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KEY NOTE PAPER

The neuroaesthetics of architectural spaces

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Abstract
People in developed countries spend over 90% of their time in built environments. Yet, we know little about its pervasive and often hidden effects on our mental state and our brain. Despite growing interest in the neuroscience of architecture, much of this scholarship has been descriptive. The typical approach is to map knowledge of the brain onto constructs important to architecture. For a programmatic line of research, how might descriptive neuroarchitecture be transformed into an experimental science? We review the literature outlining how one might consider experimental architecture first by examining the role of natural features in architectural settings. We then turn to the human experience of occupants, and hypothesized that aesthetic responses to architectural interiors reduce to key psychological dimensions. Conducting Psychometric Network Analysis (PNA) and Principal Components Analysis (PCA) on responses to curated images, we identified three components: *coherence* (ease of organizing and comprehending a scene), *fascination* (informational richness and generated interest), and *hominess* (personal ease and comfort). *Coherence* and *fascination* are well-established dimensions for natural scenes. *Hominess* was a new dimension related to architectural interiors. Central to all three communities in the PNA was emotional valence. We also reanalyzed data from an earlier fMRI study in which participants made beauty and approach-avoidance decisions while viewing the same images. 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, and *hominess* covaried with neural activity in the left cuneus only when they made approach-avoidance decisions. The visual brain harbours hidden sensitivities to architectural interiors that are captured by the dimensions of *coherence*, *fascination*, and *hominess*. These findings represent first steps towards an experimental neuroarchitecture.

Keywords Neuroarchitecture · Neuroaesthetics · Space · Cognitive neuroscience

People in materially developed countries spend most of their lives in buildings (Evans 2003). Aesthetic qualities of the built environment deeply influences people's psychological states (Adams 2014; Cooper and Burton 2014; Ellaway 2014; Kyttä et al. 2011; Kyttä and Broberg 2014). Here, we review the state of the neuroaesthetics of architecture and discuss the need for more nuanced ways of advancing this research.

The idea that aesthetic qualities of the built environment impact our sense of well-being is not new. For millennia, civilizations across the globe sought to understand how to designs of the built and natural environment can improve social, functional, and spiritual aspects of the human experience. From ancient Rome to Imperial China, cultures around the world developed sophisticated aesthetic rules to guide the construction of buildings, neighbourhoods, and cities, motivated by the belief that these aesthetic principles are as much a science as they are an art (Coburn et al. 2017; Mak and Thomas Ng 2005; Patra 2009; Vitruvius Pollio et al. 1914).

Around the middle of the twentieth century, a shift occurred in Western sensibilities that led to the widespread rejection of humanist principles of construction in favour of utilitarian design rules in which measurable variables such as cost, speed, and efficiency were prioritized over less easily quantifiable factors such as aesthetics and the experience of occupants. Although this shift delivered some progress in urban development, it also brought about unintended

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social consequences (Jacobs 1992). The evidence-based design movements of the 1970s arose in response to mid-century architectural mass-production and paved the way for research in urban sociology and environmental psychology. This early scholarship exploring the effects of architectural design on social behaviour laid the groundwork for recent research on contemporary neuroscience of architecture.

The neuroscience of architecture is just beginning to advance knowledge about how and why specific architectural features affect people. We place this research within the theoretical framework of the *aesthetic triad*, a brain-based model developed for neuroaesthetics (Chatterjee and Vartanian 2014, 2016), reformulated for architecture (Coburn et al. 2017). Importantly, we distinguish between descriptive and experimental neuroscientific claims. The former uses knowledge about brain functioning to map the biological and cognitive nature of an aesthetic experience; a mapping from which one could potentially develop falsifiable theories. Experimental neuroscience, by contrast, directly tests hypotheses, makes predictions, and yields quantitative data. For instance, Vartanian and colleagues (2013) identified increased anterior cingulate activation when participants made judgements of interior spaces during functional magnetic resonance imaging (fMRI), *experimentally* demonstrating the involvement of emotion and reward pathways. Much of the scholarship in the neuroscience of architecture to date is descriptive (see Barbara and Perliss 2006; Eberhard 2004; Eberhard and Patoine 2004). However, scholarship is gradually shifting towards using experimental methods laying the foundation for programmatic research (Coburn et al. 2019, 2020; Lavdas and Schirpke 2020; Vartanian et al. 2013, 2015).

In our model of architectural experience (Coburn et al. 2017), rooted in the *aesthetic triad* (Chatterjee and Vartanian 2014, 2016), we proposed that human-building interactions are mediated by three large-scale neural networks: the sensory-motor, knowledge-meaning, and emotion-valuation systems. The *sensory-motor* system addresses “bottom-up” processing of the features of buildings, including visual (colour, shape, size, materiality), as well as acoustic, tactile, and even olfactory and navigational features of the built environment. The brain’s *knowledge-meaning* circuitry plays an important role in mediating “top-down” processing of architectural environments. The brain’s baseline response to a building’s sensory features may be dampened or enhanced by an individual’s cultural background, identity, and education, as well as their knowledge about a space. Finally, the *emotion-valuation* system integrates information from the sensory-motor and knowledge-meaning systems, leading to aesthetic experiences. These experiences may range from profound feelings of joy or delight to interest or even fear and disgust. We postulated that these three systems interact closely to create a holistic sense of architectural spaces.

A logical starting point is the perception of nature and natural features of the built environment. Nature has served as an important sources of architectural inspiration and reflects a persistent desire to connect with nature while in the built environment (Ulrich 1993). Some of the most prominent scientific approaches to architecture are concerned with natural qualities. The *Biophilia Hypothesis* proposes a widespread human preference for natural environments, compared to urban spaces (Berman et al. 2008; Kaplan 1995). People interact with nature for recreation and relaxation; a preference observed globally and across cultures (Chang et al. 2020). Interactions with nature produce positive effects on physiological, emotional, and cognitive functioning (Joye 2007).

Kaplan’s attention restoration theory (ART; Kaplan 1995) argues that nature works by offloading effortful cognitive processing resulting in an improved ability to focus. ART draws from William James’ distinction between involuntary attention–which is automatically captured by surrounding stimuli –and directed forms of attention that rely on effortful control mechanisms (James 1985). Directed attention is presumably replenished by interactions with the nature, because natural settings reduce the burden placed on this kind of effortful attention in an urban environment (Berman et al. 2008; Joye 2007; Kaplan 1995). Consistent with ART, experimental research indicates a modest improvement in directed attention after exposure to natural environments (e.g., Berman et al. 2008; Bowler et al. 2010), although questions about individual differences and proper control conditions remain.

Several accounts argue that preferences for natural spaces are evolutionarily-based. Ulrich’s stress-reduction framework (Ulrich 1993) posits that, humans were frequently confronted by threatening stimuli, leading to a rapid cortisol response that persists until the threat abates. Unthreatening settings were typically open, calm, and warm. Present-day environments rich in these attributes may reduce stress. Ruggles and Boak (2020) emphasize the importance of designing buildings that increases the baseline tone of the parasympathetic autonomic nervous system as a target to reduce stress. Similarly, the Prospect-Refuge theory argues that environments which are both open (i.e. prospect) and convey feelings of safety (i.e. refuge) were evolutionarily beneficial and, therefore, are aesthetically preferred.

Given this preference for nature–i.e., biophilia–many designers try to bring a natural aesthetic into the built environment. An obvious way to do this is to incorporate nature directly. This use of natural elements could be as straightforward as adding plants, water features, or small fires (Joye 2007). Drawing on the ideas of prospect-refuge, architects also incorporate large windows or balconies that provide extensive vistas of the outdoors. Even more simply, people can arrange pictures or photographs of the outdoors around an interior.

An alternate approach incorporates *patterns* that occur frequently in nature into the design of human-made spaces. In one study, participants who evaluated 240 interior and exterior architectural scenes based on perceived naturalness and preference exhibited strong preferences for buildings that contained a high densities of natural visual patterns, such as edge density and contrast (measured quantitatively). Notably, these nature-like patterns explained the most of the variance in preference ratings of both architectural facades and interior scenes, even after controlling for the amount of actual vegetation visible in each scene (Coburn et al. 2019). These findings suggested that *implicit naturalness* perceived in an architectural environment might be just as important as *explicit natural elements* (i.e. water, plants, trees) in scenes.

Consistent with research showing that rooms with properties typical of the natural environment, curvilinear spaces are preferred to spaces with unnatural features such as straight edges (Vartanian et al. 2013). The salubrious effects of interacting with nature may stem from these underlying pattern preferences; in one recent study, when participants were presented with equally-preferred urban and natural images, no differences in affective state were observed (Meidenbauer et al. 2020). That is, people experienced positive emotions in natural settings because of the prevalence of preferred visual inputs, rather than because of unique qualities of nature itself. Thus, low-level features characteristic of natural environments may evoke positive affect and aesthetic appreciation if they are incorporated into the built environment, even without explicitly natural elements.

Analogous results have been demonstrated experimentally. In one study (Kravitz et al. 2011), participants viewed a series of built and natural spaces during fMRI. Results indicated that the primary factor that influenced parahippocampus place area (PPA) activation was not whether the space was natural or human-made, but rather, the openness conveyed in each image. That is, the PPA was sensitive to a particular feature (i.e. openness of the space) regardless of image categorization (i.e. natural vs. built). Viewing open spaces is also associated with activation of temporal lobe structures sensitive to visual motion (Vartanian et al. 2015), suggesting a connection between openness and a desire to move in space (Coburn et al. 2017). Consistent with these possibilities, open interior spaces are rated as more natural (Coburn et al. 2019) and beautiful (Vartanian et al. 2015), and are preferred over closed ones (Dosen and Ostwald 2016).

Another low-level feature that influences aesthetic experience is fractal scaling (i.e. "fractals"). Fractals, a hierarchy of self-similar patterns that repeat at different scales, provide a sense of "organized complexity". Fractals are common in nature; clouds, trees, plants, waves, fire, lightning, and mountains are all comprised of repeating patterned elements. When incorporated into the built environment, fractals evoke feelings of naturalness, and are preferred over non-fractal design (Joyea 2007; Lavdas and Schirpke 2020; Taylor 2021). Historically, fractal design has been used across many civilizations and architectural practices. As detailed by Taylor (2021), fractals are seen in traditional African settlements, eighth century temples, thirteenth century castles of the Holy Roman Empire, Gothic-period cathedrals, Buddhist temples, Islamic minarets, Gaudi's Sagrada Familia, and the organic houses designed by Frank Lloyd Wright. More recent initiatives incorporate fractals into the design of floors, carpets, walls, solar panels, and window shades.

Neuroscience research provides insight into the appeal of fractals. First, the visual system is proficient at grouping together repeating elements (Biederman 1987; Reber et al. 2004) and process fractals automatically and fluently (Spehar et al. 2015). Moreover, neurons in primary visual cortex appear to show preferential responses to fractals, suggesting that these patterns play a crucial role in adapting the visual system to the natural environment (Yu et al. 2005). Fractals may also partially explain associations between nature (which is often rich in fractal patterns) and stress-reduction (Joye 2007).

Higher-level visual and semantic features of an environment clearly influence aesthetic experience. In a recent fMRI study, researchers identified decodable neural representations of architectural styles and buildings in high-level visual regions but *not* in cortical regions devoted to low-level features such as the primary visual cortex (Choo et al. 2017). Ibarra et al. (2017) also demonstrated that high-level scene features–such as the shape and undulation of the skyline, the presence of water in the scene, and the distribution of buildings–mediated the relationship between low-level scene features and aesthetic preference ratings by explaining over half of their shared statistical variance. Thus, aesthetic judgements of built environments likely involve complex interactions between low-level and high-level stimulus features.

Humans experience emotional responses to beautiful objects, including architecture (Chatterjee and Vartanian 2014, 2016). Stress-reduction frameworks argue that certain visual properties convey feelings of calmness or warmth (Tyrväinen et al. 2014; Ulrich et al. 1991). In one study examining approach-avoidance responses, the anterior midcingulate cortex (aMCC) was engaged when people viewed enclosed interior spaces that elicited exit decisions (Vartanian et al. 2015). Because the aMCC receives projections from the amygdala–indicating a potential role in fear-processing –negative emotions may be involved in processing architectural spaces, particularly ones from which people wish to depart. Others report heightened fear, stress, and cortisol levels when people are immersed in a virtual simulation of an enclosed room (Fich et al. 2014). Together, this work highlights a negative emotional component (i.e. fear) that can drive aesthetic experiences of the built environment. It is important to consider, however, that emotional responses are not necessarily automatic; the involvement of prefrontal and hippocampal brain regions in beauty judgements of architecture suggest that conscious reasoning and memory retrieval exert top-down influences on initial, automatic emotional reactions (Coburn et al. 2017; Vartanian et al. 2013; Kirk et al. 2009).

Following up on previous work, Coburn et al. (2020) conducted a study in which participants evaluated 200 interior architectural scenes across a variety of aesthetic rating scales which probed 16 psychological responses. Psychometric Network and principle components analyses was conducted to search for statistical patterns of overlap among thousands of ratings. Nearly 90 per cent of the variance in responses was explained by just three underlying psychological dimensions: coherence, fascination, and hominess. *Coherence* describes the degree to which a space feels organized to the viewer. *Fascination* refers to the visual richness and complexity of a space and is closely linked to a viewer's sense of excitement and desire to explore it. *Hominess* represents the extent to which a space feels comfortable, personal, and "home-like" to the viewer. Each dimension was anchored in valance- the most basic assessment of how the space makes viewers feel.

Taking this analysis further, the authors examined whether these psychological dimensions were associated with specific neural signatures (Coburn et al. 2020). This hypothesis was tested by integrating the PCA scores of the architectural scenes with fMRI data from Vartanian et al. (2013), who had previously evaluated the same images in the scanner using approach-avoidance and beauty judgement tasks. The degree of *fascination* covaried with neural activity in the right lingual gyrus for both tasks. *Coherence* was associated with neural activity in the left inferior occipital gyrus only when participants judged beauty, and *hominess* covaried with activation of the left cuneus exclusively for the approach-avoidance task. Critically, these neural data were collected years before the three psychological dimensions had been identified, and in a different group of participants. The authors concluded that the visual cortex is sensitive to these three dimensions of psychological experience, with each dimension carrying its own distinct neural imprint. If these insights extend beyond the specific stimuli used in the study and generalize to other architectural spaces, they could critically inform how buildings and urban environments might be designed and evaluated.

Insights gained from the neuroscience of architecture can be used to improve models of how and why specific architectural features affect people in specific ways. However, as we have previously detailed (Coburn et al. 2017), several research challenges need to be addressed. Here, we briefly touch on outstanding issues, and highlight potential strategies to resolve them.

Architectural spaces encompass a wide range of functions and settings. Thus, features that relate to aesthetic experience of the built environment may not be universally shared. There are practical limitations based on physical setting; an architect cannot merely insert a large window that overlooks water or a forest into every building. Physical and financial constraints further limit potential design choices. The function of a space also cannot be overlooked, both in terms of the design features and the experiences of the inhabitants. For instance, the experiences of a patient in a hospital are distinct from those of a student in a school or someone inside their own home. Design elements that foster wellness are unlikely to be consistent across different settings, which complicates the ability to generalize findings from one set of stimuli to another or to make broad generalizations.

Measurement of aesthetic experience in architecture is another challenge. To date, most neuroarchitecture studies use 2-D images (often with participants lying horizontally in an MRI scanner). This approach overlooks features such as scale and texture, denies movement, and introduces additional confounds associated with presenting images in a loud machine. Experimental stimuli are also typically selected and/or modified to control for potentially confounding variables like lighting and pixilation. While this controlled approach makes it easier to identify the source of an observed effect (e.g., differences in beauty judgements are not related to the "crispness" of an image), generalizability is difficult. These problems are further complicated since buildings are three-dimensional, immersive, interactive, and multisensory. The wide range of contextual (e.g., outside noise, surrounding environment) and functional (e.g., hospital, museum, school) factors cannot be adequately conveyed by images. Advances in virtual reality have the potential to mitigate some of these problems, but are still unlikely to fully capture the multidimensional and multimodal experience of architecture.

Another challenge concerns temporal dynamics of aesthetic experiences. Repeated viewings of the same stimulus can be associated with more positive appraisals (Bornstein and D'agostino 1992), thus spending more time in a building is likely to be associated with fluctuations in aesthetic judgements. Most research studies present participants with an image for only a few seconds, even though it is fairly well established that aesthetic experiences vary over longer durations (Chatterjee and Vartanian 2014; Coburn et al. 2017). This raises issues both methodological (e.g., how long should participants view an image?) and theoretical (when can aesthetic experience be most accurately measured? Do we need to obtain multiple aesthetic judgements at different timepoints?).

Perhaps the best way to address the above issues is to move experiments out of the laboratory and into the "wild". Rather than present people with images, data can be collected at actual buildings or structures. This approach has been successfully used to measure feelings of nostalgia at heritage sites (Prayag and Del Chiappa 2021). Experience sampling methods could be paired with this approach to obtain aesthetic judgements on different spatial and temporal scales. For instance, participants could respond to a series of prompts on their cell phones at specific times or locations. Further, thanks to recent advances in mobile EEG and fNIRS, researchers can potentially pair behavioural ratings with neural data across a wide range of settings. Mobile imaging techniques are beginning to provided novel insights about neural processing in art museums (Kontson et al. 2015) and collaboration in the classroom (Dikker et al. 2017) and are now being applied to architecture (Djebbara et al. 2021). While these data will be inherently "messy", results gained in the field may be more ecologically relevant than those collected in the laboratory.

The neuroscience of architecture is a very young field in the midst of a decade of significant progress. The field represents an important arm of evidence-based architectural research that focuses on understanding psychological dimensions of human experiences in response to architectural design. Many subtle aspects of architectural and aesthetic experience are addressable with modern research tools that enable researchers to observe more closely mechanisms of the mind and brain that mediate human-architectural interactions. We are ready to move beyond descriptive approaches to test specific hypotheses about how people perceive and respond to their built environment.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any primary studies with human participants or animals performed by any of the authors. The data and procedures referred to in previous studies conducted by the authors in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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