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Relaxing Floors: Fractal Fluency in the Built Environment

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Abstract: *This year's cover artists are members of a newly formed team of designers and scientists known as the Science and Design Laboratory, along with flooring manufacturing experts from the Mohawk Group. This unique collaboration creates patterns for installation on the floors of versatile commercial, public and private spaces including airports, hospitals, offices and homes. Their goal is to create human-centered designs based on psychology experiments that investigate the positive impacts of viewing fractal patterns. These include reduced physiological stress levels, enhanced cognitive skills, and heightened concentration. Here, the fractal construction process and the resulting fractal characteristics of these designs are explained.*

Key Words: *biophilia, biophilic design, human–centered design, fractals, stress-reduction*

INTRODUCTION

Although the term *biophilia* was first used by psychologists in the 1960s (Fromm, 1964), the associated movement gained momentum in the 1980s when Edward Wilson defined the Biophilia Hypothesis in terms of people's "urge to affiliate with other forms of life" (Wilson, 1984). Around this time, pioneering experiments demonstrated that exposure to natural scenery had striking, positive consequences for the observer, even causing patients to recover more rapidly from major surgery when exposed to the visual qualities of nature (Ulrich, 1981; Ulrich, 1993; Ulrich & Simons, 1986). Over the past two decades, interdisciplinary teams have sought to confirm a specific hypothesis – that the aesthetic qualities of fractals are inducing these striking effects (Abboushi, Elzeyadi, Taylor, & Sereno, 2018; Aks & Sprott, 1996; Bies, Blanc-Golhammer, Boydston, Taylor, & Sereno, 2016; Cutting & Garvin, 1987; Field & Brady, 1997; Hagerhall, Purcell, & Taylor, 2004; Hagerhall et al., 2008; Hagerhall et al., 2015; Geake & Landini, 1997; Juliani, Bies, Boydston, Taylor, & Sereno, 2016; Knill, Field & Kersten, 1990;

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Marlow et al., 2015; Spehar, Clifford, Newell, & Taylor, 2003; Spehar & Taylor, 2013; Spehar et al., 2015; Spehar, Walker, & Taylor, 2016; Street et al., 2016; Taylor, 1998, 2002, 2006; Taylor & Spehar, 2016; Taylor & Sprott, 2008; Taylor, Spehar, von Donkelaar & Hagerhall, 2011; Taylor et al., 2017; Taylor, Juliani, Bies, Spehar, & Sereno. 2018). This hypothesis was informed by the prevalence of fractals in nature (Mandelbrot, 1982) and also by their appearance in cultural artifacts spanning many centuries, ranging from Hellinic friezes (300 B.C.E) to Jackson Pollock's poured paintings (1950s) (Taylor, 2002; Taylor, Micolich, & Jonas, 1999; Taylor, Micolich, & Jonas, 2002; Taylor et al., 2007). Their role in art and design continues to grow and diversify, as demonstrated by this journal's previous cover artists.

In addition to providing a deeper understanding of the relationship between the human visual system and nature's visual stimuli, fractal aesthetics studies have the potential to radically improve the built environment, particularly given that the aesthetic experience has been shown to be accompanied by significant stress-reduction. The World Health Organization declared stress to be the "Health epidemic of the 21st Century," with associated illnesses ranging from depression to schizophrenia (Smith, 2012). As people increasingly find themselves surrounded by urban landscapes, they risk becoming disconnected from nature's fractals and their stress-reduction qualities. Despite this escalating concern, the design world has yet to rise to the inter-disciplinary challenge of creating fractal designs based on the science of fractal aesthetics.

The Science and Design Laboratory (*SDL*) was formed in 2017 in response to this challenge. The goal of this collaboration between the Austrian design team and the US science team is to generate fractal patterns informed by both fields. To transform these patterns into the built environment, SDL collaborates with the *Mohawk Group* - one of the world's largest flooring manufacturers with a reputation for forward-looking strategies such as their use of sustainable materials. Known as *Relaxing Floors*, our designs were launched in Spring 2019 and immediately won the *Metropolis Likes Award* and an honorary *Interior Design NYCxDESIGN Award* at New York's *Design Week* and the *Best of Show Innovation Award* and the *Interior Design HiP Award* at Chicago's *NeoCon* trade show. This year's cover art works are based on the fractal principles developed for these flooring designs.

FRACTAL FLUENCY

Given the prevalence of fractal patterns across nature, art and science, our first challenge was to narrow our focus and choose from the vast variety of fractal patterns which could be used for our designs. In particular, fractals fit into two families – "exact" and "statistical." Whereas exact fractals are built by repeating a pattern at increasingly fine magnifications, "statistical" fractals introduce randomness into their construction. This disrupts the precise repetition so that only the pattern's statistical qualities (e.g., density, roughness, and complexity) repeat. Consequently, statistical fractals simply look similar at different size scales. Whereas exact fractals exhibit the cleanliness of artificial shapes, statistical fractals reveal the organic signature of nature's scenery. Although our initial explorations used exact fractals, we gravitated to statistical fractals because of our biophilic mission.

Our next challenge was to ensure that our statistical designs exhibited the fractal characteristics shown by the psychology experiments to induce positive responses in the observer. These experiments demonstrated that visual complexity was the key component. Compared to the simplicity of Euclidean shapes, the fractal repetition of patterns at different scales results in fractal shapes that are inherently complex. To quantify this visual intricacy, we followed the lead of the psychology experiments and used the pattern's fractal dimension *D* (Fairbanks & Taylor, 2011; Spehar et al., 2015). For a smooth Euclidean line (containing no fractal structure) *D* has a value of 1, while for a completely filled area (again containing no fractal structure) its value is 2. However, the repeating patterns of the fractal line cause the line to begin to occupy space. As a consequence, its *D* value lies between 1 and 2. By increasing the amount of fine structure in the fractal mix of repeating patterns, the line spreads even further across the two-dimensional plane and its *D* value therefore moves closer to 2. For the low *D* fractals, the small content of fine structure builds a very smooth sparse, shape. However, for fractals with *D* values closer to 2, the larger amount of fine structure builds a shape full of intricate, detailed structure. More specifically, because the *D* value charts the ratio of fine to coarse structure, it is expected that *D* will serve as a measure of the fractal's visual complexity. Behavioral research (Cutting & Garvin, 1987; Spehar et al., 2016) confirms that the complexity perceived by observers does indeed increase with the image's *D* value.

Significantly, although images of natural objects are quantified by *D* values across the full range from 1.1 to 1.9, the most prevalent fractals lie in the narrower range of 1.3 to 1.5 (Aks & Sprott, 1996; Taylor et al., 2018). For example, many examples of clouds, trees and mountains lie in this range. This forms the basis of the 'fractal fluency' model, which proposes that our eyes have become fluent in nature's visual language of fractals. More specifically, the visual system has adapted to efficiently process the mid-complexity patterns of these prevalent fractals (Taylor et al., 2011; Taylor & Spehar, 2016; Taylor et al., 2018). The model also proposes that our increased capability to process mid-*D* fractals results in enhanced performances of visual tasks when viewing them (Taylor, & Spehar, 2016; Taylor et al., 2018). For example, behavioural studies have demonstrated participants' heightened sensitivity to mid-*D* fractals (Spehar et al., 2015). These studies used fractal images displayed on a monitor and when the pattern contrast was gradually reduced until the monitor displayed uniform luminance, participants were able to detect the mid-*D* fractals for much lower contrasts than the low and high *D* fractals (Fig. 1a) (Spehar et al., 2015). Similarly, participants displayed a superior ability to distinguish between fractals with different *D* values in the mid-*D* range (Fig. 1b) (Spehar et al., 2015). Furthermore, the increased beta response in qEEG studies suggested a heightened ability to concentrate when viewing mid-*D* range fractals (Hagerhall et al., 2008).

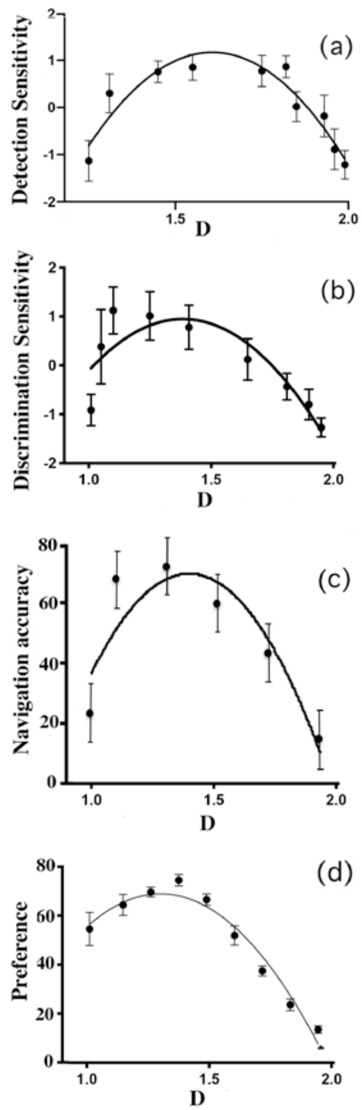

Fig. 1 Capability tasks and preference ratings plotted against the fractal's *D* value. Refer to the text and associated references for details of the measurements and the relevant y-axis scale. Note how all of the behaviors peak in the mid-*D* range.

There is also evidence to suggest that pattern recognition capabilities increase for mid-*D* fractals. For example, we are all familiar with imaginary objects induced by clouds. A possible explanation is that our pattern recognition processes are so enhanced by these fractal clouds that the visual system becomes "trigger happy" and consequently we see patterns that aren't actually there (Taylor & Spehar, 2016). This agrees with studies of Rorschach ink blots, in which the capacity to perceive shapes in the fractal blots peaks in the lower *D* range (Taylor et al., 2017). Fractal fluency also leads to an enhanced processing of visual spatial information and therefore to a superior ability to navigate through environments characterized by mid-*D* fractals. This was demonstrated using avatars that participants navigated through virtual fractal environments (Juliani et al., 2016). They were instructed to search as quickly as possible for an object randomly placed within the landscape. In each case, completion speeds and accuracy were measured, and the overall performance was found to peak at the mid-*D* complexity predicted by the fluency model.

All of these enhanced performances raise a crucial question for our biophilic carpet designs: does fractal fluency create a unique aesthetic quality because we find mid-*D* fractals relatively easy to process and comprehend? Behavioral experiments have confirmed the importance of fractal aesthetics, showing that ninety-five per cent of observers prefer complex fractal images over simple Euclidean ones (Taylor, 1998). Fractal aesthetics experiments have also shown that preference for mid-*D* fractals (Fig. 1d) is universal in the sense that it is robust to the specific details of how the fractals are generated (Spehar et al., 2003). For example, fractal aesthetics generated by nature, mathematics and art all show the same *D*-dependence. In addition to the laboratory-based behavioral experiments, a computer server has been used by Scott Draves (the 2008 cover artist) to send screensavers to a large audience of 5000 people. In Draves's experiments, new fractals were generated by an interactive process between the server and the audience, in which users voted electronically for the images they preferred (Taylor & Sprott, 2008). In this way, the parameters generating the fractal screensavers evolved with time, much like a genome, to create the most aesthetically preferred fractals. The results re-enforced the preference for mid-*D* fractals found in the laboratory-based experiments.

Significantly for our project, preference for mid-*D* values breaks down when moving from statistical to exact fractals (Bies et al., 2016). Given that the fluency model is founded on people's adaption to nature's statistical fractals, it is not surprising that exact fractals induce a different aesthetic impact. Observers were found to prefer higher *D* values for exact fractals, with the peak *D* depending on the specifics of the fractal pattern (Bies et al., 2016). In particular, patterns with high degrees of symmetry induced the highest *D* preferences and it is thought that the associated order increases the observer's tolerance for fractal complexity. For fractals featuring fewer symmetries, the reduced order decreased this tolerance and the preference fell to lower fractal complexities. This concept of complexity tolerance is further supported by recent experiments which project statistical fractal images on walls rather than exhibiting them on computer monitors as done in most of the previous experiments (Abboushi et al., 2018). The observer then witnesses the fractal pattern embedded within the simplicity of a blank wall. This integration of Euclidean simplicity again increases the tolerance for high fractal complexity and the peak preference rises to D ~ 1.5 - 1.7 (Abboushi et al., 2018).

All of the above experiments establish the design frame for our fractal floors. Similar to the fractals projected on the wall, the fractal flooring will be embedded within simple spaces defined by the surrounding walls and ceilings. Based on the fractal projection results, our target D values for inducing the fractal aesthetic effect using floor designs lie in the range 1.5-1.7. Previous qEEG (Hagerhall et al., 2008; Hagerhall et al., 2015) and skin conductance measurements (Taylor, 2006) indicate that the resulting 'aesthetic resonance' will induce a state of relaxation. To generate this effect, our designs must be restricted to statistical fractals rather than their exact counterparts. However, the universality observed for statistical fractals and its associated robustness to a variety of fractals opens up a freedom for us to explore a range of possible designs.

RELAXING FLOORS

Our *Relaxing Floors* collection consists of two categories of pattern, each of which is based on the eye's reliance on fractal geometry. The first category, *Growing Fractals*, is based on the fractal motion adopted by the eye in order to optimize its visual search when looking at fractal scenery (Taylor & Spehar, 2016; Taylor et al., 2011; Fairbanks & Taylor, 2011). The second category, *Fractal Connections*, is based on the fractal structure of the retinal neurons which optimizes the transfer of signals from the photoreceptors to the optic nerve and on to the brain (Watterson et al, 2016; Watterson et al., 2017; Watterson et al., 2018). By choosing these two themes for our collection, our designs serve as a celebration of the connection between human vision and fractals.

First, we consider the eye motion patterns. If the eye's gaze is directed at just one location within the fractal scenery the peripheral vision only has sufficient resolution to detect coarse patterns (Fairbanks & Taylor, 2011). Therefore, the gaze shifts position to allow the eye's fovea to detect the fine scale patterns at multiple locations. This allows the eye to experience the coarse and fine scale patterns necessary for confirmation of fractal character of the stimulus. The reason the eye adopts a fractal trajectory when performing this task can be found in studies of animals foraging for food in their natural terrains (Viswanathan et al., 1996). Their foraging motions are also fractal. For example, the short trajectories allow a bird to look for food in a small region and then to fly to neighboring regions and then onto regions even further away, allowing efficient searches across multiple size scales. The eye adopts the same motion when 'foraging' for visual information.

We use these fractal trajectories as the starting point for the *Growing Fractals* designs (Fig. 2a) and generate them using Lévy statistics (Fairbanks &

Taylor, 2011). Then, much like the bird dropping a seed whenever it lands, a seed pattern is generated at the locations between the flight trajectories. Although the seed in Figures 2b-d has a circular shape, in principle the seed can assume any shape. Lines and triangles are used for the flooring patterns shown in this article. Note how the seed's size is scaled relative to the length of the previous flight (Fig. 2d) in order for the flight trajectory's scaling properties to be transferred to the seed. Whereas Fig. 2 shows a seed consisting of one simple pattern, for the flooring design the seed is repeated at different scales to generate a fractal seed. This process is shown in Fig. 3 for a line seed generated using a Sierpinski process for 5 iterations. A Koch process was also used for other examples of our flooring patterns.

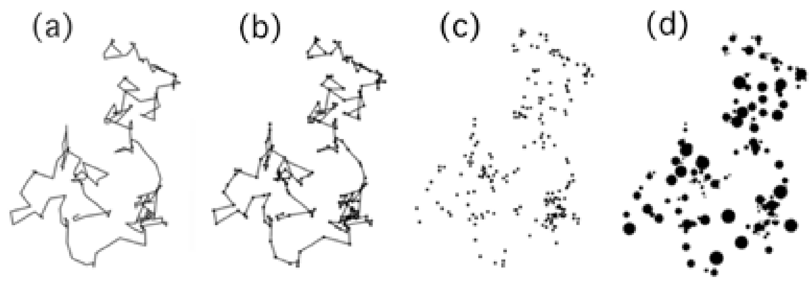

Fig. 2 Fractal Flights: (a) Lévy flight trajectories used by the eye and birds when searching, (b) Circular seed patterns are added to the 'landing' locations between these trajectories, (c) the trajectories are removed, (d) the sizes of the circles are scaled based on the length of the previous flights.

The completed pattern of fractal seeds embedded at fractal flight locations is shown in Fig. 4 (top). Note that this exotic integration of fractal seeds and fractal flights was chosen based on design sensibilities. In other words, the team exploited the flexibility offered by the universal quality of the fractal aesthetics process to develop patterns that were intriguing from the design perspective. Preservation of the desired fractal aesthetics was ensured by inputting the appropriate scaling parameters when generating the fractal trajectories and seeds, and also by using the traditional box-counting technique (Fairbanks & Taylor, 2011) to analyze the completed pattern to confirm that it scales according to the target *D* value of 1.6. Fractal scaling was confirmed from the minimum pattern size of 0.2 inches (0.5cm) up to 24 inches (61cm). The box-counting method cannot confirm fractal scaling at scales larger than 24 inches due to a limited number of boxes at these scales (Fairbanks & Taylor, 2011). However, based on the fractional input parameters, it is expected that fractal scaling continues beyond the confirmed range. We note that even this restricted range of confirmed fractal scaling exceeds the magnification factor for typical physical

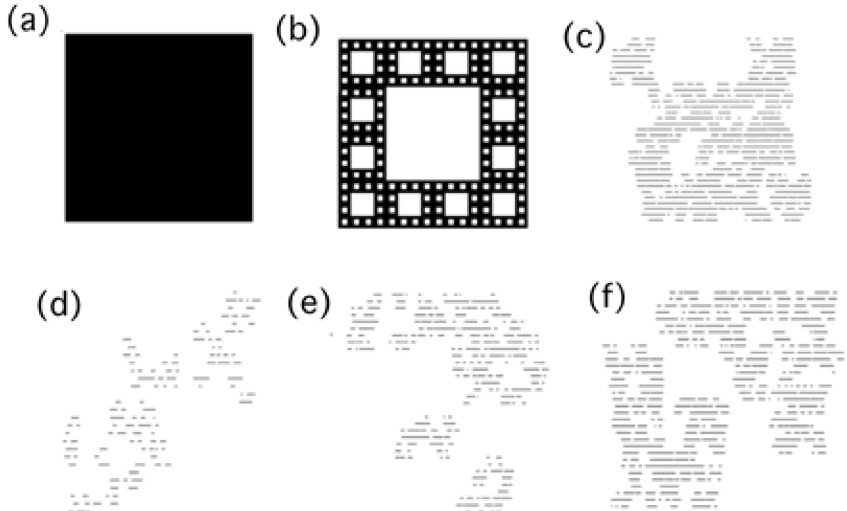

Fig. 3 Fractal seeds: (a) A square-shaped seed, (b) The seed is used to grow a fractal pattern, in this case based on a Sierpinski generation process, (c) the exact fractal is then randomized to morph the exact fractal into a statistical fractal. At the same time, each component square is replaced by a line. The *D* value of the final fractal is inputted during this growth process. Three examples are shown here: (d) 1.3, (e) 1.5 and (f) 1.7.

fractals, for which the coarsest pattern is 25 times larger than the smallest (Avnir et al., 1998). Crucially, this factor of 25 was used for the stimuli used in most of the previous psychology experiments revealing the positive observation effects (Taylor et al., 2017; Taylor et al., 2018). The scaling ranges of our designs therefore exceed those known to induce the positive effects.

One final challenge remained. For manufacturing demands, the 6ft (15cm) by 12ft (30cm) pattern of Fig. 4(top) is divided into either 2ft by 2ft "tiles" or 1ft by 3ft "planks," which will then be randomly re-assembled when installed. We therefore had to simulate this division process to ensure that it didn't disrupt the design aesthetic (in particular, that any discontinuities at the tile or plank edges fit well within the overall pattern) nor the fractal aesthetic (in particular that the *D* value didn't shift out of the required range of $D = 1.5 – 1.7$ (Abboushi et al., 2018)). Figure 4 (bottom) shows an example of the randomized flooring pattern. Figure 5 shows further examples of patterns using our flight-seed integration approach.

Whereas the *Growing Fractals* collection grows fractals using computer simulations based on nature's processes, the *Fractal Connections* collection deliberately takes a more direct approach. For this second collection, we use images of nature's fractals - retinal neurons - as the starting point for our designs

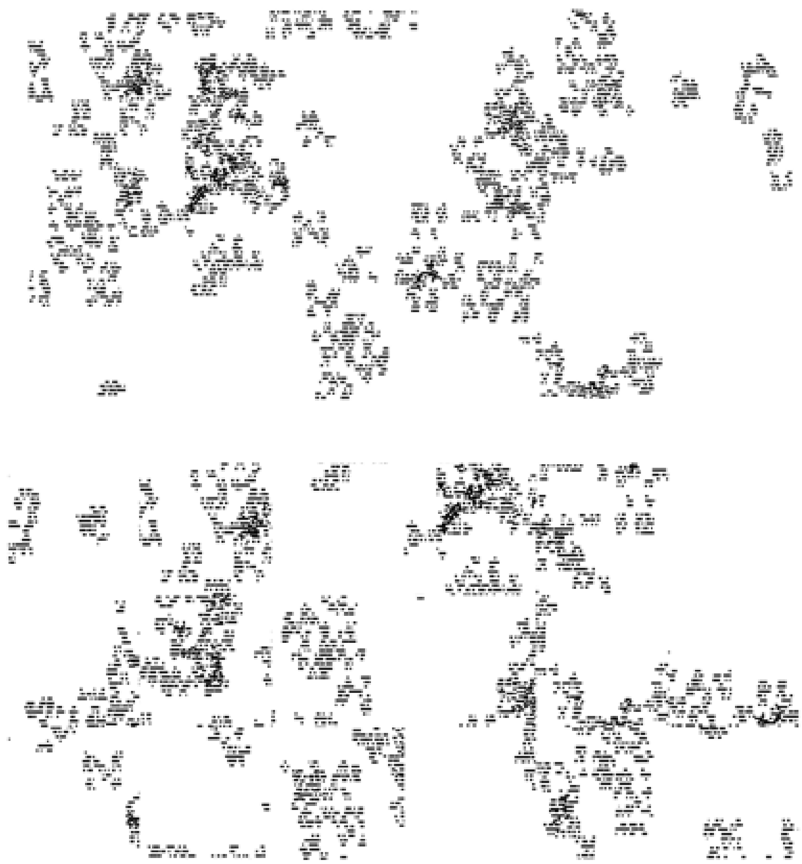

Fig. 4 An example image from the *Growing Fractals* collection: (top) the original pattern, (bottom) the randomized pattern. These patterns represent an integration of the flights of Fig. 2 with the seeds of Fig. 3, and are called *MellowD*.

(Fig. 6, left). These images were obtained as part of a research project which develops retinal implants to restore vision to patients with diseases such as macular degeneration (Watterson, Moslehi, Smith, Montgomery & Taylor, 2016; Watterson, Montgomery, & Taylor, 2017; Watterson, Montgomery, & Taylor, 2018). This research focuses on the principle of 'fractal resonance' – an effect which predicts that signals will pass more efficiently from the implant's electrodes to the neurons if their fractal characteristics are matched. Fluorescence microscopy is used to acquire detailed images of the retinal neurons in order to

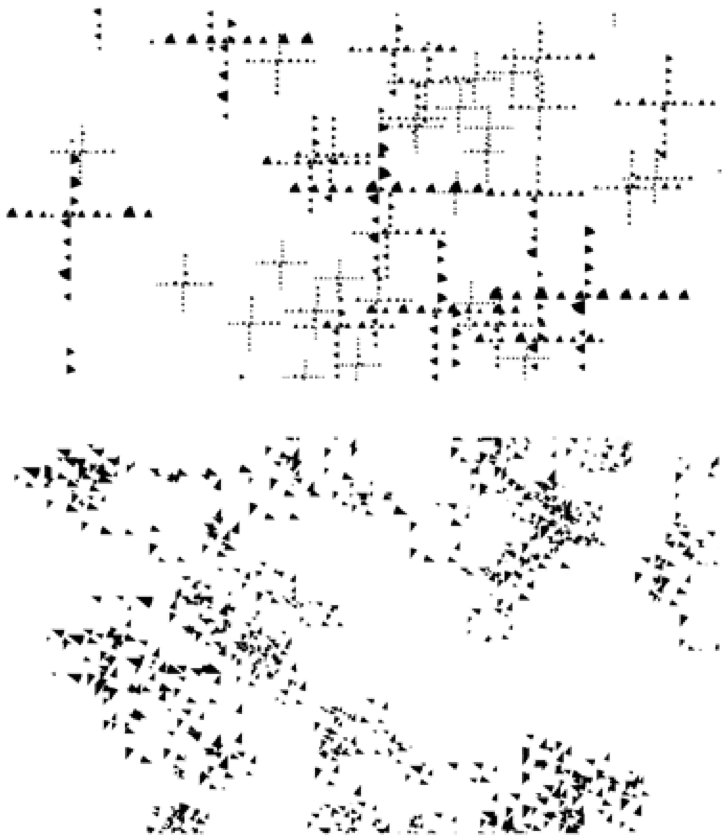

Fig. 5. Further examples of the *Growing Fractals* collection. These patterns use triangular seeds constructed using (top) Koch processes and (bottom) Sierpinski processes embedded within the fractal flights. The two patterns are called *ChillD* (top) and *CalmD* (bottom).

quantify parameters such as their *D* values (Fig. 6, left). For the flooring designs, the images are converted into grayscale versions and then contoured (Fig. 6, middle). We initially expected to use software to manipulate the *D* values of the neuron contours but, fortuitously, the selected image's *D* value of 1.7 fell within the target range of *D* = 1.5 – 1.7 necessary for the fractal aesthetics (Abboushi et al., 2018). As with the *Growing Fractals* collection, the 6ft by 12ft pattern is divided into tiles or planks, which will then be randomly re-assembled when installed (Fig. 6, right). Again, this process did not significantly impact the overall pattern's *D* value.

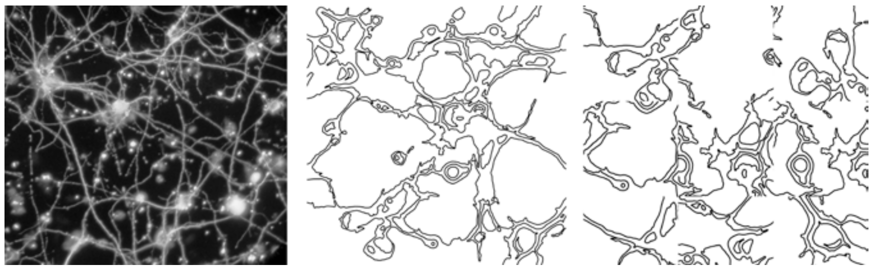

Fig. 6. The *Fractal Connections* collection: (left) fluorescence image of retinal neurons, (middle) contours extracted from the greyscale image of the neurons, (right) randomized tiles of the contour pattern. This pattern in called *RestD*.

Fig. 7. Images of three carpet patterns (*MellowD*, *ChillD* and *RestD*).

DISCUSSION

The original research on stress-reducing fractals (Taylor, 2006) was funded by NASA with the aim of maintaining the health of astronauts during long missions away from Earth's scenery. The project described in this article aims to broaden the original scope to include Earth-bound, everyday stressful activities ranging from catching a plane to students taking their exams. Floors represent a common, expansive space for exposing people to fractals. In addition to their stress-reduction, the psychology experiments summarized here suggest further positive impacts such as 'effortless looking' (characterized by an increased engagement and prolonged concentration) and increased mental skills such as pattern recognition and navigation. The experiments also indicate that fluency does not require long exposure times and requires only environmental exposure (in other words, the observer doesn't need to look directly at the pattern for the positive effects to be induced). We note that, although participants in the psychology experiments viewed the stimuli with an upright orientation, the carpets will most likely be viewed at an angle. However, previous studies suggest that tilting doesn't reduce pattern recognition abilities (Shepard & Metzler, 1971).

Figure 7 shows the patterns as they appear on the carpets. Although they capture the essence of nature's fractals, they are more than simple replicas, inspiring the Collection's slogan "Relaxing floors are second nature." As discussed earlier, true to the spirit of biophilia they have been adapted from nature to account for the fact that they are embedded in the artificial, built environment. In particular, their *D* values have been raised higher (1.6 - 1.7) than those of common fractal scenery in nature (1.3-1.5) to accommodate for the simplicity of the surrounding walls and ceilings (Abboushi et al., 2018). In addition to this tuning of pattern characteristics to achieve the fractal aesthetics, the patterns also need to translate well to the carpet format seen in Fig. 7. The tufted carpet background had to be textural enough to hide the tile edges without creating a pattern that would alter the intended *D* value. New tufting techniques which hide unused yarns to create controlled texture were used to achieve an optimized construction for aesthetics, performance, and accessible price points. Furthermore, *Relaxing Floors* meets the stringent requirements of the Living Product Challenge, using petal-certified flooring solutions by the International Living Futures Institute, ensuring that the product is healthy and free of toxins, socially responsible, and has a net positive impact for people and the environment.

Finally, we hope that our project serves as an inspiration for others looking to benefit from the complementary skills of scientists, designers and manufacturers. In terms of practical operations, it is worth noting that one aspect of our success lay in the development of software operated both by the scientists in Eugene and the designers in Graz. At times, this allowed patterns to be developed on a 24-hour schedule – when designs were completed at the end of the Austrian day, the patterns were sent over at the start of the Oregon day. It is also worth emphasizing the expertise of the three teams – the "design police," the "fractal police," and the "manufacturing 'police" ensured that there were no weak links as the designs progressed towards their completion. As with all great inter-disciplinary endeavors, creativity was an emergent phenomenon beyond the capabilities of the individual teams.

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