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Published in:
Journal of Experimental Psychology : Human Perception and Performance

DOI:
10.1037/xhp0000105

Journal of Experimental Psychology:
Human Perception and Performance
2016, Vol. 42, No. 1, 103–114

0096-1523/16/$12.00 http://dx.doi.org/10.1037/xhp0000105

When Complex Is Easy on the Mind: Internal Repetition of Visual Information in Complex Objects Is a Source of Perceptual Fluency

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Across 3 studies, we investigated whether visual complexity deriving from internally repeating visual information over many scale levels is a source of perceptual fluency. Such continuous repetition of visual information is formalized in fractal geometry and is a key-property of natural structures. In the first 2 studies, we exposed participants to 3-dimensional high-fractal versus low-fractal stimuli, respectively characterized by a relatively high versus low degree of internal repetition of visual information. Participants evaluated high-fractal stimuli as more complex and fascinating than their low-fractal counterparts. We assessed ease of processing by asking participants to solve effortful puzzles during and after exposure to high-fractal versus low-fractal stimuli. Across both studies, we found that puzzles presented during and after seeing high-fractal stimuli were perceived as the easiest ones to solve and were solved more accurately and faster than puzzles associated with the low-fractal stimuli. In Study 3, we ran the Dot Probe Procedure to rule out that the findings from Study 1 and Study 2 reflected differences in attentional bias between the high-fractal and low-fractal stimuli, rather than perceptual fluency. Overall, our findings confirm that complexity deriving from internal repetition of visual information can be easy on the mind.

Keywords: perceptual fluency, fractal geometry, visual complexity, cognitive performance, natural structures

Imagine taking your eyes off this article and looking around you. Inevitably, the scene that enters your visual field will require a certain amount of effort to process, and this processing can range from highly effortful to quite effortless (Alter & Oppenheimer, 2009). For example, if the room you are in contains very few objects, then it makes intuitive sense to think that perceiving the room will require considerably less effort than perceiving a room cluttered with many objects. But does the intuition that visual complexity is less easy on the mind than simplicity always and necessarily hold (Orth & Wirtz, 2014)? In this article, we challenge this idea and explore the conditions under which visual complexity can actually require less processing effort than visual simplicity.

The experience of easy perceptual processing of particular perceptual and formal stimulus features is commonly referred to as perceptual fluency (Alter & Oppenheimer, 2009; Oppenheimer, 2008). Different perceptual characteristics and features have been found to positively affect perceptual fluency, including visual clarity (Oppenheimer & Frank, 2008), symmetry (Bertamini, Makin, & Rampone, 2013), and figure-ground contrast (Reber & Schwarz, 1999; Reber, Winkielman, & Schwarz, 1998). Perceptual fluency, in turn, is only one of the many "tribes" of the more general phenomenon of processing fluency (Alter & Oppenheimer, 2009). Well-known examples of processing fluency are retrieval fluency (Winkielman, Schwarz, & Belli, 1998) and conceptual fluency (Whittlesea, 1993), respectively referring to the ease with which information is retrieved from memory, and with which particular concepts can become activated and semantically integrated.

Like other kinds of fluency, perceptual fluency can both have an objective and subjective component (Reber, Wurtz, & Zimmermann, 2004), depending on whether there is conscious awareness of easy processing. Objective fluency occurs at the fringe of consciousness (Reber, Wurtz, & Zimmermann, 2004; Winkielman, Schwarz, Fazendeiro, & Reber, 2003) and refers to the fact that processing a particular stimulus is characterized by low cognitive resource demands, which is reflected in high accuracy and high speed of processing. Subjective fluency, on the other hand, refers to the metacognitive subjective experience of easy processing a particular stimulus (Reber, Wurtz, & Zimmermann, 2004; Winkielman et al., 2003) and can be assessed by asking individuals directly about their feelings of ease of processing the stimulus (Alter & Oppenheimer, 2006).

According to the hedonic fluency model (Winkielman et al., 2003), a central characteristic of the experience of fluency is that it is hedonically marked. Concretely, this means that experiencing high fluency can cause a mild positive affective response in individuals. It has been argued that such a response takes place,

This article was published Online First August 31, 2015.

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Part of this research was funded by a postdoctoral research grant from the Research Fund—Flanders (FWO). We thank Danny Vanpoucke and Sylvia Wenmackers for designing the program to construct the high-fractal and low-fractal stimuli; Stratis Karras and Karen Fischer for assistance during programming the studies and data collecting; and Ben Lewis-Evans, Maja Fischer, and Agnes van den Berg for giving useful comments on this article.

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primarily because experiencing fluency signals a positive state of affairs about the environment (e.g., the environment is safe and/or familiar) or about ongoing cognitive processing (e.g., processing is successful, or there are enough resources available for processing; Winkielman et al., 2003). This fluency–affect link has been established using both self-reports and psychophysical indicators of positive affect (e.g., electromyography (EMG); Winkielman & Cacioppio, 2001).

Of crucial importance to the current article is that the hedonic marking of fluency can influence people's evaluations of the fluent stimulus. Specifically, individuals tend to misattribute fluency-caused positive affect to fluent stimuli, leading to greater aesthetic liking and increased perceived attractiveness of fluent as opposed to disfluent stimuli (Reber et al., 1998; Winkielman, Halberstadt, Fazendeiro, & Catty, 2006). Based on the misattribution of positive feelings to the fluent stimulus, Reber, Schwarz, and Winkielman (2004) have formulated their processing fluency theory of aesthetic pleasure, according to which aesthetic responses to stimuli are ultimately rooted in the processing dynamics underlying stimulus perception. The crux about this theory is that people's positive aesthetic responses to stimuli reflect fluent processing of these stimuli.

The processing fluency theory of aesthetic pleasure has, however, not remained without criticism. One of the main critiques is that people also often derive aesthetic pleasure from viewing complex and visually challenging objects or scenes (Armstrong & Detweiler-Bedell, 2008; Biederman & Vessel, 2006). One illustration of this is people's aesthetic responses to natural environments and elements. Research has amply demonstrated that complex, vegetation-dominated natural landscapes are aesthetically preferred over visually simpler built settings (e.g., Kaplan & Kaplan, 1989; Kaplan, 1995; Kaplan & Berman, 2010). It is furthermore well known that complex cultural creations, ranging from Gothic cathedrals to expressionist Jackson Pollock paintings (Taylor, Spehar, Van Donkelaar, & Hagerhall, 2011), can spark intense positive aesthetic responses in individuals (Keltner & Haidt, 2003). The fact that people thus derive aesthetic pleasure from such complex structures and phenomena undermines, or at least severely limits, a fluency account of aesthetic pleasure.

The root of the problem is that perceptual fluency research shows that especially simple objects, or organizational features that introduce simplicity into visual objects (e.g., repetition or symmetry; Bertamini et al., 2013; Reber, 2002) are more perceptually fluent than comparatively more complex elements and objects (e.g., Oppenheimer, 2008; Orth & Wirtz, 2014; Reber, Schwarz, & Winkielman, 2004; Winkielman et al., 2003). If perceptual simplicity is indeed one of the main drivers of perceptual fluency, and of concomitant positive aesthetic responses, then it becomes difficult to see how a perceptual fluency account of aesthetic pleasure can still accommodate complexity—where complexity is understood as the number and variety of elements present in a visual scene or image (Marin & Leder, 2013). Or, to put it more sharply: How can a fluency theory of aesthetic pleasure be right if there are instances where complex structures are preferred to simplicity?

We aimed to demonstrate that this (seeming) incompatibility between visual complexity and fluency theory does not always or necessarily hold, building upon seminal insights from the late French mathematician Benoît Mandelbrot. More than three decades ago, Mandelbrot demonstrated that Euclidean geometry was inadequate for describing the geometry of many real-world phenomena, and especially the geometry of most natural elements and environments (Mandelbrot, 1983). As he aptly noted, "Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line" (Mandelbrot, 1983, p. 1). To account for the complexity, irregularity, and fractured character of many natural phenomena, shapes and scenes, Mandelbrot developed "fractal geometry" (Mandelbrot, 1983).

Fractals are complex mathematical structures, and their complexity derives in a large part from the fact that they often display an internal repetition of similar, but increasingly smaller, pieces of visual information across a large number of scale levels (Figure 1). As a result, the details of a fractal structure often look like small-scale copies of the whole structure—a property referred to as "self-similarity" (Peitgen, Jürgens, & Saupe, 1992). Fractal geometry is often regarded as the "geometry of nature" because this deep internal repetition of similar but smaller pieces of visual information is abundantly present in nature (Figure 1), but much less characteristic to the visual outlook of modern urban environments (Mandelbrot, 1983; Peitgen et al., 1992; Voss, 1988).

How could insights from fractal geometry help to reconcile visual complexity and perceptual fluency? One line of reasoning is that many fractal structures—while being visually highly complex—can be generated using a very simple recursive rule (Peitgen et al., 1992). For example, the Koch Snowflake depicted in Figure 2 is the result of recursively replacing all sides of the original triangle by smaller triangles. Given that a simple computational rule underlies the geometric complexity of fractals, such structures might be easily parsed, possibly translating into relatively low processing demands (Martins, Laaha, Freiberger, Choi, & Fitch, 2014). A closely related idea is that internal repetition of visual information in fractals makes that such geometrically complex structures are characterized by higher levels of visual redundancy than objectively simpler shapes, perhaps leading to comparatively easier processing (Joye & Van den Berg, 2011; this point has also been made by fluency researchers: Reber, Schwarz, & Winkielman, 2004). Another speculative reason why fractals might be relatively fluent is based on the assumption that the visual brain evolved in a fractal/natural world, and that—as a result—it became

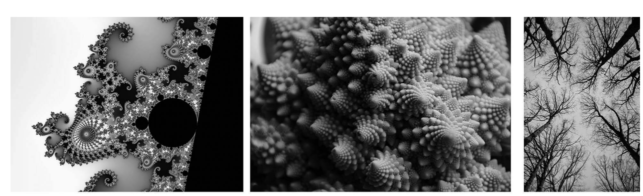

Figure 1. Pictures of one mathematical and two natural fractals, respectively, a fragment from the Mandelbrot Set (a), retrieved from https://en.wikipedia.org/wiki/Mandelbrot_set#/media/File:Mandel_zoom_03_seehorse.jpg (Creative Commons BY - SA 3.0), a picture of a romanesco cauliflower (b), retrieved from https://en.wikipedia.org/wiki/Self-similarity#/media/File:Flickr_-_cyclonebill_-_Romanesco.jpg (Creative Commons BY - SA 2.0), and a photo of tree canopies (c), credits: Tom Godber; retrieved from https://www.flickr.com/photos/26332965@N00/370848361 (Creative Commons BY - SA 2.0). All three structures have easy-to-appreciate fractal characteristics: Because there is a continuous internal repetition of visual information, the small-scale elements of the structures are (approximate) copies of the whole structure.

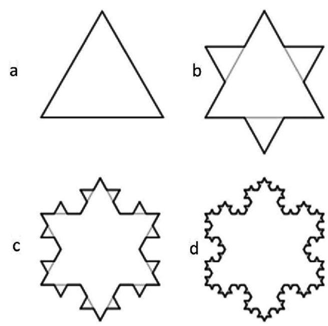

Figure 2. The Koch Snowflake—that is, (d)—is generated by recursively replacing all straight line segments by smaller triangles. Retrieved from https://commons.wikimedia.org/wiki/File:KochFlake.svg#/media/File:KochFlake.svg (Creative Commons BY - SA 3.0).

optimally adapted to efficiently code and process scenes or objects with fractal characteristics (Redies, 2007).

The foregoing arguments thus suggest that, while fractals might be visually and geometrically highly complex, they are at same time relatively simple from a computational point of view—either because of an evolved bias or because of simple generative rules underlying fractals. Up until this day, however, no research has tried to experimentally confirm whether fractal structures can indeed be easy on the mind. With the current studies, we aimed to address this void and investigated whether visual complexity that derives from an internal repetition of information—as can be found in fractal shapes—is perceptually fluent.

The Present Studies

In three studies, we examined whether visual structures high on fractal characteristics were perceptually more fluent than structures low on fractal characteristics. In the first two studies, participants had to watch pictures of three-dimensional block structures, which were characterized by either a relatively high (i.e., high-fractal stimuli) or low level of internal repetition (i.e., low-fractal stimuli) of visual information (within-subjects design). As noted earlier, the recurrence of similar visual information on lower structural scale levels is a crucial property of fractal structures. During (Study 1) and after (Study 2) viewing these block structures, participants had to perform a cognitively effortful task, consisting of deciding as fast and as accurate as possible whether a string of geometric shapes was either a target or a nontarget (see Joye, Pals, Steg, & Lewis-Evans, 2013).

Using this particular experimental paradigm, our primary aim in Study 1 and Study 2 was to test whether exposure to the two types of block structures would lead to performance differences on the effortful task. We specifically expected that, despite being visually the most complex, high-fractal stimuli would be processed more fluently than would low-fractal stimuli, as indicated by high task accuracy and speed (i.e., objective fluency), and low task difficulty/effort ratings (i.e., subjective fluency). The main measurements in Study 1 and Study 2 thus included dependent variables that had been previously used in fluency research; that is, objective (e.g., Reber, Wurtz, & Zimmermann, 2004) and subjective fluency indicators (e.g., Alter & Oppenheimer, 2006).

At the end of Study 2, we also undertook a number of control measurements. With these, we aimed to verify whether the high-fractal block structures were indeed perceived as the most complex and to assess the differential attention grabbing character of the stimuli. For exploratory purposes, we also examined the hedonic and aesthetic impact of sample stimuli of the stimulus set. Following the hedonic fluency model (Winkielman et al., 2003), we expected that the most fluent stimulus type would be associated with highest levels of positive affect and would receive the most positive aesthetic evaluations.

While we conducted Study 1 and Study 2 mainly to verify whether high-fractal versus low-fractal stimuli were indeed perceptually fluent, Study 3 was conducted to rule out possible alternative explanations. Specifically, we ran the Dot Probe Procedure (DPP; MacLeod, Mathews, & Tata, 1986; Salemink, van den Hout, & Kindt, 2007) to test for differences in attentional bias toward the high-fractal versus low-fractal stimuli. If such an attentional difference would exist, possible performance differences between the high-fractal and low-fractal condition found in Study 1 and Study 2 might reflect a differential attentional bias, rather than differences in perceptual fluency.

Study 1

We exposed participants to pictures of three-dimensional block structures, characterized by either a relatively high (i.e., high-fractal block structures) versus low level of internal repetition (i.e., low-fractal block structures) of visual information. The pictures of both types of block structures were surrounded by visual puzzles, and the cognitively effortful task consisted of solving these puzzles as fast and as accurate as possible. Based on the assumption that a relatively deep level of internal repetition of visual information is a source of perceptual fluency, we expected highest accuracy and fastest response times (i.e., objective fluency), and lowest difficulty ratings (i.e., subjective fluency) for puzzles that had been presented together with the high-fractal block structures.

Method

Participants and design. Forty students (25 women) from a large European university participated in this study. The study was a within-subjects design, with "stimulus type" (i.e., high-fractal vs. low-fractal experimental stimuli) as the within-subjects variable. Because of a saving error, we recorded no data on the gender and perceived fluency measure for three participants.

Materials.

Block structures. As illustrated in Figure 3, the experimental stimuli consisted of two main elements: (a) a grayscale image of a three-dimensional block structure, and (b) a visual puzzle, surrounding the block structure. Each block structure was built according to an iterative process that started off with four upstanding bars. On each iteration, the outward sides of each bar were surrounded by another, scaled-down upstanding bar. There was limited random variation in the scaling factor, to simulate the fact that natural structures and patterns are self-similar rather than self-same (Peitgen et al., 1992). Two types of block structures were created: 12 "low-fractal" block structures and 12 "high-fractal" block structures, which were, respectively, the result of two and five iterations.

The reason we stopped at five iterations for creating the high-fractal block structures was that the smallest upstanding bars would become

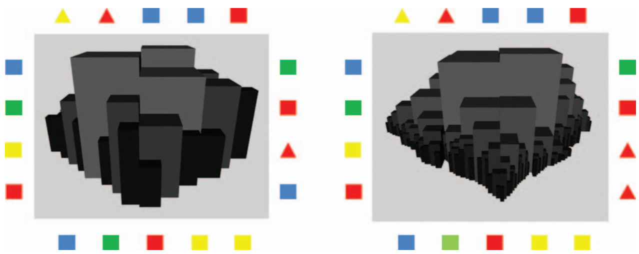

Figure 3. Sample pictures of low-fractal (left) and high-fractal (right) experimental stimuli, consisting of both a block structure and a visual puzzle. See the online article for the color version of this figure.

practically invisible on more iterations. Note also that we chose to use abstract block structures because fractal structures resembling natural objects could have confounded our results, because nature has distinct affective and symbolic connotations (Kaplan & Kaplan, 1989). The choice for three-dimensional structures was inspired by the fact that the majority of fractal structures encountered in daily life (e.g., trees) are three-dimensional.

To ascertain that the high-fractal block structures were indeed visually more complex than the low-fractal ones, we looked (post hoc) at the compressed JPEG image file size of all 12 images within each condition. Image file size has been shown to be a reliable indicator of image complexity and also predicts subjective visual complexity ratings of images (Marin & Leder, 2013). The average file size of the high-fractal block structures was 11.01 kilobytes ($SD = 0.74$), whereas the average file size of the low-fractal block structures was 7.12 kilobytes ($SD = 0.44$). A paired-samples t test revealed that this difference in file size was significant, $t(11) = -13.25$, $p < .001$, thus confirming that the images of the high-fractal block structures were indeed significantly more complex than their low-fractal counterparts.[1]

Visual puzzles. Besides block structures, we created visual puzzles. These consisted of 18 colored (red, green, yellow, and blue) geometric shapes—squares and triangles—arranged along all sides of each block structure picture. Puzzles were either "target" or "nontarget" puzzles. Targets ($n = 12$) were defined as shape sequences containing exactly four triangles, two of these triangles were adjacent, and each of the four triangles had a different color. Nontargets ($n = 12$) violated at least one of these three properties (Joye et al., 2013).

Experimental stimuli. All experimental stimuli consisted of a block structure with a puzzle arranged around it (Figure 3). We created a series of 12 high-fractal experimental stimuli by arranging the puzzles (i.e., six targets and six nontargets) around the 12 high-fractal block structures. A series of 12 low-fractal experimental stimuli was made by arranging puzzles (i.e., six targets and six nontargets) around the 12 low-fractal block structures. We controlled for puzzle difficulty across both conditions.

Procedure. On arrival in the lab, each participant was guided to a personal computer, filled out an informed consent form, and was briefed about the upcoming experiment. During the experiment, participants were shown the experimental stimuli, and their task was to decide whether the puzzle surrounding the block structure was either a target or a nontarget. Participants were briefed about what constitutes a target or nontarget. Before the actual experimental trials began, participants completed 10 practice trials, which consisted of similar puzzles surrounding images of unrelated objects (e.g., bicycles and cars) rather than block structures. They received on-screen feedback about their performance on the practice trials.

Next, participants had to complete a total of 24 experimental trials, which were presented in two consecutive phases. In the high-fractal phase, participants saw 12 high-fractal experimental stimuli (i.e., high-fractal block structures surrounded by puzzles), whereas in the low-fractal phase, they viewed 12 low-fractal experimental stimuli (i.e., low-fractal block structures surrounded by puzzles). Presentation order within each phase was randomized, whereas phase order was counterbalanced across participants to neutralize order effects. We presented the experimental trials in two consecutive phases to allow us to probe perceived difficulty of solving puzzles associated with either the high-fractal or low-fractal phase. Our rationale for not measuring perceived difficulty after each individual trial was that this could interfere with the objective fluency measurements (i.e., response accuracy and speed).

Each experimental trial always began with a fixation cross that remained in the middle of the screen for 400 ms. After that, an experimental stimulus appeared, and respondents had to indicate as fast and as accurate as possible whether the puzzle surrounding the block structure displayed was either a target (by pressing "z") or a nontarget (by pressing "m"). The time limit for responding was 8,000 ms. To probe for perceived cognitive difficulty, we asked respondents after each of the two phases how difficult they found solving the puzzles from that phase (1 = *very easy* to 7 = *very difficult*). The entire study lasted approximately 5 min.

Results

Using paired-samples t tests, we tested for significant differences between the high-fractal and low-fractal phases in average response accuracy, average response time (in milliseconds), and average perceived difficulty ratings of the puzzles.[2] The findings are summarized in Figure 4. As expected, response accuracy was significantly higher for puzzles from the high-fractal ($M = 0.96$; $SD = 0.06$) than for puzzles from the low-fractal phase ($M = 0.90$; $SD = 0.11$), $t(39) = -2.93$, $p = .006$, $d = 0.65$, 95% confidence interval (CI) [−0.10, −0.02]. Participants were on average also significantly quicker in correctly identifying target and nontarget puzzles (in milliseconds) during the high-fractal phase (M = 2,878; $SD = 768$) than during the low-fractal phase (M = 3,176; $SD = 889$), $t(39) = 3.31$, $p = .002$, $d = 0.35$, 95% CI [116, 480].[3] In addition, respondents rated puzzles from the high-fractal phase

[1] Note that JPEG compression is not based on an image's fractal characteristics to compress the image.

[2] An outlier analysis based on accuracy scores averaged across the two conditions yielded not outliers.

[3] Because of a programming error, participants in the low-fractal phase received five target and seven nontarget puzzles, in contrast to six targets and six nontarget puzzles in the high-fractal phase. Nontarget puzzles are probably easier to solve than target puzzles, because solving them depends on checking less conditions than for targets. Consistent with this, a paired-samples t test indeed showed that nontarget puzzles (M = 2,713; SD = 710) required significantly less time to solve than target puzzles (M = 3,402; $SD = 943$), $t(39) = 7.44$, $p < .001$, $d = 0.77$, 95% CI [501, 876]. If anything, this programming error very probably made the puzzles from the low-fractal phase generally somewhat easier to solve than puzzles from the high-fractal phase.

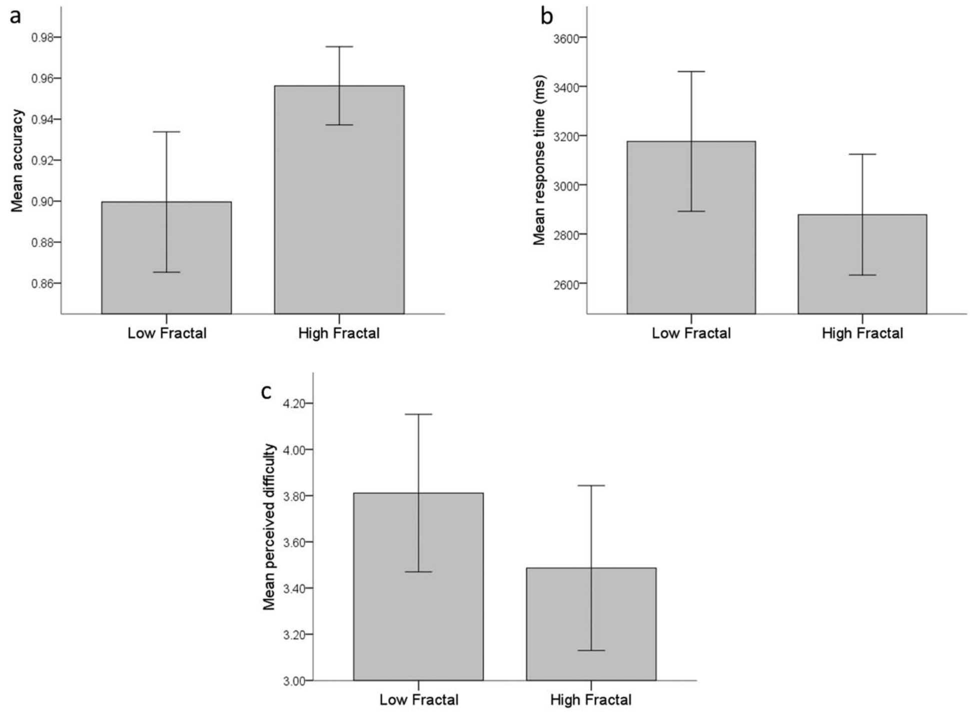

Figure 4. Study 1: mean accuracy (a), response time (b) and perceived difficulty (c) as a function of high-fractal versus low-fractal stimuli (error bars represent 95% confidence intervals).

(M = 3.49; SD = 1.07) as significantly less difficult to solve than puzzles from the low-fractal phase (M = 3.81; SD = 1.02), $t(36)$ = 2.41, p = .021, d = 0.31, 95% CI [0.05, 0.60].

Discussion

As expected, participants were most accurate and quick in solving puzzles surrounding high-fractal block structures and evaluated these as less difficult to solve than puzzles from the low-fractal phase. This suggests that high-fractal block structures were more fluent to process than the low-fractal block structures. However, we did not control for exposure times to the block structures, and we repeatedly exposed participants to the same type of block structure, which might have confounded our results. In addition, by not having included a control condition consisting of puzzles without block structures, it was not possible to ascertain whether the high-fractal and low-fractal block structures either improved or worsened performance. To strengthen our interpretation in terms of fluent processing of high-fractal block structures, in Study 2 we changed the experimental setup by decoupling the block structure and puzzle presentation and by including a control condition. We also included a number of control measurements to verify whether high-fractal block structures were indeed perceived as most complex and to examine whether they had the most positive hedonic and aesthetic impact on participants.

Study 2

Participants again watched the three-dimensional block structures, solved visual puzzles, and indicated how difficult and effortful they found solving the puzzles. We made five changes to the experimental setup from Study 1. First, we no longer displayed the block structures and puzzles simultaneously, but presented them in two consecutive phases and controlled the presentation time of each block structure. Second, we included a control condition to get a grip on participants' baseline scores for solving puzzles. Third, we randomized the presentation order of all puzzle–block structure pairs. Fourth, we measured the extent to which respondents perceived (a selection of) the high-fractal and low-fractal block structures as "complex" and "attention grabbing." Finally, because we wanted to explore the hedonic marking and the aesthetic impact of the high-fractal and low-fractal block structures, we asked participants how much (a subset of) these structures led to "a good feeling" and triggered "fascination."

Method

Participants and design. Ninety-nine students (70 women) from a large European university participated in this study. The study was a within-subjects design with experimental condition (i.e., high-fractal, low-fractal, and control condition) as the within-subjects variable. Because of a saving error, we recorded no data for two participants for all experimental trials.

Materials. The experiment again consisted of combinations of puzzles and block structures, having the same properties as the materials described in Study 1. There were three experimental conditions: a "high-fractal," a "low-fractal," and a "control" condition. Each condition consisted of 12 puzzles, which were all preceded by either a high-fractal block structure (in the high-fractal condition), a low-fractal block structure (in the low-fractal condition), or a white screen (in the control condition). All block structure—puzzle pairs from all conditions were randomly presented to the participants. The 12 puzzles within each condition always consisted of six target puzzles and six nontarget puzzles. Targets and nontargets were defined in the same way as in Study 1. We controlled for puzzle difficulty across all three conditions.

Procedure. Upon arrival in the lab, each participant was guided to a personal computer, filled out an informed consent form, and was briefed about the upcoming experiment. During the actual experiment, participants were shown block structure—puzzle pairs, with the block structure this time presented before the puzzle. Again, their main task was to decide whether the puzzle depicted was either a target or a nontarget. Participants were briefed about what constitutes a target or nontarget. Before the actual experimental trials began, participants completed 10 practice trials, with images of unrelated objects (i.e., Chinese characters or furniture) instead of block structures preceding the puzzles.[4] They received onscreen feedback about their performance on the practice trials.

Each experimental trial always began with a fixation cross that remained in the middle of the screen for 400 ms. After that, a randomly selected picture of either a high-fractal block structure, a picture of low-fractal block structure, or a white screen (control condition) was displayed for 4 s. Participants were asked to focus on the block structures or white screen. Following this, a visual puzzle appeared, and participants had to judge as fast and as accurate as possible whether it was a target (by pressing "z") or a nontarget puzzle (by pressing "m"). The time limit for responding was again set at 8,000 ms.

In addition to measuring objective fluency indicators, we also probed participants' subjective evaluations of the puzzles and block structures belonging to each of the three experimental conditions. For this purpose, we presented participants with two exemplar stimuli from each of the three conditions (e.g., two high-fractal block structure-puzzle pairs) and instructed them to solve the two exemplar puzzles of each pair in the same way as they had been doing for the experimental trials. We randomized the order with which each pair of exemplars from each condition was presented. The reason for a separate trial for these evaluations and questions was to avoid interference with the objective fluency measurements.

For the high-fractal and low-fractal condition, we asked participants how much the block structure preceding the puzzle had grabbed their attention (1 = *very little* to 7 = *very much*), and for all three conditions we asked how much effort it had taken them to solve the puzzles (1 = *very little* to 7 = *very much*), and how difficult (1 = *very easy* to 7 = *very difficult*) they found it to solve the puzzles. For each experimental condition, we calculated an effort index (reflecting subjective fluency), by averaging the scores on the effort and difficulty ratings (high-fractal condition, Cronbach's alpha = .83; low-fractal condition, Cronbach's alpha = .79; control condition, Cronbach's alpha = .84).

After having solved the two exemplar puzzles of each condition, we probed how "fascinating" and "complex" participants found a sample picture of the block-structures from the high-fractal and low-fractal condition, and how much watching that picture gave them a "good feeling" (all items coded from: 1 = *very little* to 7 = *very much*).[5] The entire study lasted approximately 10 min.

Results

Objective and subjective fluency indicators. One participant was removed because his or her total accuracy score (averaged across the high-fractal, low-fractal, and control condition) was more than 3 *SD*s below the mean accuracy ($M = 0.91$; $SD = 0.10$) for the three conditions. We performed three one-way repeated-measures analyses of variance (ANOVAs) with respectively average response accuracy, average response time, and the effort index as the dependent variables (see Figure 5 for graphs of the results).[6] For accuracy, Mauchly's test indicated that the assumption of sphericity had been met, $\chi^2(2) = 3.37$, $p = .185$. We found statistically significant differences in accuracy scores between the three conditions, $F(2, 190) = 16.07$, $p < .001$. Planned contrasts showed that participants were significantly more accurate in solving puzzles from the high-fractal condition ($M = 0.95$; $SD = 0.07$) than puzzles from the low-fractal condition ($M = 0.90$; $SD = 0.11$), $p < .001$, $d = 0.53$, 95% CI [0.03, 0.07] and control condition ($M = 0.90$; $SD = 0.11$), $p < .001$, $d = 0.52$, 95% CI [0.03, 0.07]. Accuracy scores did not significantly differ between the control condition and the low-fractal condition, $p = .907$, $d = 0.01$, 95% CI [−0.02, 0.02].

For response time, Mauchly's test indicated that the assumption of sphericity had been met, $\chi^2(2) = 5.02$, $p = .081$. There were statistically significant differences between the three conditions for response times (in milliseconds) on correct puzzles, $F(2, 190) = 7.65$, $p = .001$. Specifically, puzzles from the high-fractal condition ($M = 2{,}861$; $SD = 754$) were solved significantly faster than the puzzles from the low-fractal condition ($M = 3007$; $SD = 828$), $p < .001$, $d = 0.18$, 95% CI [−224, −67], and control condition ($M = 2{,}956$; $SD = 748$), $p = .020$, $d = 0.12$, 95% CI [−174, −16]. Although participants were faster in solving puzzles from the control condition than puzzles from those in the low-fractal condition, this difference was not statistically significant, $p = .132$, $d = 0.06$, 95% CI [−116, 15].

For the effort index, Mauchly's test indicated that the assumption of sphericity had been met, $\chi^2(2) = 1.22$, $p = .543$. Our analyses revealed statistically significant differences in the effort index between the conditions, $F(2, 190) = 3.49$, $p = .033$. Participants indicated that it took significantly more effort to solve the puzzles from the low-fractal condition ($M = 3.28$; $SD = 1.10$) than the puzzles from the high-fractal condition ($M = 3.07$; $SD = 1.11$), $p = .032$, $d = 0.19$, 95% CI [0.02, 0.40], and the control condition ($M = 3.03$; $SD = 1.19$), $p = .019$, $d = 0.22$, 95% CI [0.04, 0.46]. Puzzles from the high-fractal condition were not rated as taking significantly more or less effort to solve than puzzles from the control condition, $p = .688$, $d = 0.04$, 95% CI [−0.16, 0.25].

Evaluations of the block structures. Using paired-samples *t* tests, we tested for differences in the evaluations of the high-fractal

[4] The reason why the pictures in the practice trials of this study were different from those used in Study 1 was that the experiment was designed by another programmer.

[5] We also asked participants how "coherent" they found the block structures, and whether they found watching these structures to be "mentally refreshing" and "relaxing" (1 = *very little* to 7 = *very much*). Results for these measures are provided in the Appendix.

[6] Like in Study 1, participants in the low-fractal condition erroneously received five target and seven nontarget puzzles, in contrast to six targets and six nontarget puzzles in the high-fractal and control condition.

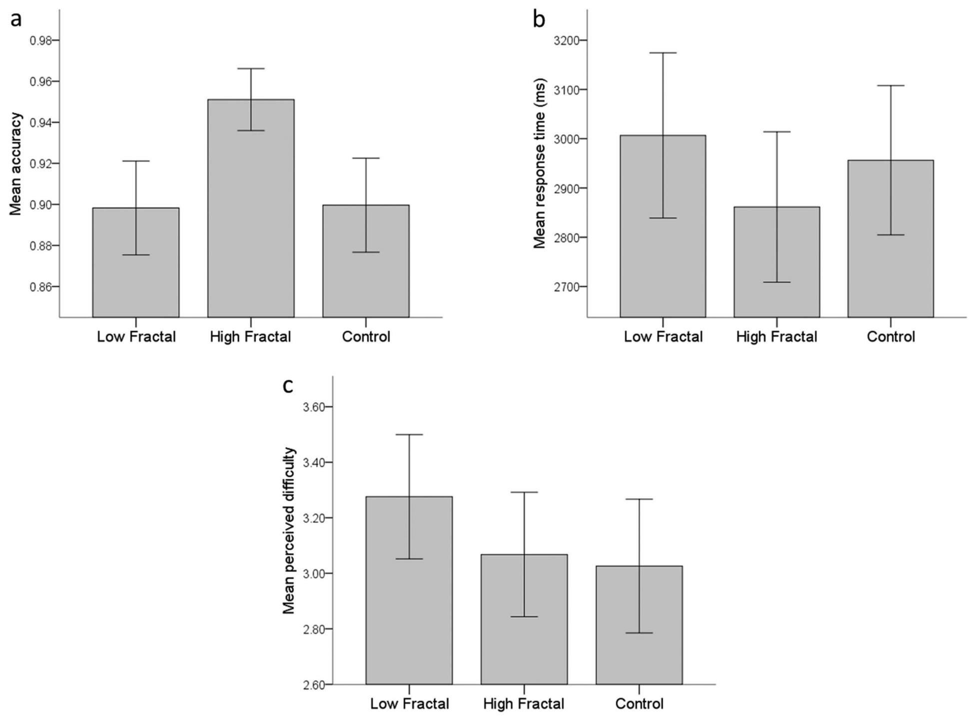

Figure 5. Study 2: mean accuracy (a), response time (b) and the effort index (c) as a function of control, high-fractal, and low-fractal stimuli (error bars represent 95% confidence intervals).

versus the low-fractal block structures. High-fractal block structures were judged as significantly more complex ($M = 4.75$; $SD = 1.47$), $t(95) = 5.88$, $p < .001$, $d = 0.57$, 95% CI [0.57, 1.16] and somewhat more attention grabbing ($M = 3.84$; $SD = 1.72$), $t(95) = 1.93$, $p = .057$, $d = 0.25$, 95% CI [−0.01, 0.85], than low-fractal block structures (complexity: $M = 3.89$; $SD = 1.54$; attention grabbing: $M = 3.43$; $SD = 1.61$). Also, participants found high-fractal block structures significantly more fascinating ($M = 3.42$; $SD = 1.65$) than their low-fractal counterparts ($M = 2.73$; $SD = 1.39$), $t(95) = 4.50$, $p < .001$, $d = 0.45$, 95% CI [0.38, 0.99]. For good feeling, there were no statistically significant differences between the high-fractal ($M = 2.36$; $SD = 1.39$) and low-fractal block structures ($M = 2.47$; $SD = 1.21$), $t(95) = -1.03$, $p = .305$, $d = 0.08$, 95% CI [−0.30, 0.10].

Finally, we performed correlation analyses within and across the high-fractal and low-fractal conditions (see Table 1 for results). Because the experience of fluency has been claimed to lead to mild positive affect and to positive aesthetic responses (Winkielman et al., 2003), we expected that the evaluation items "fascination" and "good feeling" would positively correlate with the objective fluency indicators (i.e., accuracy and response time). In partial support of this, we found a modest but positive and statistically significant correlation between accuracy and good feeling within the high-fractal condition (Table 1, left panel). Within the low-fractal condition, there was a statistically significant positive correlation between fascination and accuracy (Table 1, middle panel). When considering the correlations across the high-fractal and low-fractal condition (Table 1, right panel), the most relevant finding was a (modest) statistically significant positive correlation between fascination and accuracy.

Discussion

Despite the fact that high-fractal block structures were perceived as more complex and attention grabbing than low-fractal block structures, our results indicate that increased levels of internal repetition of visual information made a complex visual structure somewhat easier to process than an apparently simpler visual structure. Specifically, we found that participants were significantly more accurate and faster at solving puzzles from the high-fractal condition than puzzles from the low-fractal condition, and also perceived the puzzles from the high-fractal versus low-fractal condition as the easiest ones to solve.

By including the control condition, we were able to show that exposure to high-fractal block structures led to a significant improvement in accuracy and response speed compared with the control condition. While there was no difference between the low-fractal condition and the control condition on accuracy in solving puzzles, participants were somewhat faster on the trials from the control condition than after seeing low-fractal block structures. Perceived effort ratings for puzzles from the high-fractal condition did not significantly differ from those from the control condition.

Our exploration of positive aesthetic and hedonic responses toward the stimuli yielded mixed results: Participants were more fascinated by the high-fractal as opposed to the low-fractal block structures, but we did not find any significant differences in level of good feeling between the two types of block structures. However, in agreement with the hedonic fluency model (Winkielman et al., 2003), we found positive correlations between accuracy scores and good feeling in the high-fractal condition, and between accu-

Table 1
Correlations Between the Objective Fluency Indicators (Accuracy and Response Time) and the Evaluation Items "Fascination" and "Good Feeling"

	High-fractal condition				Low-fractal condition				Across conditions			
Measure	1	2	3	4	1	2	3	4	1	2	3	4
1. Fascination		.491**	.076	−.063		.570**	.216*	−.036		.502**	.198*	−.069
2. Good feeling			.226*	−.055			.096	−.072			.129	−.059
3. Accuracy				.124				.157				.112
4. Response time												

* $p < .05$ level (2-tailed). ** $p < .01$ level (2-tailed).

racy and fascination across the high-fractal and low-fractal condition. The latter findings possibly reflect the fact that participants derived a good feeling from (the experience of) fluently processing the (high-fractal) block structures, and misattributed those feelings onto the stimuli in terms of aesthetic liking.

While these results largely replicated the main findings from Study 1, they also raise two important issues. The first one relates to the finding that participants reported that the high-fractal block structures were somewhat more attention grabbing than their low-fractal counterparts. If true, this finding raises the question how attention could have been freed up for the primary task (i.e., solving puzzles) and how it could have led to superior performance on solving puzzles. A second issue is that we cannot rule out an alternative explanation for the findings; namely, that the high-fractal block structures were somewhat easier to ignore or discount than were the low-fractal ones. Such discounting might have made that participants more easily turned their attention to solving puzzles (leading to faster response times), which, under time pressure, might also have translated into higher accuracy scores. With Study 3, we aimed to tackle these two outstanding issues by more objectively testing the attention grabbing character of the high-fractal versus low-fractal block structures.

Study 3

Using the DPP, we investigated whether participants were attentionally biased to the high-fractal as opposed to the low-fractal stimuli. The DPP consists of simultaneously presenting participants two images and monitoring their performance on a subsequent spatial locating task, which consists of locating the position of a dot on either side of the computer screen as fast as possible. If individuals are indeed more attentionally biased to one of the two displayed images, they will identify the position of the dot more quickly when it appears on the former position of the attention-grabbing image. If the findings from Study 1 and Study 2 were the result of easier (attentional) discounting or ignoring high-fractal block structures, then participants should locate dots slower when they are situated on the former location of a high-fractal as opposed to a low-fractal block structure.

Method

Participants and design. Sixty-seven students (47 women) from a large European university participated in this study. The study was a within-subjects design, with "stimulus type" (i.e., high-fractal vs. low-fractal block structures) as the within-subjects variable.[7]

Materials and procedure. Upon arrival in the lab, each participant was guided to a personal computer, filled out an informed consent form, and was briefed about the upcoming experiment. The materials for this study were the (images of the) 12 high-fractal and 12 low-fractal block structures that had been used in Study 1 and Study 2. The DPP began with six practice trials, consisting of pictures of Chinese characters (MacLeod et al., 1986; Salemink et al., 2007). The actual DPP consisted of a total of 24 trials. Each DPP trial began with a focus cross that remained on the screen for 400 ms. After that, an image pair was displayed on the screen for 600 ms. Each image pair consisted of an image of a high-fractal and low-fractal block structure, both of which were randomly selected from the image set of 24 block structures that was used in Study 1 and Study 2. Each image was displayed either on the left or the right side of the screen, and the on-screen position of the two image types (left or right) was counterbalanced across all DPP trials. There were eight actual DPP trials, where a dot appeared on the left or the right side of the screen during 500 ms, immediately after image presentation. For these DPP trials, a dot appeared exactly four times on the former position of the image of a high-fractal block structure, and four times on the former position of the image of a low-fractal block structure. The 16 remaining trials were invalid DPP trials because a blank screen was displayed after image presentation during 500 ms, rather than a dot. The presentation order of the actual DPP trials and invalid trials was randomized. Our general instruction for participants was to identify as fast as possible the location of the dot on the screen (left or right), by respectively pressing the "z" or the "m" button. We recorded the time participants needed to correctly respond to the location of the dot (in milliseconds) and the accuracy with which the dots were located.

Results and Discussion

Three participants were removed from the analyses: for two participants, the overall response time (in milliseconds, averaged across the actual DPP trials) was more than 3 *SD*s above the average overall response time ($M = 326$; $SD = 144$), whereas one participant had no correct responses for dots that were located on the former position of low-fractal block structures. Using two

[7] Three further individuals participated, but we recorded no useful data or valid responses from them, because of a computer error.

paired-samples *t* tests, we tested for differences between the high-fractal and low-fractal condition on response speed and on accuracy for locating the position of the dots. These analyses revealed no statistically significant differences in response speed (in milliseconds) for locating dots that were on the former position of either low-fractal (M = 300; SD = 116) or high-fractal block structure images (M = 311; SD = 131), $t(63) = 0.77$, $p = .445$, $d = 0.10$, 95% CI [−17, 39]. Dots were located somewhat more accurately when they were in the former position of a high-fractal block structure ($M = 4.00$; $SD = 0.00$) than in the former position of a low-fractal one (M = 3.95; SD = 0.21), but this difference was not statistically significant, $t(63) = 1.76$, $p = .083$, $d = 0.31$, 95% CI [−0.01, 0.10]. We dare to give too much interpretation to this finding because it was driven by only a very small number of participants (n = 3) who did not execute the cognitive task perfectly when the dot was on the former position of a low-fractal block structure image (i.e., 3 out 4 correct).

In sum, in contrast to the finding from Study 2 that participants found the high-fractal block structures somewhat more attention grabbing than their low-fractal counterparts, the DPP revealed no evidence of an attentional bias to the high-fractal block structures. The lack of statistically significant differences on the DPP furthermore suggests that it is unlikely that task performance differences found in Study 1 and Study 2 were driven by the fact that high-fractal stimuli were somewhat easier to ignore or discount.

General Discussion

Are visually simple stimuli easier on the mind than visually more complex stimuli? Not necessarily. Inspired by insights from fractal geometry, we tested whether visual/geometrical complexity deriving from a continuous internal repetition of visual information is a source of perceptual fluency, resulting in easier processing and more positive evaluations of visually complex stimuli. Overall, our results suggest that despite their high geometrical complexity, the high-fractal block structures were actually *simpler* than the low-fractal ones in terms of processing or computational demands.

Specifically, across two studies, participants were most accurate and fastest in solving cognitively effortful puzzles associated with high-fractal block structures, and also perceived those puzzles as the least difficult and effortful ones to solve. In Study 2, we found that block structures characterized by a high level of internal repetition of information were also perceived as more complex and attention grabbing than structures with a comparatively low level of internal repetition of information. The null result on the DPP in Study 3 seems to suggest that it is unlikely that the effects found in the previous two studies were driven by differences in attention grabbing character between the high-fractal and low-fractal block structures. Together, these findings provide the first empirical evidence that complexity deriving from internal repetition of visual information—a characteristic of natural and fractal structures—is relatively easy on the mind. This also shows that a fluency theory of aesthetic pleasure (Reber, Schwarz & Winkielman, 2004) does not necessarily have validity only for simple objects, but can potentially also accommodate people's responses to certain visually complex and intricate objects.

While we thus have clear evidence of fluency effects using both objective (i.e., response times and response accuracy in Study 1 and Study 2) and subjective fluency indicators (i.e., perceived difficulty/effort ratings in Study 1 and Study 2), our results for more "downstream" fluency effects (i.e., Study 2) were mixed. Specifically, we did not find any differences between the high-fractal and low-fractal block structures for positive affect (i.e., good feeling), and did thus not directly replicate the established finding that easy processing leads to (mild) positive affect (Reber et al., 1998). Correlation analyses did however reveal that fluent processing of high-fractal block structures was moderately associated with positive feelings, potentially reflecting the (positive) hedonic marking of the experience of fluency. The finding that participants were most fascinated by the high-fractal block structures can be interpreted in terms of misattributing the positive experience of processing fluency to the fluent stimulus (Reber, Schwarz, & Winkielman, 2004).

Our results dovetail with perceptual fluency research showing that stimulus repetition is (perceptually) fluent (Reber, Schwarz, & Winkielman, 2004). However, in addition to repeating information by mirror symmetry (Bertamini et al., 2013; Reber, 2002), or by repeating it over time (e.g., the mere exposure effect: Bornstein & D'Agostino, 1994), our findings indicate that also repetition through nesting similar visual information in one and the same structure can be a source of some fluency. The results are furthermore in agreement with speculations made within the literature on fractals, according to which fractal shapes can be efficiently parsed (Martins et al., 2014), and are low on cognitive resource demands.

What could be the possible mechanism underlying the observed fluency effect? In the beginning of this article, we already hinted at speculations that easy processing of fractals might be caused by the visual redundancy characteristic of fractals (Joye & Van den Berg, 2011) and by the fact that fractals are often generated using a simple recursive rule (Martins et al., 2014). To explain the mechanism underlying the effects found in Study 1 and Study 2, we bring both speculative perspectives together. Specifically, we hypothesize that the visual redundancy that resulted from a relatively high level of internal visual repetition provided top-down contextual information that facilitated the visual interpretability of the high-fractal block structures. Specifically, high visual redundancy in high-fractal block structures made it very salient which particular rule was underlying the structural organization and generation of these complex hierarchical stimuli. The lack of deep repetition and redundancy in the low-fractal block structures entailed that there was no clear-cut generative rule to discern, which hindered easy readability of the structure, especially because our stimuli were also characterized by a certain degree of randomness.

There are of course limitations to our research. One limitation is that there may have been visual confounds, despite the fact that we have tried to vary the stimuli on only one dimension. One concern might be that the ground level contours of the high-fractal block structures (at first glance) appeared to be smoother than the ground level contours of the low-fractal ones. Because research has shown that smoothness leads to fluent visual processing and liking (Reber, 2012), the difference in smoothness of the high-fractal block structures might constitute an alternative explanation for our findings. To settle this issue, we measured the fractal dimension (FD) of the ground level contours of all block structures. Inasmuch as the FD provides an index for contour complexity and roughness (Gneiting, Ševčíková, & Percival, 2012), it should be able to detect smoothness differences between the contours of the high-fractal versus low-fractal block structures. Although our measurements showed that the difference in FD between both stimulus types was very small, the ground level contours of the high-fractal block structures ($M = 1.03$; $SD = 0.02$) had a somewhat higher FD than those of the low-fractal block structures ($M = 0.99$, $SD = 0.00$), $t(11) = 4.85$, $p = .001$.[8] If anything, these findings thus demonstrate that the high-fractal block structures were somewhat *more* rugged and complex than their low-fractal counterparts.

Another point is that by having used upstanding bars, the low-fractal block structures might have looked more like a city skyline than the high-fractal ones. In agreement with environmental psychology research, priming "city" in participants might have increased (resource-consuming) vigilance in them (Kaplan & Berman, 2010), leading to overall worse performance on identifying the visual puzzles in the low-fractal condition. Note, however, that this issue rests on the assumption that city skylines are simple and nonfractal, whereas research has shown that city skylines can have fractal aspects as well (Stamps, 2002). Still, we agree that the results of the current research need to be replicated with a variety of other visual stimuli that vary in fractal character. It will nevertheless remain difficult, if not impossible, to avoid that the high-fractal stimuli will look somewhat like natural structures, merely because internal repetition of visual information is inherent to the visual structure of many natural objects (Voss, 1988).

A third limitation is that our studies differed from other fluency research in two major respects. First, we have only indirectly measured fluency by assessing participants' performance on visual puzzles, which were unrelated to the high-fractal versus low-fractal block structures. One might therefore wonder how effectively perceptual fluency of the fractal shapes was measured, as opposed to the puzzles they were immediately associated with. In perceptual fluency experiments, however, the actual fluent/disfluent stimuli are often directly used to measure fluency (e.g., identification times of words characterized by high vs. low levels of figure-ground contrast; Reber, Wurtz & Zimmermann, 2004). While we could have asked participants to identify as fast as possible whether the block structures were fractal or not, we opted for our indirect measurement because we were concerned that they would struggle with grasping what a fractal is.[9] A second difference with other fluency research is that we have used a rather complex task to probe fluency; that is, solving visual puzzles. Future research could therefore probe for fluency by asking participants to identify only one simple shape (e.g., a triangle) instead of a complex string of shapes.

A fourth limitation is that there was only a modest link between the performance indicators in Study 2 (i.e., response times and accuracy) and the items tapping into participants' liking and positive affect (i.e., "fascination" and "good feeling"). Probably, this is because of the exploratory nature of this part of our research. This made us measure self-reported liking and positive affect only after our primary fluency measurement, using only randomly sampled pictures from the entire picture set. Further research is therefore needed to provide additional and more conclusive evidence about a positive relationship between fluent processing of high-fractal block structures and positive affect; for example, by psychophysiologically measuring positive affect (e.g., facial EMG; Winkielman & Cacioppo, 2001) instead of using self-reports. Notice, however, that despite lacking strong evidence for these downstream effects of fluency, we had clear evidence that internal (i.e., fractal) repetition of visual information is perceptually fluent.

The fact that the current research revealed that a key-characteristic of nature's geometric language is a source of perceptual fluency might be relevant for research into nature's restorative effects (Kaplan & Kaplan, 1989; Kaplan, 1995; Kaplan & Berman, 2010). Within the field of restorative environments research, numerous experiments have shown that after exposure to natural scenes, individuals display superior performance on various cognitive and attentional tasks than after exposure to urban environments (Kaplan & Berman, 2010). Attention Restoration Theory (see Kaplan & Kaplan, 1989) interprets such positive nature effects in terms of nature recruiting bottom-up involuntary attention mechanisms via soft fascination, while simultaneously not engaging or resting top-down directed attention mechanisms.

Inasmuch as internal repetition and resulting self-similarity were associated with overall superior task performance in Study 1 and Study 2, our results are consistent with, and further support the view that fractal characteristics could be one of the crucial (visual) drivers of restorative responses and other positive psychological responses to nature (Hagerhall, Purcell, & Taylor, 2004; Taylor et al., 2011). More tentatively, our findings suggest that there might be a role for fluent processing as a mechanism underlying the positive influence of nature scenes on cognitive performance (Kaplan & Berman, 2010). We hope that future research will further explore the role of perceptual fluency in restorative nature experiences and its relation to soft fascination (Joye & Van den Berg, 2011), as well as investigate whether there exist any other types of complex stimulus organizations that are perceptually fluent.

[8] We made these measurements using the software *ImageJ*. An edge detection algorithm first detected and isolated the contours of stimuli. After this, we measured the fractal dimension of the ground-level contours of all stimuli using the *ImageJ* plugin *Fraclac*.

[9] Note in this regard that in an unrelated pilot-study we found that participants had difficulties with classifying clear-cut examples of fractal structures as "fractal," despite the fact that they had been given a clear definition of what constituted a fractal.

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(*Appendix follows*)

Appendix

Means and *SD*s (in Parentheses) of the Scores for the Three Dependent Measures Not Discussed, and *t* Values and Significance Levels of the Paired Sample t Tests for These Three Dependent Measures

	High-condition	Low-fractal condition	*t*	*p*
Coherence	4.14 (1.70)	4.14 (1.48)	0.00	1.000
Refreshing	2.88 (1.65)	2.93 (1.42)	−0.27	.790
Relaxing	2.56 (1.40)	2.77 (1.45)	−1.39	.167

Received June 19, 2014
Revision received June 24, 2015
Accepted June 26, 2015 ■