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Psychological and neural responses to architectural interiors

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Abstract

People spend considerable time within built environments. In this study, we tested two hypotheses about the relationship between people and built environments. First, aesthetic responses to architectural interiors reduce to a few key psychological dimensions that are sensitive to design features. Second, these psychological dimensions evoke specific neural signatures. In Experiment 1, participants (n = 798) rated 200 images of architectural interiors on 16 aesthetic response measures. Using Psychometric Network Analysis (PNA) and Principal Components Analysis (PCA), we identified three components that explained 90% of the variance in ratings: *coherence* (ease with which one organizes and comprehends a scene), *fascination* (a scene's informational richness and generated interest), and *hominess* (extent to which a scene reflects a personal space). Whereas *coherence* and *fascination* are well-established dimensions in response to natural scenes and visual art, *hominess* emerged as a new dimension related to architectural interiors. In Experiment 2 (n = 614), the PCA results were replicated in an independent sample, indicating the robustness of these three dimensions. In Experiment 3, we reanalyzed data from an fMRI study in which participants (n = 18) made beauty judgments and approach-avoidance decisions when viewing the same images. Parametric analyses demonstrated that, regardless of task, the degree of *fascination* covaried with neural activity in the right lingual gyrus. In contrast, *coherence* covaried with neural activity in the left inferior occipital gyrus only when participants judged beauty, whereas *hominess* covaried with neural activity in the left cuneus only when they made approach-avoidance decisions. Importantly, this neural activation did not covary in relation to global image properties including self-similarity and complexity scores. These results suggest that the visual brain harbors sensitivities to psychological dimensions of *coherence*, *fascination*, and *hominess* in the context of architectural interiors. Furthermore, valuation of architectural processing in visual cortices varies by dimension and task.

1. Introduction

People in materially developed cultures spend over 90% of their lives in buildings (Evans & McCoy, 1998). Every day, the architecture we inhabit envelopes our mind and body and influences how we feel and behave (Ellard, 2015). The design of our built environment can modulate how comfortable (Baker & Standeven, 1995; Brager, Paliaga, & De Dear, 2004) or focused (Mehta & Zhu, 2009) we feel in a given moment and can influence hormonal patterns (Fich et al., 2014; Küller & Lindsten, 1992), speed of recovery from surgery (Ulrich, 1984), and long-term cardiac health (Kardan, Gozdyra, et al., 2015).

Given that the brain mediates human responses to architecture, scientific interest in the neuroscience of architecture has surged in recent years (Choo, Nasar, Nikrahei, & Walther, 2017; Coburn, Vartanian, & Chatterjee, 2017; Marchette, Vass, Ryan, & Epstein, 2015; Robinson & Pallasmaa, 2015; Vartanian et al., 2013). However, relatively little empirical research has been conducted on the psychology of architecture (L. T. Graham, Gosling, & Travis, 2015), aside from a limited body of architecture-focused literature within the field of environmental psychology (see for instance, Baum & Davis, 1980; Coburn et al., 2019; Imamoglu, 2000; Ulrich, 1984). Unlike other areas of neuroscience, such as neurolinguistics and neuroaesthetics, neuroarchitecture lacks an extensive behavioral literature from which to construct neurophysiological models and generate predictions (Coburn et al., 2017).

In the context of the built environment, important research has emerged indicating the potential psychological benefits of nature-like, i.e. *biophilic*, design patterns in architecture (Africa et al., 2019; Alexander, 2002; Joye, 2007; Kellert, 2005; Salingaros, 2007, 2015). This literature hypothesizes that biophilic architectural patterns (see for instance Alexander, 2002; Kellert, 2005; Salingaros, 2015) and design indices (Salingaros, 2019, under review) may confer beneficial effects such as improved mood, reduced stress, and enhanced overall wellbeing (Coburn et al., 2019; Joye, 2007; Ryan et al., 2014; Ryan & Browning, 2018; Salingaros, 2015). However, researchers have yet to identify the precise neural and psychological mechanisms that may mediate the predicted long-term "healing" effects of biophilic architecture (Coburn et al., 2019; Ryan et al., 2014). Furthermore, more general frameworks of architectural psychology and aesthetics (i.e., empirical frameworks outlining the various types of acute mental states that diverse architectural environments can induce) have yet to be established. Here, we seek to advance the psychology of architecture in order to lay the groundwork for a more robust line of research on the neuroscience of architecture. We hypothesize that interactions with architectural scenes can be explained by a limited number of underlying psychological constructs. This hypothesis is motivated by past studies that have identified latent psychological dimensions underlying aesthetic responses to visual stimuli in other contexts. Examples include the "preference matrix" of landscape aesthetics outlined by Kaplan & Kaplan (1989) and the core dimensions of novelty and complexity as related to arousal identified by Berlyne in his empirical investigations of aesthetic responses (Daniel E. Berlyne, 1970, 1971, 1974). To our knowledge, no such framework has been identified yet for architecture. We also hypothesize that salient design features of curvature, ceiling height, and enclosure can modulate these key dimensions of architectural experience. These features have been found to influence aesthetic responses to architecture in prior experiments (Vartanian et al., 2013, 2015). Finally, we test the exploratory hypothesis that these psychological dimensions correspond to specific patterns of neural activity in response to viewing images of architectural interiors.

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1.1. Aesthetic response measures

Viewing architectural spaces elicits a broad range of aesthetic experiences, from feelings of comfort and excitement to judgments of a building's age and style. However, few theoretical models have been developed to frame empirical research on the aesthetics of architecture. Recently, we outlined a neuroscientific model of architectural experience to serve as a foundational framework. According to the *aesthetic triad* model (Figure 1), aesthetic experiences in the built environment are mediated by three large-scale neural systems: knowledge-meaning, emotion-valuation, and sensorimotor systems (Chatterjee & Vartanian, 2014; Coburn et al., 2017).

These neural systems align approximately with three important domains of psychological processing: *cognition*, *emotion*, and *behavior* (Izard, Kagan, & Zajonc, 1988; Lench, Darbor, & Berg, 2013; Stangor, 2015). Using this adapted terminology, we propose that architectural encounters produce three general classes of psychological experiences: *cognitive judgements* associated with knowledge-meaning systems, *emotional responses* derived from emotion-valuation systems, and *behavioral-motivational responses* linked to sensorimotor activation. Within this psychological framework, we applied sixteen aesthetic rating scales that capture important aspects of architectural experience (e.g. complexity; see Table 1). These response measures have featured prominently in previous environmental psychology and empirical aesthetics research.
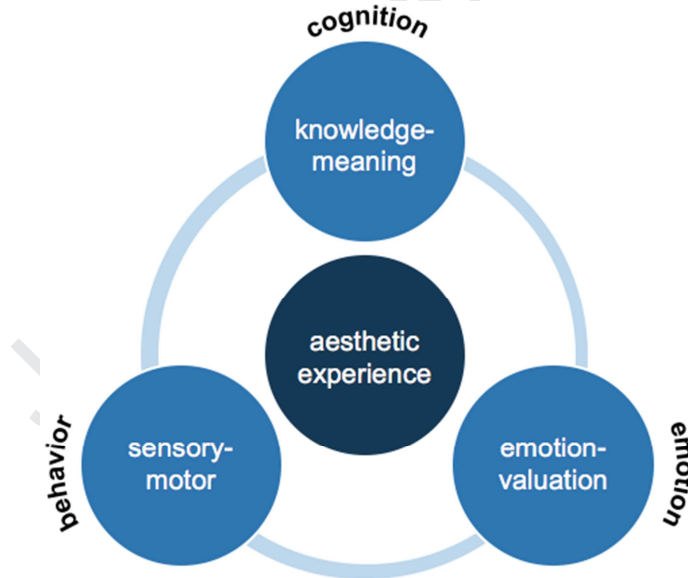

Figure 1: The *aesthetic triad* and associated psychological domains.

1.1.1. Cognitive judgements of architecture

When people enter buildings, they often make cognitive judgments about the spaces around them. We define cognitive judgments as informed by top-down knowledge people bring to evaluations made about external qualities of their surroundings, rather than self-reflective evaluations of their own inner states of being. This distinction is based on past research suggesting that extrospective and introspective evaluations likely involve dissociable neural circuitry (Di Dio, Macaluso, & Rizzolatti, 2007; Leder, Oeberst, Augustin, & Belke, 2004). Here, we discuss five key measures of cognitive judgement in the built environment: complexity, organization, modernity, naturalness, and beauty.

Visual *complexity* has drawn attention from many architectural theorists (Alexander, 2002a; Kroll, 1987; Salingaros, 2007; Venturi, Scully, & Drexler, 1977), environmental psychologists (R. Kaplan & Kaplan, 1989; S. Kaplan, Kaplan, & Wendt, 1972; Ulrich, 1983), and aesthetics researchers (Daniel E. Berlyne, 1971; Frith & Nias, 1974). Visual complexity refers to "the volume of information present in a space" (Dosen & Ostwald, 2016, p. 3) and the informational "richness" of a scene (R. Kaplan & Kaplan, 1989, p. 53). Positive, linear correlations between complexity and preference have been found in various contexts, including the evaluation of artwork (Day, 1967; Leder et al., 2004; Taylor, Micolich, & Jonas, 1999), natural landscapes (S. Kaplan, 1987; Ulrich, 1977, 1983), and built environments (Ç. Imamoglu, 2000; S. Kaplan et al., 1972). In some cases, preference ratings have been found to follow an inverted U-shaped curve when plotted as a function of stimulus complexity (Daniel E. Berlyne, 1970, 1971; Güçlütürk, Jacobs, & van Lier, 2016; Taylor et al., 1999). This relationship often depends on how complexity is operationalized (Nadal, Munar, Marty, & Cela-Conde, 2010a), which may explain the variability in findings.

Organization is also critical to the psychology of architecture. Visual order implies both an absence of randomness (Tullett, Kay, & Inzlicht, 2015) and the presence of predictable patterns like symmetry (Alexander, 2002a; Reber, Schwarz, & Winkielman, 2004; Salingaros, 2007) and structural redundancy in scenes (Kinchla, 1977; Kotabe, Kardan, & Berman, 2016b). The psychological effects of visual organization have been discussed extensively in architectural theory (Alexander, 2002a; Salingaros, 2007; Vitruvius Pollio, Morgan, & Warren, 1914) and art aesthetics literature (Birkhoff, 1933; Eysenck, 1957; Reber et al., 2004). Perception of order can also be modulated by a building's age, condition, and architectural style. These variables have been captured in past studies by measuring participants' perceptions of *modernity* in the built environment (Acking & Kuller, 1973; Ç. Imamoglu, 2000; V. Imamoglu, 1979).

Interacting with natural environments enhances many aspects of psychological functioning (Berman et al., 2012; Berto, 2005; Bratman, Daily, Levy, & Gross, 2015; S. Kaplan, 1995; Ryan, Weinstein, Bernstein, & Brown, 2010). *Naturalness* appears to be a salient measure of environmental judgement (Berman et al., 2014; Kotabe, 2016) that correlates highly with scene preference ratings (Kardan, Demiralp, et al., 2015). Recent studies also show that the perception of naturalness is not merely determined by natural content (e.g., recognition of trees and vegetation) but is also predicted by specific low-level visual patterns that can occur in both natural and man-made objects and environments (Berman et al., 2014; Coburn et al., 2019; Kardan, Demiralp, et al., 2015; Kotabe, 2016). For instance, Graham and Field (2007) found certain man-made paintings have similar low-level visual properties as natural scenes. Indeed, several scholars propose that nature-like aesthetic qualities are present, to varying degrees, in the built environment, and that naturalistic architectural spaces may confer some of the same psychological benefits as natural landscapes (Alexander, 2002a; Joye, 2007; Kellert, 2003; Salingaros, 1998).

Beauty, which is perhaps the most global measure of aesthetic judgment, is among the most frequently measured qualities in empirical aesthetics (Chatterjee, 2013; Ishizu & Zeki, 2011; Leder & Nadal, 2014; Nadal et al., 2010). Beauty has long been regarded as an important quality of architectural design in cultures around the world (Mak & Thomas Ng, 2005; Patra, 2009; Vitruvius Pollio et al., 1914). Efforts to understand environmental beauty have gained traction in both environmental psychology (Cooper, Burton, & Cooper, 2014; S. Kaplan, 1987; Zhang, Piff, Iyer, Koleva, & Keltner, 2014) and architectural research (Kirk, Skov, Christensen, & Nygaard, 2009; Vartanian et al., 2013, 2015), perhaps because of the growing view that "attractiveness is a key element in how the built environment affects our wellbeing" (Cooper & Burton, 2014), as

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well as the primary role that beauty plays in our desire to live in a place (Ritterfeld & Cupchik, 1996).

Although we provisionally categorized these five response measures as cognitive judgments, they likely depend on input from all three nodes of the aesthetic triad, rather than from cognitive processing alone. For instance, low-level spatial and color features of environmental scenes significantly predict subjective ratings of complexity, order, and naturalness (Berman et al., 2014; Kardan, Demiralp, et al., 2015; Kotabe et al., 2016b; Kotabe, Kardan, & Berman, 2017), even when the semantic content of scenes is removed (Kotabe, Kardan, & Berman, 2016a; Kotabe et al., 2016b), suggesting that these measures can be shaped by low-level sensory input. Furthermore, the experience of beauty likely involves complex interactions among sensory, emotional, and cognitive inputs (Chatterjee & Vartanian, 2014; Leder & Nadal, 2014; Leder et al., 2004).

1.1.2. Emotional responses to architecture

In addition to eliciting external judgments, architectural spaces modulate affect, emotions, and other inner states of being. Alexander (2002) emphasized the importance of judging a building not only via detached observation of its appearance, but also by examining the degree to which it "touches us in our humanity" (Alexander, 2002a, p. 300) and "stirs our feelings, our passion" (Alexander, 2002a, p. 302). Several other writers have also highlighted the introspective dimension of architectural experience (Bachelard, 1994; Heidegger, 2013; Linnet, 2012; Tanizaki, 2001). Eight measures of emotional experience in the built environment are outlined below: personalness, hominess, relaxation, comfort, stimulation, uplift, vitality, and valence.

The degree of personal feeling that a building generates is an important consideration in architectural design (Alexander, 2002a; L. T. Graham et al., 2015; Sommer, 1969; Wiking, 2017). *Personal* spaces feel warm and intimate (L. T. Graham et al., 2015; Sommer, 1969) and generate feelings of "depth, tenderness, and longing" (Alexander, 2002a, p. 302), whereas impersonal spaces often feel cold and standardized (Linnet, 2012). A related measure, the degree to which an architectural space makes a person feel cozy or "at home" (Daniels, 2015; L. T. Graham et al., 2015; Ritterfeld & Cupchik, 1996), is captured by the Canadian concept of *hominess* (Linnet, 2012; Wiking, 2017). Considerable emphasis has been placed on the degree of stress or, conversely, *relaxation* that people experience in response to environmental design (Baum & Davis, 1980; Fich et al., 2014; L. T. Graham et al., 2015; Tullett et al., 2015; Tyrväinen et al., 2014; Ulrich et al., 1991). *Comfort* is also a salient measure of occupant experience that abounds in architectural research (Baker & Standeven, 1995; Brager et al., 2004; Fanger, 1973; Nicol & Humphreys, 2002; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007).

Researchers have taken interest in understanding how design parameters modulate the degree of physiological *stimulation* that occupants experience (Acking & Kuller, 1973; L. T. Graham et al., 2015; Ritterfeld & Cupchik, 1996). A related measure is the extent to which a place feels *uplifting*, on the one extreme, and depressing, on the other (Evans, 2003). This scale may be particularly relevant to wellbeing, as the frequency of daily uplifts a person experiences predicts long-term health measures like stress and depression (Kanner, Coyne, Schaefer, & Lazarus, 1981; Vitaliano, Scanlan, Ochs, & Syrjala, 1998). Scholars have also measured the impact of environmental design on *vitality* (Ryan et al., 2010; Tyrväinen et al., 2014), which covaries with important physiological and psychological health measures (Ryan & Deci, 2008; Ryan & Frederick, 1997). Vitality has been defined as "a positive sense of aliveness and energy" (Nix, Ryan, Manly, & Deci, 1999, p. 530) and is closely related to the Chinese concept of *chi*, which Nix and colleagues defined as a source of calm energy that "can be more or less accessed by

individuals depending on their lifestyles and personal practices" (Nix et al., 1999, p. 268). A related but broader measure, *valence*, describes the degree to which an architectural space makes an occupant feel good or bad. Valence is among the most frequently studied affective measures in empirical aesthetics and is closely related to other common measures such as preference, liking, and pleasantness (Acking & Kuller, 1973; Daniel E. Berlyne, 1970; Di Dio et al., 2007; Leder et al., 2004).

Although these affective response scales are associated with neural networks regulating pleasure and emotion, it is likely that cognitive and sensory processes also influence emotional responses to architecture. For instance, *hominess* ratings are likely modulated by cognitive evaluations based on an individual's culture, upbringing, and memories of home. Pleasure responses to architectural scenes have also been shown to depend on education and expertise (Kirk et al., 2009), suggesting that *valence* may be influenced by top-down cognitive processing.

1.1.3. Behavioral-motivational responses to architecture

The final class of aesthetic response scales encompasses the psychological measures of behavior, movement, and motivation, which may be to a first approximation linked to sensorimotor processing in the brain. Here, we focus on three behavioral measures: interest, approachability, and explorability.

Interest, an important response measure in empirical aesthetics (Daniel E. Berlyne, 1971; Day, 1967; Silvia, 2005, 2012) and environmental psychology (R. Kaplan & Kaplan, 1989; Ulrich, 1983), is closely linked to sensory perception (Day, 1967) and motivation (Silvia, 2008). James (1892) described interest as an automatic psychological process that enables us to identify and attend to sensory stimuli that are important for our welfare. Environmental psychologists later applied this idea to landscape perception by proposing that sensory features of the environment are more likely to capture human interest if they prove beneficial or detrimental to our species' survival over the course of evolutionary history (Appleton, 1975; S. Kaplan, 1987; Wilson & Kellert, 1995).

Interest can also motivate motor responses to physical surroundings (Joye & Dewitte, 2016; R. Kaplan & Kaplan, 1989; Ulrich, 1983), including fundamental decisions to *approach* or avoid architectural spaces (Ritterfeld & Cupchik, 1996; Vartanian et al., 2015, 2013). Another important behavioral response to architecture is "the need to *explore*, to find out more about what is going on in one's surroundings" (R. Kaplan & Kaplan, 1989, p. 51). Although these response measures are associated with sensorimotor processing, they likely involve input from cognitive and affective domains discussed previously. Despite being strongly influenced by sensory content, *interest* has often been described as a measure of emotion (Silvia, 2005, 2008, 2012), and could be categorized as an affective response measure. Like valence and beauty, *approachability* describes a global psychological response that is likely modulated by cognitive and emotional processes.

These 16 aesthetic response measures have been widely studied in environmental psychology and represent important aspects of architectural experience. In the next section, we introduce three salient architectural variables that have previously been shown to modulate neural and behavioral responses to the built environment.

1.2. Architectural variables

1.2.1. Ceiling Height

Research suggests that *ceiling height* can affect psychological responses to architectural interiors. On average, preferences for ceiling height peak around 10 feet across a range of spatial functions (Baird, Cassidy, & Kurr, 1978). In a recent study investigating the effect of ceiling height on aesthetic perceptions and neural activity, spaces with high ceilings received higher beauty ratings than those with low spaces. Functional magnetic resonance imaging (fMRI) results showed that rooms with high ceilings differentially activated neural structures involved in visuospatial attention and exploration, such as the left middle frontal gyrus and left precuneus (Vartanian et al., 2015). These findings were consistent with previous research indicating that high ceilings increase perceptions of spaciousness (Stamps, 2011) and prime thoughts of freedom, whereas low ceilings are more likely to prime thoughts of confinement (Meyers-Levy & Zhu, 2007).

1.2.2. Enclosure

Spatial *enclosure* has been found to modulate aesthetic and psychological responses to building interiors. Appleton's prospect-refuge theory (1975) proposed that humans have evolved innate preferences for environments that offer opportunities to see (i.e., points of prospect) without being seen (i.e., points of refuge). Such places, he argued, have historically proven beneficial to our species survival by enabling humans to see and hide from threats (Appleton, 1975). In support of this theory, evidence suggests that humans generally feel safer in more open spaces (Stamps, 2005) and also tend to prefer interior environments that afford greater visual connection with external surroundings (Vartanian et al., 2015), when controlling for other factors.

In a study of psychological and neural responses to open and enclosed architectural interiors, participants were more likely to want to approach open rooms and to rate those rooms as beautiful in comparison to enclosed interiors. Open spaces also activated neural areas associated with perceived visual motion, whereas enclosed surroundings activated neural regions involved in fear processing (Vartanian et al., 2015). This finding was theoretically consistent with results from a previous study indicating that enclosed spaces, relative to open environments, increase vulnerability to stress and prolong an occupant's stress response following exposure to an induced stress test (Fich et al., 2014).

1.2.3. Curvature

Geometric contour, or *curvature*, has generated much interest from aesthetics and architectural researchers. In many contexts, people exhibit greater preferences for curvilinear than rectilinear objects (Bar & Neta, 2006; Dazkir & Read, 2012; Leder & Carbon, 2005). Rectilinear shapes and patterns also evoke more unpleasant emotions compared to curvilinear forms (Hevner, 1935; Lundholm, 1921; Poffenberger & Barrows, 1924). These perceptual effects may extend to the built environment. People prefer airport passenger areas that embody curvilinear rather than rectilinear design (Van Oel & van den Berkhof, 2013). In our study on the perception of architectural curvature, for instance, we found that curved building interiors were judged as more beautiful than rectilinear spaces. Curved buildings also activated key areas of the visual cortex, including the lingual and calcarine gyrus, when participants made approach-avoidance decisions (Vartanian et al., 2013). It has been theorized that people prefer curved forms over rectilinear forms in the built environment because curved forms are more commonly found in nature and thus feel inherently more natural (Coburn, 2019; Kellert, 2005; Salingaros, 2015). Supporting this idea, the density of curved edges has been found to correlate positively with perceptions of naturalness and aesthetic preference for images of outdoor spaces, whereas the

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density of straight edges has been shown to correlate negatively with perceptions of naturalness and preference for such spaces (Berman et al., 2014; Ibarra et al., 2017; Kardan et al., 2015). Curvature has consequently been identified as an example of nature-like or "living" structural pattern in architecture (Salingaros, 2015).

Although these three variables do not exhaustively capture the diversity of architectural geometry, they represent a useful starting point for investigating psychological responses to the built environment. The next section outlines the research questions and hypotheses that motivated our three experiments.

1.2.4. Global Image Properties

In addition to the above-mentioned architectural variables, we also tested (in Experiment 2) whether key Global Image Properties (GIPs) of architectural scenes correlated with the principal psychological components. GIPs are computed measures of global psychophysical properties of scenes. They capture quantitative information about whole scenes, thereby complementing the qualitative architectural variables (ceiling height, enclosure, and curvature).

Two GIPs were measured: *self-similarity* and *complexity*. Self-similarity implies that an image as a whole is structurally similar to its parts. Complexity represents the amount of detail in an image. These GIPs were chosen because both have consistently been found to correlate highly with aesthetic preference ratings in studies of visual art, architecture and landscapes (Redies et al., 2012; Mullin et al., 2015; Hayn-Leichsenring, Kenett, Schulz & Chatterjee, unpublished data). Architectural scholars have also emphasized the importance of self-similarity and complexity as key patterns that contribute to the beauty of architectural design (*self-similarity:* Alexander, 2002; Capo, 2004; Crompton, 2002; Goldberger, 1996; Salingaros, 2007; *complexity:* Alexander, 2002; Salingaros, 2007; Venturi et al., 1966).

1.3. Research questions

Three research questions motivated the following experiments: 1) Can aesthetic responses to architectural scenes be reduced to a few key psychological dimensions? 2) Are these dimensions sensitive to salient design features and GIPs? 3) Do these psychological dimensions correlate with neural activation patterns, and to what extent are these correlations modulated by task? We hypothesized that 1) a few key psychological dimensions would explain much of the variance underlying diverse aesthetic response measures, and that 2) these dimensions would be sensitive to ceiling height, enclosure, and curvature. Furthermore, we predicted that 3) each latent psychological dimension would be linked to a distinct pattern of neural activation.
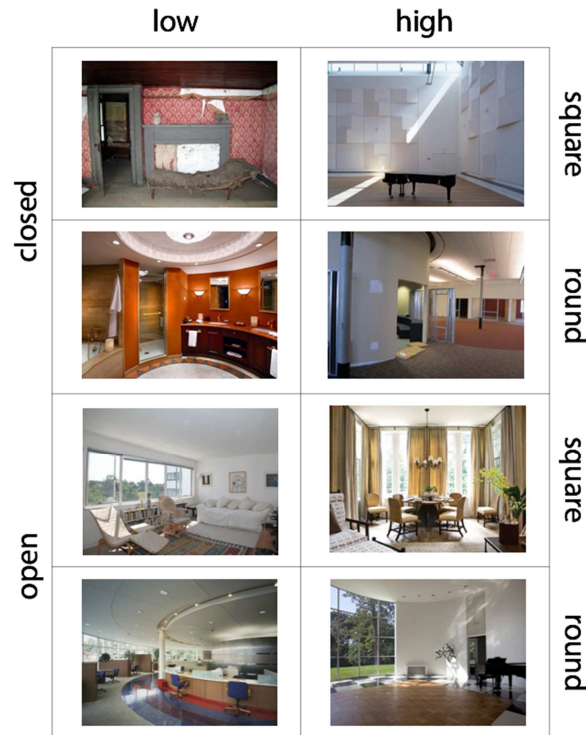
2. Experiment 1

In Experiment 1, we asked participants to rate images of building interiors on 16 aesthetic measures that capture important aspects of architectural experience. We then carried out two complementary approaches, psychometric network analysis (PNA) and principal components analysis (PCA), to identify whether or not the original 16 measures could be reduced to a few latent psychological dimensions. The stimuli were counterbalanced on three architectural variables of interest (ceiling height, enclosure, and curvature), and we examined the degree to which these spatial properties influenced psychological response measures. Finally, we investigated correlations between psychological responses and two Global Image Properties (GIPs) of architectural scenes, Self-Similarity and Complexity. These GIPs were chosen because

both have consistently been found to correlate highly with aesthetic preference ratings in studies of visual art, architecture and landscapes.

2.1. Methods

2.1.1. Materials

The stimuli for this experiment were 200 images of interior architectural spaces (the complete stimulus set is displayed in S1 and S2 of Supplementary Materials). These same images were previously used in three studies (Vartanian et al., 2015, 2013, 2019). The stimuli were selected from image databases accessed by the Department of Architecture, Design, and Media Technology of Aolborg University and The Royal Danish Academy of Fine Arts School of Architecture. Specifically, two architects independently rated every image on (a) perceived enclosure (open, closed), (b) ceiling height (high, low), and (3) contour (round, square). The image set included in the study consisted only of those images on which the two independent raters reached 100% agreement regarding its standing on each of those three dimensions. Thus, the spaces selected for the study varied on three environmental parameters. Half of the rooms were enclosed, while the other half were open. Half had high ceilings and half had low ceilings. Finally, half of the interiors had curvilinear edges ("round" condition), while the other half were rectilinear ("square" condition). This setup yielded the eight experimental conditions outlined in Figure 2 (n = 25 per condition): closed square low, closed square high, closed round low, closed round high, open square low, open square high, open round low, and open round high.

Figure 2: Eight experimental conditions (*n* = 25 per condition) were generated by counterbalancing three architectural variables (ceiling height, enclosure, and curvature) across the stimulus set.

2.1.2. Participants

We recruited 798 US-based adults (391 women, 401 men, 6 other) from Amazon's Mechanical Turk to participate in this study. Sample size was determined by our goal of obtaining approximately 50 ratings per image on each of the sixteen aesthetic rating scales. Ages ranged from 18 to 75 years (*M* = 38.06, *SD* = 11.96), and education level ranged from 5 to 22 years (*M* = 15.04, *SD* = 2.11). Participants were compensated $4.00 for their participation and the experiment took approximately 40 minutes to complete. Informed consent was obtained from each participant and the study was approved by the IRB of the University of Pennsylvania. Four participants repeated the study twice. For each of these participants, data from the second round of testing were excluded from analysis.

2.1.3. Procedures

Participants collectively rated 200 images of architectural interiors on 16 aesthetic rating scales (Table 1). Approximately 50 ratings were collected per image for each scale. The stimuli were divided into four blocks of 50 images. Each image block contained an even distribution of images from each of the eight architectural conditions, with 6-7 randomly selected stimuli represented from each condition per block (see S3 in Supplementary Materials). This blocking scheme ensured that participants had approximately equal exposure to each architectural condition for each rating task they completed. The aesthetic rating scales were also divided into rating groups, with four response measures in each group. Sixteen rating groups were created, each containing a unique combination of four rating scales (see S4 in Supplementary Materials).

At the start of the experiment, participants were presented with a slideshow of all 200 images shown in random order. This was intended to familiarize them with the full range of stimuli

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before they rated any images. Participants were subsequently assigned, at random, to one of the sixteen rating groups. They were then presented with one of the four image blocks and were asked to rate every image within that block on one of the four ratings scales from their assigned rating group. Next, they rated images from a second image block on a second rating scale, images from a third block on a third rating scale, and images from the final block on the fourth rating scale. Ratings were entered on a 7-point sliding semantic differential scale displayed below the image. Prompts and scale anchors are shown in Table 1. The presentation order of the four image blocks and the assigned order of the four rating tasks were randomized. Images within each block were also presented to participants in a randomized sequence. This design allowed participants to experience a variety of rating tasks while minimizing the cognitive demands of frequent task switching (Monsell, 2003). It also ensured that images received an equal number of ratings on each scale and minimized ordering effects by assigning diverse combinations of rating task sequences to different participants. After completing the study, participants were asked to fill out a brief demographics questionnaire.

Table 1: Prompts and end anchors of 7-point rating scales for the aesthetic rating scales.

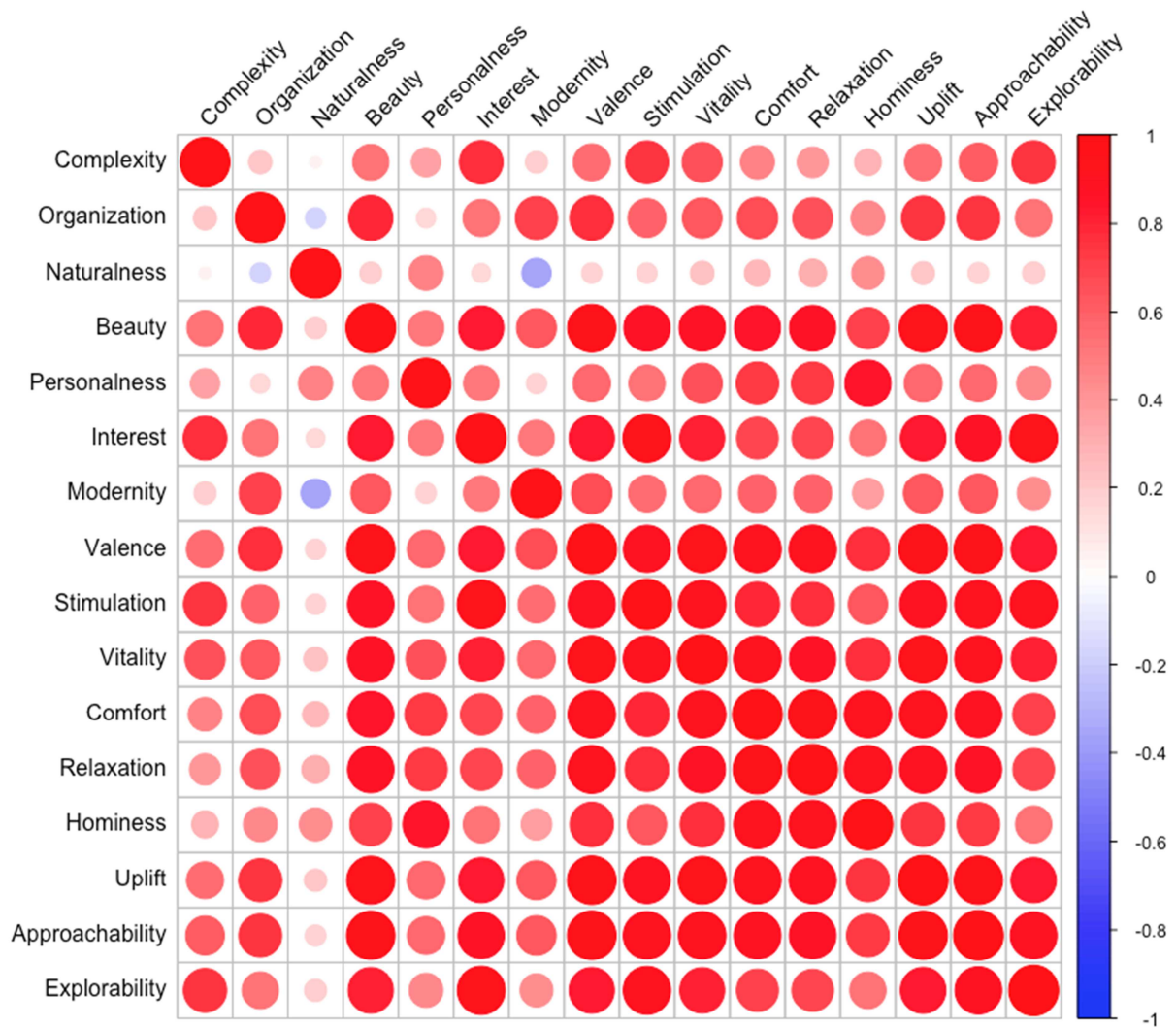| Aesthetic Rating Scale	Rating Prompt	Low Anchor	High Anchor
Complexity	*This room looks…*	Simple	Complex
Organization	*This room looks…*	Disordered	Organized
Naturalness	*This room looks…*	Artificial	Natural
Beauty	*This room looks…*	Ugly	Beautiful
Personalness	*This room looks…*	Impersonal	Personal
Interest	*This room looks…*	Boring	Interesting
Modernity	*This room looks…*	Aged	Modern
Valence	*This room makes me feel…*	Bad	Good
Stimulation	*This room makes me feel…*	Bored	Excited
Vitality	*This room makes me feel…*	Lifeless	Alive
Comfort	*This room makes me feel…*	Uncomfortable	Comfortable
Relaxation	*This room makes me feel…*	Stressed	Relaxed
Hominess	*This room makes me feel…*	Alienated	At home
Uplift	*This room makes me feel…*	Diminished	Uplifted
Approachability	*If I saw this room, I'd…*	Leave	Enter
Explorability	*If I saw this room, I'd…*	Ignore it	Explore it

2.2. Analysis & Results

Data analysis was carried out at the item level. This analysis was achieved by calculating the average rating for each image on every aesthetic rating scale. To identify the principal psychological components of architectural experience, we applied two complementary approaches: a psychometric network analysis (PNA; Christensen, Kenett, Aste, Silvia, & Kwapil, 2018) and principal component analysis (PCA; Field, Miles, & Field, 2014). Next, three-way factorial ANOVAs were calculated to determine the degree to which the three architectural variables predicted principal component scores.

2.2.1. Psychometric network analysis (PNA)

A novel approach to studying multidimensional psychological constructs is through network science (Christensen et al., 2018). This approach is applied at the cognitive and psychological levels to study cognitive phenomena (Baronchelli, Ferrer-i-Cancho, Pastor-Satorras, Chater, & Christiansen, 2013; De Deyne, Kenett, Anaki, Faust, & Navarro, 2016; Isvoranu, Borsboom, van

Os, & Guloksuz, 2016; Isvoranu, van Borkulo, et al., 2016; Karuza, Thompson-Schill, & Bassett, 2016). Recent research has applied psychometric network analysis (PNA; Christensen et al., 2018; Epskamp, Maris, Waldorp, & Borsboom, 2016) to investigate the intricate interactions of psychopathology and personality (Costantini et al., 2017). The network approach defines psychological constructs as complex systems—phenomena that emerge from the causal interactions between dimensions of a multidimensional construct (Borsboom & Cramer, 2013; Schmittmann et al., 2013). Such an approach can offer a unique perspective for examining the psychological components of architectural experience, by defining the 16 measures of architectural experience as nodes in an "aesthetic network" and examining the interaction between these nodes. Constructing this network allows us to examine the structure of the network, to investigate how the nodes cluster into "communities," and to map interactions between nodes.

Figure 3: Correlation matrix of 16 aesthetic rating scales. This figure was created using the *stats* (R Core Team, 2016) and *corrplot* (Wei & Simko, 2016) packages in R.

We first constructed a psychological response network. In this network, nodes represent the sixteen measures of architectural experience and edges represent the rating associations between items, i.e., the similarity of average ratings across items for different measures. To prepare the data for network analysis, a correlation matrix (Figure 3) was plotted across the sixteen aesthetic response measures using the *stats* (R Core Team, 2016), *corrplot* (Wei & Simko, 2016), and *psych* (Revelle, 2016) packages in R (R Core Team, 2016). The rating

correlation matrix was examined as an adjacency matrix of a weighted, undirected network. With this approach, each aesthetic response measure represents a node in the network and the edges between two measures represent the correlation between them. The weight (i.e., correlation) of the edge is indicated by the correlation between two nodes. Therefore, an adjacency (or connectivity) matrix corresponds to an *n x n* matrix, where *n* is the number of measures (nodes) and each cell represents a correlation between two measures. Most of the edges will have small values or weak correlations, which represents noise in the network. To minimize such noise and possible spurious correlations, the Planar Maximally Filtered Graph (PMFG) method was used, which constructs a sub-graph, capturing the most relevant information (i.e., removal of spurious connections and retaining high correlations) within the original network (Kenett, Kenett, Ben-Jacob, & Faust, 2011; Tumminello, Aste, Di Matteo, & Mantegna, 2005).

To visualize the networks, we applied the force-directed layout of the Cytoscape software (Shannon et al., 2003). In these 2D visualizations (Figure 4), nodes (i.e., aesthetic response measures) are represented as circles and edges between them are represented by lines. Since these networks are unweighted and undirected, the links merely convey symmetrical (i.e., bidirectional) relations between two nodes. Analyzing the structure of the network, three communities were found. Community 1 was closely associated with three aesthetic response measures (organization, modernity, and beauty); five measures comprised Community 2 (naturalness, personalness, relaxation, hominess, and comfort); and four communities clustered onto Community 3 (explorability, complexity, interest, and stimulation). The four remaining aesthetic measures (uplift, valence, vitality, and approachability) were grouped at the intersection of the three communities. The discovery of these three communities motivated a PCA to further identify the psychological dimensions of architectural experience.
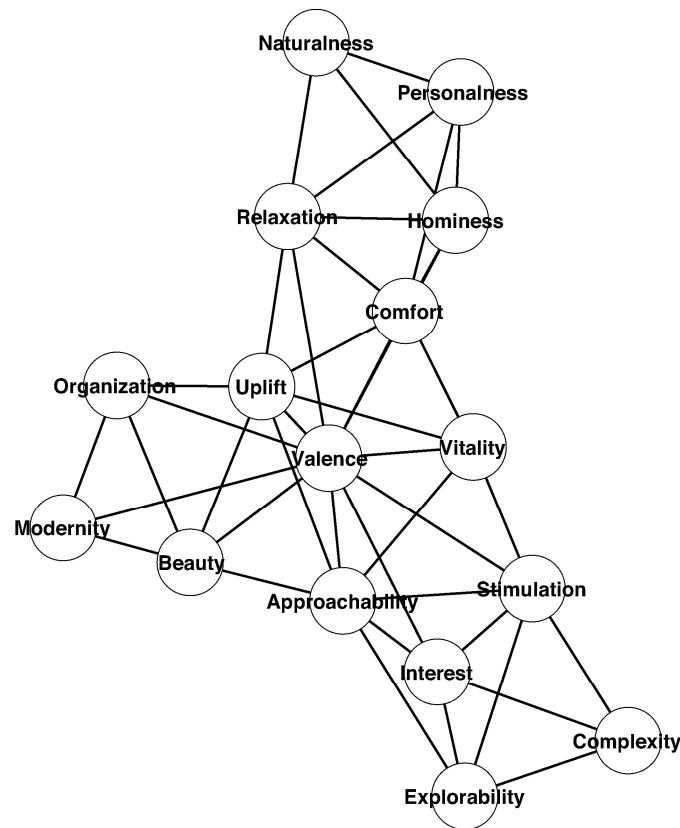
Figure 4: Visualization of the aesthetic network.

2.2.2. PCA of aesthetic response measures

A PCA was carried out to identify the principal components underlying the sixteen aesthetic response measures. The correlation matrix that was plotted in the previous analysis (Figure 3) revealed a high degree of covariance across many of the original aesthetic measures. The determinant of the correlation matrix (DCM) was calculated using the *stats* R package (R Core Team, 2016), yielding a value of 6.3 x 10^{-14}. This value was substantially below the minimum threshold of $1x10^{-5}$ recommended by Field et al. (2014), indicating that the multicollinearity among the dependent variables was too high to perform an accurate factor analysis. To remedy this problem, six variables were excluded from factor analysis because each exhibited high bivariate correlations (above 0.9) with at least one of the retained variables. The excluded variables were vitality (0.92 correlation with valence), uplift (0.96 correlation with valence), comfort (0.91 correlation with valence), relaxation (0.91 correlation with valence), stimulation (0.93 correlation with interest), and explorability (0.92 correlation with interest). Modernity was also excluded from factor analysis to further reduce redundancy, and because it was deemed the least theoretically relevant of the remaining 10 rating scales. After excluding these variables from the analysis, the DCM for the nine retained measures yielded a value of 4.8 x 10^{-6}, which was within an acceptable range of the recommended threshold (Field et al., 2014). For further discussion of the methodological reasons for excluding redundant variables in PCA, see (Field et al., 2014, Chapter 17).

PCA was performed on the 9 retained variables with oblique (oblimin) rotation, using the "principal" function in the *psych* R package (Revelle, 2016). The Kaiser-Meyer-Olkin (KMO) index score of 0.83 confirmed the sampling adequacy for the PCA, and all KMO values for individual variables were above 0.63. KMO values were calculated using the "KMO" function of the *psych* package in R (Revelle, 2016). Bartlett's sphericity test indicated that correlations between variables were sufficiently high for PCA (χ^2= 2392, p < .001). Bartlett's test was run using the "cortest.bartlett" function of the *psych* package in R (Revelle, 2016). An initial PCA was carried out with 9 components retained to determine eigenvalues for each component in the data. The first three components were retained, given that all three had eigenvalues exceeding Jolliffe's criterion of 0.7 and together explained 90% of the variance. The decision to retain three components was also consistent with the identification of three communities in the preceding network analysis (Figure 3).

Table 2 shows the factor loadings, eigenvalues, and explained variance for each of the three retained principle components after oblimin rotation. The variables that cluster on each component suggest that PC1 represents a sense of *coherence*, PC2 represents the feeling of *hominess*, and PC3 captures the experience of *fascination*. In any PCA analysis, the naming of components is a challenging task, as this process requires some degree of interpretation from the authors. We chose the terms *coherence* and *fascination* as names for PC1 and PC3, respectively, because these were two important terms use frequently in the Kaplans' foundational research on landscape aesthetics (Berman, Jonides, & Kaplan, 2008; S. Kaplan, 1995; S. Kaplan & Berman, 2010; S. Kaplan & R. Kaplan, 1989). We felt that the particular combination of variable loadings for these components suggested a close alignment with these two concepts that the Kaplans had previously identified as important dimensions of landscape experience (see discussion). Naming PC2 was more challenging because there was no clear term in architectural scholarship or environmental psychology that clearly unified the concepts of naturalness, personalness, and hominess. We ultimately chose one of the loading variable

names, *hominess*, as the component name. *Hominess* is a term frequently used in Canadian culture to describe an intimate environmental experience, and we felt that this concept would be straightforward for most English speakers to understand. One of us (AC) has presented these data several times to non-neuroscientist and non-architect audiences. Anecdotally, from his informal querying of these audiences, people resonate with and understand hominess more easily than naturalness and personalness. Alternative component names and concepts for PC2 are further addressed in the discussion.

Figure 5 displays these PCA results in graphical form. Each arrow represents a discreet psychological variable, and each axis represents a principal component. The size and direction of the arrows indicates the proximity of the original variables to the latent principal components. Finally, Figure 6 displays the correspondence of the network structure identified in the aesthetic network and the 3 PCs. The arrows display each PC overlaid on the corresponding "community" (i.e. cluster of nodes) of the network.

Table 2: Factor loadings on the three principal components.

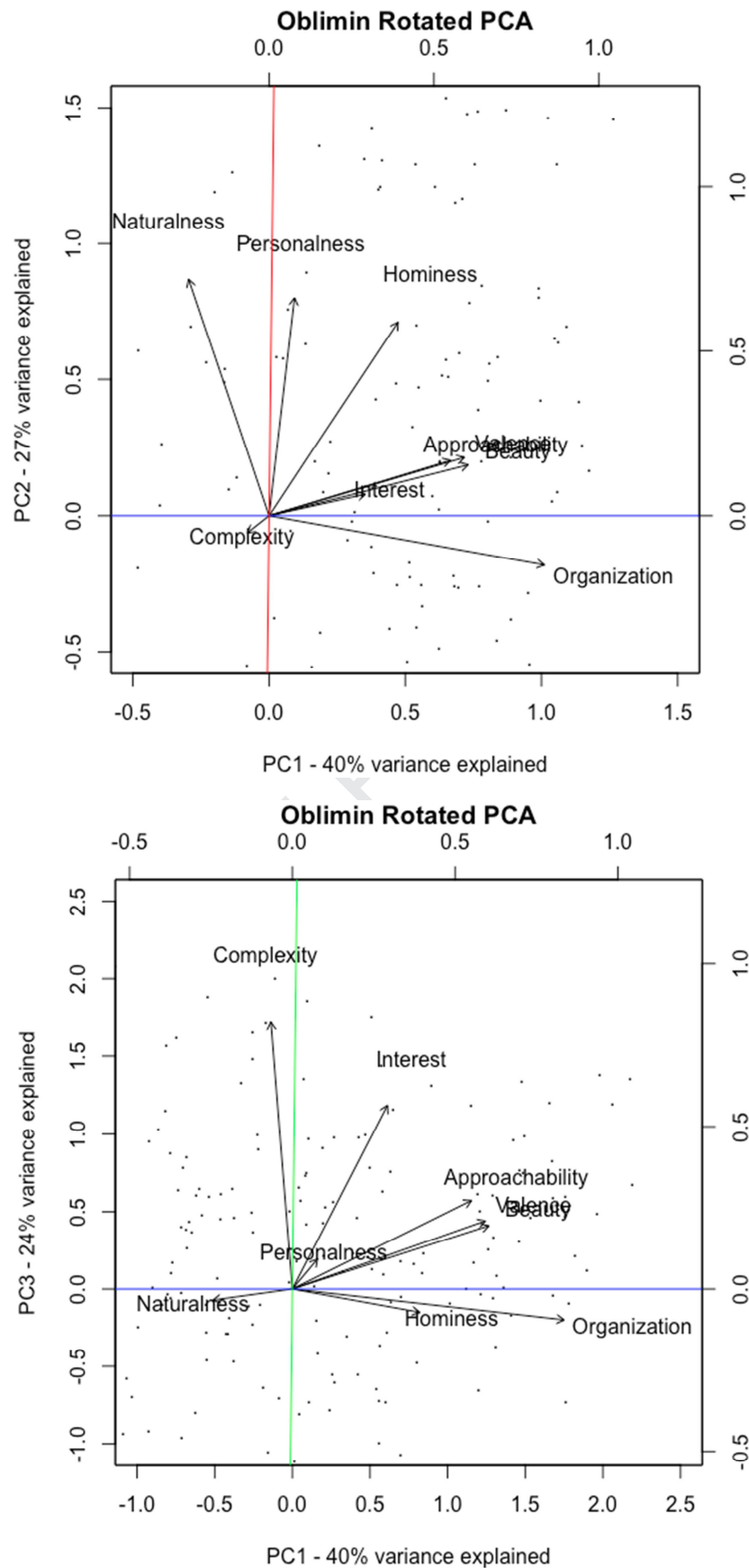| Aesthetic Rating Scale	PC1 (Coherence)	PC2 (Hominess)	PC3 (Fascination)
Complexity	-0.08	-0.06	**1.02**
Organization	**1.04**	-0.19	-0.12
Naturalness	-0.31	**0.90**	-0.04
Beauty	**0.76**	0.19	0.24
Personalness	0.10	**0.83**	0.11
Interest	0.37	0.08	**0.71**
Valence	**0.74**	0.22	0.26
Hominess	0.49	**0.73**	-0.09
Approachability	**0.69**	0.21	0.34
Eigenvalue	**3.57**	**2.39**	**2.16**
Variance Explained	**40%**	**27%**	**24%**
Cumulative Variance	**40%**	**66%**	**90%**

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Figure 5 (Top): Factor loadings on PC1 (X-axis) and PC2 (Y-axis). (Bottom): Factor loadings on PC1 (X-axis) and PC3 (Y-axis). Graphics were created using the "biplot" function of the *stats* R package (R Core Team, 2016).
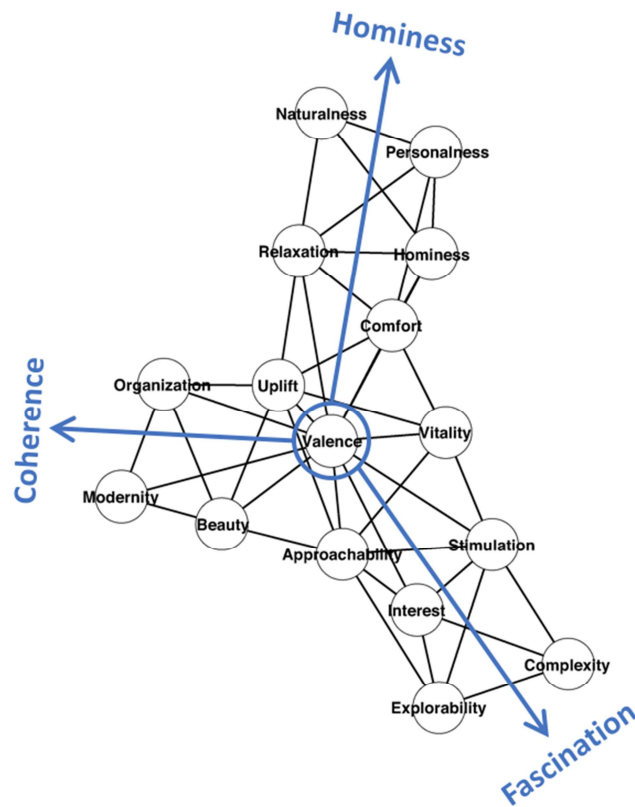
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Figure 6: Diagram of 3 principal components overlaid onto the aesthetic network. Each blue arrow represents a principal component corresponding to a community (cluster of nodes) in the network. Note that seven of the variables included in the PNA were excluded from the PCA due to multicollinearity.

2.2.3. Architectural variables predicting principal component scores

3-way factorial ANOVAs were carried out using the *stats* (R Core Team, 2016) and *ez* (Lawrence, 2016) R packages to determine the relationship between principle component scores and the three architectural variables of interest. Graphical and statistical results of this analysis are displayed in Figure 7. There were significant main effects of ceiling height [F (1,192) = 13.56, $p <$ .001, η_p^2 = 0.08], enclosure [F (1,192) = 5.21, p = .024, η_p^2 = 0.03], and curvature [F (1,192) = 14.94, $p <$ .001, η_p^2 = 0.09] on PC3 (*fascination*) as well as significant main effects of enclosure on PC1 [*coherence*; F (1,192) = 6.39, p = .012, η_p^2 = 0.03] and PC2 [*hominess*; F (1,192) = 10.94, p = .001, η_p^2 = 0.05]. No significant interaction effects were found among the three architectural variables.
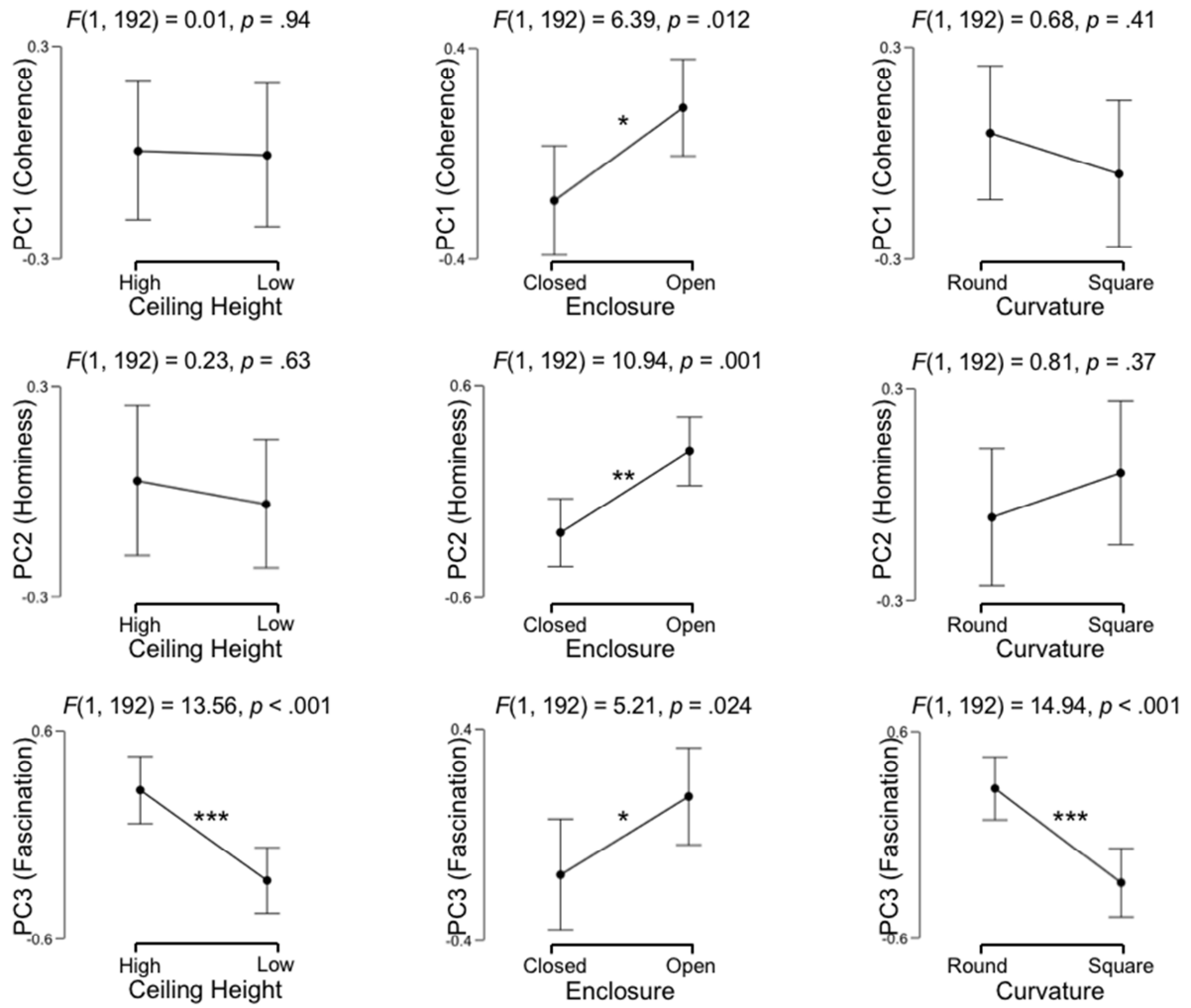
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Figure 7: 3-way factorial ANOVA results and plots of principal component scores as a function of architectural variables. Error bars represent 95% confidence intervals of PC scores for each condition. Visualizations were created using JASP statistical software (Wagenmakers, 2016).

2.2.4. Global Image Properties (GIPs) of scenes predicting principal component scores

In the next analysis, we set out to determine whether key Global Image Properties (GIPs) of architectural scenes correlated with the three principal psychological components identified in the preceding sections. Two GIPs were measured in this analysis: *self-similarity* and *complexity*. Self-similarity implies that an image as a whole is structurally similar to its parts. Complexity represents the amount of detail in an image.

Quantitative measures of self-similarity and complexity were calculated for the 200 architectural images. Self-similarity was measured using the Pyramidal Histogram of Oriented Gradients (PHOG) method. For every image, mean strength of luminance gradients is binned over orientations resulting in histograms of oriented gradients (HOGs). Then, the image is divided into 4 (level 1), 16 (level 2) and 64 (level 3) rectangles of similar size. To obtain a measure for self-similarity, the HOG features of the entire image are compared with the HOG features of the sub-images (see Dalal & Triggs, 2005; Bosch, Zisserman, & Munoz, 2007). Complexity was measured using the HOG Complexity method. Here, the mean strength of the gradients across all orientations is used as measure for image complexity (for a detailed description of both methods, see Braun et al., 2013). These calculated values were then

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regressed on principal component scores of individual images in order to determine correlations between GIPs and psychological components of architectural experiences.

The results of this analysis are shown in Table 3. Self-similarity was found to correlate positively with PC3 (*Fascination*) scores (r = .242, *p* < .001) and negatively with PC1 (*Coherence*) scores (r = -.198, *p* = 0.005). In other words, images exhibiting a high degree of self-similarity were perceived as significantly more fascinating but less coherent, relative to those with a low degree of self-similarity. Complexity correlated positively with PC2 (*Hominess*) scores (r = .175, *p* = .013) and PC3 (*Fascination)* scores (r = .519, *p* < .001), indicating that more complex scenes were perceived as more home-like as well as more fascinating, compared to less complex scenes.

Table 3: GIPs predicting Principal Component Scores

Global Image Property	PC1 (Coherence)	PC2 (Hominess)	PC3 (Fascination)
Self-Similarity	r = -.198; *p* = .005	r = .112; *p* = .113	r = .242; *p* < .001
Complexity	r = -.063; *p* = .378	r = .175; *p* = .013	r = .519; *p* < .001

2.3. Summary

In Experiment 1 we applied two data-driven approaches—PNA and PCA—to identify latent psychological dimensions underlying aesthetic ratings of architectural scenes. PNA revealed three communities in an "aesthetic network" showing the relationships between 16 aesthetic response measures. These communities motivated our PCA analysis which replicated the three-component structure. We interpret these three components as *coherence* (PC1), *hominess* (PC2), and *fascination* (PC3). Furthermore, analyses revealed that responses along these three dimensions were sensitive to key qualitative variables of architectural design (ceiling height, enclosure, and curvature), as well as to quantitative global image properties (self-similarity and complexity).

In order to prevent participant fatigue in Experiment 1, we had each participant rate all images on only four of the 16 aesthetic measures. This study design may have reduced the reliability of the PCA given that each participant was exposed to only a subset of the dependent variables. This design also required us to undertake item-level analysis for the network analysis and PCA. We were therefore unable to account for within-participant ratings across items in the PCA, which reduced the variability of our data set. In order to address these limitations, we designed a replication study (Experiment 2) in which participants rated a subset of images across all dependent variables. This study is described in the next section.

3. Experiment 2

In Experiment 2, we conducted a replication study to investigate the robustness of our findings from Experiment 1, by determining if a different experimental design would yield the same three principal components. Whereas each participant in the Experiment 1 rated all 200 architectural images on a subset of 4 aesthetic rating scales, participants in Experiment 2 were asked to rate a subset of architectural images on all 9 non-redundant aesthetic rating scales. This new design enabled us to perform a more robust PCA that accounted for each participant's within-participant ratings for each architectural condition across all of the dependent measures of interest.

3.1. Methods

3.1.1. Participants

614 American adults (305 women, 307 men, 2 other) were recruited from Amazon's Mechanical Turk to participate in this study. Data from 12 additional participants was excluded from analysis due to non-adherence to experimental instructions. Sample size was determined by our goal of obtaining approximately 50 ratings per image on each of the nine aesthetic response measures. Ages ranged from 19 to 72 years (M = 35.68, SD = 10.87), and education level ranged from 2 to 26 years (M = 15.26, SD = 2.31). Participants were compensated $2.40 for their participation and the experiment took approximately 20 minutes to complete. Informed consent was obtained through the IRB of the University of Pennsylvania.

3.1.2. Procedures

The 200 architectural images were divided into the eight experimental conditions shown in Figure 2 (n = 25 per condition): closed square low, closed square high, closed curved low, closed curved high, open square low, open square high, open round low, and open round high. Each of these conditions was then split into a low-beauty group and a high-beauty group, based on the images' beauty scores from Experiment 1, yielding a total of 16 groups of images. Images that received the median beauty score within each 25-image condition were alternately assigned to either the low-beauty group or the high-beauty group for that condition. This median split was introduced along the beauty dimension to ensure that each participant was exposed to examples of both high and low beauty scenes within each architectural condition.

Each participant rated a batch of 16 images on all nine dependent psychological measures. Batches were created by randomly selecting one image from each of the 16 groups. This design ensured that each participant rated one low-beauty image and one-high beauty image from each experimental condition. Participants rated all 16 images on one dependent measure before moving onto the next rating task to minimize fatigue from frequent task-switching (Monsell, 2003). The order of image presentation was randomized within each individual rating task, and the order in which the nine ratings tasks were assigned was also randomized within each participant. After completing the study, participants were asked to fill out a brief demographics questionnaire.

3.2. Analyses & Results

3.2.1. PCA of aesthetic response measures

Correlations among the nine psychological measures were analyzed using the *stats* (R Core Team, 2016), *corrplot* (Wei & Simko, 2016), and *psych* (Revelle, 2016) packages in R (R Core Team, 2016). The correlation matrix (Figure 8) yielded a DCM value of 7.7 x 10^{-3}. This was above the recommended minimum threshold of $1x10^{-5}$ (Field et al., 2014), indicating that multicollinearities among the psychological variables were sufficiently low to perform a reliable principal components analysis.

Figure 8: Correlation matrix of 9 psychological variables from Experiment 2.

We performed a PCA on the 9 dependent variables with oblique (oblimin) rotation. As in Experiment 1, all analyses were completed using the *psych* package in R (Revelle, 2016). The Kaiser-Meyer-Olkin (KMO) index score was 0.9, confirming the sampling adequacy for the PCA. KMO values for all individual variables were above 0.86. Bartlett's sphericity test showed that correlations among variables were sufficiently high for PCA (χ^2= 47843, p < .001). An initial PCA was carried out with 9 components retained to determine eigenvalues for each component in the data. The first three components had eigenvalues exceeding Jolliffe's criterion of 0.7 (Field et al., 2014) and together explained 76% of the variance. These three components were retained.

Table 3 displays the factor loadings, eigenvalues, and variance explained for each of the three retained principle components after oblimin rotation. A similar factor structure emerged as we found previously in Experiment 1. In the replication, PC1 captured the feeling of *hominess*, PC2 represented *coherence*, and PC3 described the experience of *fascination*. Thus, Experiment 2 closely replicated the PCA results of Experiment 1, with the exception that *hominess* explained more of the overall variance than *coherence* in the follow-up study.

In order to quantify the similarity of factor structures, we identified coefficients of factor congruence using the 'factor.congruence' function in the *psych* package of R. Factor congruences are the cosines of pairs of vectors defined by the loadings matrix. Across the two PCAs, each component of the replication PCA had a factor congruence of 0.98 with the corresponding component of the original PCA (accounting for the fact that PC1 and PC2 of the original study were "flipped" in the replication study). This calculation suggests a very high degree of similarity between the factor structures of the two PCAs.

Table 3: Factor loadings on the three principal components.

Aesthetic Rating Scale	PC1 (Hominess)	PC2 (Coherence)	PC3 (Fascination)
Complexity	-0.10	-0.10	**0.98**
Organization	-0.15	**0.97**	-0.13
Naturalness	**0.90**	-0.15	-0.19
Beauty	0.28	**0.57**	0.31
Personalness	**0.79**	-0.04	0.14
Interest	0.24	0.27	**0.59**
Valence	0.42	**0.53**	0.20
Hominess	**0.74**	0.20	0.04
Approachability	0.37	**0.52**	0.26
Eigenvalue	**2.73**	**2.28**	**1.83**
Variance Explained	**30%**	**25%**	**20%**
Cumulative Variance	**30%**	**56%**	**76%**

3.2.2. Determining the influence of architectural variables on psychological ratings

3-way factorial ANOVAs were carried out using the ANOVA function in JASP statistical software (Wagenmakers, 2016) to determine the effect of the three architectural variables on principle component scores (Figure 9). There were significant main effects of ceiling height [F (1, 9816) = 15.23, $p < .001$, $\eta_p^2 = 0.002$], enclosure [F (1, 9816)= 118.43, $p < .001$, $\eta_p^2 = 0.012$], and curvature [F (1, 9816) = 20.95, $p < .001$, $\eta_p^2 = 0.002$] on PC1 (*hominess*). For PC2 (*coherence*), there were also significant main effects of ceiling height [F (1, 9816) = 28.25, $p < .001$, $\eta_p^2 = 0.003$], enclosure [F (1, 9816) = 180.39, $p < .001$, $\eta_p^2 = 0.018$], and curvature [F (1, 9816) = 13.58, $p < .001$, $\eta_p^2 = 0.001$]. Finally, significant main effects were found for ceiling height [F (1, 9816] = 243.00, $p < .001$, $\eta_p^2 = 0.024$), enclosure [F (1, 9816) = 61.21, $p < .001$, $\eta_p^2 = 0.006$], and curvature [F (1, 9816) = 232.83, $p < .001$, $\eta_p^2 = 0.023$] on PC3 (*fascination*). No significant interaction effects were found.
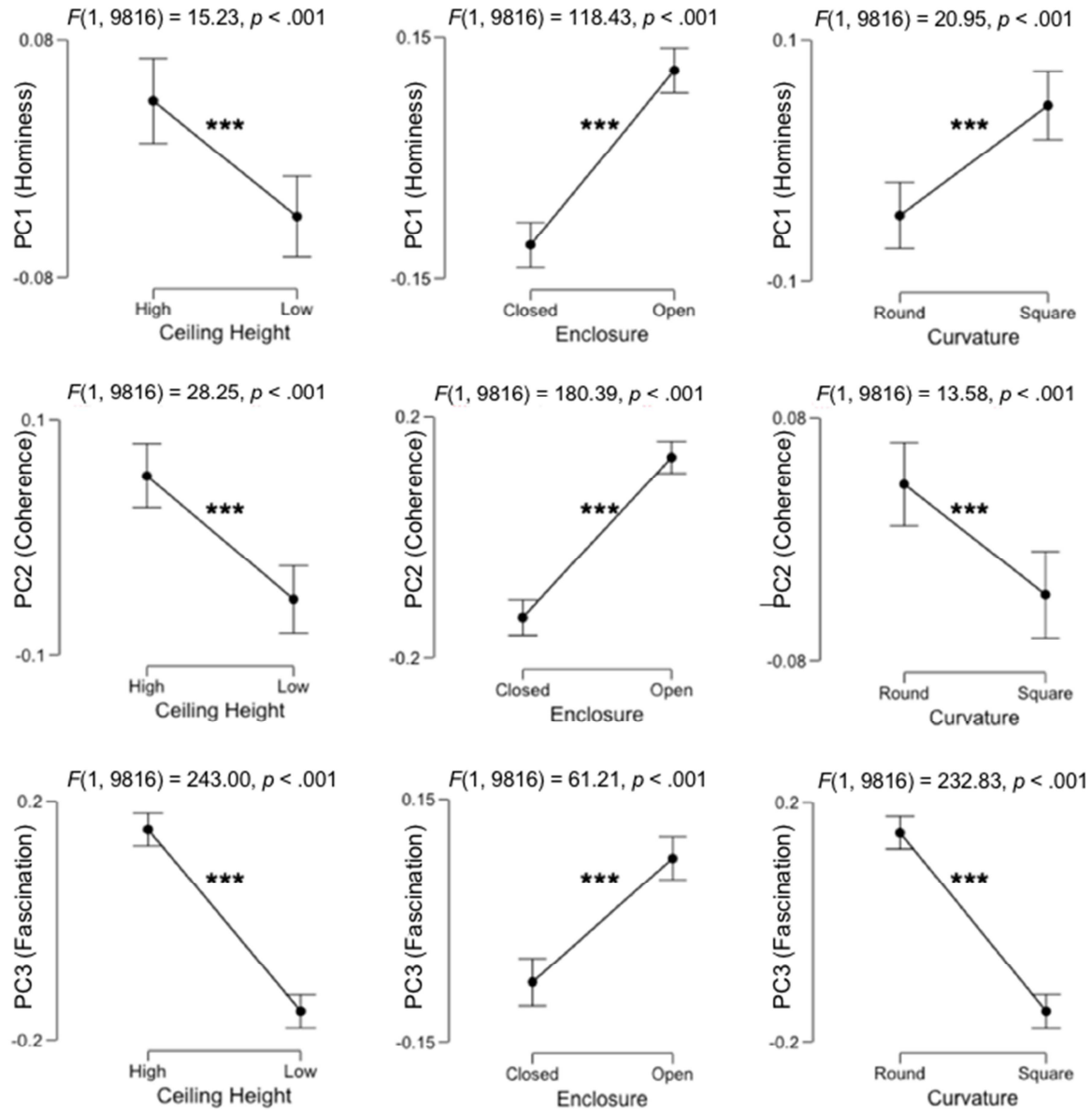
Figure 9: 3-way factorial ANOVA results and plots of principal component scores as a function of architectural variables. Error bars represent 95% confidence intervals of PC scores for each condition. Visualizations were created using JASP statistical software (Wagenmakers, 2016).

3.3. Summary

In Experiment 2, we replicated the findings of Experiment 1 using a different study design in which participants rated a subset of architectural images on all nine non-redundant aesthetic response measures. Importantly, our findings replicate the three latent dimensions identified by the PNA and PCA analyses in Experiment 1 (Figure 6). These dimensions are *coherence* (ease with which one organizes and comprehends a scene), *fascination* (a scene's informational richness and generated interest), and *hominess* (extent to which a scene feels like a personal space). Furthermore, analyses revealed that responses along these three dimensions were sensitive to key variables of architectural design (ceiling height, enclosure, and curvature). The directions of correlation between the three architectural variables and the three psychological dimensions were the same in the replication experiment as in the original study, although all nine combinations of these correlations were statistically-significant in the replication study,

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compared to only five of nine in the original study. The next section investigates the neural correlates of the three latent psychological dimensions.

4. Experiment 3

In Experiment 3, we reanalyzed data from two previously published fMRI studies (Vartanian et al., 2015, 2013) in relation to the principal components of architectural experience identified in Experiments 1-2. In those previous studies, the authors investigated the effects of curvature (Vartanian et al, 2013), ceiling height, and perceived enclosure (Vartanian et al., 2015) on aesthetic judgements and neural activity. Participants were shown the images in the fMRI scanner and were asked to make beauty judgements or approach-avoidance decisions in two separate tasks (i.e., runs). The authors then identified neural regions that covaried with the architectural variables (curvature, ceiling height, and enclosure) for each aesthetic judgment task. The motivation behind those original studies was to identify regions of the brain that were sensitive to variations in curvature, ceiling height, and enclosure in architecture. In addition, the authors predicted that people's responses to those features and the neural correlates that accompany them would vary as a function of the task they were instructed to perform (i.e., beauty judgment vs. approach-avoidance decisions). For example, whereas people might find curvilinear spaces beautiful, they may not necessarily indicate a willingness to enter them. Indeed, the authors of those previous studies found that although participants judged spaces that had high ceilings and were curvilinear as more beautiful, they did not demonstrate a corresponding willingness to enter them. In turn, the authors found differences in the neural correlates of curvature, ceiling height, and perceived enclosure as a function of the task under consideration. Based on independent samples of architects and undergraduates and using a subset of the same images, the same authors have since replicated the moderating effect of the task (i.e., beauty judgment vs. approach-avoidance decisions) on ratings in a follow-up study (Vartanian et al., 2019).

In the present investigation, we reanalyzed the neural data from the two previous studies described above to address a different research question altogether. Specifically, we sought to determine whether the three latent psychological dimensions (i.e., principal components) identified in the preceding experiments would correlate with specific patterns of neural activation. Embedded within that primary question, we also tested whether these correlational patterns would vary as a function of task. Correlations between principal components and neural activity would indicate the brain's sensitivity to core aspects of our psychological responses to architectural scenes. Because processing of the three latent dimensions under consideration (i.e., *coherence*, *hominess*, and *fascination*) necessarily relies at least in part on visual inspection of scenes, we suspected that we would observe sensitivity in relation to these dimensions in dissociable regions within the visual cortex. Given that variations in the neural correlates of architectural features (i.e., contour, ceiling height, and enclosure) as a function of task had been observed in previous studies (Vartanian et al., 2013, 2015), we were interested in determining whether similar task-based differences would be observed for *coherence*, *hominess*, and *fascination* in the present context. Finally, since the results of Experiment 1 demonstrated that GIPs (i.e., complexity and self-similarity) predicted *coherence*, *hominess*, and *fascination* scores, we also tested to see whether there would be any overlap between the neural correlates of *coherence*, *hominess*, and *fascination* and those related to the GIPs under consideration. If so, one might conclude that any covariation observed between *coherence*, *hominess*, and *fascination* and neural activity might be in part driven by a shared neural architecture that is also sensitive to variation in GIPs.

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4.1. Methods

To undertake this task, we re-analyzed data from Vartanian et al. (2015, 2013). In those studies, healthy participants (*n* = 18, 12 females, 6 males, average age = 23.39 years, *SD* = 4.49) viewed the same 200 photographs of architectural interiors used in Experiments 1 and 2 during a functional MRI scan. Participants viewed the images under two different conditions (administered as counterbalanced runs): in the beauty judgment condition, they were presented with 100 stimuli, and on each trial indicated with a button press whether the image was "beautiful" or "not beautiful." In the approach-avoidance condition, they were presented with the remaining 100 stimuli, and on each trial indicated with a button press whether they would opt to "enter" or "exit" the space. The details of the neuroimaging acquisition parameters are reported in S5 of Supplementary Materials (see also Vartanian et al., 2015, 2013).

The original analyses conducted by Vartanian et al. (2015, 2013) required the use of categorical contrasts. Our focus here was different because we tested the hypothesis that there would be a correlation between neural activation and variations in *coherence, fascination*, and *hominess* scores associated with each image (derived from Experiment 2). To test this hypothesis, we conducted parametric analyses of fMRI data using Statistical Parametric Mapping (SPM12) software. Specifically, the presentation of each stimulus was treated as an event, coupled with its *coherence, fascination, hominess, self-similarity* and *complexity* ratings associated with it as the five parameters of interest. Specifically, for each of the 200 stimuli in the dataset, ratings of *coherence, fascination*, and *hominess* were derived from the PCA of aesthetic response measures (Experiment 2). In turn, for the same 200 stimuli, ratings of *self-similarity* and *complexity* were derived from the analysis of GIPs (Experiment 1). These five ratings per stimulus were entered as the five parameters in the parametric analysis. Because we were interested in testing linear relationships, the parameters were entered as 1st order polynomial expansions into the model. In turn, the motor response and the inter-stimulus-interval (ITI) were entered into the analysis and treated as events of no interest (this enabled us to model but remove brain activation associated with the presentation of the "+" in the ITI and motor movement associated with a button press). Furthermore, because the participants had completed the original study under two different task conditions, we conducted the aforementioned parametric analysis separately for the beauty judgment and approach-avoidance decision runs.

This analytic strategy enabled us to (a) determine whether the same brain regions would exhibit sensitivity to variations in scores associated with *coherence, fascination*, and *hominess* under different contexts (i.e., tasks), (b) conduct a conjunction analysis to see if there was a statistically significant overlap between the regions associated with any of the three components under *both* conditions, and (c) to identify any possible overlap between the neural correlates of *coherence, hominess*, and *fascination* and the neural correlates of the two GIPs under consideration (i.e., self-similarity and complexity). In terms of (a) our null hypothesis was that no region would exhibit covariation with *coherence, fascination*, or *hominess* ratings when the task involved beauty judgment or approach-avoidance decisions. In terms of (b) our null hypothesis was that there would be no statistically significant overlap between the regions associated with any of the three components under *both* conditions of beauty judgment and approach-avoidance decisions. In terms of (c) our null hypothesis was that there would be no statistically significant overlap between the regions that exhibit covariation with *coherence, hominess*, or *fascination* and those that exhibit covariation with self-similarity or complexity. For the reporting of our results, we adopted a combination of voxel-level and cluster-size correction

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to control against false-positives. Specifically, using a random effects analysis, we report activations that survived whole-brain voxel-level intensity threshold of $p < 0.001$ (uncorrected for multiple comparisons), and a cluster-level correction of $p < .05$ (corrected for multiple comparisons using whole-brain family-wise error). All brain regions are reported in relation to the MNI (Montreal Neurological Institute) coordinate system.

4.2. Results

Fascination. The results demonstrated that in approach-avoidance decisions brain activation in the left lingual gyrus covaried with *fascination* scores, whereas in beauty judgments brain activation in the right lingual gyrus covaried with *fascination* scores. Note that under both approach-avoidance and beauty judgment conditions, the clusters of activation were bilateral. A follow-up conjunction analysis demonstrated that brain activation encompassing the right lingual gyrus covaried with *fascination* scores under both beauty judgment and approach-avoidance conditions (Table 4 and Figure 10a). These clusters were also bilateral.

Hominess. The results demonstrated that when making approach-avoidance decisions, brain activation encompassing the left cuneus covaried with *hominess* scores. Note that the clusters of activation were bilateral (Table 4 and Figure 10b). In turn, when making beauty judgments, brain activation did not covary with *hominess* scores. Here no conjunction analysis was conducted because in the case of beauty judgments no statistically significant effect was discovered.

Coherence. The results demonstrated that when making approach-avoidance decisions, brain activation did not covary with *coherence* scores. By contrast, when making beauty judgments, brain activation encompassing the left inferior occipital gyrus covaried with *coherence* scores (Table 4 and Figure 10c). The extent of this cluster was also bilateral. Here no conjunction analysis was conducted because in the case of approach-avoidance decisions no statistically significant effect was discovered.

GIPs. The results demonstrated that when making beauty judgments or approach-avoidance decisions, brain activation did not covary with *self-similarity* or *complexity* scores.

Table 4: The neuroanatomical correlates of Fascination, Hominess, and Coherence. (BJ = beauty judgment; AA = approach-avoidance decisions; CJN = conjunction analysis).

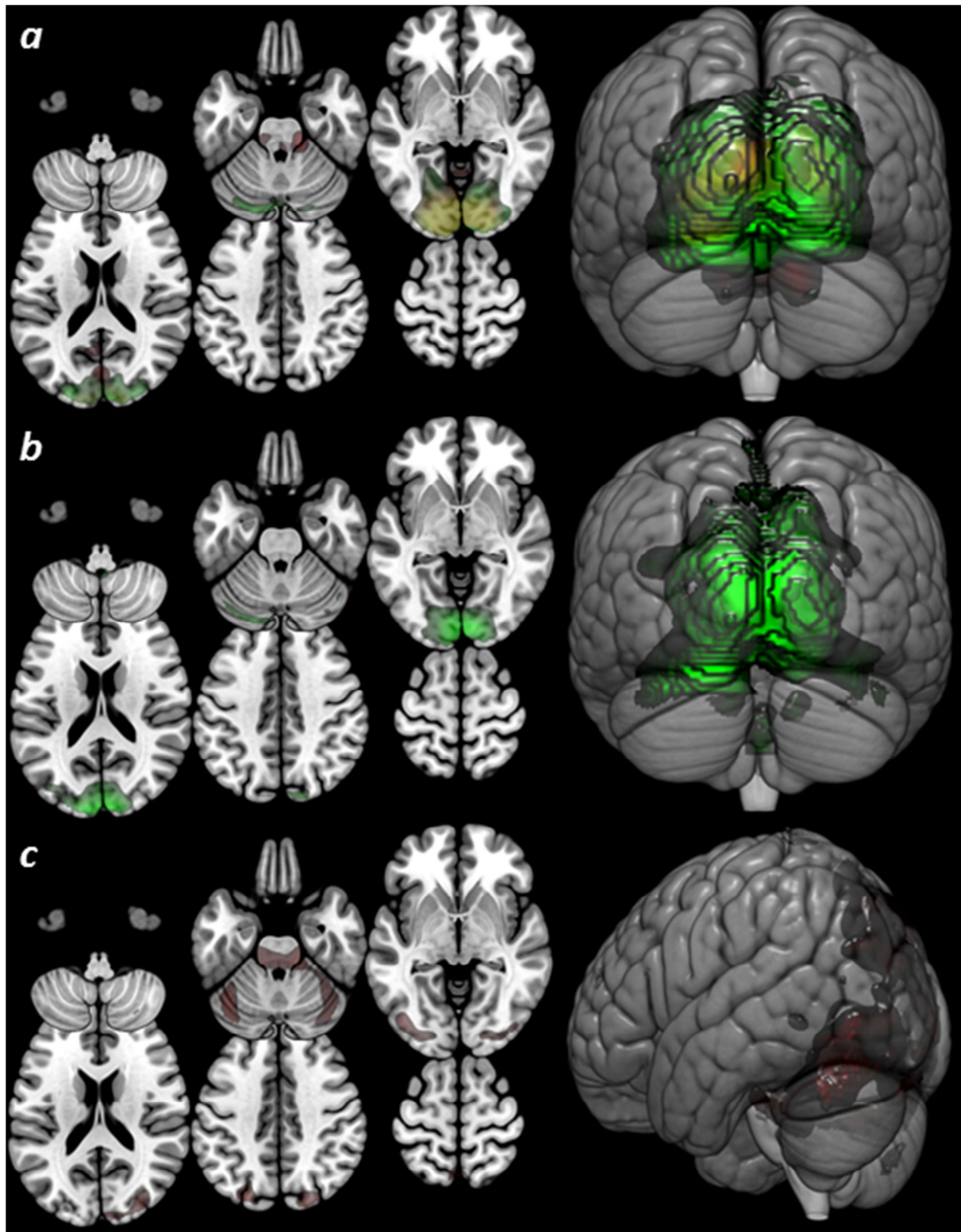| Dimension	Task	Structure	Coordinates (*x, y, z*)	*T*-score	Cluster size (K_E)
Fascination	BJ	Lingual gyrus	26, 80, 6	6.70	3154
	AA	Lingual gyrus	14, 100, 8	9.04	6145
	CJN	Lingual gyrus	26, 80, 8	6.65	2819
Hominess	AA	Cuneus	10, 92, 4	5.45	2040
Coherence	BJ	Occipital gyrus	34, 88, ▯	5.08	332

Figure 10. Brain regions where activation covaried in relation to (a) Fascination, (b) Hominess, and (c) Coherence. Regions of the brain that exhibited covariation under the *beauty judgment* condition appear in red, whereas regions of the brain that exhibited covariation under the *approach-avoidance* condition appear in green. Regions of the brain that exhibited covariation under both conditions (conjunction analysis) appear in yellow. The mosaic slices shown in the left column were selected at the following z coordinates: -50, -27, -4, 18, 41, and 64. Images were generated using MRIcroGL. For illustration purposes, the images depicted in MRIcroGL show activations that extend beyond those that survived our whole-brain family-wise correction for multiple comparisons reported in the manuscript.

4.3. Summary

Parametric analyses demonstrated that, regardless of the task, the degree of *fascination* covaried with neural activity in the right lingual gyrus. In contrast, *coherence* covaried with neural activity in the left inferior occipital gyrus only when participants judged beauty, and *hominess* covaried with neural activity in the left cuneus only when they made approach-avoidance decisions. Importantly, neural activation in the aforementioned regions did not covary in relation to GIPs including self-similarity and complexity scores. Our results suggest that the valuation of architectural processing in the visual cortices varies by dimension, as well as by task in the case of *coherence* and *hominess* dimensions. These imaging results build on our previous behavioral results by demonstrating that the brain exhibits sensitivity to the three dissociable psychological dimensions of architectural experience identified in Experiments 1 and 2. Furthermore, the brain's sensitivity to these dimensions may vary by function of task.

5. General Discussion

5.1. Summary of results

In three experiments, we set out to identify key psychological dimensions that are important aspects of architectural experience. We further investigated how these dimensions relate to brain activity. Specifically, we tested three hypotheses: 1) aesthetic responses to architectural scenes can be reduced to a few latent psychological dimensions, 2) these dimensions are sensitive to design variables of ceiling height, enclosure, and curvature, and 3) each psychological dimension evokes a distinct neural response in the brain.

We used two complementary data-driven approaches to test the first hypothesis: PNA and PCA. PNA enabled us to map out relationships between 16 aesthetic measures in Experiment 1 as nodes within an "aesthetic network." This analysis revealed that the aesthetic measures clustered into three distinct communities. We further analyzed the relationships between aesthetic rating scales using PCA in Experiments 1 and 2 and found that three principal components – *coherence*, *hominess*, and *fascination* – explained most of the variance in ratings across two independent samples.[1] These components closely resembled the communities from the PNA (see Figure 6). We interpreted these three communities/components as representing latent psychological dimensions in response to architectural scenes. ANOVAs were also conducted in Experiments 1 and 2, revealing that the three psychological dimensions were sensitive to salient architectural features of ceiling height, enclosure, and curvature. In Experiment 1, these dimensions were also found to be sensitive to two GIPs of the architectural images: self-similarity and complexity.

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[1] The replication of this factor structure in two independent samples is notable given that people generally exhibit less agreement when making aesthetic judgments of architectural stimuli compared to natural scenes (Vessel, Maurer, Denker, & Starr, 2018).

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In Experiment 3, parametric and conjunction analyses of fMRI data revealed that *fascination* scores covaried systematically with neural activity in the right lingual gyrus regardless of whether participants were engaged in beauty judgments or approach-avoidance decisions. In contrast, *coherence* scores covaried with neural activity in the left inferior occipital gyrus only when participants were judging beauty, whereas *hominess* scores covaried with neural activity in the left cuneus only when they made approach-avoidance decisions. Together, these results suggest that aesthetic responses to architectural scenes are explained by a few psychological dimensions that are associated with distinct neural signatures in the brain. Importantly, we were able to show that neural activation in the aforementioned regions did not covary in relation to GIPs including self-similarity and complexity scores. In other words, the observed patterns of neural activity are more likely to be driven by psychological responses that are not mediated directly by psychophysical properties of the images.

5.2. Psychological dimensions of architectural experience

The analyses in Experiments 1 and 2 yielded three latent psychological dimensions underlying aesthetic ratings of architectural scenes: *Coherence*, *Hominess*, and *Fascination. Coherence* accounted for 40% and 25% of the variance in image ratings for Experiments 1 and 2, respectively. Organization, beauty, valence, and approachability loaded on this component in both studies.[2] The close relationship between organization and these three global response measures is consistent with fluency theory, which argues that ordered arrangements of a scene's composition – including structural redundancy, balance, and symmetry – heighten aesthetic appeal by increasing the efficiency, or fluency, of information processing in the visual system (Arnheim, 1971; D. J. Graham & Redies, 2010; Oppenheimer & Frank, 2008; Palmer, Schloss, & Sammartino, 2013; Ramachandran & Hirstein, 1999; Reber et al., 2004). Previous empirical work has indeed demonstrated that order and related constructs are reliable predictors of aesthetic responses to visual art (Birkhoff, 1933; Eysenck, 1957; Oppenheimer & Frank, 2008; Palmer et al., 2013) and landscapes (R. Kaplan, 1973; R. Kaplan & Kaplan, 1989; S. Kaplan, 1987). Environmental disorder, by contrast, is linked to heightened anxiety (Tullett et al., 2015), increased rule-breaking behavior (Kotabe et al., 2016b), reduced cognitive performance (Evans, Gonnella, Marcynyszyn, Gentile, & Salpekar, 2005), and a diminished sense of meaning in life (Heintzelman & King, 2014). Building on these past findings, our results suggested that the *coherence* component was primarily driven by the perception of organization but also involved multiple domains of psychological processing, including cognitive, affective, and behavioral responses to architectural scenes.

The *hominess* component explained 27% and 30% of the variance in image ratings for Experiments 1 and 2, respectively. In both studies, three psychological measures converged on this component: personalness, hominess, and naturalness. These aesthetic measures relate to the Danish concept of *hygge*, which describes "a feeling of coziness, warmth, and togetherness" (Wiking, 2017, p. 25) that is often felt in the presence of intimate spaces and social settings.[3] Environments that generate this mood generally feel "personal and authentic" (Linnet, 2012, p. 403) and "echo the feeling of home" (Wiking, 2017, p. 24). *Hygge* relates closely to the concept of *wholeness*, which Alexander described as a spatial quality that makes occupants feel more

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[2] Four of the excluded measures – vitality, uplift, comfort, and relaxation – proved to be nearly redundant measures of valence in Experiment 1 and were therefore most closely associated with this first principal component.

[3] Although this concept has received particular emphasis in Danish culture, *hygge* has close translations in many languages, including the Canadian *hominess*, the Dutch *Gezelligheid*, the Norwegian *koselig*, and the German *gemütlichkeit* (Linnet, 2012; Wiking, 2017)

intimately connected to their surroundings and more liberated to express their authentic personalities (Alexander, 1977, 1979, 2002a). Linnet described a similar phenomenon of "rooting," or increased connectedness, that occurs in the presence of *hygge* (Linnet, 2012, p. 407). Like wholeness, *hygge* has both social and spatial connotations. Spaces that create *hyggelig*[4] atmospheres often feel "organic" and "not strongly controlled" (Linnet, 2012, p. 405), qualities that align with the measure of naturalness in our study. Wholeness has similarly been linked to naturalistic visual patterns in architecture (Alexander, 2002a) and to loose, organic construction processes (Alexander, 2002b). Thus, the experience of *hominess* may depend on interactions between sensory inputs (i.e., naturalistic stimuli) and affective processing mechanisms (i.e., feelings of belonging).

The third component, *fascination*, explained 24% and 20% of the variance in image ratings in Experiments 1 and 2, respectively. In both studies, this component represented the vector sum of two variables, complexity and interest. In Experiment 1, explorability and stimulation also exhibited such high bivariate correlations with interest that they were considered redundant variables. The close relationships that emerged between these four measures are consistent with previous research. Interest ratings of visual art have been shown to correlate closely with stimulus complexity (Daniel E. Berlyne, 1971; Silvia, 2005, 2012). Complexity has also been found to predict stimulation responses to both art and architectural images (Daniel E. Berlyne, 1970, 1971; Heath, Smith, & Lim, 2000; Taylor et al., 2005). In response to the widespread proliferation of minimalism in post-war Western architecture, several architectural theorists emphasized the importance of visual complexity and ornament for generating interest and excitement in the built environment (Alexander, 2002a; Salingaros, 2007; Venturi et al., 1977). Kaplan and Kaplan (1989) proposed that complex landscapes provide a richness of information that triggers visual interest and motivates exploration. Early studies in empirical aesthetics also revealed close associations among these four response measures (D. E. Berlyne, 1963; Day, 1967). Here, we extend these past findings to the built environment by reporting that complexity, interest, stimulation, and exploration all loaded on one multi-modal dimension of architectural experience.

The three-part factor structure that emerged from our studies on architectural interiors is reminiscent of the pivotal psychological framework that Kaplan and Kaplan (1989) proposed for outdoor environments. Their seminal "preference matrix" outlined two psychological dimensions that contribute to aesthetic experiences of outdoor landscapes: *understanding* and *exploration*. *Understanding* describes "the need to make sense of what is going on" (R. Kaplan & Kaplan, 1989, p. 51) in a landscape and is influenced by environmental features such as "coherence" (how ordered a scene looks) and "legibility" (how easily a scene can be recognized, interpreted, and remembered). This psychological dimension aligns closely with the *coherence* component of our study, which describes how easily information in an architectural scene can be processed. The Kaplans' *exploration* dimension encompasses the human desire to "find out more about what is going on in one's surroundings" (R. Kaplan & Kaplan, 1989, p. 51). Environmental features that stimulate exploration include complexity (the informational richness of a scene) and mystery (the promise of hidden information waiting to be revealed). This dimension echoes the component we described as *fascination*, a term that S. Kaplan later

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[4] Translation: "*hygge*-like" (Wiking, 2017)

adopted in his research on Attention Restoration Theory (Berman, Jonides, & Kaplan, 2008; S. Kaplan, 1995; S. Kaplan & Berman, 2010).[5]

Intriguingly, the Kaplans' framework for landscape aesthetics offers no equivalent to our *hominess* component, suggesting that this dimension of psychological experience may be specifically relevant to architectural interiors. Perhaps owing to the widespread influence of Kaplans' work, psychological measures related to *coherence* (e.g., fluency, order) and *fascination* (e.g., complexity, interest) have been widely studied in environmental psychology and empirical aesthetics research. *Hominess* and related constructs (e.g., personalness, coziness) have received less attention.

Our results suggest that the experiences of *coherence*, *hominess*, and *fascination* all depend on multiple domains of psychological processing, indicating that the most salient psychological experiences in the built environment are likely generated by the integration of cognitive, emotional, and sensory information. Furthermore, in both experiments, beauty, valence, and approachability loaded moderately on all three principal components. This finding suggests that the most global measures of architectural experience (how beautiful a room looks, for instance) may be influenced by all three of these underlying psychological constructs. The near orthogonality of order and complexity in the two PCA studies also supports previous theoretical claims that order and complexity are consistently perceived as independent dimensions of the physical environment (Alexander, 2002a; R. Kaplan & Kaplan, 1989; Salingaros, 2007). This finding suggests that order and complexity are perceptually salient qualities of the built environment that can be manipulated independently in architectural design strategies.

It is important to note that spatial enclosure had the strongest impact on psychological responses. In both experiments, open spaces received significantly higher scores than enclosed spaces on all three principal components, thus replicating past findings that open environments are often perceived as more beautiful (Vartanian et al., 2015), safer (Stamps, 2005; Fich et al., 2014), and more likely to stimulate movement and exploration (Vartanian et al., 2015). These results also support Appleton's theory that humans prefer environments with greater affordances of visual prospect (Appleton, 1975) and Hildebrand's hypothesis that our evolved landscape preferences extend to the built environment (Hildebrand, 1999; Vartanian et al., 2013). Furthermore, our results suggest that previously reported aesthetic preferences for high ceilings and curved interiors may be driven by sensory experiences related to visual interest, simulation, and exploration. These hypotheses are consistent with past fMRI findings that high ceilings and curved spaces differentially activate neural structural associated with visuospatial exploration and attention (Vartanian et al., 2015).

Our analyses also yielded unexpected results. We were surprised to find that open spaces and high ceilings were associated with higher *hominess* scores. Since this psychological construct is typically associated with feelings of "cozy interiority" and with spaces that create "a strong sense of being inside" (Linnet, 2012), we expected rooms with low ceilings to be linked with this component. However, many environmental variables contribute to a *hyggeligt* ambiance, including lighting, surface textures, color, and furniture arrangement (Linnet, 2012; Wiking, 2017). Since we did not control for these other variables when selecting our stimuli, it is possible that they affect ratings above and beyond the effects of enclosure and ceiling height. It is also

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[5] According to Attention Restoration Theory (ART), environments that are inherently *fascinating* are restorative, because they capture involuntary attention in an automatic, bottom-up fashion and allow directed attention mechanisms, which are controlled in top-down fashion, a chance to replenish (Berman, Jonides, & Kaplan, 2008; S. Kaplan, 1995).

possible that the low ceilings in our stimuli conveyed a sense of confinement and claustrophobia rather than coziness.

Finally, it is revealing that participants' responses along the three psychological components proved to be sensitive to two GIPs of architectural images, self-similarity and complexity. The largest effect sizes were found for *fascination* component. More self-similar and more complex scenes were perceived as significantly more fascinating than less self-similar and less complex scenes. Interestingly, the *fascination* component exhibited the largest effect sizes in response to the qualitative architectural variables of Ceiling Height, Curvature, and Enclosure, as well as for the quantitative GIPs. These results suggest that the specific visual features we measured in this study may modulate psychological responses along the *fascination* dimension more than they modulate responses along the other two dimensions. It remains to be seen whether perceptions of *fascination* are also highly sensitive to other architectural variables and visual patterns beyond those measured in this study. We were also surprised to find that the self-similarity measure correlated negatively with the *coherence* dimension, as we expected that more self-similar scenes would be perceived as more organized and coherent than less self-similar scenes. One possible explanation is that participants perceived images with strong focus points as more coherent, as these images are generally less self-similar.

5.2. Neural responses to architectural scenes

Our imaging results demonstrated that various regions in the visual cortex are differentially sensitive to core dimensions of our psychological responses to architectural scenes. The fact that in all cases neural activity was observed in the visual cortex is not surprising, given that processing the three latent dimensions under consideration (i.e., *coherence*, *hominess*, and *fascination*) necessarily relies at least in part on visual inspection of scenes. Interestingly, the degree of *fascination* drove neural activity in the right lingual gyrus regardless of whether participants were engaged in beauty judgments or approach-avoidance decisions. In contrast, the degree of *coherence* evoked neural activity in the left inferior occipital gyrus only when participants judged beauty, whereas the degree of *hominess* evoked neural activity in the left cuneus only when they made approach-avoidance decisions.

We underscore two important points about these findings. It has been known that parts of visual cortex evaluates objects in addition to classifying them into such categories as faces, places, and objects (Chatterjee, Thomas, Smith, & Aguirre, 2009). Our findings suggest that this kind of neural response is likely a top-down influence on object processing that segregates along psychological dimensions. The second point is about the stability of these neural responses. *Fascination* evokes relatively stable responses, given that the associated neural activity was not affected by the behavioral task in which people were engaged. By contrast, *coherence* only modulated visual responsiveness when people made beauty judgments, whereas *hominess* only modulated visual responsiveness when people made approach-avoidance decisions. Our data do not allow us to infer why the effect of *fascination* was stable across tasks, whereas *coherence* and *hominess* exerted different degrees of influence on neural processing in the context of beauty judgments vs. approach-avoidance decisions. In addition, despite the fact that all the regions identified in the present study reside within the visual cortex (Wandell, Dumoulin, & Brewer, 2009), we suspect that these neural signatures represent top-down influences on visual valuation rather than bottom-up psychophysical properties of the visual images.

One final point is worth emphasizing. Our psychological components were derived from responses by participants in the U.S.. The neural data were derived from participants in the Canary Islands a few years earlier, indicating considerable generalization of our claims. At the

time of fMRI data collection, we were ignorant of the psychological components now used to model the data. Yet, these responses were present in the brains of our participants while being hidden from us because we did not know to ask the question of the relationship between *fascination*, *hominess*, and *coherence* and neural responses.

5.3. Limitations

We used images of architectural interiors as our stimuli in order to limit our focus to visual perception of interior spaces and to expose participants to a wide variety of architectural spaces within a reasonable timeframe. However, we relied on two-dimensional stimuli, which limits the generalizability of our findings to three-dimensional built spaces. Future research could leverage more immersive technologies like virtual reality to answer similar questions using more lifelike simulations of architectural environments (see Banaei, Hatami, Yazdanfar, & Gramann, 2017; Shemesh et al., 2017). We also chose to focus our study on visual perception of architecture. In doing so, we are agnostic about the contribution of nonvisual senses to architectural experiences. Finally, our studies considered three basic architectural design variables, which together capture a limited proportion of a building's visual properties. Indeed, it is likely that a more complete understanding of the impact of architectural design variables on human thinking and behavior will require examining more design variables and psychological outcome measures of interest.

5.4. Conclusions

Here, we investigated the primary psychological dimensions of architectural experience. In a pair of studies, we found and replicated the observation that three latent psychological constructs – *coherence*, *fascination*, and *hominess* – collectively explained most of the variance across a range of aesthetic response measures. The first two components align closely with the psychological dimensions outlined in the Kaplans' pivotal "preference matrix" of landscape aesthetics (R. Kaplan & Kaplan, 1989). Indeed, *coherence* and *fascination* are well-established dimensions in assessing natural scenes and visual art. *Hominess*, however, emerged as a new dimension in relation to architectural interiors that has received scant attention to date in empirical research. In our third study we found that variations in the three latent psychological constructs were associated with brain activation in dissociable regions within the visual cortex. These results provide new insights on how architectural design influences subjective human experiences and reveal that the visual cortex is sensitive to specific psychological valuations in our encounters with architectural interiors.

These findings have several practical implications for architectural design. First, it would be useful for architects to test the psychological impact of proposed design schemes (before they are constructed) along the dimensions of the three principal components identified in these studies (*coherence*, *fascination*, and *hominess*). These dimensions offer a specific framework for incorporating behavioral feedback into design iterations before a building is constructed. Secondly, these components could be used for post-occupancy evaluations of buildings. Architects and researchers could test occupant responses along these components (e.g. by having occupants rate a space along each of the three psychological dimensions) and use this behavioral feedback to guide future decisions related to interior design and construction. Finally, architects might weigh these components differently, depending on the kind of building being designed. The optimal balance of these components for a home, hospital, library, or a museum might be different. More generally, the identification of these three psychological

components and their neural signatures advance our understanding of how people experience interior spaces. This has far-reaching implications for architectural design and research alike.

Acknowledgements & further information

No part of the study procedures or analysis plans was pre-registered prior to the research being conducted. We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. The data, R script, and stimuli for this research have been uploaded to Open Science Framework. All files for the study can be accessed using the following link: https://osf.io/mc3aj/?view_only=e2d881780fcb4e66ab2d210dc5d5e0ec

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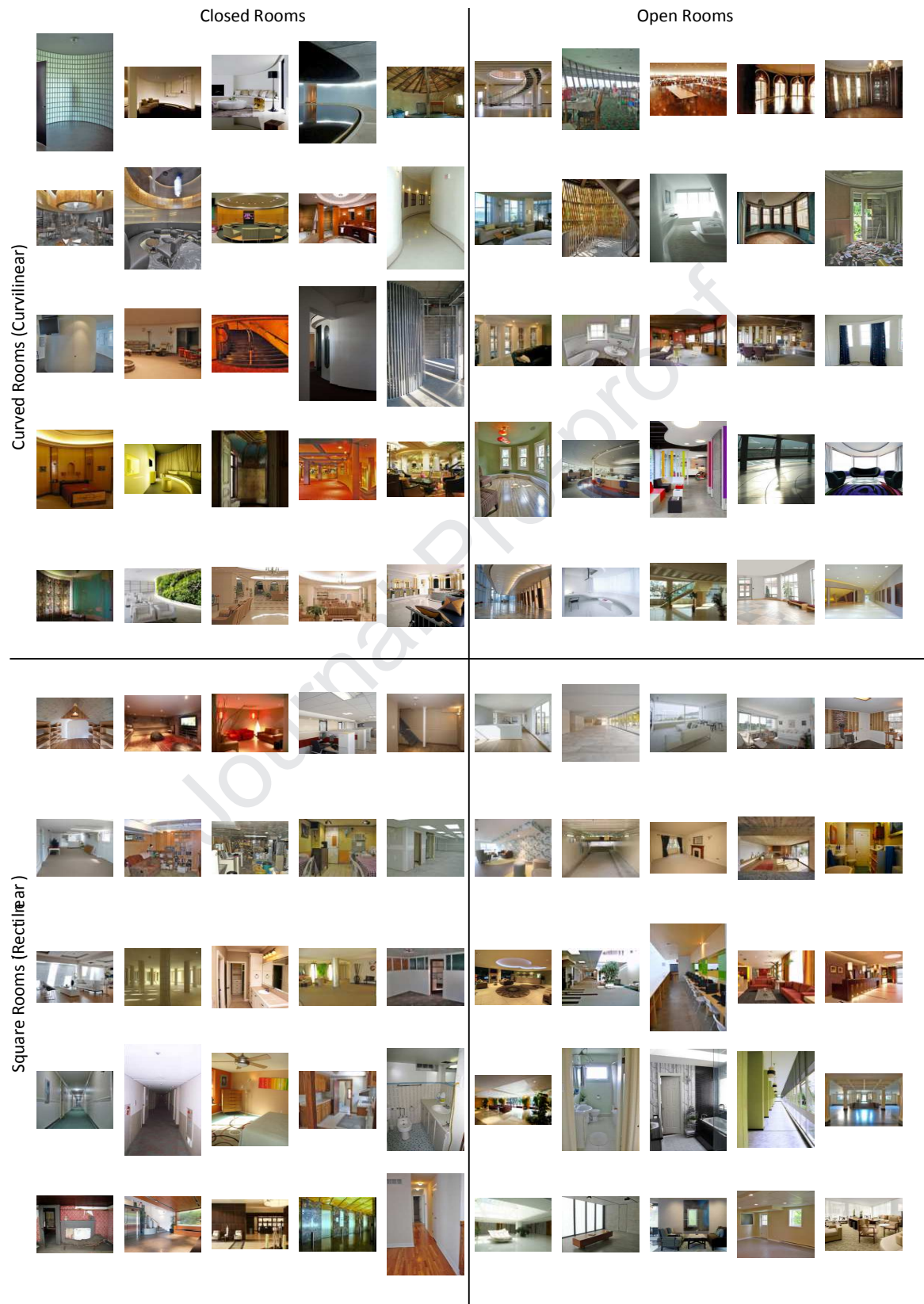
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Supplementary materials

S1: Architectural images (low ceilings)

Closed Rooms | Open Rooms

Curved Rooms (Curvilinear)

Square Rooms (Rectilinear)

S2: Architectural images (high ceilings)

Closed Rooms

Open Rooms

Curved Rooms (Curvilinear)

Square Rooms (Rectilinear)

S3: Experiment 1 blocking scheme for image presentation

Summary of stimulus distribution within each image block. Architectural conditions are labeled as follows: high ceilings (H), low ceilings (L), open (O), enclosed (C), square (S), round (R).

	H-C-S	H-C-R	H-O-S	H-O-R	L-C-S	L-C-R	L-O-S	L-O-R	Total Images
Block 1	7	7	6	6	6	6	6	6	50
Block 2	6	6	7	7	6	6	6	6	50
Block 3	6	6	6	6	7	7	6	6	50
Block 4	6	6	6	6	6	6	7	7	50
Total Images	25	25	25	25	25	25	25	25	200

S4: Experiment 1 rating groups for aesthetic rating scales

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Complexity	Personalness	Stimulation	Homeyness	Organization	Interest	Vitality	Uplift
Organization	Interest	Vitality	Uplift	Naturalness	Modernity	Comfort	Approachability
Naturalness	Modernity	Comfort	Approachability	Beauty	Valence	Relaxation	Explorability
Beauty	Valence	Relaxation	Explorability	Personalness	Stimulation	Homeyness	Complexity

Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16
Naturalness	Modernity	Comfort	Approachability	Beauty	Valence	Relaxation	Explorability
Beauty	Valence	Relaxation	Explorability	Personalness	Stimulation	Homeyness	Complexity
Personalness	Stimulation	Homeyness	Complexity	Interest	Vitality	Uplift	Organization
Interest	Vitality	Uplift	Organization	Modernity	Comfort	Approachibility	Naturalness

S5: Experiment 3 neuroimaging parameters (see Vartanian et al., 2013).

A 3-Tesla MR scanner with an eight-channel head coil (Signa Excite HD, 16.0 software; General Electric) was used to acquire T1 anatomical volume images (1.0 × 1.0 × 1.0-mm voxels). For functional imaging, T2*-weighted gradient echo spiral-in/out acquisitions were used to produce 35 contiguous 4-mm-thick axial slices [repetition time (TR) = 2,000 ms; echo time (TE) = 21.4 ms; flip angle (FA) = 90°; field of view (FOV) = 260 mm; 64 × 64 matrix; voxel dimensions = 4× 4 × 4.0 mm], positioned to cover the whole brain. The first 10 volumes were discarded to allow for T1 equilibration effects. The number of volumes acquired was 430 (+ 10 dummies).

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