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Visual Perception of the Built Environment in Virtual Reality: A Systematic Characterization of Human Aesthetic Experience in Spaces With Curved Boundaries

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Visual perception of architectural spaces and human aesthetic experience in these spaces have recently received considerable interest in cognitive science. However, it has been difficult to construe a common understanding of aesthetic experience for architectural space, since different studies use different scales to measure aesthetic experiences. In this interdisciplinary study spanning cognitive science and architecture, we aim to provide an empirically driven systematic characterization of human aesthetic experience and investigate what aspects of the architectural spaces affect aesthetic experience. To this end, we manipulated various architectural variables including the shape of the curvilinear boundaries of architectural spaces as well as their size, light, texture, and color in virtual reality. We then had people evaluate these spaces by exhausting a large list of commonly used scales in the literature and applied principal component analysis to reveal the key dimensions of aesthetic experience. Our findings suggest that human aesthetic experience can be reduced to 3 key dimensions, namely familiarity, excitement, and fascination. Each of these dimensions are differentially affected by the various architectural variables revealing their differences. In sum, our study provides a comprehensive framework to characterize human aesthetic experience in virtual architectural spaces with curved boundaries.

Keywords: aesthetic experience, spatial cognition, emotion, environmental psychology, virtual reality

People spend approximately 90% of their time in buildings with enclosure and they interact intimately with these spaces (Evans & McCoy, 1998; Klepeis et al., 2001; Vartanian et al., 2013). Despite their prominence in our lives, most research in cognitive science to date has focused on how we perceive and interact with the objects and people in these buildings (Caspers et al., 2010; DiCarlo et al., 2012) rather than the built environment itself. There is a growing body of research between cognitive science and architecture, specifically focusing on the aesthetic experience of people in built environments (Chatterjee & Vartanian, 2014, 2016). Aesthetic experience can be defined as a set of cognitive and emotional processes that are elicited by the qualities of a designed space and result in action-driven behavior (Locher et al., 2010; Schubert et al., 2016). In what follows, we review a number of theoretical and empirical studies that attempt to characterize human aesthetic experience in architectural spaces. Then, we describe some of the important properties of architectural spaces and how they affect aesthetic experience. Finally, we explain the limitations of previous work and provide a comprehensive framework to characterize the aesthetic experience in the built environment focusing some of its most important properties.

Aesthetic Experience in Architectural Spaces

In the early stages of the 20th century, many studies indicated that aesthetic experience of architecture have great impact on people's cognitive assessment, emotional well-being, and behavioral approach (Adams, 2014; Cooper et al., 2014; Gifford, 2002; Hartig, 2008; Joye, 2007). Accordingly, there have been several theoretical models that attempt to explain aesthetic experience in the architectural spaces. In their psychological model, Leder et al. (2004) characterize aesthetic experience in five stages including 1) perception, 2) explicit classification, 3) implicit classification, 4) cognitive mastering/interpretation, and 5) evaluation. In this model, they specifically highlight the interdependence of aesthetic experience and emotions, in which the latter serve as the source of the aesthetic experience and the former is the output of affective-emotional states.

Following Hekkert (2006), Leder et al. (2004) suggests that affective evaluation consists of two processes: an automatic

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process, which corresponds to stages 1, 2, and 3 in Leder et al. (2004)'s model, and where one detects whether a perceived object is novel or familiar, and a cognitive-emotional process, which corresponds to stages 3, 4, and 5 of Leder et al. (2004)'s model, and where cognitive and emotional processes dominate the experience. Aesthetic experiences are considered to be the result of these two processes.

Grounded on these previous studies, Chatterjee and Vartanian (2014) propose an aesthetic triad model of architectural experience and aim to provide a broader framework in the field. According to this model, aesthetic experience in the built environment consists of three main elements, each having a corresponding neural system. These elements are considered to relate to the stages 3, 4 and 5 of Leder et al. (2004) psychological model of aesthetic experience. Chatterjee and Vartanian (2014) named these elements as knowledge-meaning, emotion-valuation, and sensory-motor, respectively. In this model, the knowledge-meaning element is informed by personal experiences, culture, and education, as well as with exposure to the built environment. The emotion-valuation element is considered to mediate the feelings and emotions engendered by buildings and urban spaces (Leder et al., 2004). The sensory-motor element is considered to recruit the visual, auditory, somatosensory, olfactory, and vestibular systems, and trigger motor responses (approach-avoidance; Chatterjee & Vartanian, 2014, 2016; Coburn et al., 2017).

Coburn et al. (2020) extends the Chatterjee and Vartanian (2014)'s aesthetic triad model and adapts three important domains of information processing associated with the three elements in this model: cognition associated with knowledge-meaning element, emotion associated with the emotion-valuation element, and behavior that is linked to the sensorimotor system. Below we review some empirical studies that measure aesthetic experience using a variety of scales and target each of these information processing elements.

Cognition

The first element of the aesthetic experience is cognitive judgments, and they are considered to correspond to the initial evaluation of the external qualities of the architectural spaces. In other words, one answers the question "How does the architectural space look?" in addressing the cognitive element of the aesthetic experience. Devlin and Nasar (1989) state that cognitive architectural assessments can be grouped into affective and interpretive assessments. To characterize these assessments, they asked people to rate the architectural spaces using the variables such as complexity, mystery, femininity, and safety.

Lang (1992) who focuses on the cognitive element of the aesthetic experience groups the assessment variables as affective, formal, and symbolic variables. Affective variables measure how pleasant the built environment looks or how arousing the architectural properties are. The formal variables on the other hand measure the complexities (e.g., how complex does the environment look?), rhythms, shapes, and sequences of visual words in the built environment. Finally, the symbolic variables measure the associational meanings of the environment such as how safe or mysterious the built environment looks.

Following Lang (1992), Russell (1992) groups the affective variables under two main headings as arousal and pleasantness. A number of empirical studies characterized these dimensions by asking people to rate how exciting or relaxing they thought the environment looked (Cetintahra & Cubukcu, 2014; Hanyu, 2000; Nasar, 1983, 1992a, 1992b, 1992c, 1992d; Nasar et al., 1992; Russell, 1992). Similarly, following Lang (1992), Nasar (1998) proposes two main semantic scales, namely complexity and coherence to characterize the formal variables. Many studies have investigated the influence of complexity and coherence on environmental aesthetic experience (Cetintahra & Cubukcu, 2014; Hanyu, 2000; Kaplan, 1992; Nasar, 1992d, 1992b), and found that these two semantic scales vary considerably according to space shapes, sizes, and characteristics. In addition, in many studies' safety was considered to be a symbolic variable (Cetintahra & Cubukcu, 2014; Hanyu, 2000; Kaplan & Kaplan, 1989; Nasar, 1992b; Nasar et al., 1992).

Emotion

The second element of the aesthetic experience is defined as the feelings and emotions that the physical properties of an environment could evoke in an individual. In other words, one answers the question "How does the architectural space make me feel?" in addressing the emotional element of the aesthetic experience. Mehrabian and Russell (1974) define emotion in terms of pleasure and arousal. So, the question in understanding aesthetic experience is how pleased or aroused one feels in a given environment. According to Mehrabian and Russell (1974), pleasure is demonstrated through facial gestures (such as smiling and frowning). Arousal is indicated by human activities and alertness (such as skin responses; Mehrabian & O'Reilly, 1980).

Behavior

The final element of the aesthetic experience is behavior, which is measured by scales that aim to characterize the approach-avoidance patterns and behavioral intentions. These behavioral patterns are sometimes defined as dominance (Mehrabian & O'Reilly, 1980). For instance, Russell and Mehrabian (1977) reported that the emotion-eliciting quality of an environment affects people's approach toward that environment. Similarly, Russell (1992) shows that people's behavioral responses to the environment changes as a function of the affective quality of the environment.

The Properties of Architectural Space

Space properties like size, light, texture, and color unite to make a composition form in an interior space. These properties are different than other properties such as furniture, openness, and type of wall mural in terms of space unity (Bokharaei & Nasar, 2016). Such kinds of properties can easily change in the living environment when compared to size, light, texture, and color. Various properties that affect people's attitudes and feelings toward a space are critical issues that have an impact on people's quality of life and these properties cannot easily change in the living environment. Quality of life is a concept related to cognitive and affective assessments that are based on the compatibility of one's expectations with the properties of physical space (Nasar, 1992a). Therefore, an interior architect designs spaces while concentrating on such properties of that space.

The aesthetic experience of people in the built environment depends on various properties of the architectural spaces. Some of these important properties include the shape of the space boundaries, size, light, texture, and color.

The Shape of the Space Boundaries: Curvilinear Forms in the Built Environment

One of the important properties of space perception is the shape of the space boundary. It has been consistently shown that people prefer architectural spaces with curved boundaries as opposed to other types of boundaries (Van Oel & van den Berkhof, 2013). Curved boundaries, or more generally curvilinear forms, are usually characterized by having smooth transition between the contours (e.g., walls), as opposed to sudden changes in an interior space (Elver, 2018).

A growing body of work have investigated people's aesthetic experience for curvilinear forms in the built environment using a variety of scales. Hobbs et al. (2015) examined the preference of people among four different interior spaces with curved, rectilinear, angled and mixed geometries, in Virtual Reality (VR). They report that people show higher preference for curved boundaries and rated the spaces with this type of boundaries as being pleasant, relaxing and friendly (Hobbs et al., 2015). Some other studies also showed that people find spaces with curved shapes more pleasant and safer compared to the straight ones (Bar & Neta, 2006; Papanek, 1995; Silvia & Barona, 2009). Pearson (2001) proposed that curves are more coherent to the human mind and are associated with the body. Salingaros (1998) suggested that buildings that have natural and biological forms appear to be psychologically more appropriate and perceived differently than other standard forms. Papanek (1995) reported that curved forms of internal spaces evoke emotions of joy, harmony, and well-being. Furthermore, Madani Nejad (2007) demonstrated that curvilinear forms tend to make the observers feel safer and perceive the space to be more private and pleasant, and less stressful. Also, Dazkir and Read (2012) showed that curvilinear forms elicited significantly stronger emotions (measured with the "pleasurable" scale) than rectilinear forms, and were associated with the feelings of relaxation, peacefulness, and calmness.

There are also studies that investigate individual differences in aesthetic experience for curved boundaries. Vartanian et al. (2019) found that when assessing beauty, experts (self-identified architects and designers) found rectilinear spaces less beautiful than curvilinear spaces, whereas the shape of the contour (boundary) had no effect on beauty judgments among nonexperts. In contrast, when making approach-avoidance decisions, nonexperts were more likely to opt to enter curvilinear than rectilinear spaces, whereas the shape of the contour had no effect on approach-avoidance decisions among experts. In another study, Shemesh et al. (2016) investigated the reactions of design and nondesign students to spaces with different geometries, such as square, round (domed), sharp-edged, and curved spaces in VR. They found that nondesign students show a tendency to prefer curvy-shaped spaces whereas design students prefer sharp-angled spaces. These results suggest that shape of the boundary is an important and potentially adaptive feature in architecture and design but stress the impact of expertise on its aesthetic and motivational relevance.

Moreover, Banaei et al. (2017) presented a methodology for categorizing interior architectural forms. They proposed 25 formal clusters for 343 images of living rooms that have different architectural styles and design features. Their study is a pioneer in architectural research domain that uses form as a measurable variable for categorization of interior spaces. Furthermore, Banaei et al. (2017) investigated the effect of different interior forms on perception and brain activity. The results indicated that curved geometries that affect human perception and brain activity are strongly associated with high pleasure and arousal ratings. Moreover, Banaei et al. (2020) investigated the impact of various interior forms on emotions. Pleasure, arousal, and dominance ratings were used together with personality traits to measure individual differences. They reported that the relationship between interior architectural forms and emotional states vary depending on the personality traits.

There are several explanations to people's preference for curved boundaries. One such account proposes that curves are natural forms that we are constantly exposed to in our natural environment, so they attract people's attention more than the linear ones, which are repeatedly used in the built environment (Vartanian et al., 2013). Another account suggests that the preference of the curvature originates from a negative response to angular objects (Bar & Neta, 2006). Neuropsychological investigations also give support for this account. It has been shown that angularity triggers a sense of threat and feelings of insecurity as opposed to curvature (Bar & Neta, 2007). Recent investigations also showed that the human preference for curved contours is biologically determined and is a cultural phenomenon (Gómez-Puerto et al., 2016). Furthermore, there are also studies that investigated different levels of curvature in the context of aesthetic appraisal of products (Blijlevens et al., 2013; Blijlevens et al., 2012; Ho et al., 2016; Leder & Carbon, 2005). All these studies reported that expressed levels of preference and product curvature have a quadratic relationship, increasing up to the moderate curvature level, then decreasing as level of curvature increases more. Therefore, it is concluded that moderate level of curvature is highly correlated with the highest preference level of subjects.

In sum, it has been consistently shown that people prefer architectural spaces with curved boundaries. However, different studies used different scales to measure aesthetic experience for these spaces. Thus, a comprehensive understanding of aesthetic experience is still lacking (Corradi & Munar, 2020). The primary motivation of the present study is to systematically characterize human aesthetic experience for curved boundaries that spans all these scale measures and finds the key dimensions that underlie these aesthetic experiences.

Size, Light, Texture, and Color

In addition to the shape of the space boundaries, properties like size, light, texture, and color contribute to the composition of an architectural space. Studies that focus on the perception of size of the architectural spaces show that the physical size of a space affects aesthetic experience. More specifically, people find spaces with rectangular forms larger and more spacious than the ones with square forms although both spaces are equal in size (Bokharaei & Nasar, 2016; Franz, 2006; Franz et al., 2005, Franz & Wiener, 2005; Gärling, 1970a, 1970b; Stamps, 2007, 2009, 2010). In

other words, aesthetic experiences are found to change as a function of the horizontal distance (length) of an architectural space. Another space property that affects aesthetic experience is light (Bokharaei & Nasar, 2016; Knez, 2001; Küller et al., 2006; McCloughan et al., 1999; Odabaşioğlu & Olguntürk, 2015). Many studies suggest that the light level of an architectural space affects a variety of aesthetic experience for that space (Durak et al., 2007; Kuller, 1986; Odabaşioğlu & Olguntürk, 2015; Stamps, 2007). As an interior space property, texture creates a degree of reflection or absorption on the surface of a space that results in differences in how people perceive and evaluate architectural spaces (Bokharaei & Nasar, 2016). Horizontal patterns on the boundary surface are related to depth whereas vertical patterns are associated with height (Bokharaei & Nasar, 2016). Ishikawa et al. (1998) show that when the depth of a space increases with horizontal texture, people find the space larger and more aesthetic. On the other hand, Stamps (2011) shows that people find spaces narrower if they have an increased height and vertical pattern. The color of a space is another property that affects aesthetic experience. Several studies show that cool or warm colors affect human perception differently (Bokharaei & Nasar, 2016). Yildirim et al. (2007) showed that interior spaces with cool colors, such as blue or green, were perceived larger than spaces with warm colors, such as red or orange. Some other studies show that while the use of cool color schema and desaturated colors results in high aesthetic experience, using warm and saturated color schema decreases the ratings in aesthetic experience (Franz, 2006; Odabaşioğlu & Olguntürk, 2015).

Although the effect of architectural properties such as size, light, texture, and color on people's aesthetic experience have been investigated extensively, how these properties interact with the shape of the space boundaries (e.g., curvilinear forms) and how they shape human aesthetic experience remain unknown. One of the aims of the present study is to study these interactions and provide a better understanding of the dimensions that modulate the aesthetic experience in virtual reality.

Virtual Reality (VR) as an Architectural Design Support Tool

The adoption of information technologies is considered to be an effective strategy to optimize, integrate, and support construction processes in architecture (Eastman et al., 2008; Paes, 2019). Among the many technologies, VR is a well-established research support tool in many architectural domains that focus on spatial cognition, perception, and behavior (Brade et al., 2017; De Kort et al., 2003; Higuera-Trujillo et al., 2017; Kuliga et al., 2015; Paes et al., 2017, 2021; Taşli & Özgüç, 2001) and have many advantages compared to real environments.

First, VR allows systematic environmental manipulations that cannot be effectively implemented in real environments. For instance, Kuliga et al. (2015) reported that while it would be challenging to substantially alter the spatial configuration of a real building, with the use of VR it could be possible to test the effect of several designs on user behavior without interrupting the ongoing building usage. Importantly, VR allows researchers to focus on the effects of some architectural variables while controlling the others. For instance, many VR studies use simplified models of an architectural space, for example, empty spaces or spaces with limited architectural details. This way one can control many aspects of interior spaces such as the furniture lay out, form and color of the furniture, the view of the window openings, sunlight coming from the outside or wall mural compositions, and investigate the effect of architectural variables under investigation. For instance, Franz et al. (2005) used 16 empty rectangular rooms by manipulating the window types and doors, and investigated their effects on affective ratings using 360-degree panoramic images on a spherical wide-angle projection system. Following up that work, Franz (2006) analyzed the effects of architectural elements, dimensions, and color on affective responses in these 16 empty spaces. In addition, Stamps and Krishnan (2006) investigated the relationship between spaciousness and boundary roughness of architectural spaces in VEs by starting with empty rectangular rooms, then systematically added a human figure, a carpet, and wall textures or bookshelves. They concluded that boundary roughness makes interior spaces to be perceived more spacious. Furthermore, Stamps (2011) investigated the effects of area, height, elongation, and color on perceived spaciousness by using various empty rooms (no details) with a range of different plan proportions (1:1, 1:2, and 1:9). In this study, Stamps (2011) only varied the architectural cues of the interior spaces that had no furniture. von Castell et al. (2014) investigated the effect of the furnishing on perceived spatial dimensions and spaciousness level of the interior environment by conducting two experiments. The first experiment used 1:10 scale model rooms to analyze the effect of perceived height and the spaciousness. They found that the furnished rooms were perceived higher but less spacious. In the second experiment, rooms with different surface areas and constant physical height were investigated. They reported that furnishing affected neither the perceived spatial dimensions nor the perceived spaciousness of interior environments. Bokharaei and Nasar (2016) investigated the perceived preference levels and spaciousness separately in a limited virtual office space by manipulating size, light, texture, wall mural, window size, and furniture. They concluded that perceived preference level and spaciousness depend upon the size, lightness, and window size of a preceding perceived space. Shemesh et al. (2016) investigated human reactions to spaces with different geometric forms that were designed to be colorless, soundless, with no objects (except for the one basic chair that is standing in the middle of each room as a reference to human scale) in an immersive VE. Carreiro et al. (2017) measured aesthetic experience for architectural spaces with various degrees of geometric contour using empty spaces in VR. They found that moderate curvature was more accurate rather than radical curvature rates. Simpson et al. (2018) examined the effect of wallpaper pattern on spaciousness judgments and action-based measures by using an empty VR environment. von Castell et al. (2020) investigated the stripe wall patterns and reported that the orientation (horizontal vs. vertical) and density (number of stripes per degree of visual angle) of the stripes affected perception. Similarly, Wang et al. (2020) analyzed the effect of wall texture on perception and spaciousness judgements in a virtual empty room. In sum, in all these studies reported above, VR allowed researchers to manipulate intended architectural variables while controlling the effect of others.

Another advantage of VR is that it enables researchers to dynamically simulate the whole life cycle of buildings to evaluate the performance of prospective designs (Taşli & Özgüç, 2001). This is an important benefit since buildings are living entities in some sense. Importantly, VR technologies enable users to immerse virtually in architectural spaces. VR simulations have especially become a popular technology for design review due to the

perceived benefits associated with the representation of scale, depth, and volume (Paes et al., 2021). Defining the boundaries of an architectural immersive environment imitates that of a visual living space. Therefore, it enables one to walk through the space as if one is in the existing location. Implementation of the boundaries of that space helps to create the viewer's sense of being within the environment, thus, enriching the experience.

One question that has been raised with the increasing use of VR is that whether people's responses in virtual environments (VE) would be comparable to that of in real environments (RE). Many studies investigated this question by comparing human behavior in VE and RE. De Kort et al. (2003) suggested that virtual environments (VE) have great potential to become significant new research tools in understanding human behavior in the built environment and may even replace real environments and become the future laboratory for design research. In their study, 101 participants explored an identical space, either in RE and VE. The factor analyses of bipolar adjectives showed that the key dimensions were similar in both environments suggesting that the experiences and behaviors in VEs are similar to that of in REs. In addition, Kuliga et al. (2015) compared the experience of building users in RE and VE. They found that the behavior in both environments was largely comparable. Importantly, they suggested that VR is even superior since it enables detailed observations, accurate behavior measurements, and systematic environmental manipulations under controlled laboratory circumstances. Furthermore, Brade et al. (2017) compared RE and VE with regards to presence and usability, and expanded the research on user experience. They compared CAVE-Cave Automatic and city center of Chemnitz, Germany in a between-subjects design in terms of presence and evaluated its impact on the usability and the user experience. In terms of user experience, the VE showed significantly higher hedonic quality values, whereas the RE had higher pragmatic quality values. In both VE and RE, the presence and the user experience factors were partly correlated. Their results indicated that a VE can be an alternative to REs for user experience studies when a high presence is achieved. Also, Paes et al. (2017) compared users' spatial perception using a conventional workstation (screen) versus an immersive (VE) platform. Their results showed better spatial perception in the immersive VE and suggests that VE could be beneficial in current design practices by improving professionals' understanding of spatial arrangements. Another notable study is by Higuera-Trujillo et al. (2017) who investigated the psychological and physiological responses evoked by three environments that consisted of real photographs, 360-degree panoramas, and VR, as well as the users' sense of presence in these environments. They found that 360-degree panoramas enable the closest results to reality based on the participants' psychological responses, and to VR based on the physiological responses. As a result, they concluded that researchers could use 360-degree VR environments to replicate the experiences in physical environments.

In sum, VR is an effective and commonly used tool in architectural research. In the present study, we employed VR to be able to systematically manipulate the architectural variables we are interested while controlling the others and investigate their effects on human aesthetic experience.

Aim of the Present Study

As outlined above, most of the studies that aim to understand human aesthetic experience in the built environment employ individual ratings or scales by manipulating various properties of the architectural space (Osgood et al., 1957). While these studies have been informative about what people experience in these spaces, they fell short in providing a more general characterization of the aesthetic experience as they used only a limited number of scales to rate the architectural stimuli and thus focused on only a few aspects of the aesthetic experience. On the other hand, theoretical work suggests that aesthetic experience is complex and has many dimensions including the cognitive, emotional, and behavioral elements. What is lacking in the literature is an empirically driven characterization of the multidimensional nature of the aesthetic experience for the built environment. The primary aim of the current study is to provide such a framework considering many properties of the built environment in VR. A second aim of the present study is to reveal how various properties of the built environment interact and shape human aesthetic experience.

To this end, we designed architectural spaces with curvilinear boundaries and manipulated their sizes, lights, textures, and colors in VR in an independent manner to investigate the interaction of each of these architectural properties with curvilinear boundaries. We then had people rate these spaces by including all the scales commonly used in measuring aesthetic experience for the built environment in the literature. Finally, we applied principal component analysis (PCA) on the data to reveal the key dimensions of the aesthetic experience and characterized how various properties of the architectural spaces affect each of these dimensions. This way, we provided a systematic, data-driven, and broad characterization of aesthetic experience for architectural spaces with curvilinear boundaries in a VR environment.

Method

Participants

A total of 128 graduate and undergraduate students, 54 males and 74 females participated in the study from the social science and design departments of I.D. Bilkent University. 32 participants attended the size session, 32 participated in the light session, 32 participated in the texture session, and 32 participated in the color session. All participants signed the consent form and the Ethics Committee of I.D. Bilkent University approved this study. Ishihara electronic color blindness test was used (Color-blindness.com, 2019) to check whether the participants had an intact color perception before the experiment.

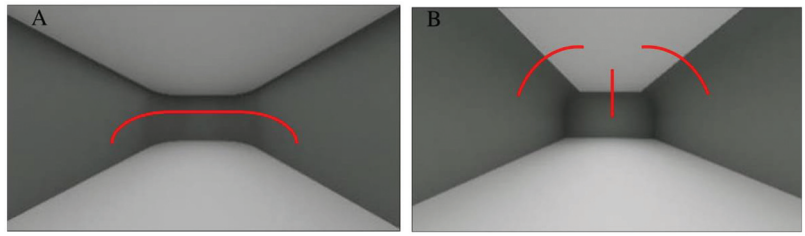
Stimuli

The experimental stimuli used in the VR has two important features: Boundary types and Space properties.

Boundary Types

Two types of curved boundary types are used: curved Horizontal Boundary (HB) and curved Vertical Boundary (VB). HB space is bounded by four walls and the boundaries of each wall are connected with horizontal concave connections (Figure 1A). There is no 90-degree edge in horizontal plane of the space as there are in standard room connections. VB space is bounded by four walls and the boundaries of each wall are connected to ceiling as

Figure 1
Two Different Boundary Types Are Used to Create the Stimuli in VR: (A) Horizontal Boundary; (B) Vertical Boundary



Note. See the online article for the color version of this figure.

vertically concave links (Figure 1B). There is no 90-degree connection of vertical walls and ceiling as standard space connections.

Space Properties

Each boundary type involved four space properties (size, light, texture, and color) of the surrounding surfaces that are composed of two levels of intensity; high and low. For size, the levels were small (S) and large (L); for light, the levels were dim (D) and bright (B); for texture, the levels were longitudinal (LT) and lateral (LR), and for color, the levels were cool (C) and warm (W) as shown in Figure 2.

Instruments and Procedure

We conducted four sessions in VR, each having 32 participants. In each session, participants viewed and rated four environments that varied in terms of boundary type (Horizontal or Vertical) and only one space property (size or light or texture or color) that has 2 levels (e.g., Size; HB-S, HB-L, VB-S, and VB-L) in a randomized order.

The aesthetic experience level of four 360-degree spaces was determined by using a Gear VR, Head Mounted Display (HMD), equipment (Samsung SM-R325 Gear VR). Visual stimuli were shown with the same layouts. There were no materials and openings in the created space in order not to affect the perception of space property with boundary type (Samsung, 2017).

VR technologies enable users to immerse virtually in architectural spaces. Defining the boundaries of an architectural immersive environment imitates that of a visual living space. Therefore, it enables one to walk through the space as if one were in the existing location. Implementation of the boundaries of that space helps to create the viewer's sense of being within the environment, enriching the experience. VE boundaries should be carefully designed to achieve the most realistic understanding regarding the spatial world.

All spaces were designed to have the same medium size (4.5 m in width, 9 m in length and 3 m in height), the lighting was nondirectional and created equal illumination in all parts of the space. The spaces have the same floor area (40.5 m^2). Only in the size condition, spaces have a floor area 25 m^2 for the small versions and 50 m^2 for the large versions. Moreover, based on the study of Hopkins et al. (1976), the moderate curve (4 ½ in.) was chosen as the curvature of the horizontal and vertical boundaries. Carreiro et al. (2017) also reported that moderate level of curvature preference is more accurate rather than radical curvature rates. Also, the movements of the participants were based on egocentric frame of reference (i.e., one's body) during simulations in VEs (Sancaktar & Demirkan, 2008). However, following the previous work (Bokharaei & Nasar, 2016; Carreiro et al., 2017; Franz, 2006; Franz et al., 2005; Franz & Wiener, 2005; Shemesh et al., 2016; Simpson et al., 2018; Stamps, 2011; Stamps & Krishnan, 2006; von Castell et al., 2014, 2020; Wang et al., 2020), these spaces were designed to be soundless without objects. Each visualization involves a door opening with the same color and texture of the space (without using any new material).

This procedure was repeated for all curved boundaries (HB and VB) for (1) size (S-L), (2) light (D-B), (3) texture (LT-LR) and (4) color (C-W) independently in four sessions. The created 3D 360-degree simulations were experienced using Gear VR by the participants.

Physical properties of the environment could affect aesthetic experience that is generated as a response to the environment. Many studies assess people and environment relationships in terms of aesthetic experience. Rafaeli and Vilnai-Yavetz (2004) emphasized that there is a strong relationship between aesthetic experience and the physical properties of the environment. They investigated how a person's description of an interior environment depend on its functionality, its aesthetic qualities, and how people attach meaning to this environment. Table 1 shows the aesthetic experience measures used in previous work together with their domains and sources.

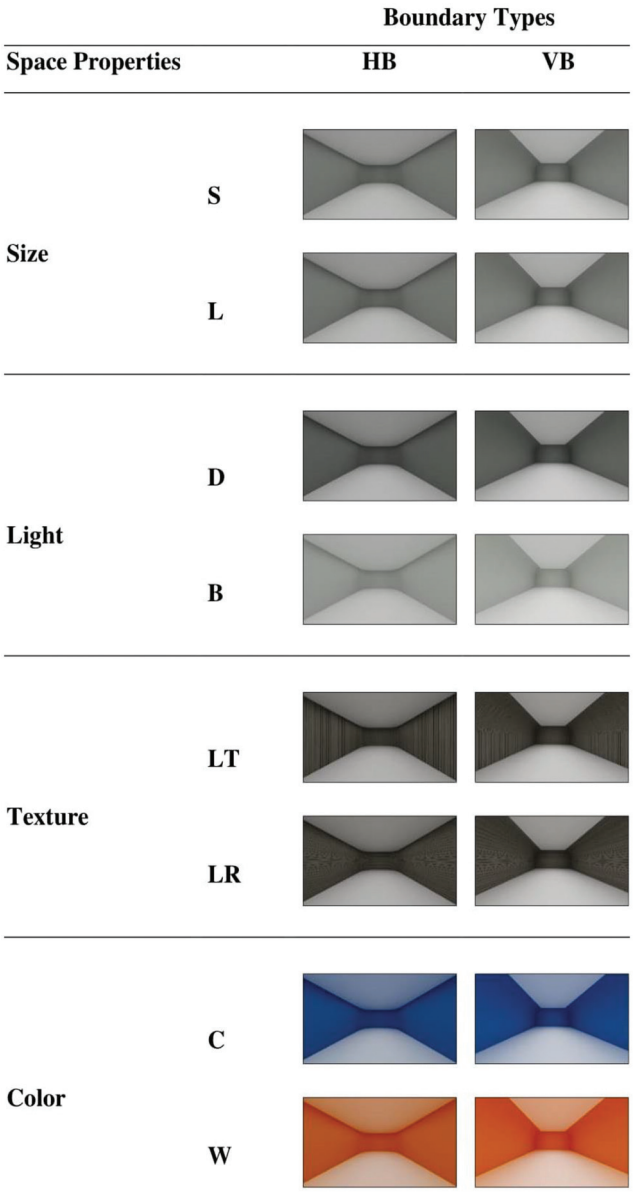
Following the triad model that is originally developed by Chatterjee and Vartanian (2014) and extended by Coburn et al. (2020), we predicted that these aesthetic experiences would be organized under cognition, emotion, and behavior domains as in Table 2.

Participants rated each interior space using 21 different bipolar adjectives on a 5-point Likert scale (−2 = describes strongly, 0 = neutral, 2 = describes strongly) in the cognition and emotion domains and using 4 items on a 5-point Likert scale (anchored by never/a few hours and not at all/very much) in the behavior domain. All participants were equally informed about the meaning of the aesthetic experiences. Each participant experienced each setting for 10 seconds.

Data Analysis

We first computed the correlation matrix of the 25 aesthetic experience based on the ratings of the 128 participants. We then applied principal component analysis (PCA) on the ratings to find out whether the measures used for aesthetic experience can be grouped into some key dimensions (principal component). Next,

Figure 2
Space Properties With the Curved Boundary Visualizations



Note. See the online article for the color version of this figure.

we ran a 2 (Boundary type) × 2 (Space property) repeated measures ANOVA on the factor loadings of each principal component for each of the four experiments.

Results

The internal validity of 25 items was tested and Cronbach's alpha indicated good reliability ($\alpha = .933$). The correlation matrix was computed across the 25 aesthetic experience using the stats, corrplot, and psych packages in R (RStudio, 2020; see Figure 3). The correlation matrix demonstrated the strength of the correlations between the different aesthetic experience.

The principal components analysis (PCA) was carried out to find out the principal components underlying the 25 aesthetic experience. One of the aesthetic experiences, feminine was eliminated from the analysis as a preliminary factor analysis showed that it was grouped as a single adjective. Accordingly, PCA was conducted with 24 variables as seen in Table 3.

The Kaiser-Meyer-Olkin measure of sampling adequacy (KMO = .942) and Bartlett's test of sphericity identity matrix ($\chi^2 = 7534.89$, $df = 300$, $p < .001$) provided evidence of statistical relationship between the scales, and indicated that the dataset was suitable for PCA. PCA results suggest that the first principal component (PC1) consists of 16 aesthetic experiences that we name as the familiarity dimension, the second principal component (PC2) consists of five aesthetic experiences that exemplify what we call the excitement dimension, and the third principal component (PC3) includes three aesthetic experiences that correspond to what we call the fascination dimension. The familiarity dimension explains 33% of the total variance, the excitement dimension explains 14% and the fascination dimension explains 8%. These three dimensions explained a total of 55% of the total variance.

Note that the naming of the principal components is not an easy task as it was also acknowledged before (Coburn et al., 2020). In naming the three principal components, we aimed to find a common term that could identify one's experience in an architectural space that is consistent with each of the single items clustered under a given component as well as a group. Accordingly, the PC1 is named familiarity as all the items under it can refer to one's aesthetic experience in familiar spaces. For instance, people may likely want to spend time in a familiar space, and find it relaxing, safe, and coherent, and may have positive experiences such as being happy or pleased. The PC2 is named excitement as it covers items that refer to positive high feelings about a given space such as being excited or frenzied. The PC3 is named as fascination since one can be fascinated by a space that is mysterious, complex, and stimulating (all the items clustered under PC3).

After identifying the 3 principal components, we ran a 2 × 2 ANOVA on the factor loadings of each of the principal components for each experiment (see Figure 4). The results of the ANOVAs are reported in Table 4.

Size

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Size: Large, Small) ANOVA on PC1 (familiarity) showed a main effect boundary type and size. Horizontal boundaries were found to be more familiar than vertical boundaries ($p = .037$, $\eta_p^2 = .13$). Similarly, interior spaces that are larger in size were found to be more familiar than the ones that have smaller in size ($p < .001$, $\eta_p^2 = .49$). There was no interaction of boundary type and size.

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Size: Large, Small) ANOVA on PC2 (excitement) showed a main effect boundary type and size as well as interaction of boundary type and size. Overall, horizontal boundaries were found to bring more excitement than vertical boundaries ($p = .044$, $\eta_p^2 = .12$). Similarly, interior spaces that are larger in size were found to bring more excitement than the ones that have smaller in size ($p = .018$, $\eta_p^2 = .17$). However, the excitement difference between horizontal and vertical boundaries were significant for large spaces but not for small spaces ($p = .003$, $\eta_p^2 = .25$).

Table 1
The Aesthetic Experience in Each Domain and the Related Literature Sources

Source	Domain	Aesthetic experience
Devlin and Nasar (1989)	Affective	Sleepy-Arousal, Unpleasant-Pleasant, Gloomy-Exciting, Distressing-Relaxing
Lang (1992)	Formal	Simple-Complex, Incoherent-Coherent
Russell (1992)	Symbolic (Interpretive)	Unsafe-Safe, Nonmysterious-Mysterious, Masculine-Feminine
Mehrabian and Russel (1974) Russell and Mehrabian (1977)	Pleasure	Annoyed-Pleased, Unhappy-Happy, Bored-Relaxed, Unsatisfied-Satisfied, Melancholic-Contended, Despairing-Hopeful
	Arousal	Unaroused-Aroused, Calm-Excited, Sluggish-Frenzied, Dull-Jittery, Sleepy-Wide awake, Relaxed-Stimulated
	Dominance	Prefer to live, Like to spend time, Enjoy exploring, Feel friendly and talkative

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Size: Large, Small) ANOVA on PC3 (fascination) showed no main effects of interaction (see Table 4 for statistics).

Light

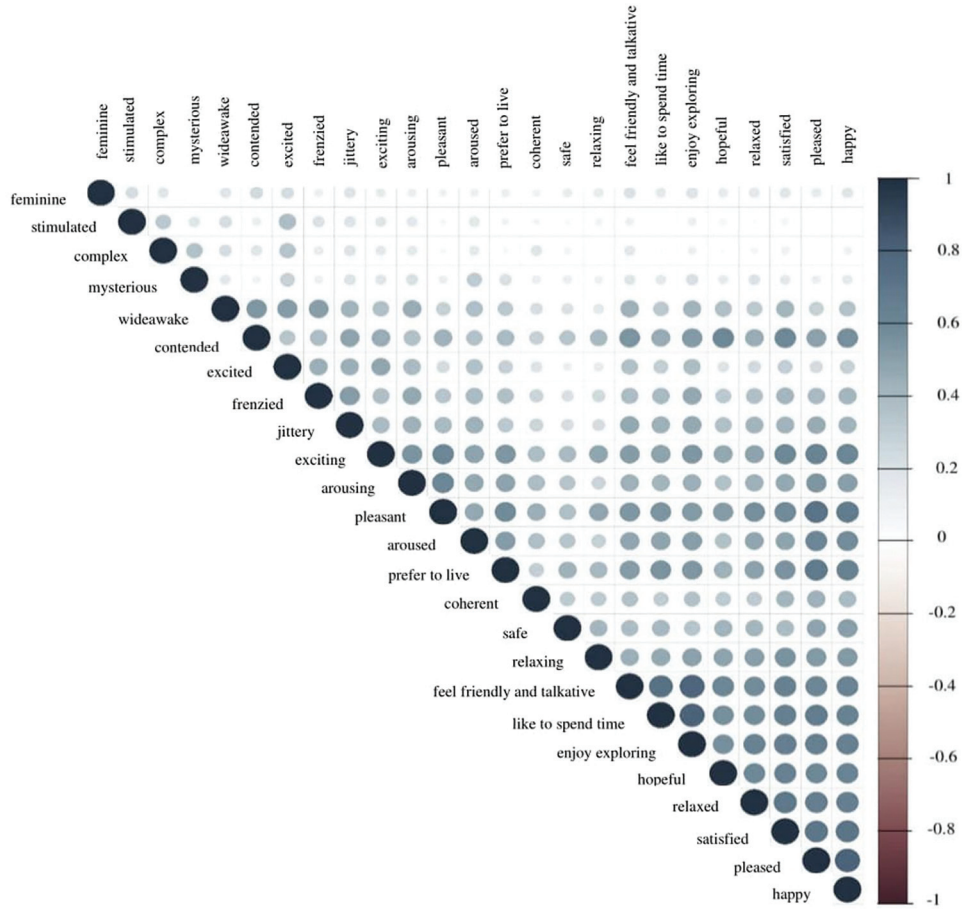
The 2 (Boundary Type: Horizontal, Vertical) × 2 (Light: Dim, Bright) ANOVA on PC1 (familiarity) showed a main effect boundary type and light. Horizontal boundaries were found to be more familiar than vertical boundaries ($p < .001$, $\eta_p^2 = .29$). Similarly, interior spaces that are brighter were found to be more familiar than the ones that have dimmer lighting ($p = .004$, $\eta_p^2 = .24$). There was no interaction of boundary type and light.

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Light: Dim, Bright) ANOVA on PC2 (excitement) showed a main effect of light as well as an interaction of boundary type and light. Interior spaces that are brighter were found to bring more excitement than the ones that have dimmer lighting ($p < .001$, $\eta_p^2 = .50$). In addition, excitement difference between horizontal and vertical boundaries were significant for bright spaces but not for dim spaces ($p = .047$, $\eta_p^2 = .12$).

Table 2
The Adopted Aesthetic Experience Components in the Study Based on the Cognition, Emotion, and Behavior Elements of the Triad Model

	Aesthetic experience		
Domain	Aesthetic scale	Low	High
Cognition (thought; space looks; how . . . is it)			
Affective	Arousing	sleepy	arousing
	Pleasant	unpleasant	pleasant
	Exciting	gloomy	exciting
	Relaxing	distressing	relaxing
Formal	Complex	simple	complex
	Coherent	incoherent	coherent
Symbolic	Safe	unsafe	safe
	Mysterious	not mysterious	mysterious
	Feminine	masculine	feminine
Emotion (feelings; space makes me feel)			
Pleasure	Pleased	annoyed	pleased
	Happy	unhappy	happy
	Relaxed	bored	relaxed
	Satisfied	unsatisfied	satisfied
	Contended	melancholic	contended
	Hopeful	despairing	hopeful
Arousal	Aroused	unaroused	aroused
	Excited	calm	excited
	Frenzied	sluggish	frenzied
	Jittery	dull	jittery
	Wideawake	sleepy	wideawake
	Stimulated	relaxed	stimulated
Behavior (interactions; behavioral intentions)			
Dominance	Prefer to live	How much would you prefer to live this place?	
	Like to spend time	How much time would like to spend in this space?	
	Enjoy exploring	How much would you enjoy exploring space?	
	Feel friendly and talkative	To what extend does this place make you feel friendly and talkative to a stranger who happens to be near you?	

Figure 3
Correlation Matrix of 25 Aesthetic Experience



Note. See the online article for the color version of this figure.

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Light: Dim, Bright) ANOVA on PC3 (fascination) showed no main effects or interaction (see Table 4 for statistics).

Texture

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Texture: Longitudinal, Lateral) ANOVA on PC1 (familiarity) showed an interaction of boundary type and texture. The differences between horizontal and vertical boundaries were significant for lateral spaces but not for longitudinal spaces ($p = .01$, $\eta_p^2 = .17$). The 2 (Boundary Type: Horizontal, Vertical) × 2 (Texture: Longitudinal, Lateral) ANOVA on PC2 (excitement) and PC3 (fascination) showed no main effects or interaction (see Table 4 for statistics).

Color

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Color: Dim, Bright) ANOVA on PC1 (familiarity) showed a main effect color. Interior spaces that have cooler colors were found to be more familiar than the ones that have warm colors ($p < .0001$; $\eta_p^2 = .38$). There was no interaction of boundary type and color.

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Color: Dim, Bright) ANOVA on PC2 (excitement) showed a main effect color. Interior spaces that have warmer colors were found to bring more excitement than the ones that have cooler colors ($p = .01$, $\eta_p^2 = .17$). There was no interaction of boundary type and color.

The 2 (Boundary Type: Horizontal, Vertical) × 2 (Color: Cool, Warm) ANOVA on PC3 (fascination) showed no main effects or interaction (see Table 4 for statistics).

Discussion

In the present study, we aim to provide a comprehensive and empirically driven framework that characterizes human aesthetic experience for architectural spaces. More specifically, we aim to reveal key dimensions of aesthetic experience and how various properties of the built environment affect these dimensions. To this end, we systematically manipulated size, light, texture, and color of architectural spaces that have curvilinear boundaries by leveraging virtual reality. We then had people rate these spaces using numerous scales commonly used in the literature. Our

Table 3
Factor Loadings on the Three Main Principal Components

Aesthetic rating scale	PC 1 familiarity	PC 2 excitement	PC 3 engrossment
Pleased	.87		
Happy	.83		
Satisfied	.78		
Pleasant	.77		
Relaxed	.74		
Like to spend time	.73		
Prefer to live	.70		
Enjoy exploring	.70		
Hopeful	.70		
Relaxing	.69		
Feel friendly and talkative	.67		
Exciting	.65		
Safe	.62		
Aroused	.58		
Arousing	.53		
Coherent	.52		
Wideawake		.73	
Excited		.64	
Frenzied		.62	
Jittery		.59	
Contended		.58	
Mysterious			.68
Complex			.67
Stimulated			.54
Eigenvalue	8.42	3.54	2.01
Variance explained	33%	14%	8%
Cumulative variance	33%	47%	55%

findings suggest that human aesthetic experience in spaces with curvilinear boundaries can be reduced to three key dimensions, namely familiarity, excitement, and fascination, and different architectural properties affect these dimensions differently.

Key Dimensions of Human Aesthetic Experience in Spaces With Curvilinear Boundaries

Our study suggests that human aesthetic experience in spaces with curvilinear boundaries can be characterized with three main dimensions: familiarity, excitement, and fascination. The familiarity dimension includes assessments such as how pleased, satisfied or relaxed one feels in an environment, how safe and coherent they think the environment looks, and how they would like to behave in this environment such as whether they would like to spend time or enjoy exploring. Considering this structure, the framework (triad model) given by Chatterjee and Vartanian (2014) and its extension by Coburn et al. (2020) in which aesthetic experience is characterized by separate cognitive, emotional, and behavioral elements (accordingly the classification provided in Table 2 in the present study) has a more holistic approach based on these broad domains in psychology. Our study on the other hand shows that this a priori categorization can be revised by data-driven approaches, and the model may be more complex for architectural spaces with curvilinear boundaries. More specifically, our study shows that aesthetic experience for architectural spaces with curvilinear boundaries can be characterized by three key dimensions which include elements that overlap between the cognitive, emotional, and behavioral elements of the triad model. Figure 5 shows the a priori categories (i.e., cognition, emotion, behavior) of the aesthetic experiences that fall under the three key dimensions revealed in our study.

Our study shows that, at least in spaces with curvilinear boundaries, the familiarity dimension of the aesthetic experience spans elements that are a priori categorized under cognition (e.g., safe), emotion (e.g., relaxed), and behavior (e.g., want to spend time). This is consistent with Meijering et al. (2019) who suggest that people find a place familiar when they have a cognitive, emotional, and behavioral link to that place. Our findings also provide supportive evidence for Wickelgren (1979) who predicted that as people become more familiar with a particular interior space, it may appear more dominant, thus leading people to interact more with that space. The familiarity dimension may also be conceptually related to the "hominess" dimension that is proposed by Coburn et al. (2020) in which they investigate the human aesthetic experience by manipulating some different architectural variables such as ceiling or enclosure in addition to curvature. People may see their home safe and coherent, feel pleased, satisfied, and relaxed, and would like to spend time at their homes. In other words, familiarity dimension may represent a state of belonging to a space like home.

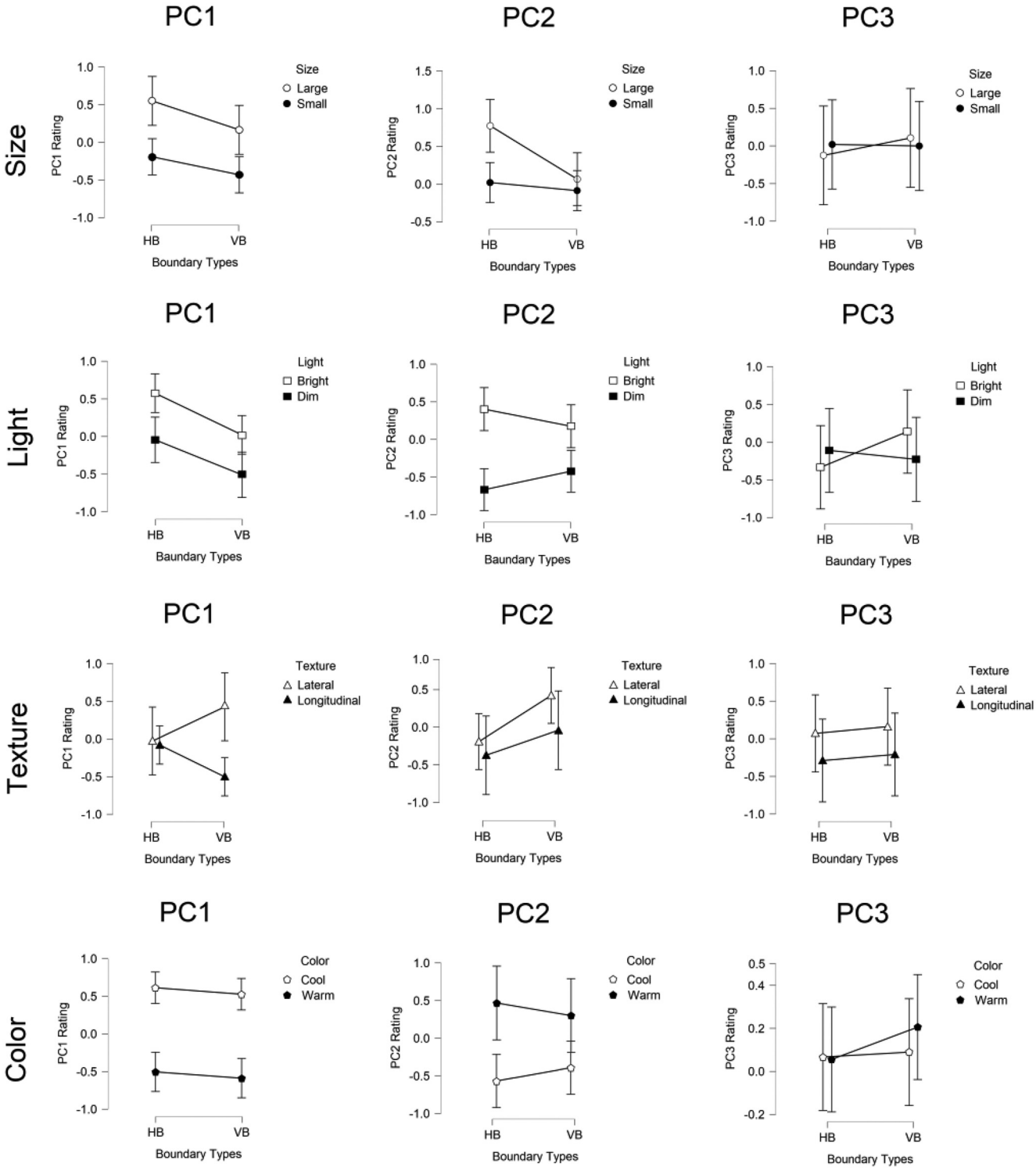
The second dimension revealed as a key dimension of human aesthetic experience in spaces with curvilinear boundaries in the present study is excitement. This dimension includes assessments such as how excited, frenzied, jittery or contended one feels in an environment. Considering the theoretical framework of Chatterjee and Vartanian (2014) and Coburn et al. (2020), this dimension maps nicely on the emotional component of the triad model and the classification provided in Table 2. In other words, this dimension characterizes how one feels in an architectural space.

The third dimension revealed by the present study is fascination. This dimension includes assessment such as how mysterious or complex an environment looks or how stimulated one feels in that environment. Within the framework of the triad model of Chatterjee and Vartanian (2014), this dimension includes both cognitive and emotional elements of aesthetic experience (also see their classification in Table 2). It is also conceptually related to the 'fascination' dimension that is proposed by Coburn et al. (2020) in which they investigate aesthetic experience by manipulating ceiling, enclosure and curvature as architectural variables.

In sum, our study revealed three key dimensions of human aesthetic experience in architectural spaces with curvilinear boundaries using virtual reality. The close examination of the structure of these dimensions shows that the cognitive, emotional, and behavioral elements of human aesthetic experience as proposed by earlier work may not reveal themselves as separate components in characterizing human aesthetic experience. In that sense, our study extends previous work by Marković (2012) and Polovina and Marković (2006) who suggest that aesthetic experience is closer to interestingness, which corresponds to fascination dimension in the present study than the other dimensions of subjective experience, such as a positive hedonic tone, which is conceptually close to the excitement dimension, and regularity, which is close to the familiarity dimension in the present study. In the next section, we explain how these dimensions differ from each other by discussing how they are affected by different architectural variables.

Figure 4

The Effect of Architectural Variables (Space Properties and Boundary Types) on the Principal Components



Note. PC = principal component. The ANOVA results are shown in Table 4. PC1 is familiarity, PC2 is excitement, PC3 is fascination.

Table 4
Factorial ANOVA of the Key Dimensions on the Space Properties and Boundary Types

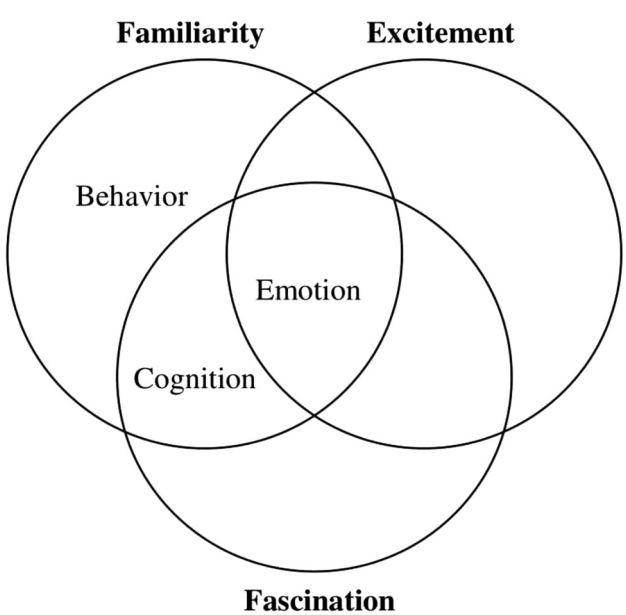
	PC1	PC2	PC3
Size & boundary			
Main effect of boundary	*$F(1, 31) = 4.75$, $p = .037$, $\eta_p^2 = 0.13$	*$F(1, 31) = 4.39$, $p = .044$, $\eta_p^2 = 0.12$	$F(1, 31) = 0.07$, $p = .78$
Main effect of size	*$F(1, 31) = 30.03$, $p < .001$, $\eta_p^2 = 0.49$	*$F(1, 31) = 6.19$, $p = .018$, $\eta_p^2 = 0.17$	$F(1, 31) = 0.004$, $p = .95$
Interaction of boundary & size	$F(1, 31) = 0.28$, $p = .6$	*$F(1, 31) = 10.58$, $p = .003$, $\eta_p^2 = 0.25$	$F(1, 31) = 0.36$, $p = .55$
Light & boundary			
Main effect of boundary	*$F(1, 31) = 12.43$, $p < .001$, $\eta_p^2 = 0.29$	$F(1, 31) = 0.003$, $p = 0.96$	$F(1, 31) = 0.31$, $p = .58$
Main effect of light	*$F(1, 31) = 9.64$, $p = .004$, $\eta_p^2 = 0.24$	*$F(1, 31) = 31.68$, $p < .001$, $\eta_p^2 = 0.50$	$F(1, 31) = 0.03$, $p = .85$
Interaction of boundary & light	$F(1, 31) = 0.12$, $p = .73$	*$F(1, 31) = 4.28$, $p < .047$, $\eta_p^2 = 0.12$	$F(1, 31) = 1.82$, $p = .18$
Texture & boundary			
Main effect of boundary	$F(1, 31) = 0.002$, $p = .96$	$F(1, 31) = 4.03$, $p = .05$	$F(1, 31) = 0.08$, $p = .78$
Main effect of texture	$F(1, 31) = 3.41$, $p = .07$	$F(1, 31) = 1.50$, $p = .23$	$F(1, 31) = 1.38$, $p = .25$
Interaction of boundary & texture	*$F(1, 31) = 6.44$, $p = .01$, $\eta_p^2 = 0.17$	$F(1, 31) = 0.45$, $p = .50$	$F(1, 31) = 0.001$, $p = .98$
Color & boundary			
Main effect of boundary	$F(1, 31) = 0.65$, $p = .43$	$F(1, 31) = 0.0001$, $p = .98$	$F(1, 31) = 0.47$, $p = .49$
Main effect of color	*$F(1, 31) = 19.37$, $p < .0001$, $\eta_p^2 = 0.38$	*$F(1, 31) = 6.41$, $p = .01$, $\eta_p^2 = 0.17$	$F(1, 31) = 0.07$, $p = .79$
Interaction of boundary & color	$F(1, 31) = 0.0001$, $p = .99$	$F(1, 31) = 1.22$, $p = .28$	$F(1, 31) = 0.31$, $p = .58$

Note. PC = principal component.
*$p < .05$ (Bonferroni corrected).

The Effect of Architectural Variables on Key Dimensions of Human Aesthetic Experience

In the present study, we manipulated several architectural variables including the type of curvilinear boundaries, as well as size, light, texture, and color of the architectural spaces, and measured how these variables affected the key dimensions of human aesthetic experience in virtual reality. Our findings show that the three key dimensions of aesthetic experience in curvilinear boundaries are distinguished from each other by exhibiting different modulations by different architectural variables.

Figure 5
Key Dimensions of the Current Study Based on the Triad Model and Its Extension



Note. The relationship of the A priori categorizations (Cognition, Emotion, Behavior) on the triad model (Chatterjee & Vartanian, 2014, and its extension by Coburn et al., 2020) and the key dimensions revealed in the current study (Familiarity, Excitement, Fascination).

The familiarity dimension is affected by the size, color, and light of the architectural space (in that order, following the magnitude of effect sizes). The spaces with larger sizes, brighter lights, and cooler colors are found to be more familiar than spaces with small sizes, dimmer lights, and warmer colors, respectively. In addition, the type of the curvilinear boundary affects the familiarity dimension, especially when the space is presented with different sizes or lights. More specifically, architectural spaces with horizontal boundaries are found to be more familiar than spaces with vertical boundaries regardless of their sizes or light level. On the other hand, the texture of the architectural spaces interacts with the type of curvilinear boundary in determining how familiar people find the space. In particular, when the space has a vertical boundary, people find spaces with lateral patterns more familiar than spaces with longitudinal patterns, whereas when the space has a horizontal boundary, people find spaces with lateral and longitudinal patterns equally familiar.

The excitement dimension is also affected by the light, size, and color of the architectural space (light affecting more than color and size) but with some different patterns. Spaces with larger sizes, brighter lights, and warmer colors bring more excitement than spaces that have smaller sizes, dimmer lights, and cooler colors. In addition, the type of the curvilinear boundary affects the excitement dimension, especially when the space is presented with different sizes. In particular, spaces with horizontal boundaries are found to bring more excitement than spaces with vertical boundaries regardless of their sizes. On the other hand, the light level of the architectural space interacts with the type of curvilinearity in determining how much excitement the space brings to people. More specifically, when the space has a horizontal boundary, spaces with brighter lights bring more excitement than spaces with dimmer lights, whereas when the space has a vertical boundary, spaces with dimmer lights bring more excitement than spaces with brighter lights.

These results are consistent and extend previous work that shows that aesthetic experience increase as the size of the space gets larger (Bokharaei & Nasar, 2016; Franz, 2006; Franz et al., 2005; Franz & Wiener, 2005; Gärling, 1970a, 1970b; Stamps, 2007, 2009, 2010), as the level of the lighting increases (Durak et al., 2007; Odabaşioğlu & Olguntürk, 2015; Stamps, 2007), and as the colors become cooler (Franz, 2006; Odabaşioğlu & Olguntürk, 2015). In the light of previous work, the main contribution of our study is that it finds the key dimensions that underlie a wide range of scales independently used in previous work, and shows which architectural variables affect each of these dimensions such as familiarity and excitement. So, in that sense, our study provides a detailed, data-driven, and systematic characterization of human aesthetic experience.

The fascination dimension is affected by none of the architectural variables manipulated in the present study. These results are inconsistent with some previous work that shows that the shape (Archea, 1977), size (Aiello, 1987; Baum & Paulus, 1987), texture (Evans & McCoy, 1998), color and light (Berlyne, 1971; Mehrabian & Russell, 1974) of a space can increase the level of stimulation in that space. One primary reason may be that the stimuli we used in the present study were too simple to elicit fascination. In other words, it is possible that people find architectural spaces fascinating when they are more complex and natural and feature a combination of numerous architectural variables such as size, light, texture, and color. Future work can employ more naturalistic spaces to find out whether this dimension is affected by a variety of architectural variables.

Limitations

There are several limitations of our study. First, we used simple and well-controlled stimuli to be able to study the effects of space properties (size, light, color, and texture) and curved boundaries on aesthetic experience by isolating the effects of other visual variables. Considering the fact that the built environment we perceive in our daily life is much more complex, future studies could build upon this work by creating more complex and naturalistic stimuli and measuring aesthetic experience. A second and related limitation of our study is that the effects of space properties and their relationship with curved boundaries were investigated separately. Future work could extend this work by exploring the space of space properties and curved boundaries, that is, by creating spaces that feature a combination of the space properties (e.g., size, light, texture, and color) and curved boundaries instead of studying them in isolation. This will give us an opportunity to find out which space properties may interact in our perception of the built environment. This may also allow us to understand whether the 45% unexplained variance in our PCA can be explained by the interaction of various space features. A final limitation is that we only used visual stimulation in the present study as VR restricts us to stimulate other sensory modalities such as touch or smell. Future work can extend this work in real environments and manipulate the texture or odor of the environments to measure their effects on aesthetic experience.

Conclusion and Future Research

In the present study, we provided a systematic characterization of human aesthetic experience in architectural spaces with curvilinear boundaries, and how various properties of the architecture affected the aesthetic experience. Future work can build on this work by investigating the neural basis of aesthetic experience using neuroimaging methods while people explore architectural spaces (Chatterjee & Vartanian, 2014, 2016; Eberhard, 2008). This will help us built spaces that are neuro-ergonomic for their users.

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