

Buildings, Beauty, and the Brain: A Neuroscience of Architectural Experience

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Abstract

■ A burgeoning interest in the intersection of neuroscience and architecture promises to offer biologically inspired insights into the design of spaces. The goal of such interdisciplinary approaches to architecture is to motivate construction of environments that would contribute to peoples' flourishing in behavior, health, and well-being. We suggest that this nascent field of neuroarchitecture is at a pivotal point in which neuroscience and architecture are poised to extend to a neuroscience

of architecture. In such a research program, architectural experiences themselves are the target of neuroscientific inquiry. Here, we draw lessons from recent developments in neuroaesthetics to suggest how neuroarchitecture might mature into an experimental science. We review the extant literature and offer an initial framework from which to contextualize such research. Finally, we outline theoretical and technical challenges that lie ahead. ■

INTRODUCTION

Two thousand years ago, the Roman architect Vitruvius highlighted beauty as one of three core dimensions of architectural design. His seminal Vitruvian triad (Figure 1) illustrated that a building must be strong and structurally stable (*firmitas*), meet the functional needs of its occupants (*utilitas*), and appeal to their aesthetic sensibilities (*venustas*; Vitruvius Pollio, Morgan, & Warren, 1914). Cultures across the globe have regarded aesthetic experience as a vital consideration in human construction. For millennia, ancient Eastern construction practices like the Indian *vaastu shastra* and the Chinese *feng shui* offered concrete guides to creating spatial harmony and aesthetic coherence in the built environment (Patra, 2009; Mak & Thomas Ng, 2005). Architectural aesthetics was a topic of serious inquiry in the European intellectual tradition as well, generating attention from philosophers like Goethe and Ruskin (Hultzs, 2014). The considerable attention devoted to this subject across time and culture reflects a shared belief that aesthetic qualities of buildings have a meaningful impact on human experience.

In the 20th century, the aesthetic dimension of the built environment was de-emphasized. Modern building science generally focused on improving utilitarian measures like fire safety, construction costs, and efficient uses of space (Vaughan, 2013). Advances in material design and structural engineering led to the construction of taller and sturdier buildings than ever before (Ali & Moon, 2007). This trend mirrored a philosophical shift in West-

ern architectural practice that began about a century ago, when the concept of buildings as machines and the associated creed of “form follows function” influenced architects to optimize the measurable and often mechanistic aspects of the built environment while discarding long-observed aesthetic conventions like ornamentation and human scaling. The minimalist, reductive form that resulted from this philosophy came to embody a new aesthetic ideal, reflecting a view of architectural beauty as nothing more than a byproduct of functionalist design (Venturi, Scott Brown, Rattenbury, & Hardingham, 2007). This perspective pushed the study of aesthetic experience to the periphery of architectural investigation. In Vitruvian terms, *venustas* was subsumed by *utilitas*.

Recent decades, however, have witnessed a surge of interest in the experience of the built environment. Today, many people spend upwards of 90% of their lives in buildings (Evans & McCoy, 1998). Studies indicate that aesthetic qualities of architecture have an impact on our mood, cognitive functioning, behavior, and even mental health (Adams, 2014; Cooper, Burton, & Cooper, 2014; Hartig, 2008; Joye, 2007). This evidence coincides with a flourish of interest in the intersection of neuroscience and architecture (Dance, 2017; Robinson & Pallasmaa, 2015; Mallgrave, 2010; Eberhard, 2008). However, relatively little work has been conducted on the neuroscience of architecture. We advocate going beyond inferences from neuroscientific knowledge applied to architecture to direct experimental work in which architectural experience itself is the target of neuroscientific research.

In this study, we apply lessons from recent developments in neuroaesthetics, a discipline that investigates

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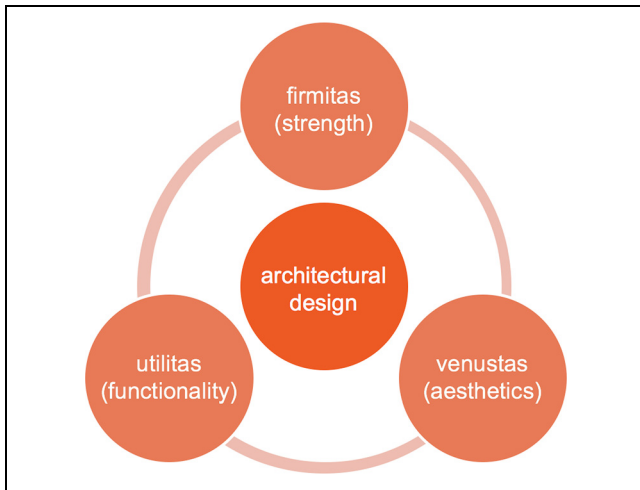


Figure 1. The Vitruvian triad.

the neurobiological underpinnings of aesthetic experiences of beauty and art (Chatterjee & Vartanian, 2016), to the neuroscience of architecture. These ideas and methods can be used to study aesthetic experiences in the built environment (Eberhard, 2009). An emerging “neuroscience of architecture” promises an empirical platform from which to study the experiential dimensions of architecture that have been largely overlooked in modern building science.

Around 2004, neuroaesthetics arrived at a pivotal point in its development both empirically and theoretically. The first papers using fMRI to identify neural responses to art (Vartanian & Goel, 2004) and to critically review the neuropsychology of art (Chatterjee, 2004a, 2004b) were published. In concert and perhaps more importantly early models outlining key cognitive and neural systems involved in aesthetic experience were set forth (Chatterjee, 2004a; Leder, Oeberst, Augustin, & Belke, 2004). Previous research had been primarily descriptive in that most studies generated qualitative observational claims relating facts of the brain to aesthetic experiences (Chatterjee & Vartanian, 2014). The pivot initiated a shift from descriptive hypothesis-generating research to empirical hypothesis-testing studies and helped launch the discipline into the mainstream of scientific investigation (Chatterjee, 2011).

We propose that the neuroscience of architecture is on the verge of a similar pivot. Currently, descriptive research predominates in this young field (Brown & Lee, 2016; Mallgrave, 2010; Eberhard, 2008). Several empirical studies have recently emerged reporting neurophysiological responses to architectural parameters (Choo, Nasar, Nikrahei, & Walther, 2017; Shemesh et al., 2016; Marchette, Vass, Ryan, & Epstein, 2015; Vartanian et al., 2013, 2015). These studies represent a first step. However, they remain untethered to a general theoretical framework and are difficult to place in the context of programmatic research on the neuroscience of architecture.

Here, we apply a general neural model of aesthetic experience to architectural experience and contextualize past and future empirical studies. In the process, we also outline challenges ahead for the field as it matures.

THE AESTHETIC TRIAD

The aesthetic triad, originally created to frame aesthetic experiences in neural terms (Chatterjee, 2013; Shimamura, 2013), also applies in a general way to the neuroscience of architecture. According to this model, three large-scale systems generate aesthetic experiences: sensorimotor, knowledge-meaning, and emotion-valuation systems (Figure 2). Architecture engages multiple sensory networks, presumably visual, auditory, somatosensory, olfactory, and vestibular systems, and triggers motor responses such as approach and avoidance (Vartanian et al., 2015). Meaning-knowledge systems informed by personal experiences, culture, and education also shape one’s encounters with the built environment. Finally, emotion-valuation networks mediate feelings and emotions engendered by buildings and urban spaces (Leder et al., 2004).

Below, we discuss each of these systems in greater detail and consider the relative contribution of each to emergent aesthetic experiences of architecture. We also consider how these networks might respond differently to architecture than to visual art. Key differences include the immersive and multisensory nature of buildings and the prolonged time span of architectural encounters as compared with typically 2-D images and brief engagement with artworks. Along the way, we discuss how aesthetic experiences could mediate the effects of architecture on behavior, health and well-being, and how differences in building types (e.g., homes, hospitals, office space, museums) might modulate the nature of these experiences.

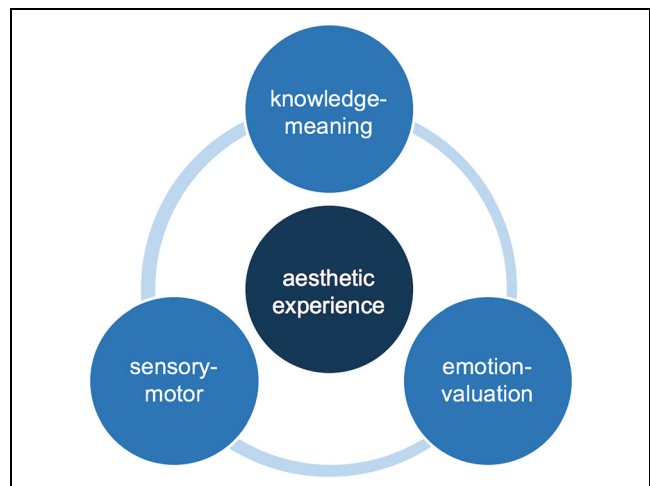


Figure 2. The aesthetic triad. Adapted from Chatterjee and Vartanian (2014).

A general question that arises in neuroaesthetics is whether art objects are special and whether aesthetic experiences of art are different than aesthetic experiences of natural or nonart objects. A similar question could be raised for architecture. We suggest that there are similarities and differences in people's responses to built versus natural environments. There are likely systematic differences in the sensory properties (color, texture, shapes) of built and natural spaces and that architectural knowledge or familiarity of these spaces are likely to introduce differences in their respective experience. Understanding these similarities and differences are themselves of scientific interest.

Sensory-Motor Systems

Edmund Burke remarked that "beauty is, for the greater part, some quality in bodies acting mechanically upon the human mind by intervention of the senses" (Burke, 1767, p. 175). Indeed, sensory networks can be considered the gatekeepers of architectural experience. Environmental features differentially stimulate our visual, auditory, somatosensory, vestibular, and olfactory neural networks. These sensations are tied to downstream motor responses such as the affordances of objects, approach and avoidance reactions, and navigation through built spaces.

Vision

Vision dominates research in perception of architectural spaces. Basic low-level visual attributes such as luminance, color, and motion and intermediate levels like grouping are processed (Chatterjee, 2004a) before integration into higher-level processing areas such as the parahippocampal place area, the retrosplenial cortex, and the occipital place area (Marchette et al., 2015). The parahippocampal place area responds specifically to environmental scenes, including landscapes, building interiors, and urban neighborhoods, and also plays a critical role in spatial navigation (Mégevand et al., 2014; Epstein & Kanwisher, 1998). This area also codes for the expansiveness of spaces (Kravitz, Peng, & Baker, 2011). Recent work suggests that the occipital place area is involved in processing perceptual features like building materials, windows, and architectural motifs that might be relevant to recognizing the interior and exterior of buildings. By contrast, the retrosplenial cortex retrieves information that allows people to orient themselves within a remembered or imagined spatial environment (Marchette et al., 2015). Hippocampal and entorhinal cortices contribute to different aspects of spatial navigation, which would be relevant for architectural experiences (Spiers & Barry, 2015).

A prominent idea in visual aesthetics is the notion of fluency (Reber, Schwarz, & Winkielman, 2004). That is, by hypothesis, humans prefer configurations with some

degree of complexity that are also processed easily or fluently. The visual system is sensitive to features like contrast, grouping, and symmetry (Ramachandran & Hirstein, 1999). Retinal cells and neurons in the occipital cortex are more responsive to edges or areas of high visual contrast than to regions of homogenous luminance in a scene (Geisler, 2007; Brady & Field, 2000; Ramachandran & Hirstein, 1999). High-contrast regions often capture visual attention and interest because they contain a high density of useful visual information for object identification (Hagerhall, Purcell, & Taylor, 2004; Leder et al., 2004; Alexander, 2002; Ramachandran & Hirstein, 1999). Grouping, a fundamental Gestalt principle, describes the process by which the visual system orders repeated, statistically correlated information in a scene, like alternating columns and archways in an architectural colonnade or organized patterns of blue and yellow hues dispersed throughout a stained glass window (Alexander, 2002). Grouped features (e.g., of color or form) trigger synchronized action potentials among associated neurons responsible for processing those features (Ramachandran & Hirstein, 1999; Singer & Gray, 1995). These visual mechanisms may mediate the pleasure response associated with viewing ordered patterns of form and color in architecture (Alexander, 2002).

Balance, of which symmetry is the most straightforward example, also contributes to fluency and aesthetic preference (Wilson & Chatterjee, 2005). The evolutionary importance of symmetrical information as a reproductive fitness indicator for human survival may underlie experimentally observed preferences for more symmetrical faces and geometric shapes (Jacobsen, Schubotz, Höfel, & Cramon, 2006; Ramachandran & Hirstein, 1999; Rhodes, Proffitt, Grady, & Sumich, 1998; Frith & Nias, 1974). Alexander and Carey reported that the number of local symmetries in a given pattern strongly predicts the ease with which a participant can find, describe, and remember that pattern (Alexander & Carey, 1968). Patterns with more symmetries enable more efficient recognition. The fundamental importance of symmetry may help explain why this pattern appears ubiquitously in human design and construction at many scales, from Persian rugs to Shaker furniture to ancient Greek temples (Alexander, 2002).

The visual system is sensitive to various statistical properties of images. One such property is fractal geometry, defined as "fractured shapes [that] possess repeating patterns when viewed at increasingly fine magnifications" (Hagerhall et al., 2004, p. 247). Fractal geometry provides a mathematical description of mountains, coastlines, and many other complex shapes in nature (Hagerhall et al., 2004). A fractal dimension is a statistical index of complexity. For example a simple curve has a fractal dimension close to 1, whereas a densely convoluted line that approximates the appearance of a surface has a fractal dimension closer to 2. Aesthetic preferences for natural scenes, visual art, and computer-generated patterns seem to correlate moderately with fractal dimensions ranging

from about 1.3 to 1.5 (Taylor et al., 2005; Spehar, Clifford, Newell, & Taylor, 2003), although these claims remain deeply controversial (Jones-Smith & Mathur, 2006). In general, quantifiable image statistics do contribute to the psychophysics of aesthetic responses (Graham, Schwarz, Chatterjee, & Leder, 2016; Kotabe, Kardan, & Berman, 2016; Berman et al., 2014; Graham & Redies, 2010; Graham & Field, 2007; Redies, 2007), which would also apply to built environments.

Beyond formal mathematical definitions, colloquial notions of complexity, defined as “the volume of information present in a space” (Dosen & Ostwald, 2016, p. 3), may influence the ease with which we identify objects and extract information from the built environment. Salingaros suggested that buildings stripped of visual complexity, like prisons, deny the information-seeking visual system access to meaningful information (Salingaros, 2003). Empirical findings tentatively support this view, suggesting that people generally prefer at least a moderate level of visual complexity when viewing both art and architectural interiors (Dosen & Ostwald, 2016; Leder et al., 2004; Frith & Nias, 1974). As Berlyne postulated many years ago, preferences tend to follow an inverted U-shaped curve in relation to complexity (Güçlütürk, Jacobs, & van Lier, 2016; Imamoglu, 2000; Berlyne, 1970, 1971). More recent evidence suggests that the relationship between complexity and aesthetic preference varies as a function of how the former is conceptualized (e.g., amount, variety or organization of elements within a scene; Nadal, Munar, Marty, & Cela-Conde, 2010). Excess architectural complexity may also overwhelm the visual system, particularly if the information is experienced as disorganized (Kotabe et al., 2016; Salingaros, 2003, 2007).

Appleton’s habitat theory offers an evolutionary framework to explain psychological responses to architectural spaces. According to habitat theory, humans evolved to prefer landscapes containing visual features and spatial configurations that favor survival (Appleton, 1975). People may have an innate visual preference for moderately complex, savannah-like environments (Joye, 2007; Balling & Falk, 1982), because these areas signal both safety and nourishment. The frequent patches of trees scattered throughout the savannah (Joye, 2007) likely offered early hominids places to hide from predators and survey the plains in search of resources, mates, and prey (Appleton, 1975). A review by Dosen and Ostwald indicates that both prospect (a clear view of the environment) and refuge (safe places to hide) predict visual preferences for natural settings and that these preferences also extend to built environments (Dosen & Ostwald, 2016). People often prefer architectural interiors and urban spaces that are more open and visually connected to their surroundings compared with enclosed environments (Dosen & Ostwald, 2016). In an fMRI study of architectural interiors, we found that participants judged open rooms as more beautiful than enclosed rooms (Vartanian et al., 2015).

Open interiors activated structures in the temporal lobes associated with perceived visual motion, including the left middle temporal gyrus and the right superior temporal gyrus (Vartanian et al., 2015). Participants in this study also preferred rooms with higher ceilings over those with lower ceilings, which could be interpreted as a preference for greater visual prospect. Supporting this interpretation, high ceilings activated structures associated with visuospatial attention and exploration, including the left precuneus and the left middle frontal gyrus (Vartanian et al., 2015).

E.O. Wilson’s biophilia hypothesis proposes that our sensory systems developed heightened sensitivity to living and life-like stimuli of the natural world (Wilson, 1984). Kaplan and colleagues proposed that inherently fascinating visual stimuli in natural landscapes, like vegetation, wildlife, and “the motion of leaves in the breeze” (Kaplan, 1995, p. 174), capture the attention of our visual system in a bottom-up fashion (Berman et al., 2014; Berman, Jonides, & Kaplan, 2008; Ulrich & Parsons, 1992). This body of work suggests that within nature humans are more likely to orient and attend to these “soft fascinations” (Kaplan, 1995, p. 174) associated with living objects.

Biomorphic features are also prevalent in human construction. Builders throughout history have often endowed their structures with nature-like visual qualities by drawing inspiration from the “monumental design model” (Kellert, 2003, p. 36) of plants and animals in the design of ornamentation, scaling, proportionality, and even structural support schemes (Joye, 2007; Alexander, 2002). Several authors have speculated about the potential sensory and emotional benefits of naturalistic patterns in architecture, like curvilinear form and fractal scaling (Joye, 2007; Salingaros, 2007; Alexander, 2002). We, for instance, found that images of curvilinear architectural interiors activated the lingual and the calcarine gyrus in the visual cortex more than images of rectilinear interiors when participants made approach-avoidance choices (Vartanian et al., 2013).

Nonvisual Experiences of Architecture

Relatively little empirical research has been conducted on nonvisual aspects of architectural experiences. Odor affects an occupant’s emotional response to a building (Barbara & Perliss, 2006), perhaps because of the direct link between the olfactory and limbic system (Ward, 2015). Olfaction can revive memories of past experiences in a place, like a childhood home, by activating neural structures governing memory, affect, and meaning (Lehrer, 2008).

Acoustics also play a key role in shaping an occupant’s experience. Audition helps provide inhabitants with useful information about the size and shape of an architectural space (Ward, 2015). Acoustic parameters like reverberation time affect the fullness and complexity of the sound

perceived and probably contributes to whether a place is designed for contemplation as in a monastery or for excitement as in a stadium.

The somatosensory cortex mediates an occupant's tactile and thermal sensations of buildings. A building's temperature, for instance, influences an occupant's comfort, emotional state, and perception of beauty (Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007; Nicol & Humphreys, 2002; Fanger, 1973). The tactile nature of materials used undoubtedly plays a role in the experience of interior spaces, but this sensory quality has not received experimental scrutiny.

Motor Responses to Architecture

Navigating buildings involves planning and execution of movement, and it is likely that architectural design differentially impacts neural areas responsible for motor planning and navigation. Beauty evaluations of architecture can vary with neural activity in the global pallidus (Vartanian et al., 2013), perhaps suggestive of motor responses (Nambu, Tokuno, & Takada, 2002). Aesthetic parameters like enclosure has an impact on decisions to approach or avoid a space (Vartanian et al., 2015), which may be governed by reward and emotion processing areas like the nucleus accumbens, the anterior insula, and the basolateral amygdala (Vartanian et al., 2013). Intriguingly, Joye and Dewitte found that exposure to images of tall buildings—which were associated with heightened feelings of awe—caused participants to experience greater immobility and to respond more slowly on a manual clicking task than exposure to images of low buildings (Joye & Dewitte, 2016). These findings suggest that our evaluations of architectural stimuli can propel or inhibit motor activity and influence the specific qualities of the viewers' experiences.

Knowledge-meaning Systems

Education, memories, and the context in which a person encounters an aesthetic object or a built environment can have an impact on the person's experience. Expertise, for instance, is known to influence aesthetic experiences. In one fMRI study, architecture students recruited different cortical areas when viewing buildings than students from other disciplines (Wiesmann & Ishai, 2011). Another experiment showed that architects, compared with nonarchitects, had increased activation of reward circuitry, including the bilateral medial OFC and the subcallosal cingulate gyrus, when making aesthetic judgments about buildings (Kirk, Skov, Christensen, & Nygaard, 2009). Architects also exhibited greater activation of the hippocampus and precuneus compared with control participants when viewing buildings but not faces, suggesting that memories rendered by education and professional experience contributed to their affective responses.

A person's past experiences in a built environment can modulate their present interactions with that space. Exposure to an environment generates a cognitive map using place and grid cells of the hippocampus (McNaughton, Battaglia, Jensen, Moser, & Moser, 2006; O'Keefe & Nadel, 1978), which in turn facilitates more efficient navigation in future encounters (Astur, Taylor, Mamelak, Philpott, & Sutherland, 2002; Maguire et al., 2000). Grid cells encode memories of both events and the places in which they occur (Edelstein et al., 2008). Because familiarity influences liking (Montoya, Horton, Vevea, Citkowitz, & Lauber, 2017), we suspect that familiarity and ease of navigation would influence the aesthetic experience of spaces. How might expectations, context, and meaning affect a person's architectural experience? Expectations about control influence thermal comfort. Occupants who control environmental parameters affecting building temperature, such as operable windows, fans, and thermostats, tolerate a wider range of indoor temperatures than inhabitants with restricted control over their indoor climate (Nicol & Humphreys, 2002). The mere perception of environmental control can increase the range of temperatures within which an occupant feels comfortable (Brager, Paliaga, & De Dear, 2004; Bauman et al., 1994). Context and cultural meaning also have an impact on aesthetic experience (Leder et al., 2004). Kirk and colleagues found that participants were more likely to judge abstract visual art as beautiful if they were labeled as gallery pieces than if they were classified as computer-generated images (Kirk, Skov, Hulme, Christensen, & Zeki, 2009). Art randomly assigned the "gallery" label generated increased activity in prefrontal, orbitofrontal, and entorhinal cortices than those assigned the "computer" label, indicating that participants' expectations about the aesthetic value of the artworks influenced their emotional responses.

Similar to the gallery condition for art, a building's advertised cultural significance could shape an occupant's expectations and alter his or her experience of the space. For example, this effect might bias people to enjoy and appreciate expensive buildings, buildings designed by famous architects, buildings perceived as sustainable, or buildings associated with a particular historical period, event, or style. Knowledge of a structure's intended function could similarly bias an occupant's expectations before their architectural encounter. The prospect of visiting a prison, for example, would likely bring on a different frame of mind than when preparing to enter a Buddhist temple. Thus, the knowledge and expectations that a person brings to the space they occupy almost certainly influences their aesthetic experience of that space.

Emotion-valuation Systems

The emotions people feel in the presence of beautiful architecture are likely mediated by the brain's reward circuitry. In a meta-analysis of neuroimaging studies investigating positive-valence aesthetic appraisal, Brown

and colleagues proposed that the processing of aesthetic emotions occurs through a core neural circuit involving the OFC, the BG, the ACC, and the anterior insula (Brown, Gao, Tisdelle, Eickhoff, & Liotti, 2011). Our study revealed that curvilinear building interiors are judged as more beautiful and pleasing than rectilinear spaces and that beauty ratings of curved rooms correlated with increased activation of ACC (Vartanian et al., 2013). ACC is connected with both the OFC and anterior insula and is often coactivated with these regions in neuroimaging studies rewards (Brown et al., 2011).

A follow-up experiment found that participants' inclinations to exit enclosed rooms, compared with open rooms, were associated with activation of the anterior midcingulate cortex (Vartanian et al., 2015). The anterior midcingulate cortex receives direct projections from the amygdala (Vogt & Pandya, 1987) and is involved in fear processing (Whalen et al., 1998), pointing out that brain circuitry governing negative emotions almost certainly play a role in architectural experience. Another group of researchers found that study participants immersed in a virtual simulation of an enclosed room without windows exhibited greater reactivity to a stress test than participants who undertook the test in a virtual room with windows (Fich et al., 2014). Those who took the test in the enclosed virtual space experienced both heightened and prolonged spikes in salivary cortisol compared with participants immersed in the more open environment. In these two studies, the same design parameter, enclosure, produced both fear and elevated levels of stress hormones, presumably because emotion-regulating limbic structures like the amygdala modulate downstream activity of the neuroendocrine and autonomic nervous systems (Ulrich-Lai & Herman, 2009). The close association between the limbic system and stress responses represents a key pathway by which chronic exposure to maladaptive built environments might negatively impact an occupant's long-term health (Joye, 2007).

The idea that the visual and limbic systems work in concert to rapidly identify and evaluate incoming visual information is consistent with Ulrich's framework, which proposes that initial affective responses toward environments are primarily influenced by automatic, unconscious processing (Ulrich, 1983). Some studies suggest that positive and negative emotional responses to environmental scenes occur rapidly and automatically (Joye & Dewitte, 2016; Valtchanov & Ellard, 2015; Hietanen & Korpela, 2004; Korpela, Klemettilä, & Hietanen, 2002). Such a quick emotional response could be adaptive by relieving people of the cost imposed by learning an environment through actual lived experience (Joye, 2007; Kaplan, 1987; Ulrich, 1983).

If there is indeed an evolutionary basis for aesthetic sensation and emotion, then architects could manipulate the design parameters of their buildings to heighten these adaptive responses. Builders throughout history may have been doing just that. Alexander and colleagues

identified a series of visual patterns—including contrast, grouping, and symmetry—which, they contend, appear ubiquitously throughout global vernacular architecture precisely because of their inherent emotional appeal (Salingaros, 2007; Alexander, 1977, 2002). Further research is needed to understand the neural underpinnings of complex emotional responses to architecture like contemplation, comfort, curiosity, and awe.

In addition to emotions, aesthetics researchers often measure judgments as a means of gauging a participant's evaluative response to art or architecture. Participants are typically asked to judge visual stimuli on dimensions such as beauty or attractiveness. In one study, beauty judgments of architecture were shown to vary with activity in various regions of the pFC, including the frontopolar cortex and the superior frontal gyrus, as well as brain regions involved in memory retrieval, such as the parahippocampus (Vartanian et al., 2013). These neural regions are somewhat distinct from reward circuitry associated with emotions. Activation of the pFC suggests that conscious reasoning and analysis can play a significant role in aesthetic judgment, whereas parahippocampal activation may mean that memories generated from education or past experience may influence this analytical process. Increased activity in both of these neural regions implies that aesthetic judgment may be particularly influenced by inputs from the knowledge-meaning systems such as expertise, cultural trends, and an understanding of a building's intended function.

If evaluative and emotional responses to architecture involve distinct neural circuitry, then it would be reasonable to expect that what an occupant thinks about a building could be different from how they feel while spending time there.¹ These two dimensions of architectural experience could also have important influences on each other. For example, Di Dio and colleagues found that aesthetic judgment tasks actually diminish emotional responses to visual art. Participants who were asked to rate the beauty of Renaissance sculptures showed decreased activation in the right insula compared with those who were merely instructed to passively observe the sculptures (Di Dio, Macaluso, & Rizzolatti, 2007). Understanding potential interactions between aesthetic emotion and evaluation will be an important area of inquiry for future research in the neuroscience of architecture.

HEALTH AND WELL-BEING

Research linking architecture and health often focuses on identifying sources of illness. For instance, chronic exposure to unwanted noise can increase blood pressure (Payne, Potter, & Cain, 2014) and hinder adolescent neural development (Gilbert & Galea, 2014). Insufficient daylight may affect circadian rhythms and impair sleep quality (Dutton, 2014). However, the design of the built environment can also modulate positive aspects of

psychological functioning such as learning, social behavior, and emotional wellness (Cooper & Burton, 2014). For example, immersion in red environments may improve performance on detail-oriented cognitive tasks whereas blue spaces might be associated with enhanced creative thinking (Mehta & Zhu, 2009). Likewise, greenery and other natural features in the built environment may improve mood (Bowler, Buyung-Ali, Knight, & Pullin, 2010), enhance working memory (Bratman, Daily, Levy, & Gross, 2015), and accelerate recovery from stress (Ulrich et al., 1991) and surgery (Ulrich, 1984). Monotonous interior architectural composition can make patients with Alzheimer's disease more likely to get lost, whereas incorporating frequent visual reference points and exterior views can improve their navigation (Passini, Pigot, Rainville, & Tétreault, 2000). These studies represent just a few examples of how aesthetics and design of the built environment can have an impact on mental and physiological health.

CHALLENGES AND FUTURE DIRECTIONS

As outlined above, we believe that the neuroscience of architecture is poised to make a transition in which the prevalent descriptive approach can be extended and grounded in experimental research programs. Here, we outline three related challenges ahead, which we refer to as the double framing, the psychology, and the measurement problems. Advances in each of these areas will provide structure to the field as it matures.

Double Framing

This problem refers to the need for both general and specific frames to guide research. As mentioned earlier, having a theoretical framework is critical to placing experimental work in context. Without such a framework, individual studies remain isolated findings untethered to programmatic advances in understanding. Neuroaesthetics was helped by the introduction of general psychological and neuroscientific models that have since been debated and refined (Chatterjee & Vartanian, 2016; Tinio, 2013; Nadal, Munar, Capó, Rosselló, & Cela-Conde, 2008; Jacobsen, 2006; Chatterjee, 2004a; Leder et al., 2004). Here, we apply one such general framework, the aesthetic triad, to architecture. However, architectural spaces encompass different functions in a way that art typically does not. For a hospital, a school, a museum, a train station, and a home, what makes the space beautiful might differ and be related to its function. Furthermore, the context in which these spaces are experienced makes a difference. The anxiety of a patient in a hospital, the desire to learn in a school, the navigational demands of a train station, and the comfort and safety of a home might all be relevant factors in the experience of a person within those spaces. This variability based on the purpose of the building and the inhabitants' expectations and states

of mind need to be considered in any research involving the experience of such spaces.

Psychology of Architecture

Empirical aesthetics has a long and rich scholarly tradition of research in the psychology of aesthetics and the arts. This tradition includes Fechner's original contributions emphasizing the experience of the viewer as a critical variable in aesthetic understanding (Fechner, 1876), as well as Arnheim's perceptual psychology (Arnheim, 1954), Berlyne's concerns with complexity and arousal (Berlyne, 1971), and Martindale's historical-cultural analysis (Martindale, 1990), among many others. Neuroscientists can draw on this rich body of scholarship in guiding experimental work. Although there are relevant pockets of research in environmental and human factors psychology (Graham, Gosling, & Travis, 2015), a similarly rich tradition of research situated specifically within a psychology of architecture does not exist. We do not think that an insightful neuroscience of architecture can develop without a well-developed psychology of architecture. Recent academic meetings suggest that such a discipline might yet develop,² which would undoubtedly bolster the neuroscience of architecture.

Measurement Challenges

Four aspects of a neuroscience of architecture make measurement especially challenging. These aspects are dimensionality, multimodality, temporality, and depth of psychological processing. To some extent, these aspects are relevant to the neuroscience of art, but they are magnified when considering architecture.

Most neuroaesthetics research involves 2-D images. This makes sense when the stimuli viewed are flat paintings, although issues of scale and visual texture remain relevant in so far as experiments are typically conducted on a computer screen in a laboratory. Even architecture-specific investigations have relied on flat visual stimuli to represent 3-D architectural space and thus might be treated more like artwork than buildings in these experiments. Real buildings induce more immersive and multisensory experiences than images of architecture or visual art. The specific experience of being in such a space might be more difficult to capture experimentally. A similar issue arises with installation art, which has not been investigated in any systematic way in neuroaesthetics. Perhaps in the near future virtual reality techniques will permit a reasonable approximation of the experience of immersion in an architectural space.

We mentioned earlier the multidimensional nature of architectural experiences. Yet, research has focused primarily on visual aspects of architecture. How to incorporate different modalities and probe the neural underpinnings of an integrated sensory-motor experience remains a challenge to be addressed.

People inhabit architectural spaces. This ongoing engagement with space differs from our engagement with art. Investigators have probed early and a slightly later response to artwork, but such research is still confined to experiences that last less than a few seconds in duration (Cela-Conde et al., 2013). There is recognition that aesthetic experiences vary over longer durations than a few seconds (Chatterjee, 2014; Leder & Nadal, 2014), although the average museum patron spends less than 20 sec engaging with works of art (Smith, Smith, & Tinio, 2017; Smith & Smith, 2001). Architectural encounters, by contrast, tend to be prolonged and are often habitual in the case of frequently visited buildings like one's home, school, or office. How best to sample neurophysiological data over time and "in the field" is a question that will need to be resolved over time (Gramann, Ferris, Gwin, & Makeig, 2014). Mobile EEG has begun to be used in museum studies and innovative approaches to data collection have begun to emerge (Kontson et al., 2015; Tröndle & Tschacher, 2012). Technological issues of sampling and separating signal from noise and theoretical issues of how best to use such technology in a hypothesis-testing framework remain, but these methods have great promise.

Within empirical aesthetics, there is an increasing appreciation that the field needs to expand its scope beyond the study of simple preferences to include a focus on deeper psychological states (Silvia, 2012). This need is also relevant within the context of the neuroscience of architecture. For example, certain built spaces have the ability to facilitate deep contemplation that extends beyond mere preference, and it is important to understand design features that drive such effects. Other spaces might be designed to induce social cohesion or a sense of refuge and comfort, and poorly designed spaces might increase individual alienation. The field would benefit from the development of ecologically valid approaches to the measurement of mental states that capture deep psychological engagement with built spaces.

Conclusions

Philosophers since ancient Roman times have emphasized the experiential importance of architectural aesthetics. Only in the past decade or so have scientists started to investigate this topic with rigor. Here, we describe how an existing model—the aesthetic triad—can serve as a useful initial framework for researching *venustas*, the relatively neglected dimension of the Vitruvian triad. We suggest that sensory and emotional response patterns shaped by bioevolutionary forces may form the foundation of architectural experience, but also that this experience is substantially modified by a person's education, cultural upbringing, and personal experience.

Despite individual differences, consistent patterns of neural activity are emerging from this line of research that in the future could help architects design brain-

informed buildings. Researchers in environmental psychology and social epidemiology have tried to identify design characteristics that might improve our physical and mental health. Increasing evidence from these investigations suggests that "attractiveness is a key element in how the built environment affects our wellbeing" (Cooper & Burton, 2014, p. 13). In conjunction with increased precision in defining design concepts (Stamps, 1999), the neuroscience of architecture is well positioned to study the biology of architectural beauty. Much work remains to be done. The hope is to improve human experience and well-being by optimizing built structures that surround us for much of our lives.

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Notes

1. By no means is this a new idea. The merits of these potentially distinct modes of architectural experience, thinking and feeling, were infamously argued by two leading architectural theorists, Christopher Alexander and Peter Eisenmann, in a heated debate at Harvard University in 1982.
2. See, for instance, www.psychologyofarchitecture.org/.

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