squares to create a symmetrical pattern. Figure by Nikos Salingaros.

Let me describe the iterative procedure that produces the entries shown in figure 4, above. The original filled-in square (on the left in Figure 4) is taken as the zeroth iteration: nothing has been done yet. The first iteration (in the middle of Figure 4) cuts the original black square to leave five smaller black squares each of side $L/3$. The second iteration (on the right of Figure 4) further cuts the five smaller squares into twenty-five even smaller black squares, each of side $L/9$. In general, the side x_i of each square in the i-th iteration is as follows: $x_0 = L$, $x_i = L/3^i$. The number N_i of non-empty squares (their multiplicity) at each iteration is: $N_0 = 1$, $N_i = 5^i$. From these values, we compute the fractal dimension as $D = -\Delta \ln(N_i)/ \Delta \ln(x_i) = \ln 5/\ln 3 = 1.46$. (I refer the reader to standard descriptions for how this formula arises).

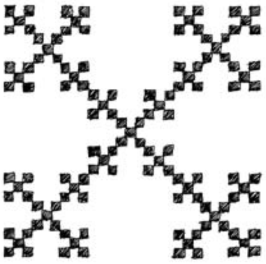

Figure 5. Third iteration of the fractal gasket. At this stage, it resembles a fractal line, and is remarkably similar to traditional crochet needlework and cross-stitch embroidery patterns. Figure by Nikos Salingaros.

Without getting into mathematical details, the fractal dimension depends upon both the fractal's scaling ratio and the geometrical denseness/sparseness of the design. Elsewhere (Salingaros, West 1999), I compute the fractal dimensions of the two best-known mathematical fractals in a plane: the von Koch snowflake ($D = 1.26$), and the triangular Sierpinski gasket ($D = 1.58$). The method for obtaining these results is outlined there.

Though evidence is mostly anecdotal, folklore tells us that stitching and creating crochet patterns such as the fractal with mid-range dimension shown in Figure 5 helps to relax a person. Indeed, for centuries before we had television and home entertainment, women did exactly that. Needlework has traditionally been identified as a particularly relaxing activity that calms the nerves, though it doesn't tell us anything about the effects of particular patterns. The American Home Sewing, Craft Association (AHSCA) commissioned a study by psychologist Robert H. Reiner, who reported that women who sew experienced significantly lower blood pressure, a drop in heart rate, and lowered perspiration rate (Reiner 1995); unfortunately, details of this experiment are not available.

ORNAMENT AND TRADITIONAL ART GENERATE A HEALING ENVIRONMENT

A basic confusion has been encouraged in our times, by a culture that copies superficial visual traits without attempting to understand the underlying reason for the forms. This practice has led to a false understanding of what traditional artifacts and ornament represent. Many learned writers state that ornament is "imitative of nature", but this is a backhanded compliment. And it is misleading. Traditional Art, and ornament in particular, are nothing less than human mental creativity expressed in the most direct and immediate manner. Ornament is simply the first step in the generation of innovative structure towards coherently complex forms. Almost every other positive human achievement points in the same direction, and arises from the same creative process that generates organized complexity.

The incredible mathematical sophistication of traditional material culture is simply not seen in our times, because design professionals tend to be obsessed with either "pure" forms or with the quest for innovation at all costs. The extremely rich traditions of fractal design in urbanism, architecture, and artifacts worldwide are simply dismissed as "not modern"; misinterpreted as an inability of those outside a narrow 20th century artistic and intellectual élite to create exact industrial forms (Eglash 1999). The excuse typically given is that such objects are "not utilitarian". But nothing could be further from the truth: these are the eminently practical tools for creating a healing artificial environment. People wiser than us in these matters figured out that surrounding themselves with fractal objects provides an antidote to life's daily stresses (Figure 6).

When we confront the industrial products of the past several decades, we can hardly find a fractal. The popular interpretation for this paucity is that an anti-fractal aesthetic was necessary to reflect the needs of the machine age. But this is pure propaganda based on ideology. Late nineteenth-century and early twentieth-century industrial utilitarian designs and objects were in fact fractal, just like earlier traditional ones. Early industrial furniture and household objects and utensils were designed to also give nourishing feedback from their everyday use. The later radical simplification of forms was an ideological imposition by the Bauhaus and its successors: ever since the 1920s, people tend to judge a "modern" object by whether it conforms to this peculiar and intolerant aesthetic, not because it employs the latest technology.

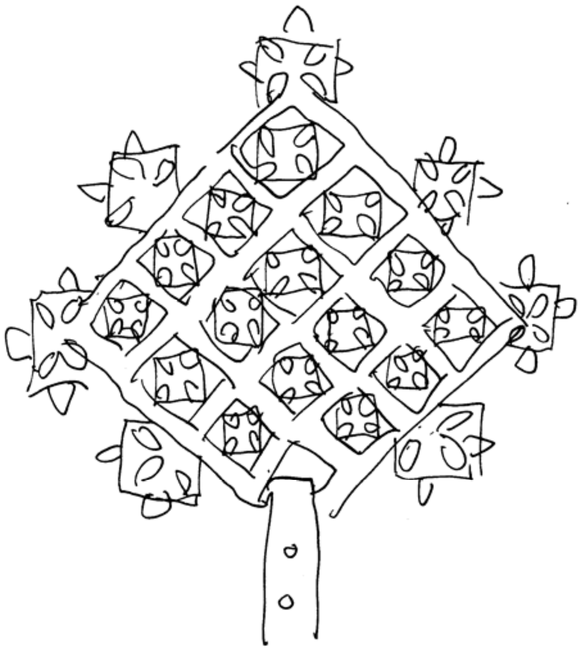

Figure 6. Ethiopian silver cross is an obvious fractal. Figure by Nikos Salingaros.

Taylor startled the Art world by proving that the paintings of Jackson Pollock are fractal (Taylor 2006; Taylor *et al.* 2011). Here we have an example of totally abstract art that is nevertheless fractal. The conjecture is that this is the reason why people find it attractive. Taylor's claim aroused excitement, with some researchers questioning whether the scaling in Jackson Pollock's paintings obeys a consistent scaling ratio, or if it extends to a sufficient number of scales for a true fractal (Jones-Smith, Mathur 2006). Taylor's rebuttal settled the issue (Taylor *et al.* 2006) and a number of groups subsequently performed their own fractal analysis on Pollock's paintings. This discussion encourages art historians to look at paintings and traditional products of material culture from a new, fractal perspective. Fractal art does not necessarily have to copy natural forms directly: what fractal art copies is the generative process that nature follows.

An important question raised by the discussion on Pollock is: "*how many orders of magnification are required for a self-similar visual to appear fractal?*" It turns out that the eye can perceive fractal structures with just a few multiples of scaling. For example, the design shown in Figure 5 has only three iterations yet we respond to it as a fractal. Its scaling factor equals 3, thus two consecutive magnifications equal 9x, or approximately one order of magnitude (10x), at which one still sees the cross pattern (middle of Figure 4). At three consecutive magnifications 27x, we lose the pattern and get a square (left of Figure 4). Taylor finds that a design which is statistically self-similar at between one and two orders of magnitude (i.e., from 10x to 100x) works as a fractal.

A related but distinct question is how many orders of scaling are necessary in architecture. This time the answer is not so simple, because the user's eye perceives extremely fine detail in the materials. If a fractal structure or design is not hierarchically anchored onto the smallest scales, then any large-scale fractal will seem detached. That is, it will appear fractal but as something superimposed on the structure (and cognitively detached from it) rather than an integral part of it. Architects designing abstract fractals today don't include the number of iterations that take advantage of the stress-reducing effects. Contrast this with the fractal quality of traditional and vernacular architectural languages, right up to and including Art Nouveau and Art Deco, which do indeed connect to the materials.

FRACTAL TUNING AND SEVEN CLUES TO COGNITIVE RESONANCE

Goldberger, Joye, Taylor, Wise, and I (and other researchers in this field) agree on one fundamental point: there appears to be a certain resonance between our cognitive apparatus and environments that possess fractal properties. Furthermore, not all fractals elicit the same degree of positive emotion leading to physiological stress reduction, but specifically mid-range fractals with fractal dimension around $D = 1.4$. Human beings seem naturally attuned to a visual signal of fractal character and particular fractal dimension. The brain is constantly computing characteristics of our environment, evaluating features that are essential for our survival, so this resonance has deep meaning. Lacking a satisfactory explanation for why our body is built in this way, we have only clues as to the underlying mechanism. I list some of them below

First clue: from the structure of the mind. The mammalian body, and especially the brain, is organized according to fractal morphology. The brain is a structured system of hierarchically-organized anatomical modules existing on distinct levels of scale. Measurements of magnetic resonance images (MRI) of the human brain confirm its essentially fractal anatomy (Kiselev *et al.* 2003). Evidence from associative memory points to a parallel between thought processes and the brain's fractal physical structure (Mikiten *et al.* 2000). Going further, Mikiten, Yu, and I conjectured that signal reception works like tuning a radio to a specific type of signal, which is consistent with the notion of resonance of our mind with fractals of a specific fractal dimension. Functional magnetic resonance imaging (fMRI) and magneto-encephalography (MEG) studies of the human brain reveal both spatial and temporal synchronizations among different regions of the active brain. Significantly, space and time measures in the brain separately show fractal patterning (Pincus 2009).

Second clue: from fractal antennas. In a recent technological development, the discovery of fractal resonators in microelectronics by Nathan Cohen (Cohen 2005) opens up the exciting possibilities of studying a parallel mechanism in electronic hardware. Antennas built using fractal geometry have been found to significantly outperform linear antennas. Indeed, a fractal antenna built on the design of Figure 5 proves to be extremely efficient in geographical locations with weak signal, where ordinary antennas cannot function properly. Advantages of fractal antennas include significant reduction in size without loss of receiving ability; and extremely wide bandwidth compared to linear antennas, which obviates the need for an additional tuning unit. That is, fractal antennas are able to capture different frequencies without either geometrical or electronic tuning. Conjecturing by analogy, fractal physiological structures that make up our body could somehow resonate with fractal structures in the external environment.

Third clue: from dynamic fractals in human physiology. So far in this discussion we have considered geometrical objects containing different scales. The same phenomenon exists in time, where fractals in the temporal dimension contain signals of different duration. The electrocardiogram (ECG) time-series of the human heart has fractal properties (West, Deering 1995). The dynamics of the human heart contain many frequencies that describe the variability of the basic rate at 70 beats per minute, which in a healthy heart goes up and down from 50 to 110 in a temporal pattern with fractal components. In a remarkable observation, pathologies of the heart are associated with a departure from a fractal spectrum, when the electrocardiogram becomes more linear, or when the distinct temporal scales decouple. That signals the onset of a heart attack. The West-Goldberger hypothesis states: "*a decrease in healthy variability of a physiological system is manifest in a decreasing fractal dimension*" (West, Goldberger 1987). These results on dynamic physiological processes suggest similar patterns occurring on spatial scales, which we already know.

Fourth clue: from the Savannah hypothesis. Several researchers, each starting from a different direction of reasoning, come to a similar conclusion about the influence of our presumed ancestral environment. The mid-range fractal dimension of a savannah landscape provides survival advantages such as effortless conveyance of basic structural information (Joye 2007; Kellert *et al.* 2008). Environments with higher fractal dimension, such as forest, can hide predators and thus present more danger, whereas environments with much lower fractal dimension are both too open and too exposed to offer protection and sources of food. If we are indeed tuned to this particular fractal environment because of our evolution, then we should respond with increased stress in environments with fractal dimension very different from a Savannah: those with considerably less or considerably more than the mid-range value around $D = 1.5$.

Fifth clue: from eye motions. Taylor and his associates propose an explanation for fractal resonance derived from measurements made on eye motions while scanning a picture. The eye executes a search procedure all over a visual in what is called “saccadic” motion consisting of many jumps of different length. The path itself is not regular, but follows regions of highest contrast (Yarbus 1967). Other than picking out the regions of maximal contrast, the irregular motions correspond to a stochastic fractal called a “Lévy flight” (Taylor *et al.* 2011). Taylor computed the fractal dimension of the Lévy flights of the eye while tracking fractal scenes of different fractal dimension. Interestingly, the fractal dimension of the eye path pattern did not change: it was fixed at $D = 1.5$. Therefore, it seems that the eye uses its own intrinsically fractal scanning procedure, which is unaffected by the fractal dimension of what is being scanned. It follows that cognitive resonance should occur for any line that has fractal dimension around 1.5.

Sixth clue: from sharks foraging for food. Animals looking for food tend to execute a stochastic search (random directions and path lengths) that resembles a Lévy flight, where a local region is searched thoroughly, and then the animal moves some distance away and searches that new location. Not only has the shark been observed to forage in this way, but also the albatross. The straight lengths of the movements combine many short paths, several paths of intermediate size, and a few paths of longer length. This is the characteristic inverse-power scale distribution in fractals. Taylor conjectures that this efficient Lévy flight foraging search pattern applies just as well to the eye motions in seeking out information from a visual in the most efficient manner (Taylor *et al.* 2011). The stochastic Lévy fractal eye motions when scanning a scene therefore come from an evolutionary adaptation to mathematics, and are not a characteristic peculiar to the eye’s anatomy, thus supporting the fifth clue.

Seventh clue: from artwork that reduces stress. An enormous amount of art produced throughout human history needs to be evaluated for fractal properties, and, if it is indeed fractal, its fractal dimension should be measured. In a 1993 survey, Vitaly Komar and Alexander Melamid claimed that landscape paintings containing water, people, and animals were the most universally preferred by persons from all continents (Dutton 2009). Note that the presence of water in a scene lowers the fractal dimension of contours to that of a “mid-range” fractal. The publication of this survey caused uproar in the world of fine art, since realistic landscapes have long been considered “kitsch”, and thus taboo. Yet interior designers and environmental psychologists know something, because dentist offices’ waiting rooms contain precisely such visuals (along with photos of cute puppies): an application of biophilia to lower the stress of anxious patients.

While medical researchers increasingly appreciate the health benefits of fractal environments, there is diversity of opinion as to the optimal fractal dimension. Some researchers investigating this topic disagree with choosing the mid-range fractals as the ones preferred by the human perception system. Alexandra Forsythe and collaborators, while supporting the healing value of fractal surroundings, propose that the preferred fractal dimension is much higher, between 1.6 and 1.9 (Forsythe *et al.* 2010). As evidence, they present the fractal dimension of well-known paintings, such as Botticelli’s “The Birth of Venus” $D = 1.86$, Monet's "Water Lilies" $D = 1.78$, and van Gogh's "Sunflowers" $D = 1.76$. Elsewhere, Ali Lavine computed Hokusai's "Great Wave off Kanagawa" to have $D = 1.73$ (Lavine 2009). These numbers, if independently confirmed, would of course require reconciliation with the experimental data given by Taylor and others.

I offer my own two points of caution in way of explanation. First, in this paper we are most interested in paintings that are known to lower stress in the viewer. A work of art may be famous and well-liked but not necessarily have restorative properties. Indeed, it may appeal precisely because it induces excitement. Hokusai's wave is certainly fractal, but may not be good at damping environmental stress. From the distinction between stress-inducing versus nourishing kinds of excitement, we can tolerate a short exposure to a challenging and provocative artwork, but an environment with those characteristics is probably going to have adverse physiological effects on our organism because of chronic stress. Second, it is notoriously difficult to measure the fractal dimension of a picture using the box-counting method (Gonzato *et al.* 2000). If one is not careful, the result given by commonly-used software could be off by 50% or more when measuring genuine fractals. Worse still, one could actually get a value for the fractal dimension of a non-fractal visual, which is a nonsensical result. We need to be cautious about the reported numbers for fractal dimensions of artworks, and wait for more data.

CONCLUSION

The work summarized here addresses how fractal visuals influence human beings during the performance of stressful mental work. Beneficial, restorative environments dampen the inevitable rise in physiological stress while performing a necessary task requiring concentration. The opposite, those environments that actually boost the stress levels of normal mental concentration, should be considered harmful to our health in the long term. Despite the voluminous literature on learning and workplace environments, the effect of fractal scenes on reducing stress has not yet assumed the central importance it deserves. Instead, we continue to see the same stress-raising environments reproduced in new offices, work environments, and schools of all types. Apologists for continuing such typologies insist on a largely mythical industrial efficiency, stylistic "honesty", inviolability of the principles of modernist design, etc.

We could, on the other hand, use recent scientific results such as the work reported here to drastically re-design learning and working environments. There exist sufficient preliminary results to do this. It is surprising from a scientific point of view, but expected, considering the inertia of the design establishment, that direct research on how people are affected by the fractal qualities of their environment is still only of marginal interest. One would think that this ought to be a central topic for investigation, to which society should devote major effort and funding. Too much of what is taken for granted, but which is shown to be wrong by experiments, relies upon personal opinion. But when individuals are asked what they like, they invariably give back what they are taught as the prevailing opinion, thus perpetuating opinions that obscure facts. It is time for us to correct this deficit of information on the design of the built environment.

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