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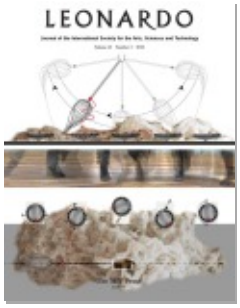

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Reduction of Physiological Stress Using Fractal Art and Architecture

R.P. Taylor

ABSTRACT

The author reviews visual perception studies showing that fractal patterns possess an aesthetic quality based on their visual complexity. Specifically, people display an aesthetic preference for patterns with mid-range fractal dimensions, irrespective of the method used to generate them. The author builds upon these studies by presenting preliminary research indicating that mid-range fractals also affect the observer's physiological condition. The potential for incorporating these fractals into art and architecture as a novel approach to reducing stress is also discussed.

In art school I was told that Monet's water lilies calm the observer, while van Gogh's sunflowers electrify. To what extent, however, do paintings really affect the observer's physical condition? The foundations of this question date back to 1890, when the connection between psychological states and physiological states was first considered [1]. However, the health trends of modern society cause this question to take on new urgency.

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Stress is woven deep into our daily experiences. One in four people in the U.S.A. suffers from stress, and the associated annual cost to society is estimated to be $300 billion [2]. Consequently, researchers are searching for effective ways to reduce stress. One hope lies in adapting the interior and exterior of buildings to create environments that are more "in tune" with physiological responses to visual stimuli. Such projects offer the potential for interdisciplinary collaborations among scientists, artists and architects.

There are several characteristics of artworks that might be engineered to induce a desirable physiological response. These include subject matter, color and compositional form. I will focus on the latter characteristic. Furthermore, given the prevalence of natural landscapes in art and the popularity of windows that offer views of nature's scenery, a useful starting point lies in the investigation of art composed from nature's patterns.

For this reason, I will focus on fractal patterns. A diverse range of natural objects are fractal, including mountains, clouds, rivers and trees [3,4]. Furthermore, computers have led to the popularity of mathematically generated fractals. Fractals have also assumed a rapidly expanding role as an art form. This has been emphasized by my own discovery of fractal patterns in the works of Jackson Pollock [5,6].

Owing to fractals' growing impact on cultures around the world and their prevalence in nature, they constitute a central feature of our daily visual experiences. How, then, do we respond to their visual characteristics? In this article, I address this issue by analyzing the results of an experiment performed by the National Aeronautics and Space Administration (NASA), in which skin conductance measurements were used to measure people's physiological responses to natural images [7,8]. My fractal analysis of these images provides a preliminary demonstration that certain forms of fractal patterns might be used to reduce physiological stress.

Over the past 30 years, the visual appeal of fractals has been celebrated frequently [9–12], culminating in the dramatic identification of them as "the new aesthetic" [13]. The dis-

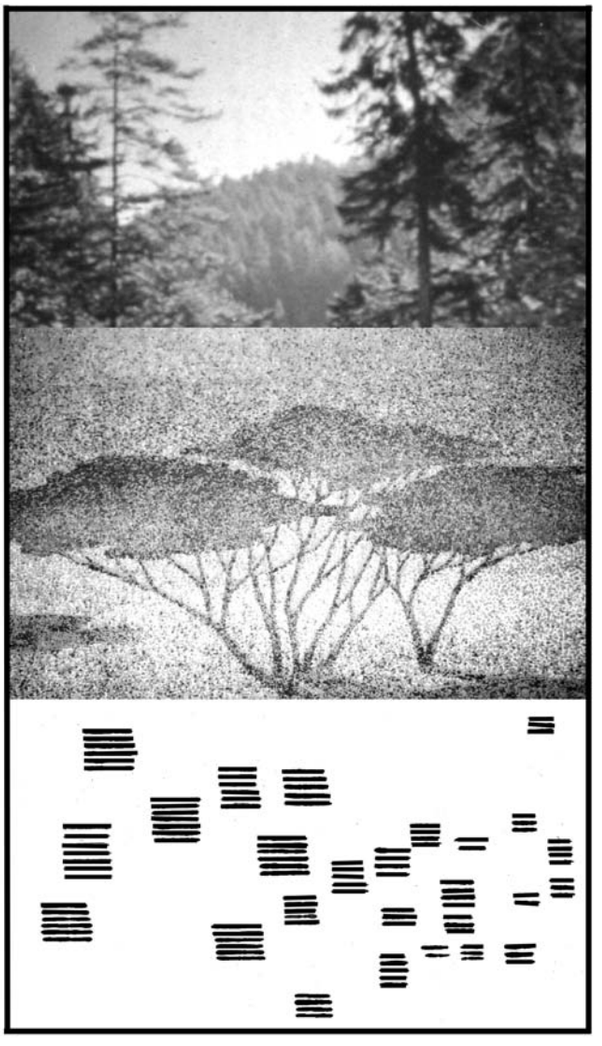

Fig. 1. A photograph of a forest (top); an artistic rendition of a landscape (middle); and painted lines (bottom). (© Richard Taylor)

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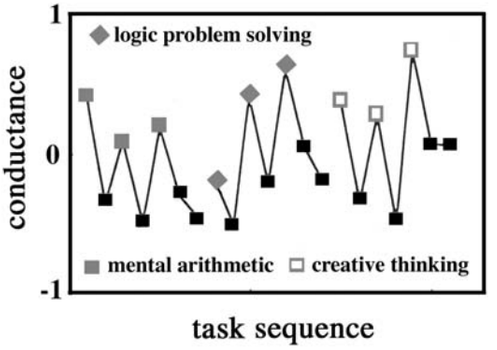


Fig. 2. The conductance change during the task sequence (black squares indicate rest periods) for participants who were continuously exposed to the control image. (© Richard Taylor) The procedure for generating this plot was as follows: First, to establish a common conductance scale for these participants, each participant's conductance was transformed to Z-scores. Then, for each task in the sequence, these Z scores were averaged across participants. This mean Z conductance was then plotted for the whole sequence of tasks [75].

covery that this aesthetic quality might be accompanied by a positive response in the observer's physiology lends considerable support to previous proposals for fractal art and fractal architecture [14–18]. I therefore consider the artistic and architectural challenges of incorporating fractal imagery into buildings to affect people's perceptual and physiological responses.

Stress Measurement

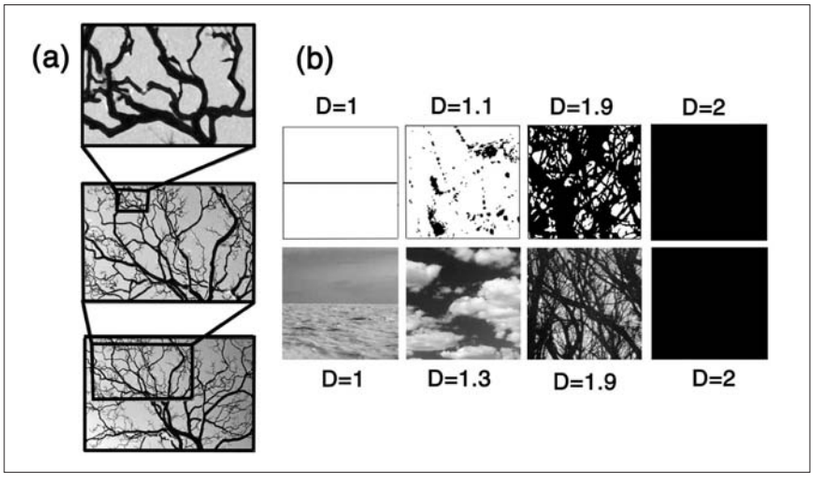
Measurement of an observer's skin conductance might appear to be an unusual tool for judging people's responses to art. However, electro-dermal measurements are a well-established method for quantifying changes in an observer's physiology [19]. In a 1986 NASA study, James Wise used skin-conductance measurements to investigate the physiological effects of observing art [20]. The three artworks used, each measuring 1 × 2 m, are shown in Fig. 1: a photograph of a forest (top), an artistic reproduction of a savannah landscape (middle) and an abstract pattern (bottom). An additional white panel served as a control.

Participants were seated one at a time in a room facing 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). Task periods were separated by 1-minute recovery periods, thus creating a sequence of alternating high- and low-stress periods. To measure the participants' physiological responses to the stress induced by mental work, skin conductance was monitored continuously during this sequence.

Consistent with previous skin-conductance studies [21], conductance peaked during periods of induced stress and decreased during the low-stress periods. For example, Fig. 2 shows the rise and fall measured over the work-rest sequence for participants continuously exposed to the control image. The procedure for the generation of this plot is presented in detail elsewhere [22]. Significantly, an analysis of the 24 participants' responses revealed that the change in conductance ΔG between work and rest periods depended on which image was observed. For the "artificial" pattern (Fig. 1, bottom image), ΔG was 13% *greater* than for the control image, indicating that the artificial pattern increased the physiological response to stress. In contrast, the ΔG values for the "natural" images were 3% (top image) and 44% (middle image) *lower* than for the control [23]: These images *dampened* the physiological response to stressful work.

These intriguing results indicate the potential for the use of art to influence people's physiological condition, in particular stress. The fact that the two artworks featuring "natural" images (the top and middle images) delivered a positive impact on the observers' physiology is consistent with earlier research in environmental psychology that explored the physiological health benefits of using window views of natural environments [24]. The results also support findings in landscape architecture research demonstrating people's preference for natural landscapes [25]. However, based on these earlier investigations, the top rather than the middle image is expected to be most effective, because it is an accurate photograph rather than an artistic rendition of a natural scene. What visual characteristic of this rendition triggered such a dramatic impact on the participants? To answer this crucial question, it is necessary to explore the aesthetic qualities of natural scenery in greater depth.

Fig. 3. (a) Fractal tree patterns repeating at different magnifications. (b) Patterns and their D values. (© Richard Taylor)
Top row, left to right: a smooth line (D = 1), two fractal poured paintings (D = 1.1 and 1.9) and a filled area (D = 2). Bottom row, left to right: the horizon line (D = 1), clouds (D = 1.3), a forest (D = 1.9) and a filled area (D = 2).



Fractal Aesthetics

At the time of the experiment, the traditional studies of perceptual and environmental psychology assessed the aesthetics of nature using vague qualities such as the degree of "naturalness" of the scene [26] or the dominance of selected topological features such as water or hills [27]. No unified theory existed to describe the visual information that determines aesthetic responses to natural scenery. Instead, theories were limited to discussions concerning optimal amounts of balance between order and disorder [28] and simplicity and complexity [29]. Other studies overlooked the subtle complexity

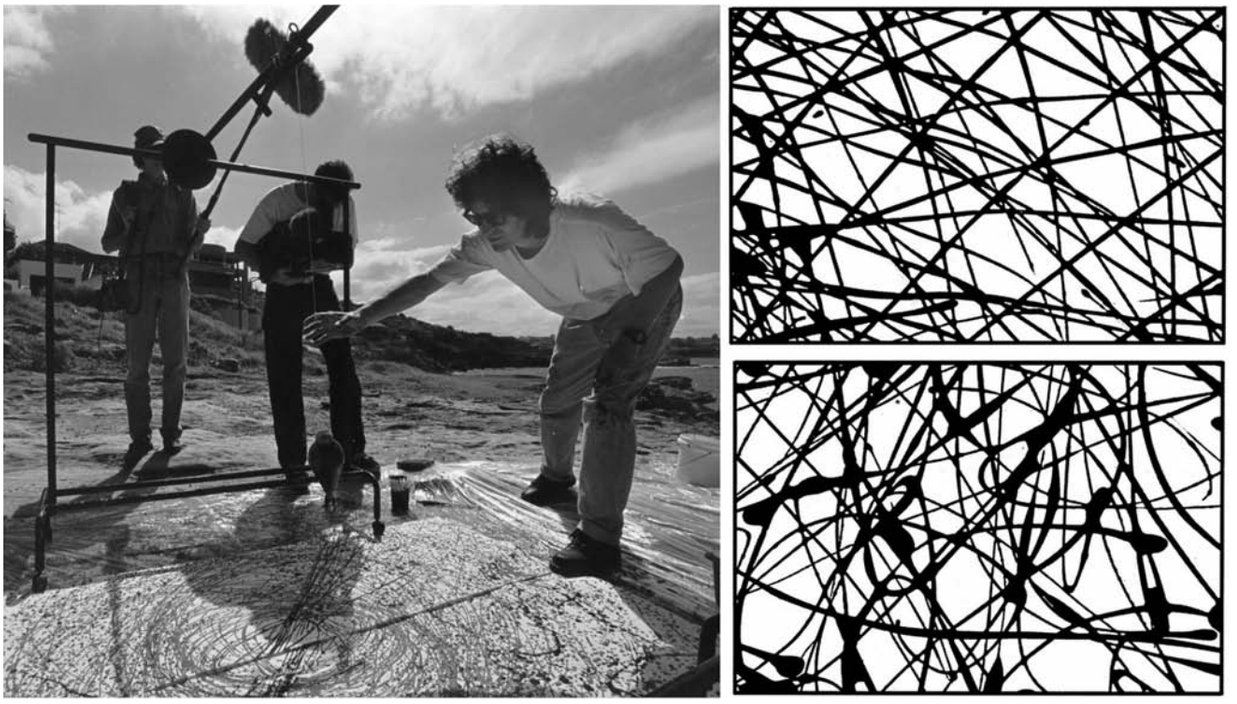


Fig. 4. The chaotic pendulum (left) employed to generate non-fractal (top right) and fractal (bottom right) poured paintings. (© Richard Taylor)

of nature's patterns and focused on simplified representations based on Euclidean shapes [30].

An important step in the understanding of nature's visual characteristics occurred when Benoit Mandelbrot emphasized that the complexities and apparent irregularities of nature's organic patterns could not be modeled using Euclidean geometry [31]. Instead, many natural objects belong to fractal geometry, consisting of patterns that recur at increasingly fine magnifications (see, for example, the fractal tree in Fig. 3a). Fractal patterns' visual characteristics necessitate the use of descriptive approaches that are radically different from those of Euclidean geometry. The fractal dimension D is a central parameter and quantifies the fractal scaling relationship between the patterns observed at different magnifications [32]. For Euclidean shapes, dimension is a familiar concept described by integer values—a smooth line has a D value of 1, whereas a completely filled area has a value of 2. For the repeating patterns of a fractal line, D lies between 1 and 2. Figure 3b demonstrates how a fractal's D value has a profound effect on its appearance.

Although the term "fractal" was introduced in the 1970s, it was not until the 1990s (long after Wise's experiment) that visual perception experiments focused on fractal aesthetics [33]. In one of the first such experiments, performed in 1994, I used a chaotic pendulum [34] to generate fractal and non-fractal patterns. In perception experiments based on these images, 95% of participants preferred the fractal to the non-fractal patterns [35]. Figure 4 shows two of the patterns used. Given the impact of D on the appearance of fractals, do observers base aesthetic preference on D? Pioneering studies by Clint Sprott and Deborah Aks conducted from 1993 to 1996 used computer-generated fractal images and revealed a preferred D value of 1.3 [36].

In 1999, my discovery that Pollock's paintings are fractal [37] reinvigorated interest in fractal aesthetics. My analysis revealed that the D values of Pollock's paintings evolved during the period 1943–1952 in the direction of aesthetic reliance on D [38]. Collaborating with Branka Spehar, Ben Newell and Colin Clifford, I performed aesthetic-preference experiments incorporating three categories of fractals: photographs of natural objects, computer-generated images and Pollock paintings. Our results showed that the preference for mid-range D values revealed by Sprott's computer-generated fractals was "universal" in the sense that this preference extended to fractal imagery found in nature and art [39]. For a wide variety of fractals, visual appeal peaks for the mid-range D values of 1.3 to 1.5. Figure 3 shows examples of fractals that lie within and outside this range. 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 this D preference [40].

Significantly, prevalent patterns in nature have D values in this range (for example, clouds and coastlines), raising the possibility that the eye is aesthetically "tuned" to the fractals surrounding us in nature. In light of this speculation, we extended our studies to consider aesthetic preferences for natural scenes [41]. Our previous experiments had focused on simple natural images featuring just one form of fractal (for example, the clouds or trees shown in Fig. 3). In contrast, typical natural scenes are composed of a range of fractal objects. Although the characteristics of typical scenes are therefore quite complex, their fractal statistics are well charted [42]. How, then, does the preference for mid-range D values of simple fractal objects [43] extend to these visually intricate fractal scenes?

Owing to a typical scene's complexity, it is necessary to select a dominant characteristic of the scene and examine its impact in detail. Research indicates that edge contours play a dominant role in defining perception of fractals [44]. The importance of edge contours is sup-

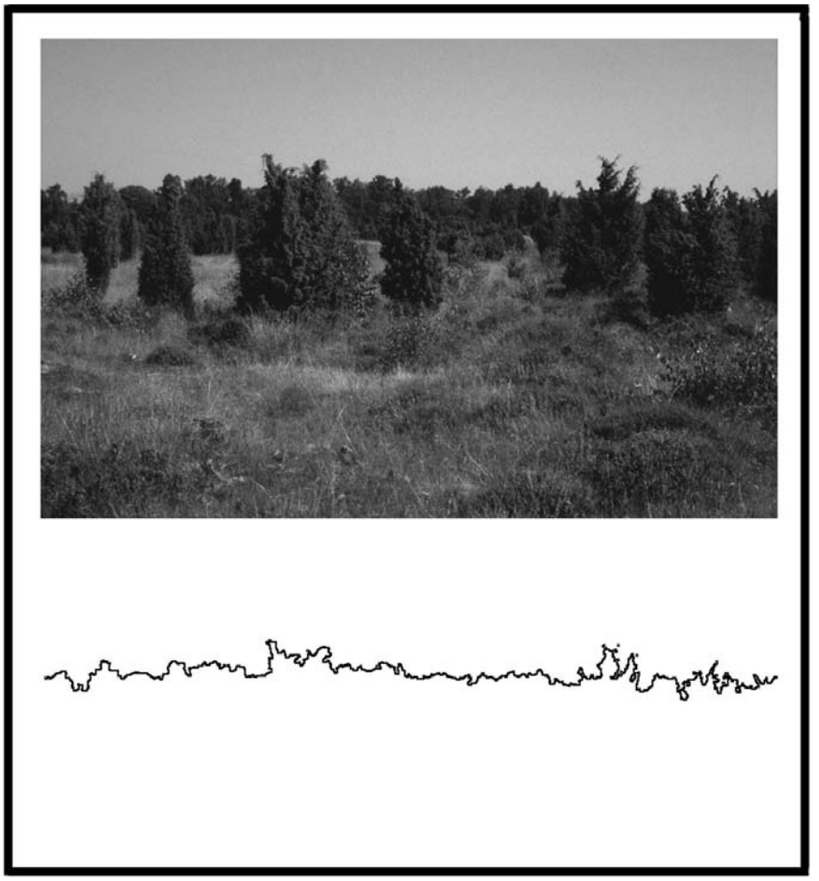


Fig. 5. A photograph of a natural scene (top) used in preference experiments, along with the extracted skyline contour (bottom). (Photo © Caroline Hagerhall)

ported by "eye-tracking" experiments that monitor direction of gaze. These experiments show that the eye fixates predominantly on edges when examining a scene [45]. Therefore, a promising approach to investigating a fractal scene is to select a prominent edge and determine its aesthetic impact. The skyline forms the dominant contour in many scenes, with the D value depending on the objects that define the contour [46]. I collaborated with Caroline Hagerhall and Terry Purcell in preference experiments showing that the most preferred scenes had fractal skylines with a D value of 1.3 [47]. Figure 5 shows a typical natural scene and the skyline's fractal contour. The results offer a clear demonstration that the preference for mid-range D values revealed for simple fractal shapes extends to the fractal characteristics of more intricate fractal scenery.

Fractal Stress Reduction

Does this appreciation for mid-D values (1.3–1.5) explain the physiological response induced by the middle image of Fig. 1? To answer this, I collaborated with Ted Martin and James Wise to analyze the art featured in the original NASA experiment. Adopting the edge analysis techniques discussed above [48], I performed a fractal analysis on the pattern established by the combination of the edge contours of all the objects in the image. This approach has met with success in previous investigations of fractals found in art and nature [49].

To perform the fractal analysis of the edge pattern, I employed the "box-counting" method, in which the pattern is covered with a mesh of identical squares [50]. The pattern's statistical scaling qualities are then determined by calculating the proportion of squares occupied by the pattern. This process is repeated for increasingly fine meshes. Reducing the square size is equivalent to looking at the pattern at finer magnification. In this way, the pattern's statistical qualities can be compared at different magnifications. Specifically, the number of squares, N(L), that contain part of the pattern are counted, and this is repeated as the size, L, of the squares is reduced. For fractal behavior, N(L) scales according to the relationship $N(L) \sim L^{-D}$, where D lies between 1 and 2 [51]. The D values, which chart the scale invariance, were extracted from the gradient of a graph of log N(L) plotted against log L.

Using this analysis, the artificial pattern (Fig. 1, bottom image) was found not to be fractal, while the forest photograph (top image) and artwork of the natural scene (middle image) were fractal, with D values of 1.6 and 1.4, respectively. Significantly, this result is consistent with the above investigations of people's visual perception of fractals. The savannah scene, which provided the greatest dampening of physiological response, has a D value that falls into the aesthetically pleasing range, while the forest D value falls outside this range.

Fig. 6. The Sydney Opera House, designed by Jorn Utzon. (© Richard Taylor)

Implications for Fractal Art and Architecture

These results suggest that the observer's physiological condition might be influenced positively by mid-D fractals. It is important to emphasize the preliminary nature of the results, which are based on only four images. In particular, D is just one of a number of visual characteristics that vary between the 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 and scenes, paintings and computer patterns), D was found to be a significant factor for determining aesthetic preference.

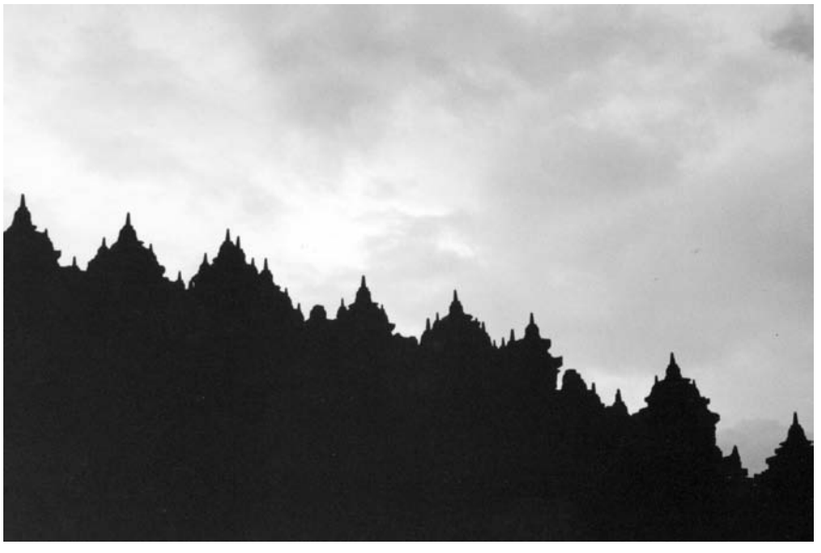
An appealing consequence of this work lies in the rich variety of images that might be used for dampening physiological response to stress. Whereas previous proposals for stress reduction concentrated on natural images [52], our results emphasize that natural scenery represents a small subset of the fractal images that might be effective in stress reduction. These include computer-generated fractals and abstract paintings. For example, Sprott has previously advocated the use of computers for generating a rich variety of fractals [53]. Furthermore, my own research has demonstrated the ease with which a chaotic pendulum creates paintings where the fractal content can be tuned [54]. These approaches could be used to produce a library of fractal images to be used to improve people's physiological condition.

Our investigations of fractal skylines [55] indicate that stress-reducing images need not be restricted to simple fractal patterns. The presence of a mid-range fractal contour buried within a scene is sufficient to affect the aesthetics. Thus it should be possible to use paintings depicting people and buildings and to add the fractal content into the background contours of the scene. This prospect adds to the variety of potential images, and also presents the opportunity to combine fractal patterning with other stress-reducing factors such as the painting's subject matter and color.

Not all fractal art will be suitable for dampening physiological responses to stress, however. An important consequence of the above research is the demonstration that, contrary to the previous proposals of using window views and photographs of natural scenes, "naturalness" of the image is not sufficient to produce the desired effect. The effectiveness will depend on the image's specific D value. For example, the fractal landscape of Fig. 1 (top) produced a relatively mild dampening despite being an accurate photographic depiction of a natural scene.

The concept of fractal architecture builds on earlier proposals of "biophilia" and the drive to incorporate nature into urban landscapes [56]. However, these earlier strategies are often impractical for cities, where building density limits exposure to nature. Furthermore, the research presented here shows that naturalness is not enough to induce physiological responses—specific D values are required. Thus, it is necessary to design buildings' fractal geometry to feature specific D values.

Fig. 7. The repeating patterns of the Borobodur Temple. (© Richard Taylor)



Is it practical to create buildings with a fractal appearance? One approach is to construct the building's framework based on fractal geometry. A less radical approach is to use a Euclidean shape for the building's basic structure and incorporate fractals into the design using, for example, paint, lighting or attached structures. Regardless of the approach, the challenge, of course, lies in the ability to repeat the patterning process at different scales. However, this challenge may not be as difficult as it seems.

One practical consideration concerns the magnification range over which the patterns must follow fractal behavior in order to induce the desired physiological response. Whereas mathematical fractals extend from the infinitely large to the infinitesimally small, "physical" fractals (generated by nature and artists) are limited to a finite magnification range. For Pollock's paintings, fractal behavior is charted from the finest speck of paint up to the canvas size, representing a magnification range of 1,000 [57]. For the natural scenery, the skyline D value was observed over a factor of 250 [58].

However, these large observation ranges are unusual for physical fractals—typically, the smallest pattern is only 25 times smaller than the largest [59]. Motivated by this fact, the images used in our perception experiments were displayed such that the smallest resolvable pattern was approximately 25 times smaller than the largest [60]. This limited magnification range was sufficient to induce the D preferences discussed above. Therefore, fractal architecture can effectively be limited to patterns spanning a magnification range of 25.

Other crucial factors also demonstrate that response-based fractal architecture is an achievable proposition. First, our perception results indicate that relatively *simple* (mid-D) fractals are sufficient to induce a preference. This is highlighted by the images shown in Fig. 3—the intricate, rich structure found in high-D fractals would be a much greater challenge than the relatively simple structure of low-D fractals. Secondly, traditional architectural studies demonstrate that façade complexity influences aesthetic preference significantly less than complexity in the building's skyline [61]. This indicates that research should be directed at establishing fractal skylines of buildings instead of the more involved strategies that would be required to establish fractal texture across façades. Thirdly, recent preference studies show that it is not necessary to match a building's fractal skyline to background frac-

tal scenery [62], limiting contextual concerns. In particular, the fractal skyline does not have to be matched to fractal cloud patterns, thus excluding the highly unfeasible prospect of having to match the fractal designs of buildings to prevalent weather conditions.

Finally, perhaps the most important practical consideration to be researched concerns the degree to which shapes can deviate from fractal behavior and still induce the desired response. For example, although the Sydney Opera House, shown in Fig. 6, is not strictly fractal, the pattern created by simple shapes at several sizes might be sufficient to mimic fractals and induce the desired physiological response. If future investigations show this to be the case, this relaxation of practical conditions will make fractal architecture a highly realistic proposition.

CONCLUSIONS

Although preliminary, the results discussed above have enormous potential —the motivation of this article is therefore to trigger further investigations. In particular, it is important to extend the physiological measurements beyond electro-dermal responses to include cardiovascular, eye-tracking and pupillography responses. In addition, future experiments should narrow the precise fractal character of the patterns that maximize the responses by considering additional parameters such as lacunarity and the full spectrum of dimensions obtained from a multi-fractal analysis [63].

These experiments could provide a fascinating insight into the impact that fractal art and architecture might have on an observer's perceptual and physiological responses. Stress reduction is of enormous benefit to society, and this novel approach of using fractals might prove particularly useful for therapeutic environments such as hospitals or in situations where people are deprived of nature's fractals—for example, in windowless rooms or research stations in the Antarctic and in outer space. NASA's motivation for conducting the experiments was to explore methods of maintaining low stress for astronauts, an aim that has become topical with the recent calls for manned missions to Mars.

The challenges of incorporating fractals into the interiors and exteriors of buildings will require an interplay between scientific, artistic and social considerations. In particular, the manner in which people are exposed to the patterns should be unobtrusive. Certainly, a future world where we are required to stare at fractal images for an allotted daily period conjures up unappealing visions of Orwell's *1984*! Fortuitously, the experiments described here indicate that the responses can be induced without prolonged exposure to fractals. The perception studies showed that observation periods of less than 10 seconds were sufficient to trigger aesthetic appeal. Furthermore, the participants in the NASA experiments were not instructed to look directly at the fractals, which were located on a far wall. This suggests that the fractals could be incorporated into the background environment. A swift glance at a painting on a corridor wall might be sufficient to induce the desired effect. Also, research into the fractal dynamics of music indicates that this subtle visual exposure might be integrated with sonic fractals [64].

Could a common set of fractal images be used for everyone? Although the majority of participants in the perception experiments preferred mid-range fractals [65], there is some evidence that creative people prefer the greater complexity of high-D patterns [66], raising the question of whether fractal images will have to be tuned to individual preferences. Furthermore, to prevent saturation of the relaxation effect, the fractal images would have to be varied over time, perhaps through the use of electronic screens or evolving lighting conditions. If these challenges seem daunting, it is worth stressing that we may already be using this approach to stress reduction without knowing it. Take, for example, staring into the flickering flames of a fire or looking up at tree branches swaying in the wind. The patterns in both cases vary with time while preserving their fractal qualities. The combination of their fractal content, along with other factors such as color and subjective associations, almost certainly reduce our stress.

The prevalence of artificial fractals suggests the possibility that we have been making use of fractal stress reduction throughout history. We expect our findings to apply to a range of fractal patterns appearing in art, architecture and archaeology, spanning five centuries! One example, shown in Fig. 7, is the skyline of the temple of Borobodur built in Java during the 8th century. Other examples include the Nasca lines in Peru (pre–7th century) [67], Gothic cathedrals (12th century) [68], the Ryoanji Rock Garden in Japan (15th century) [69], Leonardo's sketch *The Deluge* (1500) [70], Hokusai's woodcut print *The Great Wave* (1846) [71], Eiffel's tower in Paris (1889) [72], Pollock's early poured paintings (1943–1944) [73] and Lloyd Wright's Palmer House (1950) [74].

Acknowledgments

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