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Perceptual and Physiological Responses to the Visual Complexity of Fractal Patterns

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Abstract: *Fractals have experienced considerable success in quantifying the complex structure exhibited by many natural patterns and have captured the imagination of scientists and artists alike. With ever widening appeal, they have been referred to both as "fingerprints of nature" and "the new aesthetics." Our research has shown that the drip patterns of the American abstract painter Jackson Pollock are fractal. In this paper, we consider the implications of this discovery. We first present an overview of our research from the past five years to establish a context for our current investigations of human response to fractals. We discuss results showing that fractal images generated by mathematical, natural and human processes possess a shared aesthetic quality based on visual complexity. In particular, participants in visual perception tests display a preference for fractals with mid-range fractal dimensions. We also present recent preliminary work based on skin conductance measurements that indicate that these mid-range fractals also affect the observer's physiological condition and discuss future directions based on these results.*

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DRIPPED COMPLEXITY

The art world changed forever in 1945, the year that Jackson Pollock moved from downtown Manhattan to Springs, a quiet country town at the tip of Long Island, New York. Friends recall the many hours that Pollock spent on the back porch of his new house, staring out at the countryside as if assimilating the natural shapes surrounding him (see Fig. 1) (Potter, 1985). Using an old barn as his studio, he started to perfect a radically new approach to painting that he had briefly experimented with in previous years. The procedure appeared basic. Purchasing yachting canvas from his local hardware store, he simply rolled the large canvases (sometimes spanning five meters) out across the floor of the barn. Even the traditional painting tool - the brush - was not used in its expected capacity: abandoning physical contact with the canvas, he dipped the stubby, paint-encrusted brush in and out of a can and dripped the fluid paint from the brush onto the canvas below. The uniquely continuous paint trajectories served as 'fingerprints' of his motions through the air.

These deceptively simple acts fuelled unprecedented controversy and polarized public opinion of his work. Was this painting ‘style’ driven by raw genius or was he simply mocking artistic traditions? Sixty years on, Pollock's brash and energetic works continue to grab public attention and command staggering prices of up to $40M. Art theorists now recognize his patterns as a revolutionary approach to aesthetics. However, despite the millions of words written about Pollock, the real meaning behind his infamous swirls of paint has remained the source of fierce debate in the art world (Varnedoe & Karmel, 1998).

One issue agreed upon early in the Pollock story was that his paintings represent one extreme of the spectrum of abstract art, with the paintings of his contemporary, Piet Mondrian, representing the other. Mondrian’s so-called "Abstract Plasticism" generated paintings that seem as far removed from nature as they possibly could be. They consist of elements - primary colors and straight lines - that never occur in a pure form in the natural world. In contrast to Mondrian’s simplicity, Pollock’s "Abstract Expressionism" speaks of complexity – a tangled web of intricate paint splatters. Whereas Mondrian’s patterns are traditionally described as "artificial" and "geometric", Pollock’s are "natural" and "organic" (Taylor, 2002a). But if Pollock’s patterns celebrate nature’s organic shapes, what shapes would these be?

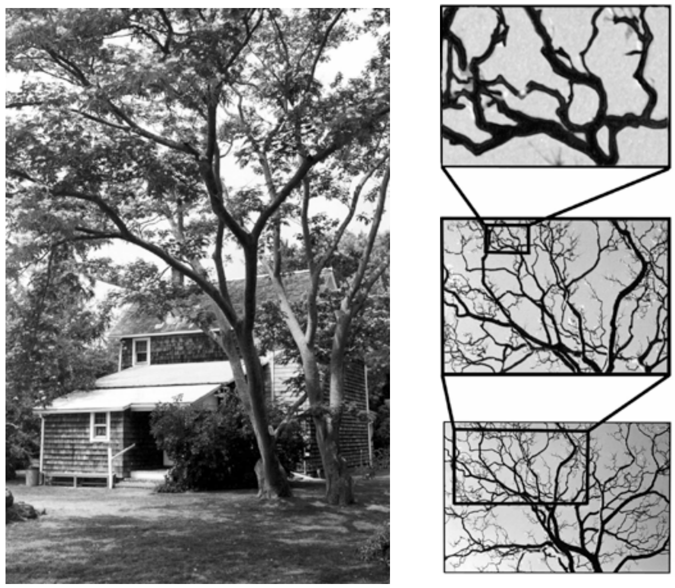

Fig. 1. Left: Pollock's house on Long Island. In contrast to his previous life in Manhattan, Pollock perfected his drip technique surrounded by the complex patterns of nature. Right: Trees are an example of a natural fractal object. Although the patterns observed at different magnifications don't repeat exactly, analysis shows them to have the same statistical qualities (photographs by R.P. Taylor).

NATURE'S FRACTALS

Since the 1970s many of nature's patterns have been shown to be fractal (Barnsley, 1993, Gouyet, 1996, Mandelbrot, 1977). In contrast to the smoothness of artificial lines, fractals consist of patterns that recur on finer and finer scales, building scale invariant shapes of immense complexity. Even the most common fractal objects, such as the tree shown in Fig. 1, contrast sharply with the simplicity of artificial shapes.

An important parameter for quantifying a fractal pattern's visual complexity is the fractal dimension, *D*. This parameter describes how the patterns occurring at different magnifications combine to build the resulting fractal shape (Mandelbrot, 1977). For Euclidean shapes, dimension is described by familiar integer values - for a smooth line (containing no fractal structure) *D* has a value of one, whilst 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 (Mandelbrot, 1977). For fractals described by a low *D* value, the patterns observed at different magnifications repeat in a way that builds a very smooth, sparse shape. However, for fractals with a *D* value closer to two, the repeating patterns build a shape full of intricate, detailed structure. Figure 2 (left column) demonstrates how a pattern's *D* value has a profound effect on the visual appearance. The pattern established by clouds (left, top) has a *D* value of 1.3, while the pattern established by the trees (left, bottom) has a *D* value of 1.9. Table 1 shows *D* values for various natural forms.

POLLOCK'S FRACTALS

In 1999, we published an analysis of twenty of Pollock's dripped patterns showing that they are fractal (Taylor, Micolich & Jones, 1999a). To do this we employed the well-established 'box-counting' method, in which digitized images of Pollock paintings were covered with a computer-generated mesh of identical squares (or "boxes"). The statistical scaling qualities of the pattern were then determined by calculating the proportion of squares occupied by the painted pattern and the proportion that are empty. This process was then repeated for meshes with a range of square sizes. Reducing the square size is equivalent to looking at the pattern at finer magnification. In this way, we could compare the pattern's statistical qualities at different magnifications. Specifically, the number of squares $N(L)$ that contained part of the painted pattern were counted and this was repeated as the size, L, of the squares in the mesh was reduced. The largest size of square was chosen to match the canvas size (L~2.5m) and the smallest was chosen to match the finest paint work (L~1mm). For fractal behavior, $N(L)$ scales according to the power law relationship $N(L) \sim L^{-D}$, where $1 < D < 2$. This power law generates the scale invariant properties that are central to fractal geometry. The *D* values, which chart this scale invariance, were extracted from the gradient of a graph of log $N(L)$ plotted against log L. Details of the procedure are presented elsewhere (Taylor, Micolich & Jones, 1999b). We note that the standard deviation associated with fitting the data to the fractal scaling behavior is such that D can be determined to an accuracy of two decimal places (Taylor, 2000).

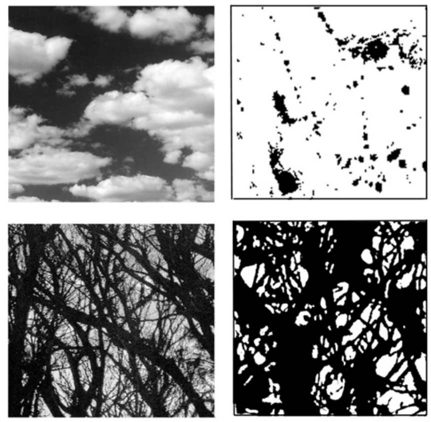

Fig. 2 Examples of natural scenery (left column) and drip paintings (right column). Top: Clouds and Pollock's painting *Untitled* (1945) are fractal patterns with *D* = 1.3 and 1.10 respectively. Bottom: A forest and Pollock's painting *Untitled* (1950) are fractal patterns with *D* = 1.89. (Photographs by R.P. Taylor).

Table 1. Fractal Dimensions (*D*) for Various Natural Fractal Patterns.

Natural pattern	*D*	*Source*
Coastlines: Australia, Britain South Africa,	1.05-1.25	Mandelbrot, 1977
Coastlines: Norway	1.52	Feder, 1988
Galaxies (modeled)	1.23	Mandelbrot, 1977
Cracks in ductile materials	1.25	Louis et al., 1986
Geothermal rock patterns	1.25-1.55	Campbel, 1993
Woody plants and trees	1.28-1.90	Morse et al., 1985
Waves	1.3	Werner, 1999
Clouds	1.30-1.33	Lovejoy, 1982
Sea Anemone	1.6	Burrough, 2003
Cracks in non-ductile materials	1.68	Skjeltorp & Meakin, 1988
Snowflakes (modeled)	1.7	Nittman et al., 1987
Retinal blood vessels	1.7	Family et al., 1989
Bacteria growth pattern	1.7	Matsushita et al., 1993
Electrical discharges	1.75	Niemeyer et al., 1984
Mineral patterns	1.78	Chopard et al., 1991

Recently, we described Pollock's style as ‘Fractal Expressionism’ (Taylor, Micholich & Jones, 1999b) to distinguish it from computer-generated fractal art. Fractal Expressionism indicates an ability to generate and manipulate fractal patterns *directly*. In many ways, this ability to paint such complex patterns represents the limits of human capabilities. Our analysis of film footage taken at his peak in 1950 reveals a remarkably systematic process (Taylor, Micolich & Jones, 2002). He started by painting localized islands of trajectories distributed across the canvas, followed by longer extended trajectories that joined the islands, gradually submerging them in a dense fractal web of paint. This process was very swift with the fractal dimension rising sharply from D = 1.52 at 20 seconds to D = 1.89 at 47 seconds. He would then break off and later return to the painting over a period of several days, depositing extra layers on top of this initial layer. In this final stage he appeared to be fine-tuning the D value, with its value rising by less than 0.05. Pollock's multi-stage painting technique was clearly aimed at generating high D fractal paintings (Taylor et al., 2002).

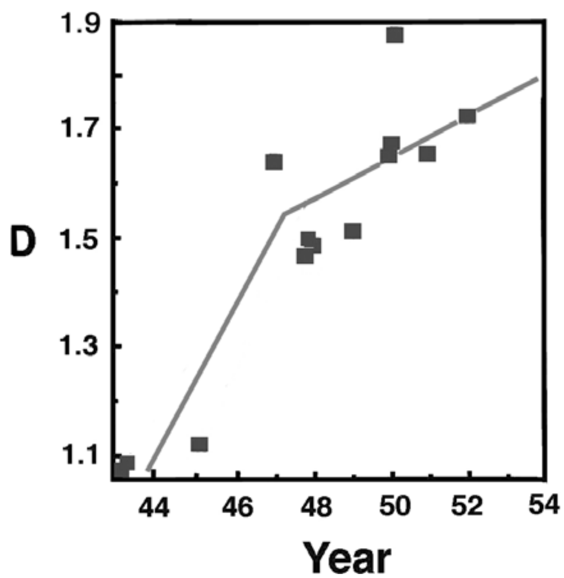

Fig. 3. The fractal dimension D of Pollock paintings plotted against the year in which they were painted (1943 to 1953). See text for details.

As shown in Fig. 3, he perfected this technique over ten years. Art theorists categorize the evolution of Pollock's drip technique into three phases (Varnedoe & Karmel, 1998). In the 'preliminary' phase of 1943-45, his initial efforts were characterized by low *D* values. An example is the fractal pattern of the painting *Untitled* from 1945, which has a D value of 1.10 (see Fig. 2). During his 'transitional phase' from 1945-1947, he started to experiment with the drip technique and his *D* values rose sharply (as indicated by the first gradient in Fig. 3). In his 'classic' period of 1948-52, he perfected his technique and D rose more gradually (second gradient in Fig. 3) to the value of $D = 1.7$. During his classic period he also painted *Untitled* (see Fig. 2), which has an even higher *D* value of 1.89. However, he immediately erased this pattern (it was painted on glass) prompting the speculation that he regarded this painting as too complex and immediately scaled back to paintings with $D = 1.7$. This suggests that his ten years of refining the drip technique were motivated by a desire to generate fractal patterns with $D \sim 1.7$. Whereas this distinct evolution has been proposed as a way of authenticating and dating Pollock's work (Taylor, 2002b) it also raises a crucial question for visual scientists - do these higher D value fractal patterns have a special aesthetic quality?

Fig. 4. The chaotic pendulum (left) employed to generate non-fractal (top right) and fractal (bottom right) drip paintings. This technique was documented by the ABC television in 1998.

The Aesthetics of Fractals

The prevalence of fractals in our natural environment has motivated a number of studies to investigate the relationship between a pattern's fractal character and its visual properties (Cutting & Garvin, 1987, Geake & Landini, 1997; Gilden, Schmuckler & Clayton, 1993; Jang & Rajala 1990; Knill, Field, & Kirsten, 1990; Pentland, 1984; Rogowitz, & Voss, 1990). Whereas these studies concentrated on perceived qualities such roughness and complexity, other studies have focused on aesthetics and the quantification of the 'visual appeal' of fractal patterns (Aks & Sprott, 1996; Hagerhall, Purcell, & Taylor, 2004; Pickover, 1995; Richards, 2001; Richards & Kerr, 1999; Spehar, Clifford, Newell, & Taylor, 2003; Sprott, 1993; Taylor, 1998, 2001). In one of the initial experiments performed in 1994, we used a chaotic pendulum to generate fractal and non-fractal drip-paintings (example sections from two paintings are shown in Fig. 4). In the perception studies that followed, participants were shown one fractal and one non-fractal pattern (randomly selected from 40 images) and asked to state a preference (Taylor 1998, 2003a). Out of the 120 participants, 113 preferred examples of fractal patterns over non-fractal patterns, confirming their powerful aesthetic appeal.

Given the profound effect that *D* has on the visual appearance of fractals (see, for example, Fig. 2), do observers base aesthetic preference on the fractal pattern's *D* value? Previous ground-breaking studies have concentrated on computer-generated fractals. In 1995, Pickover used a computer to generate fractal patterns with different *D* values and found that people expressed a preference for fractal patterns with a high value of 1.8 (Pickover, 1995), similar to Pollock's paintings. However, a survey by Aks and Sprott also used a computer but with a different mathematical method for generating the fractals. This survey reported much lower preferred values of 1.3 (Aks & Sprott, 1996; Sprott, 1993). Aks and Sprott noted that the preferred value of 1.3 revealed by their survey corresponds to prevalent patterns in the natural environment (for example, clouds and coastlines have this value) and suggested that perhaps people's preference is actually 'set' at 1.3 through a continuous visual exposure to patterns characterized by this *D* value. However, the discrepancy between the two perception experiments seemed to suggest that there isn't a universally preferred *D* value but that the aesthetic qualities of fractals instead depend specifically on how the fractals are generated. The discovery of Pollock's fractals re-invigorates this question of fractal aesthetics. In addition to fractal patterns generated by mathematical and by natural processes, there now exists a third family of fractals - those generated by humans (Taylor, 2001).

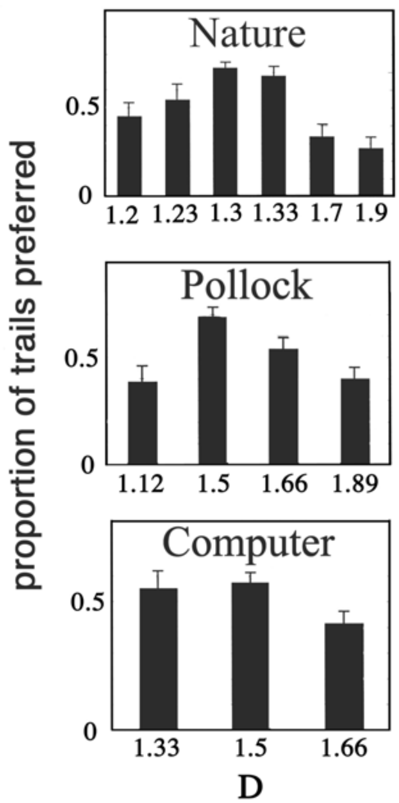

Fig.5. Visual preference tests for natural fractals (top), Pollock's fractals (middle) and computer fractals (bottom). In each case, the vertical axis corresponds to the proportion of trails for which patterns of a given *D* value were chosen over patterns with other *D* values. The uncertainty bars shown above each column represent variations between participants.

To determine if there are any 'universal' aesthetic qualities of fractals, we carried out the first experiment to incorporate all three categories of fractal pattern: fractals formed by nature's processes, by mathematics and by humans. We used 15 computer-generated images of simulated coastlines (5 each with *D* values of 1.33, 1.50 and 1.66), 40 cropped images from Jackson Pollock's paintings (10 each with *D* values of 1.12, 1.50, 1.66 and 1.89), and 11 images of natural scenes with *D* values ranging from 1.1 to 1.9. Figure 2 shows some of the images used in the survey (for the full set of images see Spehar et al., 2003). All stimuli were digitized, scaled to identical geometric dimensions and presented in achromatic mode. Within each category of fractals (i.e. mathematical, natural and human), we investigated the visual appeal as a function of *D*. This was done using a 'forced choice' visual preference technique, in which participants were shown a pair of images with different *D* values on a monitor and asked to chose the most "visually appealing". Introduced by Cohn in 1894, the forced choice technique is well-established for securing value judgments (Cohn, 1894). In our experiments, all the images were paired in all possible combinations. The presentation order was fully randomized and preference was quantified in terms of the proportion of times each image was chosen.

Although details are presented elsewhere, Fig. 5 shows the results from the experiment involving 220 participants (Spehar et al., 2003). Taken together, the results indicate that we can establish three categories with respect to aesthetic preference for fractal dimension: 1.1-1.2 low preference, 1.3-1.5, high preference and 1.6-1.9 low preference. In a control experiment, a set of computer generated random dot patterns with no fractal content but matched in terms of density (area covered) to the low, medium and high fractal patterns were used to demonstrate that aesthetic preference is indeed a function of *D* and not simply pattern density. The 'universal' character of fractal aesthetics was further emphasized by a recent investigation showing that gender and cultural background of participants did not significantly influence preference (Abraham et al., 2003).

These perception experiments deliberately focused on relatively simple fractal objects. Each image featured just one form of fractal pattern (for example, the clouds or trees shown in Fig. 2). Furthermore, the selected images provided a relatively high contrast against a uniform background, facilitating the application of the box-counting technique. In light of the speculation that the preference for mid-range *D* values is set through exposure to natural patterns (Aks & Sprott, 1996), an obvious step is to extend our studies to consider preferences for natural scenes. Although the characteristics of typical scenes are considerably more subtle than the simple shapes considered above, their fractal statistics are well-charted. Analysis has shown that typical scenes are scale invariant, following a power law behavior (Billock, 2000; Billock, de Guzman, & Kelso, 2001; Field & Brady, 1997). This behavior is thought to be due to a combination of the following factors: (a) many of the individual objects in the scene are fractal (see Table 1), (b) many scenes contain a power law distribution of object sizes (Field & Brady, 1997; Ruderman, 1997), and (c) the structure in each of the luminance edges in the scene is expected to follow a power law distribution of sizes (Switkes, Mayer, & Sloan, 1978).

A remaining challenge lies in determining how the preference for mid-range *D* values of simple fractal objects (Aks & Sprott, 1996; Spehar et al., 2003, Sprott, 1993) extends to these more visually intricate fractal scenes. One possible approach to addressing this issue would be to concentrate on the luminance properties of the overall scene. This could be done by adopting a technique that performs a spectral analysis of the spatial frequencies of the grayscale image of the scene (Billock, 2000; Field & Brady 1997). The appeal of this approach is that the grayscale analysis can be related to key variables in studies of spatial vision, such as Michelson contrast. Furthermore, the grayscale image conveys visual information about the 'textures' of a scene and previous fractals research indicates that roughness texture is an important property for perception – in particular, a strong correlation has been found between fractal dimension and perceived roughness (Jang & Rajala, 1990; Pentland, 1984).

In contrast, other research indicates that perception is determined by the edge contours of the observed fractal pattern (Rogowitz & Voss, 1990). Therefore, an alternative approach to the analysis of a fractal scene would be to select a prominent edge contour and investigate its impact on perception. The importance of edge contours to the visual system is supported by eye-tracking experiments, which show that in a free viewing situation subjects fixate semantically important regions of a scene (i.e. objects whose identity is important for understanding the scene) or visually striking regions containing luminance changes or definite contours (Rayner & Pollatsek, 1992). The dominant contour in many scenes is formed by the skyline, and consequently these contours have been the focus of previous perception studies. In particular, in architectural studies of tall building skylines, the silhouette complexity significantly affected preference scores while facade complexity was of less importance (Heath, Smith, & Linn, 2000). Furthermore, recent perception experiments using computer-generated images have investigated the impact of matching a city skyline to the background horizon formed by fractal mountains (Stamps, 2002).

Fig. 6. The processing steps used in the extraction of the skyline contour of a natural scene. Top: one of the natural scenes shown to participants. Middle: an intermediate processing step used to extract the skyline contour. Bottom: the extracted skyline contour subjected to the box-counting fractal analysis.

Due to this interdisciplinary interest, our initial investigations of fractal scenery have focused on the importance of the skyline contour for determining aesthetic preference (Hagerhall et al., 2004). The skyline contour of natural scenes has previously been found to be fractal, with the *D* value depending on the objects that define the contour (Keller, Crownover, & Chen, 1987). Our box-counting analysis of the skyline contours extracted from 80 scenes photographed in Australia, Sweden and Italy confirms this fractal behavior. The procedure for extracting the skyline contour, shown in Fig. 6, is des-cribed in detail elsewhere, including the test routines used to confirm that the extraction procedure does not affect the *D* value (Hagerhall et al., 2004). We note that previous landscape preference studies have shown that images featuring dominant water or hills have a positive impact on participants' aesthetic preference (Kaplan & Kaplan, 1982, Purcell & Lamb, 1984). Such images were therefore excluded from our visual preference tests because, for such images, preference rating might be dominated by content of the scene rather than the pattern it establishes.

The preference experiments, involving 119 participants, show the most preferred *D* value to be 1.3 (Hagerhall et al, 2004), indicating that the preference for mid-range *D* values revealed for simple fractal shapes (Aks & Sprott; 1996, Spehar et al, 2003) appears to extend to the fractal characteristics of more intricate fractal scenery. We plan to investigate this possibility further using the grayscale analysis discussed above (Billock, 2000; Field, 1989; Field & Brady, 1997). To summarize this section, our perception studies conducted on 146 fractal images in two separate experiments (15 computer-generated patterns, 40 human-generated drip patterns, 11 natural objects and 80 natural scenes) confirm the aesthetic preference for mid-range *D* values revealed in previous experiments using 7824 computer images (Aks & Sportt, 1996; Sprott, 1993). Although *D* is just one of a number of parameters required to convey the visual information of the images used in these experiments, *D* appears to be central to establishing aesthetic preference.

Physiological Response to Fractals

Does this visual appreciation for mid-range *D* values affect the physiological performance of the observer? This question motivated us to re-examine a previous study performed by one of us (J.A.W.) on the physiological restorative effects produced by exposure to different pattern types (Wise & Rosenberg, 1986). Three art works were used in the study and these are shown in Fig. 7: a photograph of a forest scene (top), a reproduction of a savannah landscape (middle) and a pattern of scattered squares (bottom). In addition, a white panel served as a control. The size of each image was approximately 1m by 2m.

In experiments performed at the NASA-Ames Research Center, twenty-four participants were seated singly in a simulated space station cabin facing a bulkhead featuring one of the four images. During continuous exposure to an image, each participant performed a sequence of three types of mental tasks designed to induce physiological stress (arithmetic, logical problem solving and creative thinking). Each task period was separated by a one minute recovery period, thus creating a sequence of alternating high and low stress periods (see Fig.8a). To measure the subject's physiological response to the stress of mental work, skin conductance was monitored continuously during this sequence (Wise & Rosenberg, 1986). Prior studies have shown skin conductance to be a reliable indicator of mental performance stress with higher conductance occurring under high stress (Ulrich & Simons, 1986).

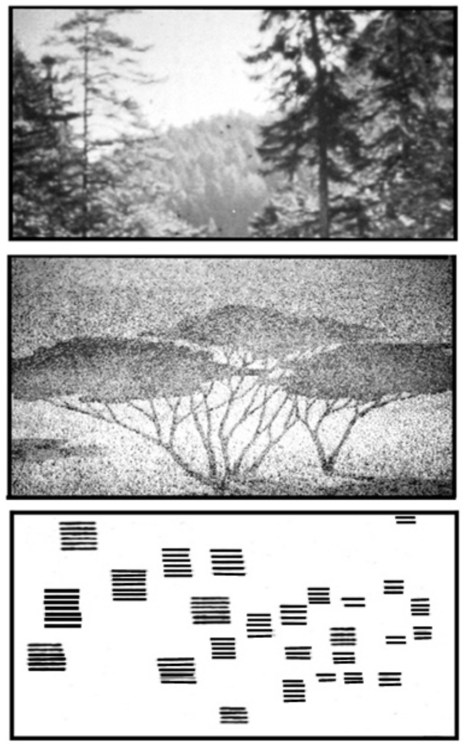

Fig. 7. Images of the artworks used in the physiological experiments (see text for details).

As an example, Fig. 8a shows the rise and fall in conductance measured over the work/rest sequence for participants continuously exposed to the control image. The procedure for generating this plot is presented in detail elsewhere (Wise & Rosenberg, 1986) and here we present a summary. First, to establish a common conductance scale for these participants, each participant's conductance was transformed to *Z*-scores. Then, for each task in the sequence, these *Z* scores were averaged across participants (Wise & Rosenberg, 1986; Wise & Taylor, 2003). This mean *Z* conductance was then plotted for the whole sequence of tasks (Fig. 8a). Equivalent plots were also produced for each of the three artworks and these also revealed a "saw-tooth" response featuring alternate rises and falls in the mean *Z* conductance.

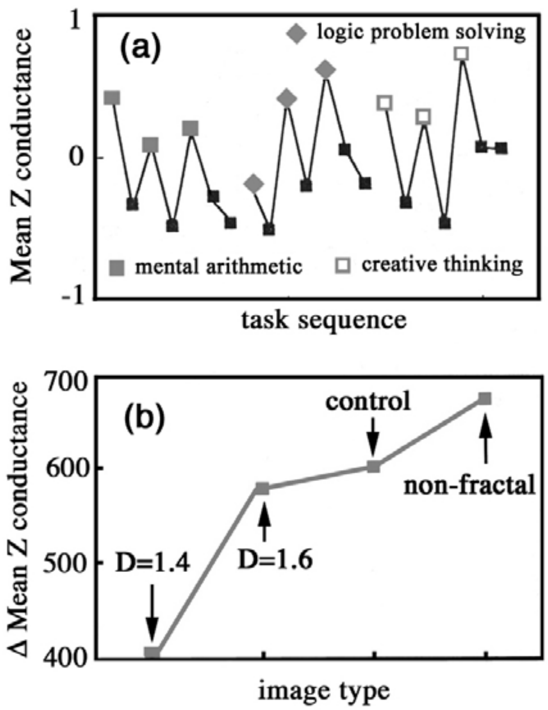

Fig. 8. Physiological response to fractals: (a) Mean *Z* conductance during the task sequence (black squares indicate rest periods) for participants who were continuously exposed to the control panel, (b) the Δ mean *Z* conductance (measured in mhos) for each image type.

Significantly, the magnitude of the change in this mean *Z* conductance between work and rest periods was found to depend on which image participants observed during their session. To quantify this change for each image, we converted the mean *Z* conductance scores into difference scores by calculating the magnitudes of the changes between consecutive work and rest periods. These values were then summed across the tasks. The resulting value was converted back into units of mhos and labeled as the Δ mean *Z* conductance. Analysis of variance (ANOVA) on the changes in mean *Z* conductance between image conditions showed the differences in responses to be statistically significant ($F_{3, 60} = 3.025$, $p < 0.05$; Wise & Rosenberg, 1986).

The forest scene was expected to be most effective in reducing the level-of-stress variation because it was a photograph of a natural scene. Instead, participants exposed to the less realistic savannah reproduction experienced the smallest physiological responsiveness to the stress of mental work. To investigate this surprising result, we performed a fractal analysis on each image. Adopting the edge analysis techniques used in our perception investigations of natural scenery (Hagerhall et al., 2004), we applied the 'box-counting' analysis to the pattern established by the combination of the edge contours of all the objects in the image. We note that fractal analysis of the combined edge pattern of the scene has been used previously to examine the fractal characteristics of patterns in art and nature (Voss, 1998). The pattern of squares was found not to be fractal, whilst the savannah reproduction and the forest photograph were both found to be fractal with *D* values of 1.4 and 1.6 respectively.

These fractal analysis results are summarized in Fig. 8b along with the Δ mean *Z* conductance for each image. For the non-fractal square pattern, the Δ mean *Z* conductance was 13% greater than for the control, indicating that the presence of this artwork actually increased the observer's level-of-stress variation. In contrast, the Δ mean *Z* conductance values for the fractal images were 3% (forest photograph) and 44% (savannah reproduction) *lower* than for the control indicating a reduction in level-of-stress variation. We note that this damping occurs for*both* the conductance rises during the stress-inducing tasks and the decreases in conductance during the recovery periods (Wise & Rosenberg, 1986). Thus, exposure to the savannah reproduction image affects the stress response of the observer in a holistic fashion, damping the entire stress and recovery period, rather than selectively diminishing stress or augmenting recovery alone. We also note that exposure to the different images did not affect task performance, only the stress variation experienced during the sequence of tasks.

The savannah scene provided the greatest damping and has a *D* value (1.4) previously identified as being in the aesthetically pleasing range (1.3-1.5) whilst the forest *D* value (1.6) falls outside this boundary. These results therefore raise the intriguing possibility that the visual appeal of mid-range *D* fractals affects the physiological condition of the observer. We emphasize the preliminary nature of the above results, which are based on only four images. In particular, *D* is just one of a number of visual characteristics that vary between the four images.

However, within this context, it is informative to return to the 'universal' quality of fractal aesthetics identified in the perception experiments – despite the diverse visual properties of the images used (natural objects, natural scenes, drip paintings paintings, computer patterns) (Aks & Sprott, 1996; Spehar et al., 2003, Hagerhall et al., 2004), *D* was found to be a significant factor for determining aesthetic preference. For this reason, our current experiments are aimed at demonstrating the 'universal' character of the physiological response, using a comprehensive library of fractal images with different origins. Furthermore, in addition to analyzing the *D* values of the patterns, these studies will systematically examine a range of visual parameters to determine their roles in influencing participants' perception of the patterns. The general aim is to identify the range of parameters required to maximize the observer's physiological response. In addition to investigating electrodermal response, we are also investigating other physiological indicators, including electrocardiograms, pulse activity and pupillography.

DISCUSSION

The leading traditional studies of perceptual and environmental psychology have assessed preferences for natural environments based on vague qualities such as the degree of 'naturalness' of the scene (Kaplan and Kaplan, 1982). Other studies overlooked the subtle complexity of nature's patterns, and instead focused on simplified representations based on Euclidean shapes (Attneave, 1954; Birkhoff, 1933). Until relatively recently, no unified theory has existed to describe what visual information leads to responses to natural scenery. Instead, previous theories have been limited to discussions concerning optimal amounts of balance between order and disorder (Attneave, 1954; Garner, 1962; Lind, 1992) and simplicity and complexity (Attneave, 1955). However, as has been noted previously, "one must understand the nature of the environment before one can understand the nature of visual processing" (Field, 1987, p. 2379). Experiments that characterize natural environments in terms of their fractal dimension therefore represent a significant step forward in studies of human perception of nature.

The link between the fractal character of natural environments and people's preference for mid-range *D* values represents a highly topical question for a number of research disciplines. The ability of observers to discriminate between fractal images based on their *D* value has been shown to be maximal for fractal images with *D* values corresponding to those of natural scenes (Geake & Landini, 1997; Knill et al., 1990) and this has triggered discussions concerning the possibility that the sensitivity of the visual system is adapted to the fractal statistics of natural environments (Gilden et al., 1993; Knill et al., 1990). Observers who displayed a superior ability to distinguish between different *D* values were also found to excel in cognitive tasks involving 'simultaneous synthesis' (the ability to combine current perceptual information with information from long term memory), with the authors hypothesizing that natural fractal imagery resides in the long-term memory (Geake & Landini, 1997). Furthermore, Aks and Sprott have speculated that the aesthetically-preferred *D* value revealed in their studies is actually *set* at 1.3 through continuous visual exposure to nature's patterns (see earlier).

Whereas the above theories relate fractal perception to the visual experiences encountered during peoples' lives, others have discussed their results in terms of evolution. For example, Richard Voss notes: "The human perception system has evolved over millions of years in a natural fractal environment. Only recently, by evolutionary time scales have we found ourselves in a primarily Euclidean environment of straight lines and few spatial scales" (Rogowitz & Voss, 1990). Indeed, it is interesting to consider our results within the context of previously-proposed evolutionary theory of aesthetics, in which a scene's attraction is related to survival instinct (Appleton, 1975; Balling & Folk, 1982; Barrow, 2003; Kaplan & Kaplan, 1989; Orians, 1986; Orians & Heerwagen, 1992; Ulrich, 1983, 1993; Wise & Hazzard, 2000). It has been speculated that observers may have preferred images with low *D* values because these images mimics African savannah scenery (Wise & Hazzard, 2000). Our ancestors spent the bulk of their evolutionary history in this landscape, and its low visual complexity facilitates detection of predators (Barrow, 2003). According to this theory, observers may have judged the high *D* images as too intricate and complicated, where detecting predators from the surrounding vegetation would be difficult.

Such theories add to the growing topic of the degree to which our aesthetic judgments are based on evolutionary or biological factors rather than, or in addition to, subjective preference based on personal experience and intellectual deliberation. An emerging concept in this regard is "neuro-aesthetics" (Zeki, 1999), which explores the relationship between the neural cells that are activated and the aesthetics of the object being observed. It is well-established that visual qualities such as color and motion are processed in separate visual centers of the brain. However, not all regions surrounding the primary visual cortex are understood in terms of their visual functionality. Although a challenging task, it is acknowledged that an empirical charting of the regions activated by different visual stimuli will constitute a major step toward understanding the brain's visual organization (Zeki, 1999). Indeed, soon after Mandelbrot introduced the concept of fractal geometry, he speculated that fractal and Euclidean shapes might be processed in different regions of the brain due to their differing visual qualities (Clark & Lesmoir-Smith, 1994). Functional magnetic resonance imaging has be used previously to determine which neural cells are activated while viewing 'Euclidean' art such as Mondrian's paintings (Zeki, 1999) – it would be revealing to extend these studies to include, for example, Pollock's fractal paintings.

A more general theory discusses fractal aesthetics in terms of the condition experienced when the fractal structure of the observed environment matches the fractal structures that underlie cognition and perception (see, for example, Briggs, 1992). For example, the spatial information in a scene is thought to be processed within a 'multi-resolution' framework where the cells in the visual cortex are grouped into so-called 'channels' according to the spatial frequency they detect. The way these 'channels' are distributed in spatial frequency parallels the scaling relationship of the fractal patterns in the observed scenery (Field, 1989, Knill et al., 1990, Rogowitz & Voss, 1990). Thus an aesthetic experience might be expected if, for example, an artwork or a view from a window matched this scaling relationship of the channels.

The aesthetic appeal of fractals can also be considered within the framework of more traditional theories of aesthetics. Although the nomenclature varies between different research disciplines, aesthetic appeal is frequently presented in terms of a balance between predictability and unpredictability of the stimulus (e.g., Gombrich, 1972; Mandelbrot, 1993). Indeed, neuroscientists using electroencephalographic data have recently shown that the electrical activity of brain cells is fundamentally chaotic and that the level of chaos depends on the observer's familiarity to a stimulus (Briggs, 1992). Neuroscientists have shown that the chaos descends into a simpler form when the stimulus presented to the observer has a predictable behavior. In contrast, unpredictability in the stimulus maintains a high level of chaos in the brain's electrical activity (Briggs, 1992). It is possible that the intricate structure and apparent disorder of fractal patterns might provide the required degree of unpredictability while the underlying scale invariance establishes an order and predictability.

In summary, the theories of fractal aesthetics and fractal perception are still a matter of lively debate. Furthermore, although discussions concerning the connection between psychological states and physiological states date back to 1890 (James, 1950), and the impact of aesthetics on the physiological condition has been explored (e.g., Parsons & Tassinary, 2002; Russell & Snodgrass, 1987; Zeki, 1999), to our knowledge there are no specific theories relating physiological response to the perceived aesthetics of fractal stimuli. Clearly, fractal patterns constitute a novel test-bed for visual and physiological studies, with the reward of providing an enhanced understanding of the perception of natural environments discussed in this article.

FUTURE STUDIES

Preference investigations and skin conductance measurements might appear to be a highly unusual tool for judging art. However, our preliminary experiments provide a fascinating insight into the impact that art might have on the perceptual and physiological condition of the observer. Our future investigations will explore the possibility of incorporating fractal art into the interior and exterior of buildings, in order to adapt the visual characteristics of artificial environments to the perceptual and physiological responses.

Incorporation of natural images into artificial environments has previously been proposed as a method for stress reduction (Ulrich & Simons, 1983). However, our results indicate that 'naturalness' may not be enough: the pattern's fractal dimension will determine its impact on visual perception and stress-reduction. Based on our preliminary findings, mid-range *D* fractal patterns could be incorporated into a range of environments to reduce stress levels, particularly in situations where people are deprived of nature's fractals – for example, in research stations in space and at the Antarctic (Taylor, 2001, 2003b).

One practical consideration concerns the magnification range over which the pattern must follow fractal scale invariance in order to induce the desired response in the observer. Whereas mathematical fractals extend from the infinitely large to the infinitesimally small, physical fractals (those generated by nature and humans) are limited to a finite range of magnifications. For Pollock's "classic" paintings, fractal behavior has been charted from the finest speck of paint up to the canvas size, representing a magnification range of approximately 1000 (i.e. the smallest pattern analyzed is 1000 times smaller than the largest) (Taylor, 2003a). For the natural scenery, the horizon *D* value was observed over a factor of 250 (Hagerhall et al., 2004).

However, these large observation ranges are unusual for physical fractals. A survey of measurements of physical fractals has shown that a typical observational range is quite limited – the smallest pattern is typically only 25 times smaller than the largest pattern (Avnir, 1998). Motivated by this survey, the images used in our perception experiments were displayed over a magnification range limited by the range over which typical physical fractals occur, ie the smallest resolvable pattern was approximately 25 times smaller than the full range of the image (Spehar et al, 2003). This limited magnification range was sufficient to induce the *D* preference shown in Fig. 5. We plan to investigate whether the observation range can be reduced further without diminishing the preference response.

Our findings might apply to a remarkably diverse range of fractal patterns appearing in art, architecture and archeology spanning more than five centuries. In addition to Pollock's dripped fractals, other examples of fractals include the Nasca lines in Peru (pre-7th century; Castrejon-Pita, Castrejon-Pita, & Sarmiento-Galan, 2003), early Chinese paintings (10-13th century; Voss 1998), the Ryoanji Rock Garden in Japan (15th century; Van Tonder, Lyons, & Ejima, 2002), Leonardo da Vinci's sketch *The Deluge* (1500; Mandelbrot, 1977), Katsushika Hokusai's wood-cut print *The Great Wave* (1846; Mandelbrot, 1977), Gothic cathedrals (Goldberger, 1996), Gustave Eiffel's tower in Paris (1889; Schroeder, 1991), Frank Lloyd Wright's Palmer House in Michigan (1950; Eaton, 1998), M.C. Escher's *Circle Limit III and IV* (1960) and Frank Gehry's proposed architecture for the Guggenheim Museum in New York (2001; Taylor, 2001).

Is Jackson Pollock an artistic enigma? According to our results, the low *D* patterns painted in his earlier years should have more 'visual appeal' than his later *classic* drip paintings. What was motivating Pollock to paint high *D* fractals? Should we conclude that he wanted his work to be aesthetically challenging to the gallery audience? It is interesting to speculate that Pollock regarded the visually restful experience of a low *D* pattern as being too bland for an artwork and wanted to keep the viewer alert by engaging their eyes in a constant search through the dense structure of a high *D* pattern. We are currently investigating this intriguing possibility by performing eye-tracking experiments on Pollock's paintings, which assess the way people visually assimilate fractal patterns with different *D* values.

We finish with a remark made by one of Pollock's friends, Ruebin Kadish, who noted, "I think that one of the most important things about Pollock's work is that it isn't so much what you're looking at but it's what is happening to you as you're looking at his particular work" (Bragg, 1987).

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