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Investigations of human EEG response to viewing fractal patterns

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Abstract. Owing to the prevalence of fractal patterns in natural scenery and their growing impact on cultures around the world, fractals constitute a common feature of our daily visual experiences, raising an important question: what responses do fractals induce in the observer? We monitored subjects' EEG while they were viewing fractals with different fractal dimensions, and the results show that significant effects could be found in the EEG even by employing relatively simple silhouette images. Patterns with a fractal dimension of 1.3 elicited the most interesting EEG, with the highest alpha in the frontal lobes but also the highest beta in the parietal area, pointing to a complicated interplay between different parts of the brain when experiencing this pattern.

1 Introduction

The investigation of human response to nature's scenery is a central research field of environmental psychology and offers the potential to improve the design of built environments. Visual-preference studies have shown that people prefer natural over common built environments (Kaplan and Kaplan 1989). A substantial body of empirical research suggests that exposure to natural environments also induces a positive impact on physiological and cognitive functions, including reducing physiological stress (Ulrich 1993) and restoring the ability to focus attention (Kaplan 1995). EEG recordings show that people are more wakefully relaxed during exposure to natural landscapes, especially vegetation, than during exposure to townscapes (Ulrich 1981), and studies of wall art in hospitals show that images with natural content have positive effects on anxiety and stress (Ulrich 1993). However, the definition of 'nature' adopted in these studies was broad and often based on a simple visual inspection of picture content such as the degree of vegetation or human-induced change in a scene. Few attempts have been made to refine this definition and investigate if there are measurable qualities in nature that can be connected to the preference and the positive effect on physiological stress.

In many of the perception studies, the highlighted predictors of preference are connected to structural spatial properties, but labelled in broad terms such as complexity, coherence, and legibility (Kaplan and Kaplan 1989); or the predictors describe elements that give the scene structure such as focal points, depth, and openness of the scene (Ulrich 1983). An objectively measurable structural quality of nature is the self-similarity observed across different size scales. This special quality of scale invariance can be identified and quantified by a parameter called the fractal dimension, *D*. Fractal geometry has been used successfully to describe many common natural patterns (Gouyet 1996; Mandelbrot 1983) and also man-made patterns in art (Frame and Mandelbrot 2002; Mandelbrot 1983), architecture (Bovill 1995; Goldberger 1996; Salingaros 2000), landscape design (Van Tonder et al 2002), and archaeology (Brown et al 2005). The powerful aesthetic appeal of fractals has also been confirmed (Aks and Sprott 1996; Hagerhall et al 2004; Spehar et al 2003). However, not all fractals are equally preferred. Visual perception research, both by members of this group and other researchers, has pointed to a preference for patterns with mid-range D values 1.3 to 1.5 (Aks and Sprott 1996; Hagerhall 2005; Hagerhall et al 2004; Spehar et al 2003). Similarly, when landscape silhouettes extracted from photographs of natural scenery were used, outlines with a fractal dimension of around 1.3 elicited the highest judgments of perceived naturalness (Hagerhall 2005). These results indicate that patterns with a fractal dimension close to 1.3 could be perceptually unique, connecting preference to qualities that are perceived as natural. These patterns may also affect psycho-physiological measurements: preliminary data for skin-conductance measurements pointed to mid-range fractal dimensions as having the largest positive effect on stress, although additional visual characteristics varied between the stimuli used in that study (Taylor et al 2005).

Assuming that fractal properties might explain some of the positive psychological and physiological responses to viewing nature, we used in the current study well-defined computer-generated fractal patterns to determine if psycho-physiological responses can be adjusted by tuning the pattern dimension in a controlled manner. The skin-conductance technique was used in the preliminary study to measure sympathetic autonomic activities. In this study quantitative electroencephalography (qEEG) was used to measure cerebral cortical activity. Although generally studied separately, it has been shown that there is probably a substantial relationship between cerebral function and autonomic arousal (Lim et al 1996). qEEG makes it possible to study the brain's responses to external visual stimulation; it is a relatively inexpensive and non-invasive method and hence enables experiments with large groups of non-clinical subjects. It is generally agreed that EEG is a good indicator of cortical arousal: in the awake brain, the alpha components of the EEG seem to be especially responsive to environmental stimulation (Küller 1991; Küller et al, accepted). When an individual is stimulated, these relatively low-frequency high-amplitude rhythms become attenuated ('phasic arousal'), and return once the individual resumes the relaxed state. Alpha power has been found to be greater when the attention is directed inward on mental imagery than when attention is directed towards external information-intake tasks (Ward 2003); it could thus also be seen as an indicator that "attention is actively suppressing cortical activity related to distractors as a part of the process of focussing attention on important targets" (Ward 2003, page 557). While the alpha component is considered to show a wakefully relaxed state, the delta component is prominent during drowsiness and deep sleep. The beta component of EEG is associated with external focus, attention, and an alert state (Kolb and Whishaw 2003). Theta and gamma have been suggested to play an active role in memory (Ward 2003). Gamma is also discussed together with alpha in relation to attention as a dynamic process (Ward 2003). It is, however, important to point out that these interpretations of the relations between various EEG frequencies are still open questions.

Three areas—frontal, parietal, and temporal—were chosen for the qEEG recordings. Processes in these three zones are thought to be complementary (Kolb and Whishaw 2003). Hence, the three selected areas are expected to reveal significant psycho-physiological impacts of exposure to fractal stimuli. Generally stated, sensory information is analysed by the parietal and temporal regions, the information then progresses to the frontal lobes, where different behavioural strategies are implemented (Kolb and Whishaw 2003). However, emerging evidence points to the possibility that brain function might be better understood as a dynamic system with recurrent networks rather than as a sequential process with things happening in different areas at various stages (Basett et al 2006; Linkenkaer-Hansen et al 2004; Stam and de Bruin 2004; Tononi and Edelmann 1998; Ward 2003). Of particular interest and relevance to this study is the emerging evidence for a frontoparietal attentional network (Fox et al 2005), where the frontal and parietal areas work together in controlling attention and response selection (Corbetta and Shulman 2002; Pessoa et al 2003). Furthermore, in this network, attended items seem to be favoured in the competition for processing resources (Pessoa et al 2003).

On the basis of the previously observed preference for mid-D fractals (Aks and Sprott 1996; Hagerhall et al 2004; Spehar et al 2003) and the possibility that these fractals might also induce a relaxed state (Taylor et al 2005), we hypothesise that mid-D stimuli will produce a maximal alpha response in the frontal areas. Additionally, we hypothesise that the different fractal dimensions will generate different levels of activation in the processing of the pattern, ie a difference in beta responses will be likely in the parietal and temporal regions.

2 Methods

2.1 *Stimuli*

The contrasting line between sky and landscape is an important aspect of natural scenes and built environments, and eye-tracking experiments have shown that definite contours and areas with luminance changes attract much attention (Rayner and Pollatsek 1992). This makes the landscape silhouette a feature of high relevance to landscape perception and experience. At the same time, the silhouette offers experimental advantages in relation to studying fractals, both when it comes to controlling and isolating the variable of interest, the fractal dimension, and when comparing with existing empirical studies on aesthetic responses and evaluations of fractal patterns, which have mostly involved simple patterns such as computer-generated grids and line drawings and contours of natural objects such as trees and clouds (Aks and Sprott 1996; Pickover 1995; Spehar et al 2003; Taylor et al 2005).

The stimuli used in this study consisted of computer simulations of fractal horizons. The fractal horizon traces were generated by a spectral synthesis technique which employs the inverse Fourier transform of a set of pre-defined spectral components $F(k)$ to generate a fractal trace $f(x)$. $f(x)$ is fractal if its Fourier power spectrum $|F(k)|^2$ is proportional to $k^{-\alpha}$, with $1 < \alpha < 3$ (Peitgen and Saupe 1988). The Fourier amplitudes of $F(k)$ are constructed via the product of $k^{-\alpha/2}$ with a set of Gaussian random numbers of normal variance and zero mean, while the phases are a uniformly distributed random set $[0, 2\pi]$. The fractal dimension of the trace $f(x)$ is then defined as $D = (5 - \alpha)/2$ (Peitgen and Saupe 1988). Re-use of the same set of random numbers for phase and amplitude preserves the underlying shape and appearance of the 'horizons', while α can be altered separately to tune D, allowing subjects to make visual comparisons based predominantly on D. Five sets of random numbers were used to create five sets of traces. Within each set, eleven horizon traces were generated with α values ranging between 1.0 and 3.0 in steps of 0.2 (note that $\alpha = 1$ and $\alpha = 3$ are, by definition, non-fractal). The $k = 0$ Fourier amplitude was set to zero in all cases in order to eliminate the constant background, causing the traces to appear more like an actual horizon. Each horizon trace was independently verified to be fractal by the variational box-counting method (Dubuc et al 1989). Four horizons, shown in figure 1, were chosen from one of the five sets of traces, with the verified D values of 1.14, 1.32, 1.51, and 1.70. To facilitate the viewing, but without introducing parameters overruling the effect of D, the horizons were made more realistic by filling the space under the horizons with uniform black.

The magnification range of the fractal stimuli is representative of many physical fractals, which typically are measured over 0.5–2 decades of magnification (Avnir et al 1998). Thus our 'limited-range' fractal stimuli, observed over 1.5 decades accurately reflect the fractal stimuli embedded in nature's scenery. Previous perception studies of fractals have shown that limited magnification ranges are sufficient for subjects to

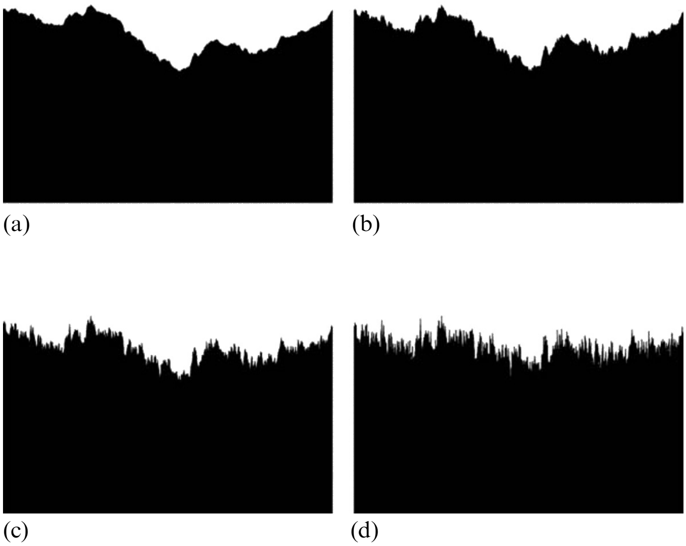

Figure 1. The silhouettes used in the study. Fractal dimension D (a) 1.14, (b) 1.32, (c) 1.51, and (d) 1.70.

distinguish between fractal stimuli with different D values and for D to determine the perceived qualities of the stimuli (Cutting and Garvin 1987; Knill et al 1990; Pentland 1984; Spehar et al 2003).

2.2 *Subjects*

Thirty-two right-handed subjects participated in the study. Subjects were interviewed concerning incidences of unconsciousness, neurological dysfunction, and medication; and tested for handedness, visual acuity, and colour deficiency. No conditions were found that would disqualify any subjects from participating. One participant had to be discarded from the analysis at a later stage owing to unreliable EEG recordings. Thus the reported results are based on thirty-one subjects, fifteen males and sixteen females in good health with age ranging from 18 to 64 years (mean = 35.2 years; median = 34 years; SD = 13.7 years).

2.3 *Procedure*

Subjects viewed the stimuli seated 70 cm from the 19 inch computer LCD screen with picture size 37 cm by 29.5 cm, ensuring that the smallest observable pattern scale (which was visually confirmed to be 2 mm) was on the order of 150 times smaller than the monitor width. The variational method confirmed fractal scaling over 1.5 orders of magnitude, with the maximum pattern scale corresponding to one-third of the monitor width. The monitor resolution was set to 1280 pixels × 1024 pixels.

The silhouettes were viewed for 1 min each and interspaced by a neutral grey picture for 30 s. A 1 min exposure period was chosen to ensure that a relaxation effect in the subjects could occur. Half of the subjects viewed the stimuli with increasing fractal dimension and the other half with decreasing fractal dimension.

During the viewing, qEEG was continuously monitored and recorded with a Nervus Digital EEG Recorder. Unipolar recordings used silver electrodes (10 mm) placed frontally (F3, F4), parietally (P3, P4), and temporally (T5, T6) on the left and right hemispheres and a centrally placed reference electrode (Cz). The positioning was based on the nasion, vertex, inion, and preauricular points and corresponded to the international 10–20 system. The recording system was electrically grounded by means of a clip attached to the subject's left ear lobe. The individual signal impedance was set at <10 kΩ. The recordings of the six EEG signals were checked for artefacts (mostly eye movements and unstable base lines), and the analyses carried out with frequencies grouped in four blocks: delta (2.25–3 Hz), theta (4.5–6 Hz), alpha (9–12 Hz), and beta (18–24 Hz). The check for anomalies and artefacts was made by a group of three researchers experienced in this procedure. First, a visual check was made of the recordings for any artefacts, with a low-cut filter at 0.5 Hz and a high-cut filter at 30 Hz. Second, the mean values for the four frequencies for the 1 min exposures of the silhouettes were checked for every subject to identify any aberrations. Finally, the information from the visual check and the check of the means was compared. This resulted in some parts of the recordings being omitted from further analysis. It can be noted that artefacts were found mostly in the delta and theta frequency ranges of the frontal part of the brain.

3 Results

The data were treated by parametric analysis with a one-way ANOVA with repeated-measures design and a two-way ANOVA with repeated measures and one grouping factor when controlling for order effects. Polynomial contrasts were used to test for trends. Owing to the number of comparisons, the significance level was set to $p = 0.02$ in order to correct for 'false discovery'. Based on the average of the whole minute each picture was viewed, significant effects of the fractal dimension were found in the frontal areas, F3 F4, for the alpha and delta waves. For the alpha waves (figure 2a), a quadratic trend was observed ($F_{1,29} = 6.38$, $p = 0.02$) with the highest alpha for the silhouette with the fractal dimension 1.32. For the delta waves (figure 2b), a cubic trend was observed ($F_{1,29} = 7.17$, $p = 0.01$) with contrarily the lowest delta for the fractal dimension 1.32. In the parietal areas P3 P4 a significant effect of the fractal dimension was found for the beta waves (figure 2c), both a quadratic trend ($F_{1,29} = 6.45$,

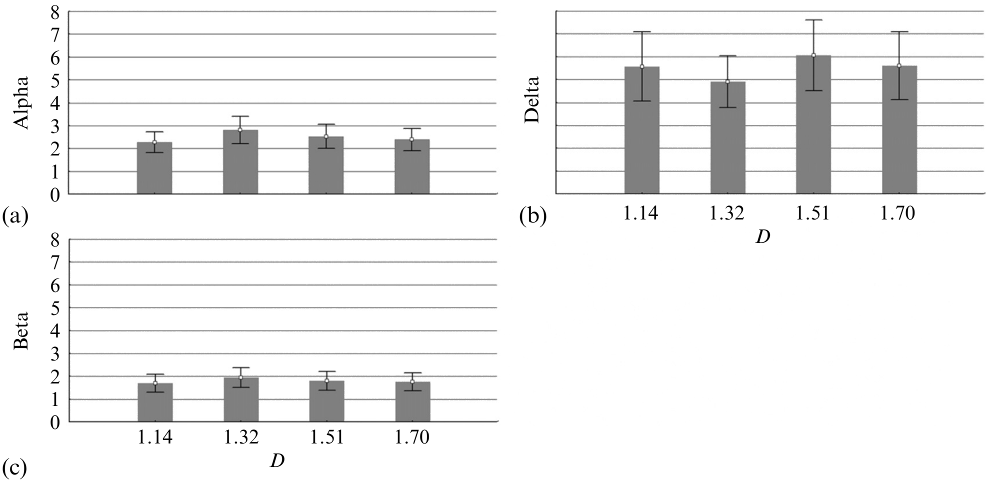

Figure 2. Significant effects of the fractal dimension D on EEG. Means and standard deviations in mV^2 (mean ± SD). Error bars represent 95% confidence intervals. (a) Alpha for frontal regions F3 F4 together for D 1.14 (2.28 ± 1.77), D 1.32 (2.80 ± 2.36), D 1.51 (2.53 ± 2.09), and D 1.70 (2.39 ± 1.88). (b) Delta for the frontal regions F3 F4 together for D 1.14 (5.57 ± 5.96), D 1.32 (4.91 ± 4.44), D 1.51 (6.06 ± 6.11), and D 1.70 (5.60 ± 5.86). (c) Beta for the parietal regions P3 P4 together for D 1.14 (1.69 ± 1.57), D 1.32 (1.95 ± 1.74), D 1.51 (1.80 ± 1.63), and D 1.70 (1.76 ± 1.54).

$p = 0.02$) and a cubic trend ($F_{1,29} = 5.62$, $p = 0.03$), with the highest beta for the fractal dimension 1.32. No other significant effects were found and there was no significant effect of stimuli presentation order.

4 Discussion

Fractal stimuli quantified by $D = 1.3$ appear to induce the largest changes in subjects' EEG response, supporting the proposal emerging from perception studies that these patterns are visually unique. These fractals generated the maximal alpha response in the frontal region, consistent with the hypothesis that they are most restorative and relaxing. At the same time, they generated the highest beta response in the parietal region, indicating that this pattern was conversely generating most activation in the processing of the pattern's spatial properties. This points to a very interesting interplay between these brain areas for mid-D fractals, which requires further investigation. In relation to the suggested existence of a frontoparietal attentional network, it is interesting to consider that mid-D fractals are parietally the most activating and thus possibly also most efficient in holding the attention. In a mixed visual environment, such patterns might thus be likely to win the competition for processing resources, and with a relaxed state as the resulting response. Concerning the significant difference in frontal delta for different D, we refrain from any advanced interpretation at this stage, since it is generally unclear how to interpret delta waves in awake people. We emphasise that, in this study, we chose relatively simple fractal silhouettes and to receive significant effects of D on psycho-physiological responses is very encouraging. We anticipate that fractals spread across a two-dimensional plane and fractals with a larger magnification range will trigger enhanced responses. Future research is motivated by the prospect of customising visual landscapes and wall art to aid human functioning and stress reduction in mentally demanding environments. More generally, fractals could play a growing role in incorporating favourable visual properties in the design of our everyday environments to foster general well-being.

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