Fractal Dimension Links Responses to a Visual Scene to Its Biodiversity

Paul Stevens

Centre for Psychological Research, University of Derby, Derby, UK.

Abstract

Humans appear to have an innate, beneficial response and preference for natural over urban scenes, yet "natural" is an ambiguous concept that varies from culture to culture. In looking for a commonality to natural scenes that tends to be lacking in built scenes, many researchers have turned to fractal geometry, finding that fractal dimension can predict preference. Here, I calculated the fractal dimension of the dominant land-sky edge at a variety of sites having varying depths of water table and levels of biodiversity (specifically, "species richness"). I then investigated changes in human physiological arousal (magnitude of skin conductance responses) in response to images of those scenes. Sites with high biodiversity were shown to have a significantly higher associated fractal dimension than low-biodiversity sites, whereas shallow versus deep water-table sites showed no significant difference. When shown the images, the magnitude of skin conductance responses for human viewers showed a negative correlation with fractal dimension. Replicating earlier findings, ranked preference for a scene showed a positive correlation with fractal dimension. Taken together, these findings suggest an evolved response to stimuli associated with a healthy ecosystem: Patterns of healthy vegetative growth determine visual fractal dimension, which reduces physiological arousal upon observation, this being experienced as a positive emotional state and expressed as a preference for that environment. Key Words: Fractal—Natural environment—Biodiversity—Restorative environment—Skin conductance response.

1. Introduction

Research concerned with wider issues of how humans and the natural environment interact has demonstrated some interesting properties of human visual perception. It has long been known that people, irrespective of culture or education, tend to express a preference for natural scenes over urban or built ones (Ulrich et al., 1991). It was later discovered that such preference appears to relate to some fundamental psychophysiological responses—arousal levels decrease, attentional capacity increases, and emotional processing occurs faster (Parsons & Hartig, 2000; Ulrich, 1983)—suggesting that we might be preferentially responding to specific features related to the natural environments within which human sensory systems evolved (Balling & Falk, 1982). However, the concept of "natural" is still relatively ambiguous, covering a huge range of scenes from lush jungle vegetation to open savanna to barren, rocky mountains. To understand the empirical findings for human preference, there needs to be some commonality to natural scenes that tends to be lacking from artificial scenes. Many researchers have turned to fractal geometry for inspiration, with some promising results.

1.1. Fractal geometry

Since Mandelbrot (1983) published his mathematical description of the complex forms found in nature, research has shown that a wide range of natural forms exhibit repeating patterns when viewed at increasingly high magnifications; that is, they have a fractal geometry. This self-similarity of pattern at differing scales can be quantified by a parameter called the fractal dimension (*D*), essentially a non-integral quantity that relates to the number of self-similar pieces that an object can be "broken into" at different scales (e.g., see Glass & Mackey, 1988, p. 53). So a simple line can be broken into as many self-similar pieces as you want at any magnification; for example, you can break it in half (a magnification of 2) to get 2 pieces, into 3 pieces at a magnification of 3, or N^1 pieces at a magnification of *N*. A square, however, can be broken into 4 self-similar pieces where each piece has sides that are half as long as the original, or 9 self-similar pieces with sides 1/3 as long as the original; that is, you get 4 pieces at a magnification of 2, 9 pieces at a magnification of 3, or N^2 pieces at a magnification of *N*. This pattern thus gives us a simple power-law-based definition of fractal dimension, $D =$ log (number of self-similar pieces)/log(magnification factor). In application to two-dimensional images (which usually do not have obvious self-similarity), a commonly used technique for estimating D for an image is the box-counting technique (Abarbanel, 1996). Essentially, this makes use of a computer algorithm which determines the number of "boxes" of linear size L needed to cover all the black points in a black-and-white image, for diminishing values of L. Plotting $N(L)$ against L will then have a line of best fit that has a gradient of $-D$.

Hagerhall, Purcell, and Taylor (2004) used this technique to explore whether fractal dimension may play a role in human preference for visual landscapes, based on previous cross-cultural findings (e.g., Ulrich, 1983) that natural scenes (i.e., the ones more likely to have a fractal geometry) tend to be preferred to urban ones. For their analysis, they focused on the fractal dimension of the silhouette outline between the landscape and the sky, this representing the most striking feature upon which people fixate according to eye movement studies (e.g., Rayner & Pollatsek, 1992). To obtain this outline, the background area (i.e., the sky) for each image was selected using the automatic "area select" tool used by many graphical editing software. A "find edges" tool was then used to isolate the edges of the selected area, resulting in a single line tracing the contour between foreground objects and the background (see Fig. 1). This line was then used to calculate D via the box-counting method, thus giving a measure of visual complexity for each image.

For a sample of 52 images of natural landscapes with no visible water or dominant hills (the visual presence of either is a factor that appears to skew scene preference studies; e.g., see Purcell et al. 1994), Hagerhall et al. (2004) found a significant positive correlation between the mean preference for an image and the fractal dimension of the extracted silhouette outline. A further study by Cheung and Wells (2004) also replicated the effect using just 12 images—six urban and six natural scenes—finding a significant correlation between mean preference rating and both mean and maximum fractal dimension. Both of these studies confirmed an earlier exploratory study by Rogowitz and Voss (1990), which suggested that preference was based on the D value of the edge of dominant shapes in a scene. This ties in well with other research showing that, based on both empirical work and models of cortical neurons involved in subtle shape discrimination, human vision is optimized to power-law relationships of the optical environment (Párraga, Troscianko, & Tolhurst, 2000).

So why should this be? The key lies in some recent studies which found that the fractal dimension of landscape features also correlates to an interesting, nonvisual property of those landscapes: They are "healthier" in terms of biodiversity (a measure of the variety of life, plant and animal, within a given area). For example, Krummel, Gardner, Sugihara, O'Neill, and Coleman (1987) showed that the fractal dimension was significantly higher for outlines of untouched versus human-affected forest, probably relating to differences in the scale of human versus natural processes. Olff and Ritchie (2002) point out that "habitat, food and resources for organisms often are found to be statistically self-similar across ecologically relevant ranges of scales" and showed that fractal dimension could distinguish between habitat loss and habitat fragmentation (the former having a lower fractal dimension and more negative effect on biodiversity than the latter). Brown et al. (2002) theorize that this is because "scaling relationships that are self-similar or fractal-like over a wide range of spatial or temporal scales" (p. 619) represent a class of emergent ecological phenomena. These relationships demonstrate underlying power laws that appear to be universal with respect to the type of organism or type of environment, offering "clues to underlying mechanisms that powerfully constrain biodiversity" (p. 619), and could help us understand "the diversity of species and complexity of ecosystems in terms of fundamental principles of physical and biological science" (p. 619).

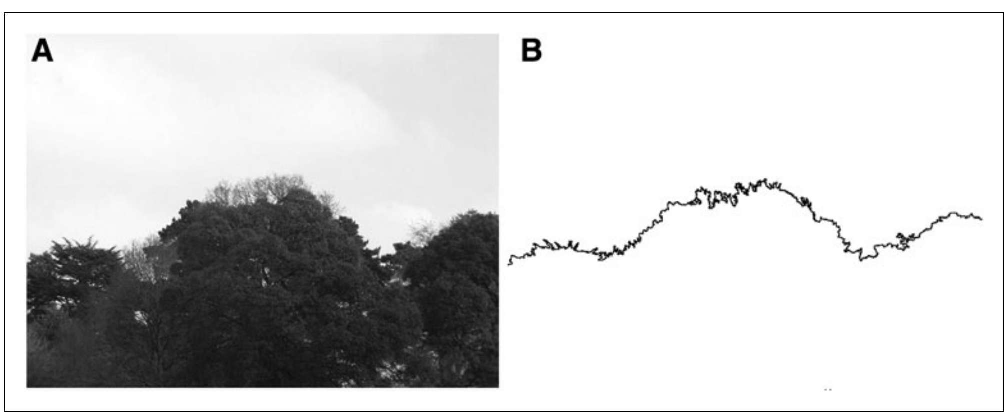

Fig. 1. Example of an extracted land-sky silhouette for fractal dimension calculation.

The present study thus had three hypotheses:

(1) The fractal dimension, D, of the dominant edge in the land-

sky silhouette would be higher in images of areas having high biodiversity.

(2) The D of the dominant edge in the land-sky silhouette would be higher in images of areas having a shallow depth (≤ 25 m) of water table.

(3) The magnitude of skin conductance response to viewing an image would be inversely correlated to the D of that image.

Hypothesis 1 aimed to establish a primary relationship that one visual aspect of healthy vegetation (as indicated by D of the land-sky silhouette) would relate to biodiversity in the area. Hypothesis 2 would explore whether this biodiversity–D relationship might be due to the amount of accessible water available to vegetation in the area. Hypothesis 3 explored whether any change in human physiological arousal, as measured by skin conductance, in response to viewing an image was also related to the fractal dimension of that image's land-sky silhouette. Hypotheses 1 and 2 were explored in Experiment 1, and Hypothesis 3 in Experiment 2 (which used a selection of images from Experiment 1).

2. Experiment 1: Fractal Dimension of Water-Depth and Biodiversity Images

2.1. Methods

All images used in the experiment were photographed to be representative of the wider location, ensuring there were clear tree lines away from roads or other sources of potential pollutants. Any obviously human-intended plantings (e.g., around entrances, visitor centers, or plantation areas) were avoided. None of the images in either category contained human-made structures (to avoid the possible negative connotations of an urban environment), visible bodies of water, or dominant hills, to avoid known preference biases (cf. Hagerhall et al., 2004). Purely urban images were also excluded, as there would be no direct link between biodiversity measures and the landscape: The fractal dimension of artificial structures would be due to the aesthetic architectural choices made rather than there being any causal link. For example, an urban scene with Gothic architecture would have higher fractal dimension than one with modernist buildings (e.g., Joye, 2007), yet this would be unrelated to biodiversity. All photos were digitally photographed, from a similar distance at the same resolution (10 MP), and within a few weeks of each other under similar weather conditions. Such precautions were taken to ensure a robust comparison, even though previous research has indicated that D values are neither sensitive to changes in scale nor dependent on the precise technique by which the land-sky silhouette is extracted (Keller, Crownover, & Chen, 1987).

2.1.1. Images of shallow/deep water-table sites. Based on the British Geological Survey hydrogeological map of Dorset (where the author was based at the time), 10 sites were identified in areas showing a range of depth of underground aquifers. Based on Jackson, Moore, Hoffmann, Pockman, and Linder's (1999) empirical determination of a maximum tree root depth of 25 m, five specific locations were determined to have "shallow" depth water table (≤ 25 m, i.e., water table is accessible to tree roots) and five to have "deep" depth water table (≥ 50 m, i.e., water table is inaccessible to tree roots). Two images were then taken to be representative of each site, giving 20 images in all: 10 shallow, 10 deep (see Table 1).

2.1.2. Images of high-/low-biodiversity sites. Species richness (the number of different species identified in a specified area) was chosen as the specific indicator of biodiversity, as there is general consensus that this is a reasonable, simple measure of an area's biodiversity (Gotelli & Colwell, 2001; Natural History Museum, 2009). Species richness were obtained from the website of the United Kingdom's National Biodiversity Network (NBN) (http://data.nbn.org.uk), which provides publicly available species lists recorded within or overlapping a specific site at 10 km resolution. Five sites were chosen based on their inclusion in the NBN site and physical accessibility

Table 1. List of Water-Table Category Sites with Depth (m) to Water Table

SITE	DEPTH TO WATER TABLE (m)	WATER-TABLE CATEGORY
Nine Stones, Winterbourne Abbas	0	Shallow
Balmers Coombe Bottom, Bulbarrow	0	
Cerne Park, Cerne Abbas	20	
Delcombe wood, Bulbarrow	20	
Horse Clump, Winterbourne Abbas	23	
Big Wood, Winterbourne Steepleton	50	Deep
Jubilee Trail, Dry Wood, Winterbourne Steepleton	55	
Twitchings Copse, Bulbarrow	65	
Woolland hill, Bulbarrow	70	
Park Dale, Cerne Abbas	110	

Table 2. List of Biodiversity Category Sites Showing Species Richness for Each Area

SITE (NUMBER OF PHOTOS)	SPECIES RICHNESS	BIODIVERSITY CATEGORY
Canford Heath (5)	3,646	Low
Sopley Common (8)	4,159	
Avon Heath (7)	4,733	
Studland Nature Reserve (8)	8,340	High
New Forest National Park (12)	21,683	

(i.e., the sites could be visited to take photographs), and to cover a range of biodiversity (from 3,646 to 21,683 species). These sites were different from the ones used for the water-table images. A total of 40 images were obtained across this range—see Table 2 for a list. For the purpose of the preplanned analysis, sites with species richness at or below the median value were categorized as low biodiversity; sites above the median value were categorized as high biodiversity.

2.1.3. Fractal dimension analysis. For each image, the technique of Hagerhall et al. (2004) described earlier was used to isolate the silhouette of the dominant edge (landscape-sky silhouette). This was done using the open source software ImageJ (available from http://rsbweb.nih.gov/ij), which was also used to calculate the fractal dimension of that edge. For each image, the JPG was converted to binary and the "find edges" tool used on the sky region. The "fractal box count" tool was then used with box sizes set to (2, 3, 4, 6, 8, 12, 16, 32, 64) to calculate the fractal dimension.

2.2. Results

An initial review of the water-table category images indicated that there were two possible outliers. This was confirmed by calculating the two standard deviation range (mean fractal dimension, $D = 1.293$, $SD = 0.043$, thus the $2SD$ range is from 1.207 to 1.379) and removing two data points outwith this range (Cerne Park site: $D = 1.207$ and 1.204). For the reduced data set, a Wilcoxon test comparing the fractal dimension for shallow versus deep sites gave a result close to significance: $W = 23$, $N = 18$, $P = 0.07$ (see Fig. 2). For the biodiversity category images, a Wilcoxon test comparing fractal dimension for high- versus low-biodiversity sites gave a significant result: $W = 25$, $N = 40$, $P < 0.001$ (see Fig. 2). A post hoc analysis of image D-value versus ranking by species diversity gave a Spearman's rho = 0.64.

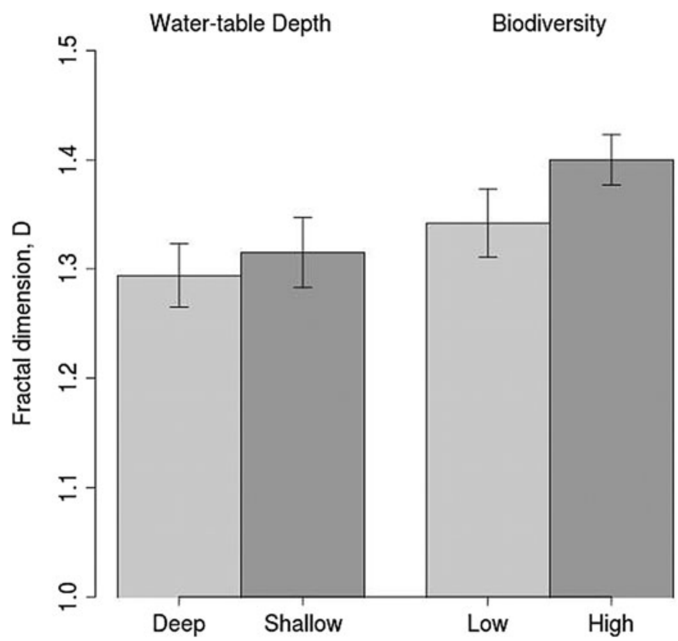

Fig. 2. Comparison of fractal dimension of image silhouette for deep versus shallow water-table and low versus high biodiversity. Error bars indicate one standard deviation.

3. Experiment 2: Physiological Reactions to and Preference for the Images

3.1. Methods

3.1.1. Participants. A total of 50 (34 females, 16 males) unselected participants—primarily university students ($M = 19$ years, ranging from 18–31 years)—participated in this study. The study was advertised on campus and via e-mail to a potential participant pool maintained by the psychology department. Students volunteered in return for course credit, and all participants were paid a small expense fee. All gave informed consent before participating, and the study had ethical approval from the psychology research ethics committee.

3.1.2. Stimuli. Five photographic images were selected from each of the two categories *water table* and *biodiversity* from Experiment 1 to cover a representative range of fractal dimension found in the whole image set ($D = 1.22$ to 1.40). The biodiversity set is shown in Fig. 3 as an example.

3.1.3. Skin conductance recording. Skin conductance (SC) was recorded for each participant via two electrodes attached to the second

Fig. 3. Images from the biodiversity set, showing increasing fractal dimension (*D*) from top to bottom.

phalanx of the index and second fingers of their nondominant hand. Electrodes were sintered Ag-AgCl round cup electrodes with an 8 mm diameter, affixed with adhesive collars and using pH-balanced aqueous gel. These were connected via preamplifier to a model SC5-SA recorder with 24-bit A/D conversion (PsyLab/Contact Precision Instruments, London, UK) and interfaced via serial port to a PC running the Windows operating system with custom-written software in Visual Basic 6.0.

Data analysis was conducted offline on a PC running Linux (Ubuntu 11.04). The raw SC data consisted of two components: the longer-term tonic response and the fast, stimulus-related phasic responses. The tonic component from each participant's data was first removed by filtering the data with a high-pass filter of 0.016 Hz (equivalent to a time constant of 10 s), using the GPL program QtiPlot (http://soft.proindependent.com/qtiplot.html). Subsequent analysis was performed using the GPL program R (http://www.r-project.org). A *z*-transform (i.e., mean-centered and expressed in units of each participant's standard deviation) was used on the SC phasic data to allow between-participant comparison and to give a more robust measure for subsequent statistical analysis (Sersen, Clausen, & Lidsky, 1978). The 200 sample (5 s) period after each stimulus was then isolated to give that participant's series of phasic skin conductance responses (SCRs), one per stimulus image.

3.1.4. Procedure. On arrival, participants were told they were taking part in a study into scene preference that combined conscious (stated preference) and unconscious (skin conductance) measures. They were seated in front of a 17" touch-sensitive TFT computer monitor and had the procedure explained to them. The SC electrodes were attached and, after listening to a 5 min piece of relaxing music (a standard procedure to ensure all participants start from close to their baseline arousal state), they viewed each set of five images in turn. Set and image order were randomized and counterbalanced for each participant, with each image being shown on the monitor for 10 s with a 10 s rest period between each one. SC data were sequentially sampled and saved to hard disk at 40 Hz throughout the session. After they had seen all five images in a set, they were asked, via touch-screen response, to rank those images in order of personal preference, "from MOST to LEAST favourite." The second set was then shown, and again, preferences recorded. Finally, they were debriefed and paid £3 expenses for their participation.

3.2. Results

Skin conductance responses were screened to remove null responses, movement, and noise artifacts, resulting in 280 usable response profiles across the participants, for all 10 images. As the *z*-transformed SCR magnitude data approximated a normal distribution, a Pearson correlation was used ($r_P = -0.11$, $N = 280$, $P = 0.03$), showing a small but significant negative relationship between normalized SCR magnitude and fractal dimension of the associated

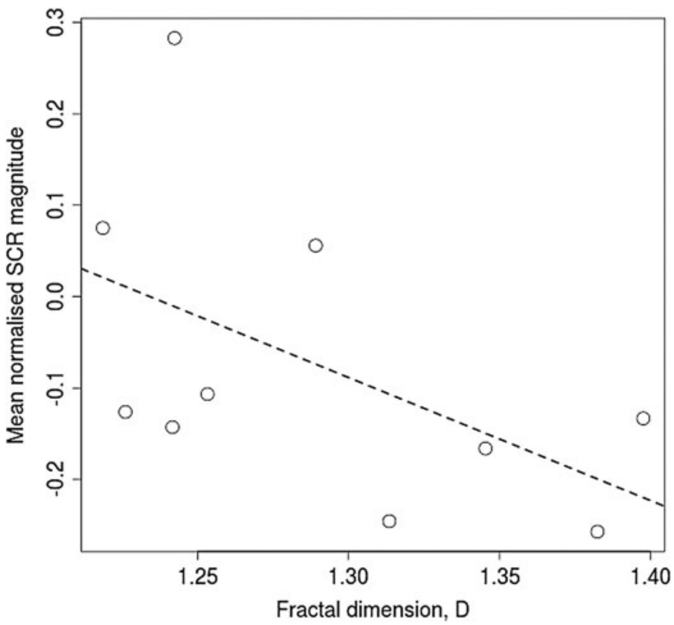

Fig. 4. Plot of mean normalized SCR magnitude versus fractal dimension, *D*.

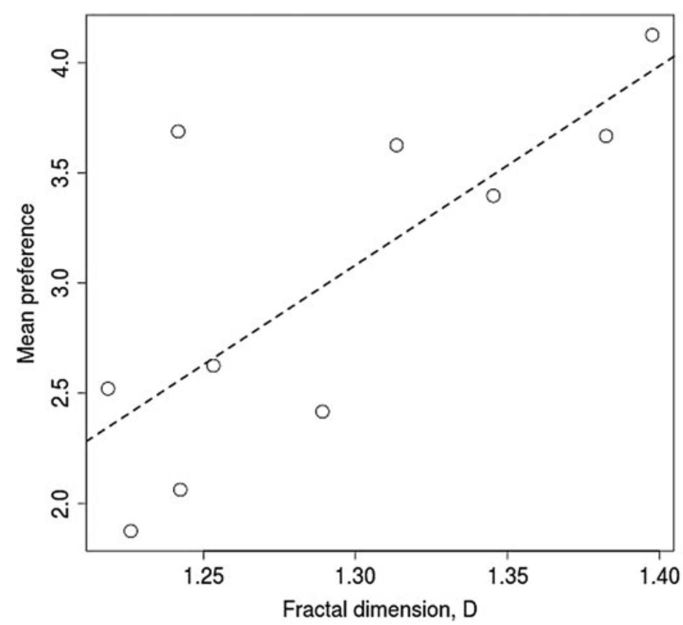

Fig. 5. Plot of mean expressed preference versus fractal dimension, *D*.

image (see Fig. 4). Image preference ratings were also correlated with *D* using a Spearman's rank correlation ($r_S = 0.37$, $N = 480$, $P < 0.001$), showing that preference was positively related to fractal dimension (see Fig. 5).

4. Discussion

This study explored the idea that fractal dimension might represent a stimulus which maps onto the basic human need to live in a healthy environment, and to better understand relationships between the fractal dimension of visual scenes, human physiological responses to such scenes, and self-reported preference for specific visual environments.

In Experiment 1, fractal dimension varied significantly between high- and low-biodiversity sites ($P < 0.001$) but not in relation to shallow versus deep water-table sites ($P = 0.07$). This suggested that the types and growth patterns of vegetation primarily reflect the ecological health of the wider area. For this experiment, the measure of biodiversity used was "species richness": the number of species—plant, animal and fungus—observed in a 10 km^2 region. The results thus suggested that a single measure of the fractal dimension of the skyline of an image taken within this region could be used as an indication of the ecological health of the region as a whole. This in itself could, if more widely replicated, provide a useful estimate of an area's biodiversity that did not rely on costly surveys.

Experiment 2 showed significant negative relationship between the magnitude of a person's physiological response and the fractal dimension of the dominant edge in a visual image, suggesting that the level of physiological arousal we experience in response to seeing that image (or scene, if we were physically present) relates to the visual complexity of that image or scene. However, as can be seen in Fig. 3, there are no obvious visual cues which would lead the perceiver to determine that complexity. This relationship was in the direction predicted by existing research in the field of restorative environments (e.g., Ulrich et al., 1991) which typically shows reduced arousal for more "natural" images (which would be expected to have higher fractal dimension) when compared to more "urban" images (which would be expected to show more linear geometry and so have lower fractal dimension). As well as directly affecting well-being via a more relaxed somatic state, lowered arousal, in the absence of any specific external affective cues, tends to be interpreted as a positive emotional state (e.g., Stevens, 2007) which in itself is associated with enhanced well-being (e.g., Lyubomirsky, King, & Diener, 2005). That the lowered arousal did result in positive affective associations was supported in this experiment by the finding that preference for an image was also positively related to fractal dimension (and thus showed a negative relationship with arousal), replicating earlier research (Cheung & Wells, 2004; Hagerhall et al., 2004; Rogowitz & Voss, 1990).

Combining the results suggests the presence of an evolved response in humans to stimuli associated with a healthy ecosystem. The ecological health of an area is expressed via patterns of vegetative growth that are exhibited as increased fractal dimension. When humans—and, given the similarity of cortical structure, other mammals—observe that scene, reduced physiological arousal occurs in response to visual complexity, and this is experienced as a positive emotional state and expressed as a preference. Simply put, it shows that the environments which we *innately* prefer are those which can help restore our well-being if they themselves are part of a healthy, functioning ecosystem.

More generally, these findings suggest a way to encourage people to realize that they are not separate from the pressing environmental issues of the day, allowing us to see "the needs of the planet and the person as a continuum" (Roszak, 1992, p. 14) by showing that the properties which allow humans to be physically and mentally healthy are the same ones which are associated with a healthy ecosystem on local and global scales. Human emotional responses to specific environments do not necessarily need to be validated purely by ideological arguments but instead can be seen as involving innate responses to places and situations that represent a meaningful, evolved means of communication between us and our environment. This could allow a reintegration of direct (emotional, reflective) experience in proenvironmental strategies rather than putting all the emphasis on "objective" arguments and perception-of-risk calculations—an idea also seen in some other psychology studies which have shown that early childhood experience of natural settings and outdoor recreation that relies on specific natural features (e.g., white water rafting) are the strongest predictors of subsequent proenvironmental behavior (e.g., Kals, Schumacher, & Montada, 1999). Rather than changing people's motivation by bombarding them with information and so-called rational arguments, evolutionary arguments also have a place by showing there are inherent motivations, intentions, and behaviors that can play a role.

However, the results of this and similar studies could be read as encouraging reductionism. That is, we do not actually need natural environments to be healthy; we just need to ensure that our built environment has a high fractal dimension[1] in terms of visual cues. Such an approach doubtlessly has a place in "customising visual landscapes and wall art to aid human functioning and stress reduction in mentally demanding environments" and "incorporating favourable visual properties in the design of our everyday environments to foster general well-being" (Hagerhall et al., 2008, p. 1492), yet to do this as our only or primary response to problematic environments would be to impoverish human experience. The intention of this study was to shed light on the pre-existing literature spanning many disciplines which shows that humans are embedded in, and so profoundly affected by, their environment (Stevens, 2010), the "natural" environments being associated with many more benefits/fewer stressors than "urban" ones. This is unsurprising, given that "natural" features are the ones we, along with all other animals, are evolutionarily adapted to, but it is hoped that the results of this study demonstrate that fractal dimension offers one way of better understanding what we mean by "natural" that goes beyond the usual socially constructed and human-centric approaches.

[1]Up to a point. Other research (Spehar, Clifford, Newell, & Taylor, 2003) has suggested that there might be a maximum plateau (approximately $D = 1.3$ to $D = 1.5$) after which the perceived appeal of fractal visual scenes decreases again.

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Address correspondence to:
Paul Stevens
Psychology
University of Derby
Kedleston Road
Derby, DE22 1GB
UK

E-mail: P.Stevens@derby.ac.uk

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