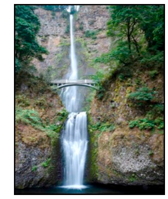
Journal of Environmental Psychology 62 (2019) 133–145

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep



Psychological responses to natural patterns in architecture

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ARTICLE INFO

Handling Editor: Florian Kaiser

ABSTRACT

In the following experiments, we examined whether perceptions of naturalness in architecture are linked to objective visual patterns, and we investigated how natural patterns influence aesthetic evaluations of architectural scenes. Experiment 1 revealed that visual patterns of architecture explained over half of the variance in scene naturalness ratings. In Experiment 2, aesthetic preference ratings were found to relate closely to natural patterns in architecture. In Experiment 3, participants completed an image arrangement task, and multidimensional scaling (MDS) analysis was performed on the data to determine the underlying dimensions that drove scene similarity judgements. Naturalness and preference ratings both correlated strongly with MDS Dimension 1. We interpreted this dimension as representing latent perceptions of *naturalistic aesthetics* and found that it mediated the effects of natural patterns on scene preference. Together, these results suggest that naturalistic visual patterns may play an important role in aesthetic evaluations of architectural scenes.

1. Introduction

The design of our physical surroundings – including landscapes and buildings – can have a meaningful impact on psychological states and wellbeing (Adams, 2014; Coburn, Vartanian, & Chatterjee, 2017; Cooper & Burton, 2014; Hartig, 2008; Joye, 2007b). The psychological benefits of *naturalness* in particular, are widely documented in the environmental psychology literature (for a review, see Bowler, Buyung-Ali, Knight, & Pullin, 2010; Kaplan & Berman, 2010). The sensory qualities of natural environments have been found to improve mood, attention, and cognitive functioning (Berman et al., 2012; Berman, Jonides, & Kaplan, 2008; Berto, 2005; Bratman, Daily, Levy, & Gross, 2015; Bratman, Hamilton, & Daily, 2012; Bratman, Hamilton, Hahn, Daily, & Gross, 2015; Kaplan, 1995; Bourrier et al., 2018), among other salubrious effects. Nature-like design features can also be found in certain built environments that exhibit visual patterns inspired by biological systems (Alexander, 2002; Goldberger, 1996; Joye, 2007b; Salingaros, 2003; Solomon, 2002). Researchers have proposed that organic patterns in architecture may be inherently preferred over synthetic forms, and that exposure to naturalistic architectural spaces may confer similar psychological benefits as interacting with nature itself (Alexander, 2002; Joye, 2007b; Kellert, 2005; Salingaros, 2007). However, these ideas have received little experimental scrutiny to date (Joye, 2007b). Here, we examine whether subjective perceptions of naturalness in architecture are driven by objective visual patterns, and investigate whether these nature-like patterns are robust predictors of similarity evaluations and preference ratings of architectural scenes. This work paves the way for future researchers to explore how naturalistic patterns in the built environment influence restoration and wellbeing.

1.1. Psychological benefits of naturalness

Previous research has shown that interacting with natural environments, compared to urban or built spaces, can confer important benefits for mental health. The salubrious effects of exposure to nature include improved mood (Barton & Pretty, 2010; Bowler et al., 2010; Valtchanov, Barton, & Ellard, 2010), reduced stress (Valtchanov et al., 2010; Villani & Riva, 2011), improved concentration and working memory performance (Berman et al., 2012, 2008; Berto, 2005; Bratman, Daily, et al., 2015; Kaplan, 1995; Bourrier et al., 2018), higher self-esteem (Barton & Pretty, 2010; Pretty, Peacock, Sellens, & Griffin,

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https://doi.org/10.1016/j.jenvp.2019.02.007
Received 23 July 2018; Received in revised form 11 February 2019; Accepted 14 February 2019
Available online 21 February 2019

2005), increased feelings of energy and vitality (Ryan, Weinstein, Bernstein, & Brown, 2010), and overall self-perceived health (Kardan, Gozdyra, et al., 2015). Views of nature have also been shown to reduce criminal behavior (Kuo & Sullivan, 2001) and improve recovery from surgery (Ulrich, 1984). In fact, merely looking at images and virtual representations of natural landscapes can induce many of these benefits (Berman et al., 2008; Berto, 2005; Valtchanov et al., 2010; Valtchanov & Ellard, 2015; Bourrier et al., 2018).

Two complementary theories, the *Biophilia Hypothesis (BH)* and *Attention Restoration Theory (ART)*, help frame these empirical findings. The BH states that humans are inherently attracted to the living and life-like forms often encountered in natural environments (Wilson, 1984; Wilson & Kellert, 1995). Proponents of BH argue that people have a genetically-rooted need to seek contact with plants, animals, and natural places, which stems from our species' evolution in "biological – not artificial or manufactured – environment[s]" (Kellert, 2005, p. 123). The word biophilia, which means "love of life," emphasizes the emotional dimension of the human-nature connection. ART, on the other hand, focuses on the cognitive benefits people derive from interacting with nature. According to ART, softly fascinating sensory stimuli in nature engage our attention in an automatic, bottom-up manner, thereby replenishing the limited cognitive resources that govern top-down executive functions, such as concentrating on difficult tasks. Nature thereby "restores" attentional resources and facilitates better performance on demanding cognitive tasks (Kaplan, 1995; Kaplan & Berman, 2010). Together, BH and ART offer complementary perspectives to explain why contact with nature might generate pleasurable and restorative psychological experiences.

In an effort to investigate these mechanisms more closely, researchers have quantified common characteristics of natural-looking environments including a high density of curved edges and high frequency of contrast changes, which also were predictive of aesthetic preference (Berman et al., 2014; Kardan et al., 2015). These findings have intriguing implications for architectural design and urban planning. Despite the salutary effects of nature, most people today spend upwards of 90% of their lives inside buildings (Evans & McCoy, 1998), which means understanding how to integrate the sensory characteristics of nature into the built environment could be a powerful tool for enhancing mental health on a large scale (Ibarra et al., 2017).

1.2. Nature-like patterns in architecture

Although natural and built environments are often classified as categorically distinct types of space (Karmanov & Hamel, 2008), many buildings across the globe exhibit nature-like characteristics. Naturalistic forms and patterns have long served as a fruitful source of inspiration for architects and builders around the world (Alexander, 2002; Joye, 2007b; Kellert, 2005; Ostwald, 2001; Salingaros, 2007). Kellert defines *organic design* as "building shapes and forms that directly, indirectly, and symbolically elicit a human affinity for natural features and processes" (Kellert, 2005, p. 128). Examples include literal imitations of animal and plant shapes in architectural ornamentation, engineering strategies that mimic the structural support mechanisms of biological organisms, and nature-like patterns of scaling and proportionality abstracted from natural systems (Fig. 1). "These architectural elements," writes Kellert, "evoke sentiments that tap into our inherent responses to the patterns, movement, light, shape, and space encountered in nature" (Kellert, 2005, p. 159).

Only a fraction of human construction, however, has arisen from the design model of nature (Kellert, 2003). Contemporary architecture often exhibits a different type of structural organization that is not rooted in nature's blueprints, but that is instead derived from intellectually-generated concepts like Euclidean geometry and the Cartesian coordinate system. Idealized shapes like rectangles, spheres, flat surfaces, and straight lines have increasingly dominated Western architecture since the Second World War (Fig. 2), yet these inorganic forms are quite alien to the complex visual structures of living, biological systems (Aldersey-Williams, 2004; Kellert, 2005). Some researchers argue that the rise of Euclidean architecture in the 20th century was driven by conscious efforts to create shocking new structures that stood out in stark contrast from nature (Alexander, 2002; Salingaros, 1998, 2007). Others contend that an increased emphasis on utilitarianism in building construction has moved architects away from using nature-based design models (Joye, 2007b), which are often perceived as incompatible with the economic incentives and production systems that drive contemporary development (Alexander, 2002). "Modern building is often dictated by efficiency and economic motives," writes Joye, "barely leaving room for symbolic and stylistic references to natural contents" (Joye, 2007b, p. 311).

How do natural vs. synthetic architectural forms impact aesthetic experiences in the built environment? Some scholars have asserted that humans are inherently drawn to architectural forms that echo the organic qualities of nature (Alexander, 2002; Joye, 2006; Kellert, 2005; Ruskin, 1849; Salingaros, 2007). This idea bears a striking similarity to the aesthetic notions of philosopher Immanuel Kant, who proposed that all truly beautiful human-made objects (including buildings) look as if they were created by nature. In Kant's view, nature is beautiful if it appears purposive (i.e., if it looks as if it was created to achieve a specific goal), and man-made objects are beautiful if they look natural. This vice versa 'as if' is the key to Kant's concept of beauty (Kant, 2001). Other researchers have argued that exposure to nature-like architectural patterns may induce similar psychological benefits as interacting with nature itself (Alexander, 2002; Joye, 2007b; Kellert, 2003; Salingaros, 2007). Kellert, for instance, writes that organic architecture "enrich[es] the human body, mind, and spirit by fostering positive experiences of nature in the built environment" (Kellert, 2005, p. 5). However, very little empirical work to date has tested theoretical claims that naturalistic architecture is either preferred or restorative (Joye, 2007b).

In the following experiments, we investigate how visual patterns distributed throughout architectural scenes influence perceptions of naturalness and aesthetic preference. We integrate two complementary strategies, one empirically-motivated and the other theory-driven, for identifying natural features of architectural design. The first strategy uses image statistics to identify low-level spatial and color properties of architectural scenes that relate to naturalness ratings. This approach builds on previous experiments showing that low-level visual features strongly predict perceptions of naturalness in outdoor landscapes (Berman et al., 2014; Ibarra et al., 2017; Kardan, Demiralp, et al., 2015) and that naturalistic spatial and color features play a role in driving scene preference ratings (Kardan, Demiralp, et al., 2015). We predict that these same low-level scene features, when integrated into architectural design, will evoke associations with the environmental quality of naturalness. 'Low-level' here is used to make a distinction between these simpler visual features that summarize statistical regularities that are quantifiable in a continuous manner for any image, as opposed to visual semantic labels such as 'tree' and 'window'. Those semantic features would constitute higher-level features (for example, see Henderson & Hayes, 2018; Kardan et al., 2017).

The second, complementary strategy is derived from the concept of living structure (Alexander, 2002). According to this theory, architecture exhibits naturalistic, or living, aesthetic qualities when the process by which it is constructed resembles the adaptive, structure-preserving processes of biological growth (Alexander, 2004). When people build as nature does, Alexander argues, buildings develop nature-like geometric patterns in their structure, which are summarized as fifteen patterns of living structure (Fig. 3). While some of these patterns are difficult to quantify, others lend themselves to empirical measurement. Intriguingly, two of the patterns – *Levels of Scale* and *Contrast* – align closely with the low-level visual features that Berman et al. (2014) and Kardan, Demiralp, et al. (2015) and Kardan, Gozdyra, et al. (2015) identified in their experimental work as predictable

Fig. 1. (A,B) The Corinthian column's biologically-inspired design is evident in its tree-like structure and floral ornamentation (Tokkoro, 2018; Warder, 2008). (C) Sagrada Familia's structure resembles the branching canopies of trees (Joye, 2007b). (D) Taj Mahal (Forget, 2009) exhibits geometric patterns characteristic of biological systems, including local symmetries and self-similar shapes.

characteristics of natural environments. These two patterns are qualitatively described in Box 1. In the subsequent experiments, we quantify them using image statistics and investigate their relationship with subjective naturalness and preference ratings of architectural scenes.

Levels of Scale	Strong Centers	Boundaries
Alternating Repetition	Positive Space	Good Shape
Local Symmetries	Deep Interlock	Contrast
Gradients	Roughness	Echoes
The Void	Simplicity and Inner Calm	Not-Separateness

Fig. 3. Fifteen patterns of living structure (Alexander, 2002).

1.3. Overview of experiments

The purpose of this research was to investigate whether perceptions of naturalness are driven by measurable spatial and color features of buildings and to determine how these naturalistic design features relate to aesthetic preference ratings and similarity evaluations of architectural scenes. In Experiment 1, we collected subjective naturalness ratings of interior and exterior architectural images and regressed these ratings on low-level image features. In Experiment 2, we collected aesthetic preference ratings on the same images and regressed these ratings on image naturalness scores from Experiment 1. In Experiment

Fig. 2. (A) Buildings in Brasilia, a city largely inspired by artificial geometric forms. (B) The design of a university dormitory in Cambridge, England is characterized by synthetic shapes.

Box 1

Descriptions of *Levels of Scale* and *Contrast*, two proposed patterns of living structure (Alexander, 2002; Salingaros, 2007).

(Left) A door with many *Levels of Scale*. (Right) A door with few *Levels of Scale*.

Natural systems often exhibit many ***Levels of Scale***, with incremental jumps between scales (Alexander, 2002). The smallest structural components are connected to the largest components through a linked hierarchy of scales. Components often double or triple in size from one scale to the next, but any given component is rarely more than ten times larger than the component at the next-smallest scale (Salingaros, 2007). This pattern is visible in the structural features of trees (trunk, limbs, branches, and twigs), cells (cell wall, organelles, nucleus, chromosomes), and rivers (bends, eddies, tributaries). In architecture, as in nature, levels of scale serve many functional purposes. In homes, variations in room size enable a variety of social functions to take place, from small alcoves that foster private contemplation to large rooms that host public gatherings. Scaling variations in doors (Left, above) enhance the structural integrity of the frame and improve wayfinding by drawing visual attention to a key navigational threshold. The door on the right, by comparison, exhibits so little differentiation that it is nearly indistinguishable from the surrounding wall.

Contrast describes visibly-discernible opposites that are widely distributed throughout natural systems (Alexander, 2002). The organization of these systems often depends on interactions among these opposites. Matter itself arises from interactions among opposite elementary particles, such as up vs. down quarks, particles vs. antiparticles, and positive vs. negative charges. Contrast is also visible, for instance, in the diurnal cycle of day and night. In architecture, contrast can take many forms, including black-white and dark-light contrasts. Contrast also arises from juxtaposing complementary colors (e.g. red-green), contradictory textures (e.g. soft-hard), and opposite forms (e.g. solid-void). The house in Figure 6 (Left) exhibits several varieties of contrast: blue-orange contrast between the hues of shutters vs. masonry; rough-smooth contrast between the texture of masonry vs. glazing; small-large contrast in the size of stone embedded in the façade; and dynamic contrasts between straight lines and curves in the edges of windows, doorframe, and stonework. These counterbalanced features serve to differentiate and define structural elements of the house, while also uniting the individual components into a complex, organic whole. The school on the right, by comparison, contains fewer examples of contrast. Its façade exhibits less differentiation in color, texture, brightness, and form, giving the building a more homogenous character.

(Left) Intense contrast in a French house (Cardesse, France). (Right) Less intense contrast in a school façade (Coventry, England).

3, we asked participants to judge the similarity of diverse architectural images using an image arrangement task. We applied multidimensional scaling analysis (MDS) to these similarity data to identify the underlying dimensions that drove participants' image arrangement decisions (Berman et al., 2014; Hout, Papesh, & Goldinger, 2013; Shepard, 1980), predicting that the way in which participants organized images would be influenced by latent perceptions of naturalistic patterns. Finally, we ran mediation models to test whether the aesthetic preferences exhibited for scenes with high amounts of Scaling and Contrast patterns were mediated by latent perceptions of naturalness.

2. Experiment 1

2.1. Identifying nature-like patterns in architecture

In this experiment, we set out to determine whether subjective perceptions of naturalness are driven by objective low-level features of architectural scenes. We predicted that low-level scene features would significantly predict naturalness ratings, and that architectural scenes exhibiting greater *Levels of Scale* and greater visual *Contrast* would be perceived as more natural.

2.2. Methods

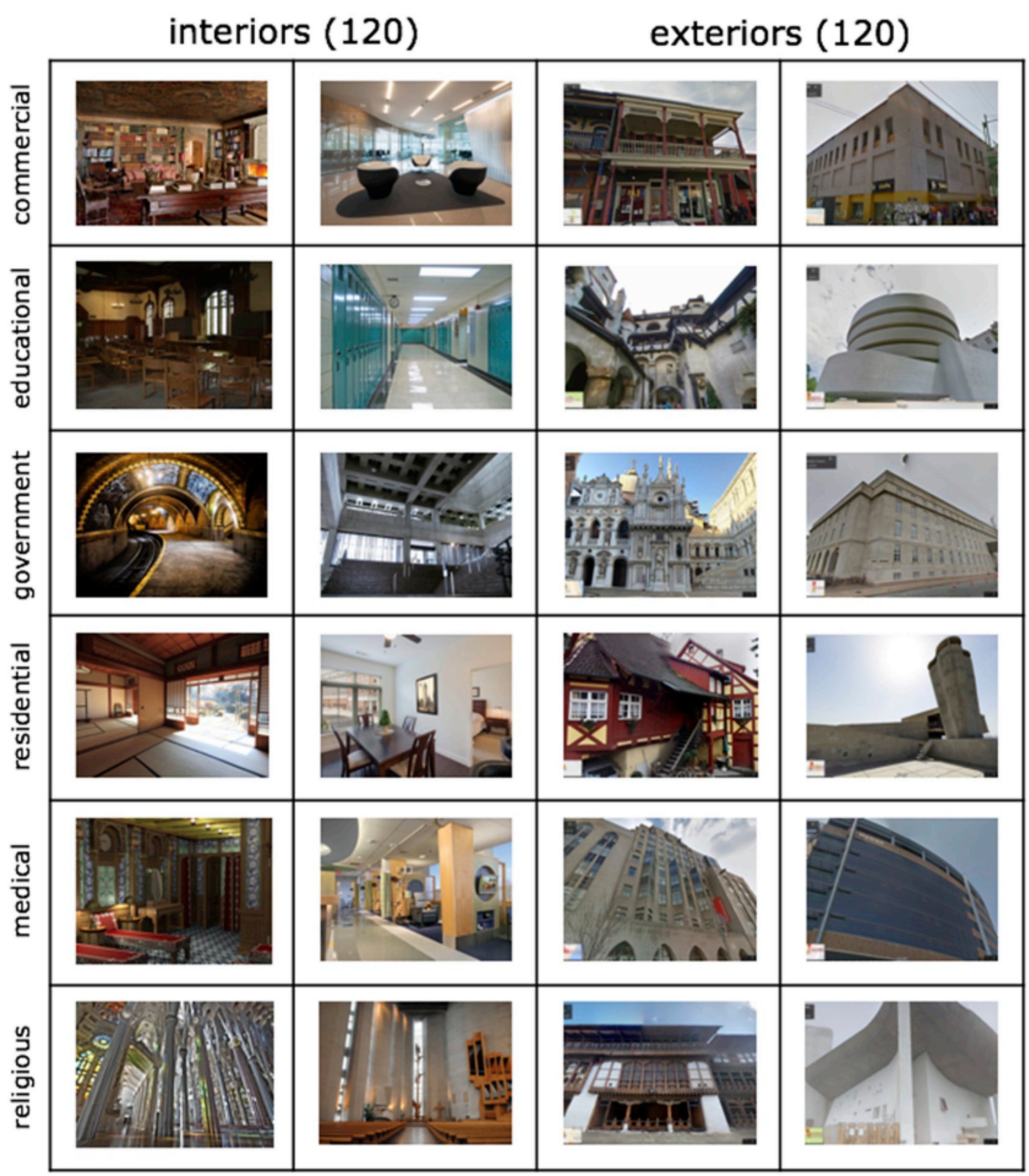
2.2.1. Participants

100 American adults (55 Women, 45 men) were recruited for this experiment from Amazon's Mechanical Turk (MTurk) to rate images of architectural spaces on their perceived level of naturalness. Sample size was determined by our goal of obtaining approximately 50 naturalness ratings per image (Kotabe, Kardan, & Berman, 2016, 2017). Half of participants (Group 1) were assigned to rate images of interior spaces (n = 50), and the other half (Group 2) were assigned to rate images of exterior spaces (n = 50). Ages ranged from 21 to 65 years (M = 34.6, SD = 9.6). Data were excluded from 8 participants who gave the same naturalness rating for 10 or more consecutive stimuli at least once during the experiment. This response pattern suggested that they were

clicking through the images and not attending to the assigned task. All participants were compensated $1.00 for their participation and the experiment took approximately 10 min to complete. Informed consent was obtained from all participants under protocol approved by the Institutional Review Board (IRB) of the University of Chicago.

2.2.2. Materials

Two sets of stimuli were used in all three experiments of this study: 120 images of architectural interiors and 120 images of architectural exteriors. Interior photographs were chosen from a variety of online public domain collections of architectural images. Exterior photographs were taken from the Street View interface of Google Earth and were restricted to head-on shots of buildings taken at a distance of 20–30 feet from the façade. Within each 120-image stimulus set, twenty diverse examples of architectural spaces were chosen for each of six building functions (commercial, educational, government, residential, medical, and religious). Although this is not an exhaustive list of possible building functions, it fulfilled the purpose of diversifying the stimuli and balancing both image sets across a range of functional categories. For each category of building function, ten natural-looking buildings and ten artificial-looking buildings were selected using the qualitative criteria derived from Alexander's theory of natural structure (see Box 1), in order to ensure that the variation in naturalness of the architectural scenes was independent of the variation in building function. This selection process enabled us to control for the potentially confounding effect of building function on naturalness ratings. It also ensured that both stimulus sets contained a similar distribution of images across all six functional categories, thus facilitating more reliable comparison between interior and exterior results. The amount of vegetation (i.e. plants, trees) depicted in the image sets was intentionally minimized in the selection process in order to reduce the confounding effects of non-architectural natural features on subjective naturalness ratings of buildings. Images were normalized to 4:3 width-to-height ratios with dimensions of 1175*881 pixels for exteriors and 1000*750 pixels for interiors to ensure dimensional consistency across each image set. The images can be downloaded here: https://github.com/alexcoburn11/Natural-Buildings-Images.



2.2.3. Procedure

Participants rated images using the online interface of Qualtrics survey software. Participants in Group 1 (n = 50) were shown the 120-image set of interior architectural spaces in a randomized order and were asked to rate each image in response to the prompt, "How artificial or natural does this building interior look to you?" Answer choices were presented on a standard 7-point Likert scale, with 1 indicating "very artificial" and 7 indicating "very natural." Participants were given unlimited time to rate each image. The same procedure was followed for participants in Group 2 (n = 50), except that they were asked to rate the set of 120 images of architectural exteriors rather than interior spaces.

2.2.4. Quantifying spatial and color properties of architecture

We measured nine low-level visual features of each scene in order to estimate the degree to which naturalness ratings could be statistically explained by these objective visual features. There are many possible ways in which visual properties of images can be analyzed (Kardan, Henderson, Yourganov, & Berman, 2016). Here, we chose to use a set of spatial and color features that were assessed in two previous studies investigating the low-level visual correlates of naturalness in outdoor spaces (Berman et al., 2014; Kardan, Demiralp, et al., 2015). We focused on these particular measures for three reasons: 1) they have straightforward interpretations; 2) they can be easily manipulated in visual stimuli by researchers and in built environments by architectural designers; and 3) they are theoretically relevant to the patterns of natural structure described in the introduction (Alexander, 2002) and have been shown to relate to the viewer's thoughts and affect (Schertz et al., 2018).

We measured three spatial features of each image: ***Edge Density*** (a measure of how many straight and curved edges are in an image), ***Fractal Dimension*** (a measure of the visual complexity of edge maps in our images), and ***Entropy*** (a measure of randomness in a scene, calculated using the scene's intensity histogram). Additionally, we measured six color properties of scenes: ***Hue*** (a scene's average color appearance), ***Saturation*** (the intensity of colors in a scene), ***Brightness*** (the average luminance of an image), standard deviation of hue (***sdHue***; the diversity of hue in a scene), standard deviation of saturation (***sdSat***; the diversity of saturation in a scene), and standard deviation of brightness (***sdBright***; the diversity of brightness in a scene). A detailed summary of calculation methods for these nine image properties is provided in Section 7.1 (Supplementary Materials).

2.2.5. Quantifying Levels of Scale and Contrast

We used these image statistics to operationalize two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast* (Alexander, 2002). When buildings exhibit many *Levels of Scale*, the smallest structural details are connected to the largest visible components through a linked hierarchy of scales. Our Fractal Dimension measure is a close approximation of this pattern, since it measures the degree to which edge patterns in an image repeat at many scales of magnification. Architectural scenes with low Fractal Dimension values (approaching 1) are likely to depict smooth, sparse surfaces with little scaling differentiation and with large jumps between scales (see Fig. 4B). Images with high Fractal Dimension values (approaching 2, since images are 2-dimensional) generally depict more intricate, detailed structures (Taylor et al., 2005), with more scales present and smaller jumps in between scales (see Fig. 4A). A high degree of scaling differentiation is also generally associated with a greater density of small-scale details, whereas less differentiated (i.e., minimalist) spaces typically contain less detail. Edge Density, which captures the amount of detailed edges in a scene, is therefore another close proxy for Alexander's *Levels of Scale* pattern. After measuring these two image features, we discovered that Edge Density and Fractal Dimension were highly correlated in both interior (r = 0.96) and exterior (r = 0.91) images. In order to reduce redundancy in our independent variables, we created a new combined variable called *Scaling* by averaging the Edge Density and Fractal Dimension values of each image.

The *Contrast* pattern was evaluated using three of our low-level color features: sdHue, sdSat, and sdBright. These three statistics serve as useful proxies for three distinct forms of visual contrast, as they directly measure the diversity of hue (sdHue), the diversity of color intensity (sdSat), and the diversity of brightness (sdBright) distributed throughout an architectural scene (see Fig. 4C and 4D). These are by no means the only types of contrast that can exist in a building (see Box 1 for more examples of contrast). However, they are straightforward and quantifiable examples of visual contrast features. We predicted that these statistical proxies of *Levels of Scale* and *Contrast* would correlate positively with naturalness ratings for both interior and exterior image sets.

2.2.6. Quantifying 'Explicit Nature'

We controlled for the natural vegetation content of our scenes first by minimizing the presence of explicit natural content (such as trees) in the stimuli during stimulus selection, as well as specifically mentioning 'the building exterior' or 'the building interior' in the rating question for the participants. Additionally, we measured the number of pixels in each scene depicting any remaining natural vegetation (e.g. grass, bushes, trees, flowerpots) using the Quick Selection tool in Adobe Photoshop, and then divided this value by the total pixel area of the scene. The resulting variable, which we called *Explicit Nature*, represented the proportion of image area occupied by vegetation in each scene. This variable was normalized by a square-root transformation and added to regression models to control for the presence of exogenous vegetation (i. e., not part of the interior or exterior architecture of buildings) in the architectural scenes. Table S1 in the Supplementary Material shows the means and ranges of the proportion of pixels attributed to explicit vegetation across the two image sets.

2.2.7. Statistical analysis

Analyses were conducted at the image level by calculating average naturalness ratings for each image across all participants. Interrater reliability scores for naturalness ratings were estimated using Shrout and Fleiss' (1979) intraclass correlation method (Class 2), which models image and rater as random effects in a two-way random effects model. The model resulted in reliability estimates of 0.985 (95% CI = 0.978 - 0.990, $p < .001$) for interior images and 0.979 (95% CI = 0.970 - 0.987, $p < .001$) for exterior images. These scores fall in the "excellent" range (Cicchetti, 1994). Using linear multiple regression models, we then examined the relationship between naturalness ratings and visual features of interior and exterior images.

2.3. Results

2.3.1. Spatial and color features predict perceptions of naturalness

First, we regressed mean naturalness ratings of the interior images on eight low-level visual features. The Explicit Nature variable was added to the regression model to control for the amount of vegetation present in the scenes. The majority of the variance in mean naturalness ratings was collectively explained by these nine visual features [$R^2_{adj} = 0.68$, $F(9, 110) = 29.44$, $p < .001$)]. Low-level visual features independently explained over half (55%) of the variance in naturalness ratings when controlling for Explicit Nature. We performed the same analysis on data collected for exterior images. The nine visual features of exterior images also significantly predicted their mean naturalness ratings [$R^2_{adj} = 0.53$, $F(9, 110) = 15.85$, $p < .001$)]. When controlling for Explicit Nature, low-level visual features independently explained 42% of the variance in naturalness ratings. The results of these two regressions build on previous work showing that low-level visual features predict the perception of naturalness in outdoor environmental scenes (Berman et al., 2014; Kardan, Demiralp, et al., 2015), many of which contained little or no built structure. Here, these past findings are

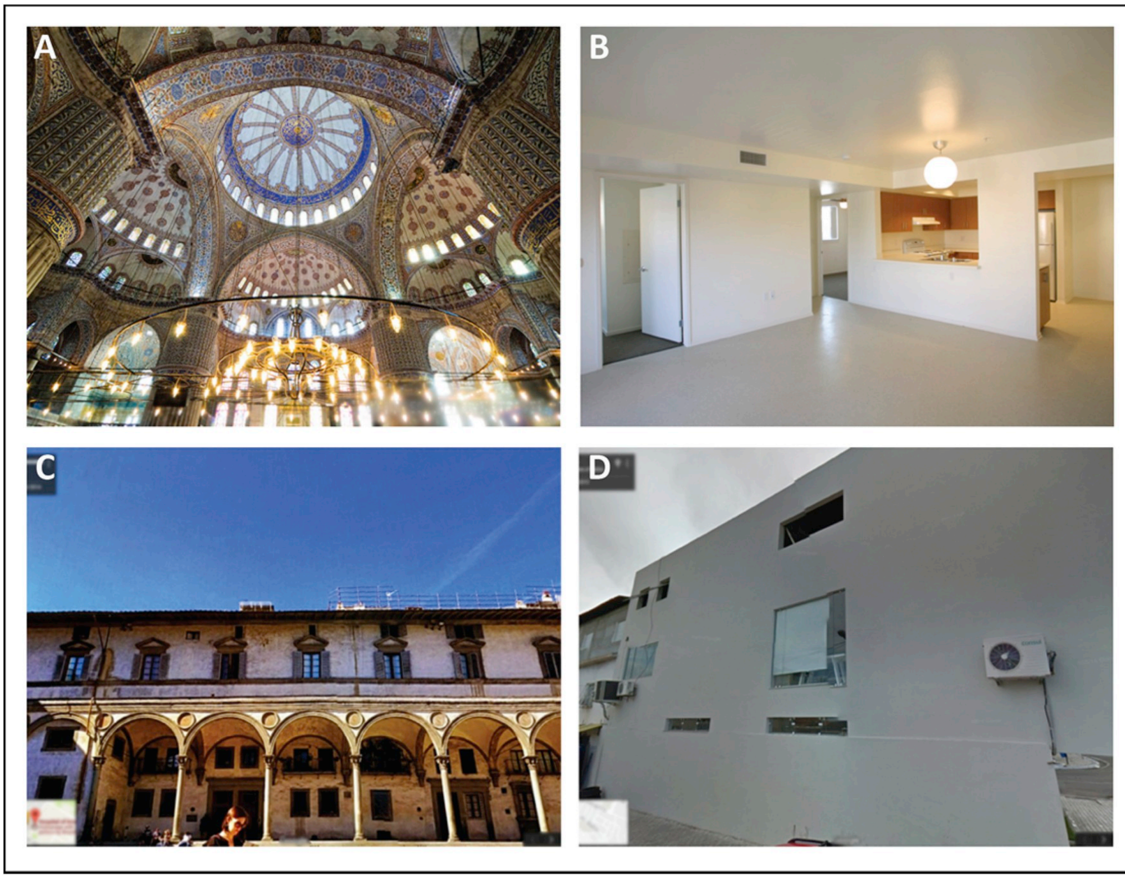


Fig. 4. (A) Interior with high values of edge density (Z = +2.56) and fractal dimension (Z = +1.77). (B) Interior with low values of edge density (Z = −2.01) and fractal dimension (Z = −2.73). (C) Exterior with high values of sdHue (Z = +0.83), sdSat (Z = +2.20), and sdBright (Z = +2.02). (D) Exterior with low values of sdHue (Z = −0.79), sdSat (Z = −1.67), and sdBright (Z = −1.70).

Table 1
Regression of naturalness ratings vs. image features (interiors).

Visual Feature	Estimate	SE	β_{ST}	*t* value	*P value*	n_p^2
Scaling***	0.464	0.061	0.522	7.625	< .001	0.346
Entropy	−0.092	0.057	−0.104	−1.616	0.109	0.023
Hue	−0.045	0.049	−0.051	−0.906	0.367	0.007
Saturation	0.136	0.086	0.154	1.582	0.116	0.022
Brightness*	−0.118	0.058	−0.134	−2.039	0.044	0.036
sdHue	−0.095	0.063	−0.107	−1.503	0.136	0.020
sdSat*	0.117	0.059	0.132	1.988	0.049	0.035
sdBright**	0.154	0.059	0.174	2.583	0.011	0.057
Explicit Nature**	2.652	0.635	0.223	4.175	< .001	0.137
$R^2_{adj} = 0.68, F(9, 110) = 29.44, p < .001$						

Table 2
Regression of naturalness ratings vs. image features (exteriors).

Visual Feature	Estimate	SE	β_{ST}	*t* value	*P value*	n_p^2
Scaling***	0.291	0.062	0.354	4.670	< .001	0.165
Entropy	−0.108	0.070	−0.135	−1.555	0.123	0.022
Hue	−0.014	0.057	−0.018	−0.248	0.805	0.001
Saturation	−0.093	0.089	−0.116	−1.053	0.295	0.010
Brightness	0.061	0.053	0.076	1.137	0.258	0.012
sdHue	0.026	0.060	0.032	0.431	0.668	0.002
sdSat***	0.338	0.089	0.421	3.795	< .001	0.116
sdBright**	0.223	0.069	0.290	3.376	0.001	0.094
Explicit Nature**	1.102	0.334	0.222	3.297	0.001	0.090
$R^2_{adj} = 0.53, F(9, 110) = 15.85, p < .001$						

extended to images of the built environment.

As shown in Tables 1 and 2, higher values of Scaling, sdSat, and sdBright significantly predicted higher naturalness scores for both interior and exterior architectural spaces. Additionally, Brightness correlated negatively with naturalness for interior scenes. Since images with high Scaling values are indicative of greater scaling differentiation in architectural design, the strong positive correlation found for this measure supports the hypothesis that incremental scaling is associated with the perception of naturalness in architectural scenes, whereas images of buildings with more abrupt changes in scale are more likely to be perceived as artificial-looking. The Scaling measure independently explained 34.6% and 16.5% of variance in naturalness ratings for interior and exterior scenes, respectively.

Furthermore, two of the three features of color contrast – sdSat and sdBright – correlated significantly with naturalness in both image sets, thus supporting the hypothesis that greater visual contrast is positively associated with the perception of naturalness in architectural scenes. This effect, however, was limited to saturation and brightness-related contrast patterns, as hue diversity (sdHue) was not a significant predictor of naturalness in either image set. The contrast-related measures independently explained 11.2% and 21.2% of variance in naturalness ratings for interior and exterior scenes, respectively.

In summary, these results show consistent relationships between low-level visual features, especially Scaling and Contrast patterns, and perceptions of naturalness for both interior and exterior architectural scenes. Since both regression models controlled for the effect of vegetation on naturalness ratings, the results imply that Scaling and Contrast patterns visible in the buildings themselves, rather than in the trees and plants surrounding them, were driving perceptions of naturalness for these two image sets. These findings are consistent with the hypothesis that two of Alexander's proposed patterns of natural structure – *Levels of Scale* and *Contrast* – are associated with perceptions of architectural naturalness.

3. Experiment 2

3.1. Does naturalness of buildings influence preference?

Next, we set out to determine whether aesthetic preferences in the built environment are influenced by perceptions of naturalness of architectural design. We predicted that people would exhibit preferences for buildings that were perceived as more natural, and that scenes exhibiting more Scaling and Contrast would generally be preferred.

3.2. Methods

3.2.1. Participants

100 American adults (63 Women, 37 men) were recruited for this experiment from Amazon's Mechanical Turk (MTurk) to make preference ratings of the two architectural image sets. Sample size was determined by the goal of obtaining approximately 50 preference ratings per image (Kotabe et al., 2016, 2017). Half of participants (Group 1) were assigned to rate images of interior spaces (n = 50), and the other half (Group 2) were assigned to rate images of exterior spaces (n = 50). Ages ranged from 20 to 60 years (M = 33.3, SD = 9.5). Data were excluded from 4 participants who gave the same preference rating for 10 or more consecutive stimuli at least once during the experiment, as this response pattern indicated that they were not attending to the task. All participants were compensated $1.00 for their participation and the experiment took approximately 10 min to complete. Informed consent was obtained from all participants under protocol approved by the Institutional Review Board (IRB) of the University of Chicago.

3.2.2. Procedure

Participants rated the interior and exterior image sets from Experiment 1 using the online interface of Qualtrics survey software. Group 1 participants (n = 50) were asked to rate how much they liked each interior image using a Likert scale ranging from 1 to 7, with 1 indicating strong dislike and 7 indicating strong preference. Group 2 participants (n = 50) followed the same procedure but made preference ratings for images of architectural exteriors rather than interiors.

3.2.3. Statistical analysis

We conducted analyses at the image level by calculating average preference ratings for each image across all participants, and by using image-level naturalness scores obtained in Experiment 1. Interrater reliability scores for preference ratings were estimated using the same method as previously described for naturalness ratings (Shrout & Fleiss, 1979), which yielded reliability estimates of 0.972 (95% CI = 0.960 - 0.982, $p < .001$) for interior images and 0.969 (95% CI = 0.956 - 0.980, $p < .001$) for exterior images. These scores fall in the "excellent" range (Cicchetti, 1994). We then looked at the Pearson correlations between the variables, with Type I error rate set at 0.01 to adjust for multiple tests. The three contrast-related variables (sdHue, sdSat, sdBright) were reduced to one variable using Principal Components Analysis (PCA). The first principal component (PC1) of these three variables, which explained 47% of variance for interiors and 54% of variance for exteriors, was used as a proxy for Contrast.

3.3. Results

3.3.1. Naturalness and natural patterns predict preference

The first analysis explored the degree to which the mean naturalness ratings of interior and exterior images predicted mean preference ratings. The perception of naturalness strongly predicted preference for both architectural interiors [$r = 0.76$, $p < .001$] and exteriors [$r = 0.67$, $p < .001$]. Additionally, Scaling and Contrast patterns were also correlated with preference ratings, with Contrast [$r = 0.48$, $p < .001$] for interiors and [$r = 0.70$, $p < .001$] for exteriors and Scaling [$r = 0.75$, $p < .001$] for interiors and [$r = 0.48$, $p < .001$] for exteriors. These results suggest that architectural scenes with more naturalistic qualities may be preferred, on average, over scenes that are perceived as more artificial. This finding extends past empirical work linking naturalness and preference (S. Kaplan et al., 1972; Kardan, Demiralp, et al., 2015) to the context of architectural scenes.

4. Experiment 3

4.1. Do naturalistic aesthetics of buildings influence perceptions of scene similarity?

In this experiment, we set out to investigate whether latent perceptions of naturalistic aesthetics in architectural scenes influence intuitive judgments of scene similarity. First, naïve participants assessed the similarity of diverse architectural images in an image arrangement task referred to as the *spatial arrangement method* (*SpAM;* Hout, Goldinger, & Ferguson, 2013; Hout & Goldinger, 2016). We then applied multidimensional scaling analysis (MDS) to these similarity data to identify the underlying dimensions that drove participants' grouping decisions (Berman et al., 2014; Hout et al., 2015; Hout, Papesh, et al., 2013; Shepard, 1980), predicting that latent perceptions of naturalistic aesthetics would strongly predict image grouping behavior. We tested this prediction by regressing dimension weights from the MDS analysis on subjective naturalness and preference ratings collected in the first two experiments. Finally, we investigated whether our operationalized measures of Alexander's nature-like Scaling and Contrast features significantly predicted scene similarity through latent perceptions of naturalistic aesthetics.

4.2. Methods

4.2.1. Participants

One hundred and sixty-seven participants, 81 from the University of Chicago, and 86 from New Mexico State University, took part in this study. Sample size was determined based on the goal of obtaining approximately 40 participants per stimulus set. All participants provided written informed consent. As compensation for their participation, University of Chicago participants were offered the choice of $10 cash payment or partial course credit towards psychology courses. Participants from New Mexico State University were compensated with partial course credit towards introductory psychology courses. Each participant completed the spatial arrangement task on one of four sets of stimuli (selection was counterbalanced across participants), which are referred to as Exteriors A (43 participants), Exteriors B (41 participants), Interiors A (41 participants), and Interiors B (42 participants).

4.2.2. Materials

The stimuli used in this study were the same 240 images of interior (n = 120) and exterior (n = 120) architectural scenes used in Experiments 1 and 2. Here, however, each 120-image set was divided evenly into two sets of 66 interior scenes and two sets of 66 exterior scenes, with 12 images overlapping between the two sets for each scene type to check across sample stability of MDS dimensions. All photographs were JPG format, resized to 360 × 270 pixels so that multiple of them could be presented simultaneously (see procedure). Stimulus presentation was controlled by E-Prime vs 2.0 (Psychological Software Tools, 2012), presented on monitors that were 62.5 cm × 32.5 cm, at a resolution of 3840 × 2160.

4.2.3. Procedure

On each trial, 20 different images were shown to the participant, randomly arranged in four rows of five items (evenly spaced along the

Fig. 5. Plotted results of MDS dimension 1 (X-axis) and Dimension 2 (Y-axis) for the first image set (Interiors A). Pictures are superimposed based on their weights on Dimensions 1 and 2. A subset of the 66 images is plotted in order to make the graph more readable.

x- and y-axes). Participants were instructed to use the mouse to drag-and-drop the images in order to arrange them according to the participant's perceived similarity of each pair (with closer in space denoting proportionately greater similarity and vice versa; see Hout & Goldinger, 2016; Hout, Goldinger et al., 2013). Participants were allowed as much time as they needed to arrange each set of pictures, and clicked on a small (100 × 100 pixels) image of a stop sign (placed in the bottom-most right corner of the display) to indicate that they were done arranging the stimuli. After clicking on the stop sign, they were provided with a prompt asking them if they were done arranging the stimuli, if they needed more time, or if they would like to start over. When the participant indicated that they were done, the program recorded the x- and y-coordinates for each image, and the Euclidean distance between each pair (for 20 stimuli, there are 190 pairwise distances). This procedure was performed 18 times, with different sets of pictures on each trial, ensuring that each image was paired with every other image at least once. Therefore, each participant provided a complete similarity matrix for the set of 66 scenes (i.e., 2145 pairwise distances; for details, see Horsley, 2017). The SpAM procedure encourages individual participants to focus on what they view as the two most important featural dimensions of the stimuli. However, it has been shown that high dimensional aggregate solutions can arise from the ratings of multiple participants (who appreciate different aspects of the stimuli across individuals), as was done here (see Hout & Goldinger, 2016; Hout, Goldinger, et al., 2013).

4.3. Results

4.3.1. MDS analysis

The results of the MDS analysis on the four sets of images are displayed in Fig. 5 and Supplementary Figs. S2, S3, S4, and S5, respectively. In those visualizations, the architectural images are superimposed on the MDS plot according to their weights on Dimension 1 (X-axis) and Dimension 2 (Y-axis). The data were scaled in six dimensions to yield the most appropriate overall spatial organization (see Supplementary section 7.1.4 *Determining dimensionality of MDS data* for

Table 3
Regression of Dimension 1 wt vs. Naturalness and Preference ratings, controlling for Explicit Nature (Interiors).

Variable	Estimate	SE	β_{ST}	*t* value	*P value*	n_p^2
(Intercept)***	−1.478	0.108	–	−13.96	< .001	–
Naturalness***	0.294	0.043	0.566	6.81	< .001	0.258
Preference***	0.127	0.035	0.299	3.61	< .001	0.058
Explicit Nature***	−1.721	0.325	−0.291	−5.30	< .001	0.139
R^2_{adj} = 0.65, *F*(3, 116) = 76.01, *p* < .001						

Table 4
Regression of Dimension 1 wt vs. Naturalness and Preference ratings, controlling for Explicit Nature (Exteriors).

Variable	Estimate	SE	β_{ST}	*t* value	*P value*	n_p^2
(Intercept)***	−1.857	0.076	–	−24.39	< .001	–
Naturalness***	0.282	0.027	0.530	10.27	< .001	0.192
Preference***	0.200	0.019	0.504	10.41	< .001	0.198
Explicit Nature	−0.149	0.104	−0.058	−1.44	0.151	0.002
R^2_{adj} = 0.85, *F*(3, 116) = 220.9, *p* < .001						

Scree plot Fig. S1 and choice of data dimensionality). However, the analysis here focused on the weights of the first two dimensions, as those dimensions explained the most variance in image similarity. At first glance, Dimension 1 appeared to code for the natural aesthetics of the architectural scenes, with scenes depicting more naturalistic buildings having higher weights on Dimension 1, and with images depicting more artificial-looking buildings having lower weights on Dimension 1. Dimension 2 was more difficult to interpret. This pattern emerged across all four sets of images.

4.3.2. Interpreting the primary dimension of MDS

To test whether Dimension 1 relates to naturalness and/or aesthetic preference, we regressed it on the naturalness and preference ratings from the previous studies, while controlling for explicit vegetation. The results (shown in Table 3) indicate that Dimension 1 is related to both naturalness and aesthetic preference (more to naturalness than preference for interiors and equally for exteriors, see partial eta-squared values in Tables 3 and 4). Together, these variables explained 65% and 85% of the variance in Dimension 1 ratings for interiors and exteriors, respectively. Hence, we can interpret Dimension 1 as the latent *naturalistic aesthetics* of interior and exterior architectural scenes. All of the following analyses were first done separately on image sets: Interiors A, Interiors B, Exteriors A, and Exteriors B. However, because the results were very similar across the A and B image sets we collapsed them into overall 120 Interiors and 120 Exteriors, similar to Experiments 1 and 2. Shapiro-Wilk normality tests (Shapiro & Wilk, 1965) were performed on the residuals of both linear regression models shown in Tables 3 and 4, resulting in $W = 0.985$, $p = .195$ for interiors and $W = 0.989$, $p = .467$ for exteriors. These results indicate that the residuals of both regression models are normally distributed.

Finally, we validated our operationalized measures of Alexander's nature-like patterns, Levels of Scale and Contrast, by investigating whether they correlated with the perceived naturalistic aesthetics (MDS Dimension 1) of architectural scenes.

Fig. 6 shows the correlation matrix between naturalness ratings, preference ratings, MDS Dimension 1 (naturalistic aesthetics), and our quantitative measures of Scaling and Contrast. Since there are significant correlations between all variables (all *p* values < .01 in Fig. 6), we can test our question regarding *how* measures of Scaling and Contrast are related to aesthetic preference of the buildings, using the mediation model depicted in Fig. 7.

4.3.3. Naturalistic aesthetics mediate effects of Scaling and Contrast on preference

The correlation matrix (Fig. 6) showed that Scaling correlated significantly with preference (Model A in Fig. 7). However, a significant proportion of this effect was mediated by MDS Dimension 1 (Naturalistic Aesthetics), as shown in Table 5. We tested the mediation pathway using a bootstrap estimation approach with 1000 re-samples (Shrout & Bolger, 2002). These results indicated that Scaling's effect on preference was fully mediated by latent perceptions of naturalistic aesthetics (Dimension 1 from MDS) for exteriors (indirect effect estimate = 0.453, $p < .01$; direct effect estimate = 0.087, $p = .16$), and was partially mediated by naturalistic aesthetics for interiors (indirect effect estimate = 0.331, $p < .01$; direct effect estimate = 0.332, $p < .01$).

We also investigated whether Naturalistic Aesthetics (MDS Dimension 1) mediated the effect of Contrast on Preference. The

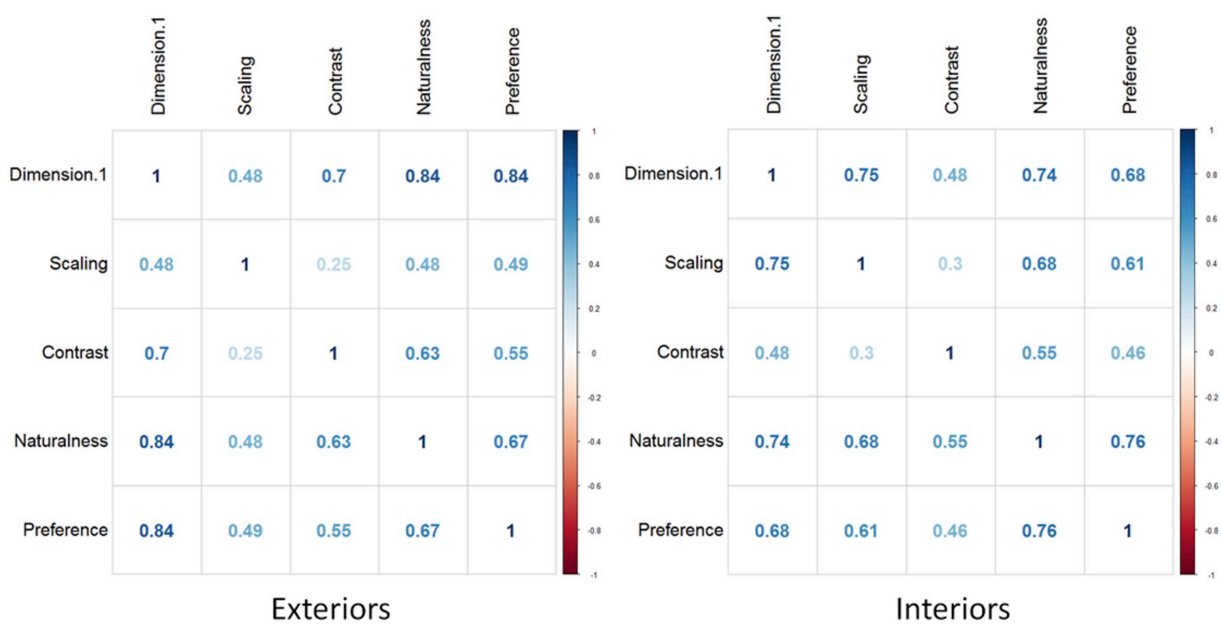


Fig. 6. Correlation matrix for MDS Dimension 1 from Experiment 3, our measures of Scaling and Contrast, and the Naturalness and Preference ratings from Experiments 1 & 2.

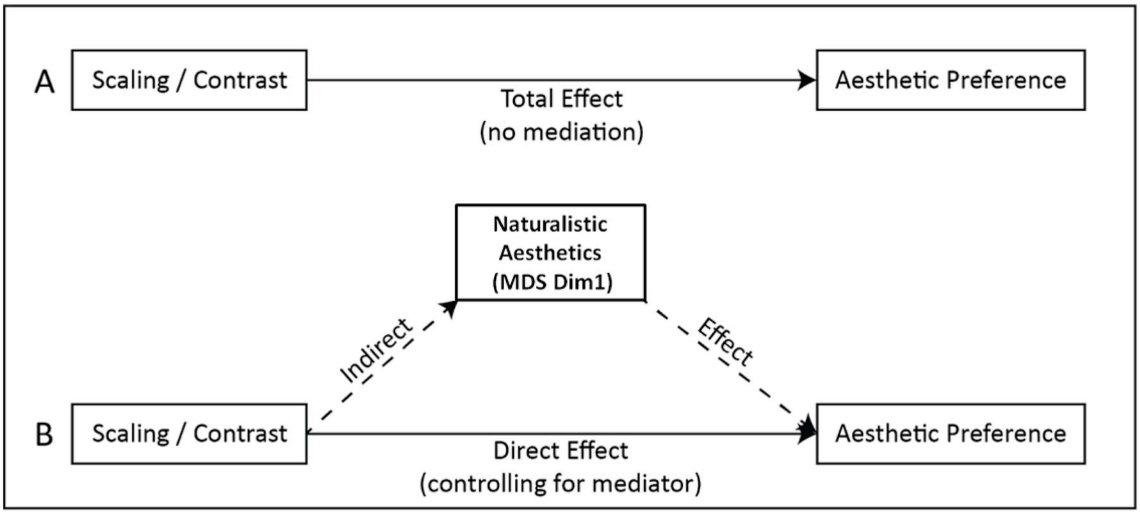


Fig. 7. Mediation models. (A) Diagram of Total Effect of Scaling and Contrast on Aesthetic Preference of buildings interiors and exteriors absent of the latent naturalistic aesthetics grouping factor from Experiment 2 (MDS Dimension 1). (B) Diagram of mediation model with Naturalistic Aesthetics (MDS Dimension 1) as mediator.

Table 5
Results of mediation analyses for Scaling and Contrast effects on Preference for Interior and Exterior scenes. The mediator is MDS Dimension 1, which is related to naturalistic aesthetics of buildings.

	Direct Effect Estimate [95% CI]	Direct Effect *p*-value	Indirect Effect Estimate [95% CI]	Indirect Effect *p*-value
Interiors (Scaling)	0.332 [0.154, 0.501]	< 0.01	0.331 [0.200, 0.468]	< 0.01
Interiors (Contrast)	0.191 [0.053, 0.324]	0.02	0.298 [0.191, 0.425]	< 0.01
Exteriors (Scaling)	0.087 [-0.035, 0.208]	0.16	0.453 [0.312, 0.601]	< 0.01
Exteriors (Contrast)	−0.71 [-0.216, 0.069]	0.33	0.684 [0.537, 0.837]	< 0.01

correlation matrix (Fig. 6) showed that Contrast correlated significantly with preference (Model A in Fig. 7). However, a significant proportion of this effect was mediated by Dimension 1 (Naturalistic Aesthetics), as shown in Table 5. For exterior scenes, Contrast's effect on preference ratings was fully mediated by Naturalistic Aesthetics (indirect effect estimate = 0.684, $p < .01$; direct effect estimate = −0.071, $p = .33$). For interior scenes, the effect of Contrast on Preference was partially mediated by Naturalistic Aesthetics (indirect effect estimate = 0.298, $p < .01$; direct effect estimate = 0.191, $p = .02$).

5. Discussion

In this study, we investigated how subjective perceptions of naturalness in the built environment relate to objective low-level features of architectural images. We also examined the degree to which nature-like architectural features predict similarity evaluations and preference ratings for interior and exterior architectural scenes. Our first experiment revealed that perceptions of naturalness covaried significantly with low-level spatial and color features of images and were significantly associated with two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast* (Alexander, 2002), across both image sets. Experiment 2 showed that aesthetic preference ratings of scenes were strongly predicted by mean naturalness scores and by Scaling and Contrast patterns. Furthermore, image similarity scores (MDS Dimension 1) derived from an image arrangement task in our final experiment correlated highly with both naturalness and preference ratings, suggesting that people may organize and evaluate architectural images based on latent perceptions of naturalistic aesthetics. In other words, people may utilize naturalistic aesthetics as a grouping method for architectural scenes even when they are not primed to do so in any way. Finally, we found that the effects of Scaling and Contrast on preference were mediated by latent perceptions of naturalistic aesthetics.

Results from Experiment 1 build on previous studies showing that subjective perceptions of naturalness are predicted by low-level spatial and color features for outdoor scenes (Berman et al., 2014; Kardan, Demiralp, et al., 2015), many of which had little to no built structure. Here, we extend these findings to architectural scenes, many of which had little to no vegetated content, demonstrating that perceptions of whether a building looks *natural* or *artificial* can also be reliably predicted by low-level scene features. Image statistics in our regression models independently explained 54% of variance in naturalness ratings for interior scenes and 42% of variance for exterior scenes when controlling for the amount of vegetation visible in the scenes. Interestingly, the same three visual features (Scaling, sdSat, and sdBright) significantly predicted naturalness scores for both interior and exterior architectural stimuli. Furthermore, two of these features (Scaling and sdSat) were previously shown to predict perceptions of naturalness in outdoor scenes (Berman et al., 2014; Kardan, Demiralp, et al., 2015). These low-level visual features are conceptually linked to Alexander's proposed patterns of natural architecture. The consistency of these results across interior and exterior image sets suggests that certain visual features associated with the quality of naturalness may transcend scene categories. In other words, patterns that make landscapes look 'natural' are also present in some types of architecture. These features may contribute to perceptions that some buildings look more natural than others.

Next, we carried out a second experiment to test whether people prefer architectural scenes that exhibit nature-like patterns of Scaling and Contrast. These visual patterns significantly predicted preference ratings in both interior and exterior image sets. Results from Experiment 3 showed that individuals may "see" naturalistic aesthetics of architecture in a systematic way. Importantly, participants may unconsciously rely on these naturalistic aesthetics to organize purely architectural scenes. Furthermore, mediation analyses demonstrated that the effects of Scaling and Contrast features on preference ratings were either partially (for interiors) or fully (for exteriors) mediated by latent perceptions of naturalistic aesthetics, as operationalized by MDS Dimension 1. One possible implication of these results is that architectural patterns of Scaling and Contrast may generate aesthetic pleasure because they remind the viewer of visual patterns often found in nature. However, further research would be required to test the causal pathway of such a conclusion.

6. Limitations

Important limitations of this study include decisions we made about stimulus selection and pattern measurement. As described in Section 2.1.2., an equal number of natural-looking and artificial-looking buildings were selected for each category of building function in order to control for the potentially confounding effect of building function on naturalness and preference ratings. This decision was made in order to minimize the influence of semantic scene content on aesthetic judgments (see Coburn et al., 2017). However, by intentionally choosing images that were either natural-looking or artificial-looking within each category, our selection process may have led to oversampling of the upper and lower tails of the naturalness distribution curve. It is possible that smaller effect sizes would be observed in a randomly-selected stimulus set. Furthermore, it is important to recognize the limitations of our approach to quantifying the Levels of Scale and Contrast patterns. These patterns were originally highlighted in descriptive rather than quantitative terms in the work by Alexander (2002). Here, we quantified these patterns using low-level visual features. However, alternative approaches to interpreting and measuring them could potentially yield different results. Additionally, our mediation results suggested that the effects of Scaling and Contrast on Aesthetic Preference were fully or partially mediated by MDS Dimension 1. However, it is important to note that other mediation pathways are theoretically possible. One of these alternative pathways (Scaling/Contrast → Aesthetic Preference → MDS Dimension 1) is analyzed and discussed in Section 7.4 of Supplementary Materials. Finally, it is likely that other features (both low-level and semantic) of architectural scenes, in addition to naturalistic patterns, contributed to participants' similarity ratings and aesthetic judgments. We intend to address this question in future studies.

7. Conclusion

The idea that humans are drawn to nature-inspired architectural forms dates back several centuries. Immanuel Kant believed that man's most beautiful creations look as if they emerged organically from the earth, because they reflect the artist's intuitive understanding of nature's underlying order (Kant, 1790). Philosopher John Ruskin later wrote that “whatever is in architecture fair or beautiful is imitated from natural forms” (Ruskin, 1849, p. 71). Contemporary proponents of biophilic design contend that humans have developed affinities for naturalistic forms in their surroundings over the course of evolutionary history (Joye, 2007b; Salingaros, 2007; Wilson, 1984; Wilson & Kellert, 1995), and that nature-inspired architectural features may foster important psychological benefits (Alexander, 2002; Joye, 2007a; Kellert, 2005; Salingaros, 1998). The experiments presented here offer evidence to suggest that naturalistic patterns in architecture may be preferred, on average, over synthetic forms and suggest that the *biophilia* phenomenon may extend into the built environment. By quantifying two visual patterns characteristic of naturalistic architecture – *Levels of Scale* and *Contrast* – this study also paves the way for future researchers to investigate whether variations in these patterns might enhance mood, cognitive functioning, or other aspects of psychological experience.

Disclosure statement

This statement confirms that the authors have no conflicts of interest to report, and that all measures, conditions, data exclusions, and methods of sample size determination have been reported for all experiments discussed in this paper.

Acknowledgements

Special thanks to Tanvi Lakhtakia, Anabella Pinton, Claire Sampson, Leah Stiff, Taj Ebanks, and Kathryn Schertz, all of whom made a valuable contribution to this paper by collecting data for Experiment 2. This research was supported by generous funding from the TKF Foundation, the John Templeton Foundation (University of Chicago Center for Practical Wisdom and the Virtue, Happiness, and Meaning of Life Scholars Group), NSF Grant BHCS-1632445 to MGB, the University of Chicago College Research Fellows Program, and the Cambridge Trusts. The funders had no role in study design, data collection, data analysis, manuscript preparation, or publication. Finally, we would like to dedicate this article to Dr. Stephen Kaplan (1936–2018), who was a great mentor, friend and advisor to M.G.B. and was an inspiration to much of this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2019.02.007.

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