Check for updates

RECOGNITION MEMORY FOR INTERIOR SPACES WITH BIOMORPHIC OR NON-BIOMORPHIC INTERIOR ARCHITECTURAL ELEMENTS

Hasti Mirkia, Ph.D., Mark S. C. Nelson, M.Arch., Heather C. Abercrombie, Ph.D., Kristin Thorleifsdottir, Ph.D. and Amir Assadi, Ph.D., University of Wisconsin-Madison, USA
Arash Sangari, Ph.D., Walmart, USA

ABSTRACT

In our study, the primary goal was to gain insights into cognition by measuring spatial memorability for two different types of approaches to geometry in interior design (biomorphic design and non-biomorphic rectilinear design). To better understand the processes behind the memorability differences, we also looked at how spatial memorability interacted with visual attention and spatial pleasantness. After extensive pre-testing, two standardized photographic stimulus sets were created and used during the experiment, controlling for variables such as novelty, complexity, pleasantness, and the number and density of interior architectural elements. Each stimulus set contained equal numbers of photographs with biomorphic elements and photographs with non-biomorphic elements. Subjects (N = 68 students, mean age = 25.4 years) viewed the first stimulus set, then were given a "distractor" task. Next, subjects viewed the second stimulus set, and for each photograph indicated whether the image was one they had seen or whether it was new. Visual attention for each photograph was monitored using eye-tracking technology, and subjects also rated the pleasantness of each environment. The data were analyzed to test for the relative strength of memorability between environments with biomorphic elements and non-biomorphic elements, as well as the links between recognition memory, visual attention, and pleasantness. The results suggest that interior spaces with biomorphic elements positively contribute to spatial memorability, are found to be more pleasant, and increase visual attention.

INTRODUCTION

Drawing from everyday life, spatial cognition can be described as the mental processes used to retrace the path to one's car in a parking garage (Carlson et al., 2010; Dalton et al., 2015). Recognition and spatial memory are the key elements used in taking a return path; memories of building spaces and their contents are recognized and assembled to retrace the previous journey. Visual attention refers to what catches one's attention, and spatial pleasantness relates to one's emotional states while experiencing the journey (passing by a beautiful flowering shrub or by a smelly waste container). While our study does not directly address parking garages or journeys, this example situates the processes, terms, and variables we use within a person's lived experience.

The value of studying memorability and its components in the context of interior design ties into multiple aspects of user experience. Research on human cognition, emotion, and visual attention shows that designed environments influence psychological functioning (Ballantyne, 2002; Dohr & Portillo, 2011; Eberhard, 2008; Robinson & Juhani, 2015). On a more practical level, it has been documented that people often experience getting lost in semi-public buildings with complicated floorplans, such as healthcare facilities, educational buildings, and shopping centers (Carlson et al., 2010; Dalton et al., 2015). This suggests that it would be useful for interior designers to access research that demonstrates ways to make interior environments more memorable.

© 2022 Interior Design Educators Council.
Journal of Interior Design 47(3), 47–66

Despite preliminary evidence supporting the positive impact of memorable designed environments on human emotion and cognition (Dohr & Portillo, 2011), limited study exists on the concrete relationship between interior spaces and human neuropsychological functions such as memory. Conversely, there is a vast literature on the emotional enhancement of memory and the contribution of visual attention to memorability outside of design research (Bojko, 2009; Olivers, 2008; Shi et al., 2020). This has been made possible by the development of new data collection tools such as eye-tracking technology, functional magnetic resonance imaging (FMRI), electroencephalography (EEG), galvanic skin response monitoring, multivariate computational models, and neural networks/machine learning. Additionally, constructs such as spatial cognition, spatial memory, visual attention, and spatial pleasantness have been integrated with these tools. Although these new tools are available for studying interiors, "...neuroarchitecture lacks an extensive behavioral literature from which to construct neurophysiological models and generate predictions" (Coburn et al., 2020, p. 218). A major roadblock in applying neuropsychological methods to the interior is that standard memorability research models focus on object memory and purposefully isolate a single object to keep all subjects focused on the same memorable/non-memorable stimuli. In contrast with object memory, spatial memorability refers to the ability to remember spatial information including form, layout, and fundamental interior architectural elements (Isola et al., 2011). Interior environments consist of multiple elements, and the concept of spatial memory rather than object memory is a useful construct; remembering an object in an environment is different from remembering the environment itself, or a subset of objects within the environment.

Interior environments consist of multiple elements, and the concept of spatial memory rather than object memory is a useful construct; remembering an object in an environment is different from remembering the environment itself, or a subset of objects within the environment.

In this study, we addressed theories and issues that have been widely discussed within the field of interior design by using approaches that draw from neuroscience-based research. Prior to the advent of neuroscience tools, researchers were required to question a subject about their experiences with an environment and infer their interactions based on responses filtered through language (Hu & Shepley, 2022). For instance, with color research, investigators in the past asked subjects about their feelings related to color. However, with neuroscientific tools, researchers could monitor brain activity using FMRI in response to a color stimulus, monitor heart rate, and galvanic skin response, and monitor other physical markers that would document the response to the stimulus.

HYPOTHESES

We theorized that meaningful data could be generated by exploring the role interior architectural elements have in the spatial recognition memory process while participants looked through images of spaces with biomorphic (organic ornamental form) interior architectural elements or non-biomorphic (rectilinear minimalist form without ornaments) interior architectural elements. To better understand the processes behind the memorability differences, we also looked at how spatial memorability interacted with visual attention and spatial pleasantness. To test these ideas, we formulated three inter-related hypotheses.

Hypothesis 1 *Spaces with biomorphic interior architectural elements are more memorable than spaces with non-biomorphic interior architectural elements*.

Hypothesis 2 *Spaces with biomorphic interior architectural elements are perceived as being more pleasant*.

Hypothesis 3 *Spaces with biomorphic interior architectural elements increase visual attention for someone looking at an interior environment*.

To test Hypothesis 1, a *recognition memory task* was used to identify whether photographs with two types of interior architectural elements (biomorphic or non-biomorphic) were remembered

more accurately. To test Hypothesis 2, a *mediation model* was used to discover which photographs of interior architectural elements were set as a predictor of memorability, both directly and indirectly, through participants' self-reported feelings of pleasantness. To test Hypothesis 3, a *moderation model* was used to evaluate the relationship between the interior architectural elements in the photos and spatial memorability of the spaces across respondents with different patterns of participants' visual attention.

LITERATURE REVIEW

OVERVIEW

Our study cuts across a broad swath of theories and methodologies in its design, implementation, and analysis. The literature review addresses two distinct threads that underpin this investigation. One thread examines topics related to neuroscience and the study of cognitive processes, including spatial memory, spatial pleasantness, total fixation duration theory, and visual attention. The other thread weaves through theories about interior environments and their relationship to biomorphic design and biophilic design.

USING NEUROSCIENCE TO STUDY THE BUILT ENVIRONMENT

Neuroscience is a new way to generate scientific insights for interior designers who wish to improve their designs for environments and contribute to human well-being (Eberhard, 2008, 2009; Zeisel & Eberhard, 2006). Using neuroscience knowledge in environment-behavior research has led to an approach called Environment/Behavior/Neuroscience (E/B/N) (Zeisel & Eberhard, 2006). E/B/N is an environmental design approach that incorporates neurological and biological functions such as perception, memory, learning, and orientation into the psychological and sociological knowledge of environment-behavior studies (Eberhard, 2009; Zeisel & Eberhard, 2006). For instance, Vartanian et al. (2013) conducted an experiment to discover the impact of curvilinear versus rectilinear geometrical forms on participants' emotions and aesthetic preferences using a neuroscientific approach. They analyzed the participants' brain activities using FMRI data and observed specific neural activation related to the emotion and preference for curved geometrical forms. Because E/B/N measures direct physical responses, it offers an opportunity to bypass cultural and other biases that filter responses to written or verbal queries.

This current investigation ties into a larger body of inquiry that references neuroscience as a tool for studying the built environment. Interestingly, while concepts from neuroscience are often referenced as a research element when studying architecture and interiors, they are less often directly applied as a data collection tool. Higuera-Trujillo et al. (2021) performed a scoping review of publications that reference neuroscience as a way to understand the built environment, termed neuroarchitecture. Their review looked at books and articles published between 2012 and 2019 across multiple disciplines. They initially identified 327,058 references. Ultimately, only 141 references were found to be directly applying neuroscience-based research to the built environment. While the idea of neuroscience drives multiple inquiries, the challenges of incorporating it into the data collection seem to be elusive.

While the idea of neuroscience drives multiple inquiries, the challenges of incorporating it into the data collection seem to be elusive.

STUDYING COGNITIVE PROCESSES

Spatial Memory

While spatial memory, and the closely related process of spatial cognition, would seem to be central to discourse within interior design research, only three articles in the *Journal of Interior Design* operationalized these concepts in relation to interior space (Cho & Suh, 2021; Juliá Nehme et al., 2020, 2021). Our study solidly brings the rich tradition of research on spatial memory from psychology into the interior design milieu.

Spatial cognition refers to how the human brain gathers, stores, organizes, and recognizes spatial information (Gifford, 2016; Levine, 1982). Spatial memory is one component of spatial cognitive processing (Gifford, 2016), which, in addition to responding to features in a physical environment, is affected by various personal factors, perceptual ability, cognitive biases, and familiarity with that environment. In one investigation structured similarly to our study that did not focus on the built environment, subjects were shown 200 images for 20 ms each. Remarkably, subjects were able to correctly recall 65% of the images (Delorme et al., 2018). Clearly, the brain is hard-wired for visual memory which is, in turn, an aspect of spatial memory.

From an architectural point of view, specific characteristics of the physical environment, such as tall buildings or unique features with a distinctive form, are usually more memorable than other features (Gifford, 2016). In an evidence-based design project case study, Zeisel and Eberhard (2006) tested the influence specific interior architectural elements including landmarks, window views, memory boxes installed on walls, personalized residence design, and three-dimensional wall art have on the memory of patients diagnosed with Alzheimer's disease. Their findings showed an increase in residents' memory performance and their ability to function independently. Similarly, Alvares (2014) investigated how the hippocampus and human senses help museum visitors discover and remember circulation patterns. They discovered there are close relationships between human perception, memory, and space circulation.

According to Berlyne's collative properties theory, features in the environment attract observers' attention and spark interest. He referred to these scene elements as "novelty" (newest to the observer), "incongruity" (something in the environment that is perceived as out of place), "complexity" (finding a large variety of elements), and "surprisingness" (unexpected elements) (Cupchik & Berlyne, 1979, p. 94). They influence human hedonic tone (aesthetics) and arousal (Gifford, 2009). Memorability is something that can be quantified and predicted; researchers have revealed that artificial neural networks are able to predict which images will be more memorable, and software has been developed that can maximize the memorability of an image (Bainbridge, 2019; Nadal et al., 2010; Rust & Mherpur, 2020). As illustrated by Bradley et al. (1992), affective dimensions have an impact on memory. In particular, stimuli and events associated with affective arousal—either pleasure or distress—are more memorable than neutral stimuli and events. Furthermore, novelty, complexity, and the number of details also affect memorability. This was important to consider when selecting photos of interior environments for our stimulus sets; the dilemma of which elements of the interior environment are providing the stimulus is not always obvious, leaving the door open for confounds. However, researchers have developed methods to identify images with potential confounds in affective dimensions that could interfere with creating balanced and standardized stimulus sets of images (Bradley et al., 1992, 2001; Lang et al., 1999). In this investigation, the arousal dimension translates to interior design as a combination of novelty and complexity, which are considered as potential confounding variables, to provide a standardized stimulus set. Moreover, we examined the valence dimension as feelings of pleasantness, which can be directly translated to the feelings of pleasantness related to the design of interior environments.

"In this investigation, the arousal dimension translates to interior design as a combination of novelty and complexity, which are considered as potential confounding variables, to provide a standardized stimulus set."

Spatial Pleasantness

Here again, there is a rich tradition of research within the field of psychology that seeks to understand the dimensions of spatial pleasantness. However, there is only one article in the *Journal of Interior Design* that addressed spatial pleasantness within the context of spatial cognition (Juliá Nehme et al., 2021). Thus, our research operationalizes this concept within the field of interior design.

A large body of inquiry in the field of psychology has demonstrated the positive effects of *spatial pleasantness* on memory performance (Buchanan & Adolphs, 2003; Kensinger & Corkin, 2003; Smith et al., 2005). Joye (2007) argued that architectural elements of natural

forms (biomorphic) such as "vegetative elements and settings containing vegetation" can be more visually appealing and are associated with "positive aesthetic reactions" (p. 307). Similarly, there is some evidence that visual complexity can be an indicator of perceptions of beauty (Nadal et al., 2010).

Emotionally based behavior or physical responses become a part of the environment. In visual experiences, the elements of composition are the visual qualities people see and respond to when viewing a space. Visual qualities can trigger many different emotions and feelings; the more positive those feelings are, the more likely people are to enjoy and use an environment (Zadra & Clore, 2011). The feeling of pleasantness, as one of the dimensions of emotion, emphasizes the contribution of two different components: *arousal* and *valence* (Lang et al., 1999; Russell, 1980). Arousal refers to how strongly an emotion is experienced, from calm to exciting, and valence is related to the subjective experience of the quality value of emotional stimulus that varies from positive to negative (Bradley et al., 1992, 2001; Lang et al., 1999).

Total Fixation Duration Theory

Our study used fixation duration to study visual attention. While this has been employed extensively outside of the interior design area, only one article in the *Journal of Interior Design*, to date, has substantively applied this neuroscience tool (Suh & Cho, 2021).

Looking outside interior design research, fixation[1] duration of different regions of a visual scene is indicative of the cognitive process load on those regions (Duchowski, 2003). Therefore, the total fixation duration within the boundaries of the object regions (area of interests [AOIs] that cover objects in an image) can be used as a measure of cognitive load associated with that object in the scene. Larger values of total fixation duration could be a result of a higher number of fixation points, longer individual fixation points, or a combination of both.

In viewing-behavior studies, eye-tracking technology helps to record participants' fixation duration by creating attention heatmaps (Bojko, 2009). The attention heatmaps are used to discover the correlation between the information extracted by participants and the memorability of images that were tested during the cognitive memory test. Eye-tracking heatmaps offer an opportunity to record which salient and object regions of the images are being looked at. Therefore, eye-tracking provides insights into the focus of the participants' visual attention (Bojko, 2009; Duc et al., 2008; Torralba et al., 2006).

Several studies have shown that visual attention plays an important role in human memory (e.g., Borkin et al., 2013; Celikkale et al., 2013; Mancas & Le Meur, 2013). Using a methodology similar to our study, Celikkale et al. conducted an experiment, which examined the impact of visual attention on the memorability of images. They were interested in discovering which regions of the images were more memorable, considering features such as: "salient, non-salient, object and non-object regions." Results indicated that salient, the most noticeable parts of the images, and object regions, areas of the images that contain objects, provide the best memorability performance. Therefore, we measured the total fixation time inside of each AOI as a quantitative measure of a participant's visual attention to that particular image using eye-tracking technology.

Visual Attention

Visual attention has extensive literature in the field of psychology, but there is only one article in the *Journal of Interior Design* that incorporated visual attention as a central concept (Suh & Cho, 2021). Humans are visual beings, and environmental perception is largely based on gathering visual stimuli from the geo-spatial environment through the observer's visual attention (Gifford, 2016). Paying attention to certain visual information in the environment helps people focus on a select amount of information to be processed in the cognitive system. Several studies suggest that higher levels of visual attention make particular environments more memorable than

Paying attention to certain visual information in the environment helps people focus on a select amount of information to be processed in the cognitive system.

the environments that draw less attention (Dzulkifli & Mustafar, 2013). Moreover, a great body of research has discovered that higher attention to a stimulus increases memory performance (Pan, 2010; Smilek et al., 2002). Suh and Cho used eye-tracking technology with 38 undergraduate interior design students who viewed environmental scenes with spatially relevant and decorative elements and found that students who exhibited increased spatial ability were more likely to focus their attention on spatially relevant scenes. While Suh and Cho measured total fixation on AOIs, our investigation differs by examining the variables of memorability and pleasantness along with spatial attention.

In addition to spatial relevance, The Salient Color Theory (e.g., Birren, 1978) indicates that colors impact visual attention and human memory (Kim, 2010). Several studies found that color increases the attentional level through the cognition process of selection information (Farley & Grant, 1976; MacKay & Ahmetzanov, 2005; Pan, 2010). In their seminal research, Farley and Grant conducted experiments to discover the impact of color versus no-color illustrations on participants' memory performance. They discovered that participants had a better attention experience looking at color illustrations, and as a result, they had better memory performance in comparison with the no-color illustrations. These insights led to the decision to eliminate color from the stimulus set in this investigation so that the participants would focus more clearly on the geometry. While there are many studies that explored the positive relationship between image memorability and visual attention (e.g., Bulling et al., 2009; Foulsham & Underwood, 2008; Mancas & Le Meur, 2013; Noton & Stark, 1971), design research measuring spatial memorability for biomorphic versus non-biomorphic rectilinear design is lacking.

THEORIES ABOUT INTERIOR SPACE: BIOPHILIA AND BIOMORPHIC DESIGN

Drawing from the diverse experiences and attributes of biophilia, we focused on the indirect experience of nature, specifically examining biomorphic interior architectural elements that are inspired by organic shapes and forms. Many theoretical studies have attempted to explain the biological significance of biomorphic design's impact on human recognition and memory, and biomorphic design has been used as a subject for the study of human perceptual psychology (Feuerstein, 2001; Joye, 2007). Feuerstein (2001, pp. 15–16) believed that the natural characteristics of biomorphic design help to create more "possible" perceptual recognition processes and suggests that the geometrical forms of biomorphic design are read by people as natural objects because of their natural characteristics. Although this theoretical evidence identifies positive effects of biomorphic design on the human mind and memory, still lacking are quantitative and experimental research in design inquiry to identify that this specific approach creates more memorable and engaging environments. Thus, biomorphic interior architectural elements are considered as one of the main constructs in our investigation.

“Although this theoretical evidence identifies positive effects of biomorphic design on the human mind and memory, still lacking are quantitative and experimental research in design inquiry to identify that this specific approach creates more memorable and engaging environments.

The application of the biophilia hypothesis in architecture is known as *biophilic design* (Kaplan, 1995). While biomorphic and biophilic design is a mainstream recurring practice for many architects and interior designers in the world of built projects, McGee et al. (2019) are the only authors in the *Journal of Interior Design* to quantitatively examine the application of biophilic theories. These authors developed a matrix based on biophilic principles that can be used by design practitioners as a design tool and cite research showing the general benefits of being exposed to nature and its abstractions within the built environment. While their research focused on the perceived usefulness of the matrix by practitioners, they cite little concrete evidence of the ability of individual elements within their matrix for specific outcomes such as memorability. Our study sheds light on and validates one aspect of their matrix that relates to natural forms. A future step using methods similar to those in this investigation would be to explore other aspects of their matrix. This discussion is not intended to denigrate the reliability of the matrix; the intent is to show that there is a

lack of research that can demonstrate the utility of specific elements of biophilia, which is something that designers would find useful.

Biomorphic forms represent natural shapes, patterns, and textures that connect human living systems to nature (Feuerstein, 2001; Kellert et al., 2008). Looking at biophilia broadly, Attention Restoration Theory suggests that human connection to nature and natural forms improves concentration, decreases human mental fatigue, and enhances visual attention (Kaplan, 1995). Natural forms and curvilinear designs for interiors have also been shown to evoke higher levels of pleasantness (Coburn et al., 2017; Joye, 2007; Vartanian et al., 2013, 2019). Researchers in perceptual psychology have attempted to explain how *biomorphic design* impacts human recognition and memory, predicting that people are more likely to remember biomorphic interior architectural elements than non-biomorphic ones (e.g., Feuerstein, 2001; Joye, 2007). Feuerstein (2001, pp. 15–16) stated, for example, that biomorphic design can help create more "possible" perceptual recognition processes and that the geometric forms are read by people as *natural objects*.

We addressed biophilia at its most fundamental level, going back to seminal theories about memorability that have seldom been tested empirically within the context of interior design. Our study takes these concepts from the theoretical to the concrete, testing whether people really do remember biomorphic elements more strongly, and whether people find interiors with biomorphic elements to be more pleasant. This is concretely useful to designers when they are making design decisions.

METHODS

OVERVIEW

Using Cupchik and Berlyne's (1979) collative properties theory and Bradley et al.'s (1992) affective dimensions, extensive pilot testing was used to create sets of photos of spaces that were matched on variables including novelty, complexity, pleasantness, and the number and density of interior architectural elements that could be easily remembered. Subsequently, the primary data collection was conducted using these standardized stimulus sets. Subjects were shown the standardized stimulus set and were then distracted with a series of unrelated tasks. Finally, subjects were shown an expanded stimulus set, were asked to identify whether they had seen each image in the previous phase and were also asked to rate each photo for spatial pleasantness.

"...extensive pilot testing was used to create sets of photos of spaces that were matched on variables including novelty, complexity, pleasantness, and the number and density of interior architectural elements that could be easily remembered."

INITIAL PRELIMINARY NORMING STUDY FOR THE CREATION OF MATCHED STIMULUS SETS

Initially, 126 photos from different semi-public spaces were selected from interior design websites: 63 with biomorphic elements and 63 with non-biomorphic elements (for this study, biomorphic is defined as organic ornamental form and non-biomorphic as rectilinear minimalist form without ornaments). As described here, an initial preliminary study was conducted to create standard stimulus sets of 30 each (biomorphic and non-biomorphic) taken from this initial set of 126 photographs (see Figure 1).

First, the images were screened for similarities and non-similarities and adjusted in size (800 × 598 pixels) and color (grayscale). Adobe Photoshop was used to remove distracting elements that might draw attention to unrelated attributes such as people and texts. An expert panel of four architects and interior designers who specialize in geometrical forms and biomorphic design assisted in classifying the images into biomorphic and non-biomorphic stimulus sets. An initial norming study was conducted in which participants rated photographs based on the following dimensions: *novelty*, *complexity*, *pleasantness*, and the *number* and *density* of interior architectural elements. An online self-administered questionnaire, Typeform, was distributed to 26 volunteer participants. The researcher invited study participation via email or LinkedIn from

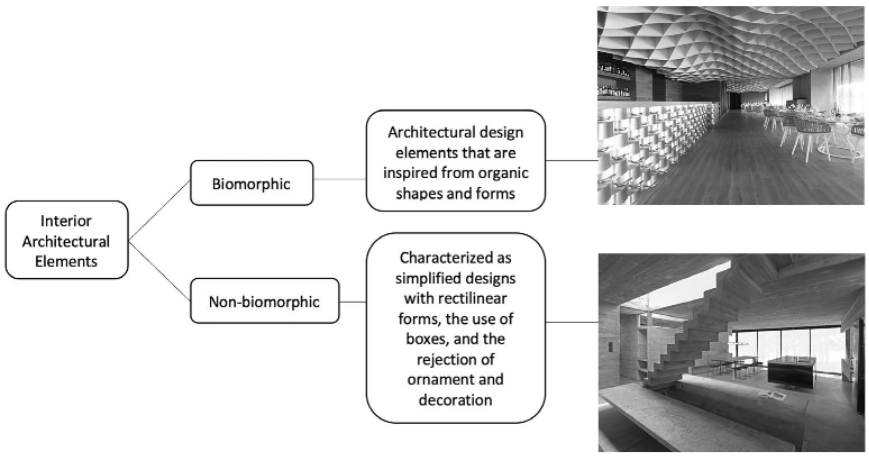


Figure 1 Two different categories of architectural design elements.

interior design groups (International Interior Design Association and Interior Architecture + Design). The norming study procedure was fully explained to the participants and informed consent was obtained. Participants' responses to the questionnaire were automatically saved and were available through the online survey tool (Figure 2).

The norming study results were analyzed using descriptive statistics to establish scores for each image to ensure that the potential confounding variables in the two settings (biomorphic and non-biomorphic) were balanced. Thirty images of biomorphic elements and 30 images of non-biomorphic elements with similar mean and standard deviations (SD) were selected for the experiment. Table 1 represents the average and SD of four dimensions of the stimuli set of the norming study before and after selecting the normalized subset of biomorphic and non-biomorphic interior design images. Comparing the before and after data, the average and SD of these dimensions for biomorphic and for non-biomorphic design images became very close and similar to each other after normalizing. Subsequently, by removing 66 photographs from the initial stimulus sets, we were able to create two stimulus sets of 30 photographs. Each set included both biomorphic and non-biomorphic images that were matched on *novelty*, *complexity*, *pleasantness*, and the *number* and *density* of interior architectural elements based on ratings from the 26 participants in this initial study. This is a strength of this research in that any of these variables could have confounded memory results in the full experimental study that followed.

FULL EXPERIMENTAL STUDY

Participants

Face-to-face recruitment for the study took place in April 2017 at social places such as libraries and study areas at the University of Minnesota, Minneapolis (which was not the researchers' home institution). Sixty-eight students (34 females, 34 males) volunteered to participate in the experiment. Psychology researchers have examined subsets of large datasets to identify lower limits for sample sizes below which confidence decreases and conversely to identify upper thresholds beyond which confidence does not appreciably increase. Bridges and Holler (2007) suggested a minimum sample size of 50 and noted that having more than 70 subjects did not significantly increase the confidence. A more recent study found that some types of datasets required a sample greater than 70, while other types of datasets would ideally fall between 30 and 70 subjects (Piovesana & Senior, 2018). Therefore, a sample size of 68 is strong based on either interpretation.

When participants arrived at the study lab on a predetermined day and time, they were asked to sign a written consent to participate in a picture viewing and eye-tracking experiment. Eligibility criteria included unimpaired vision and no previous experience with an experiment of this type. Demographic data was collected during the distraction phase (i.e., between the initial

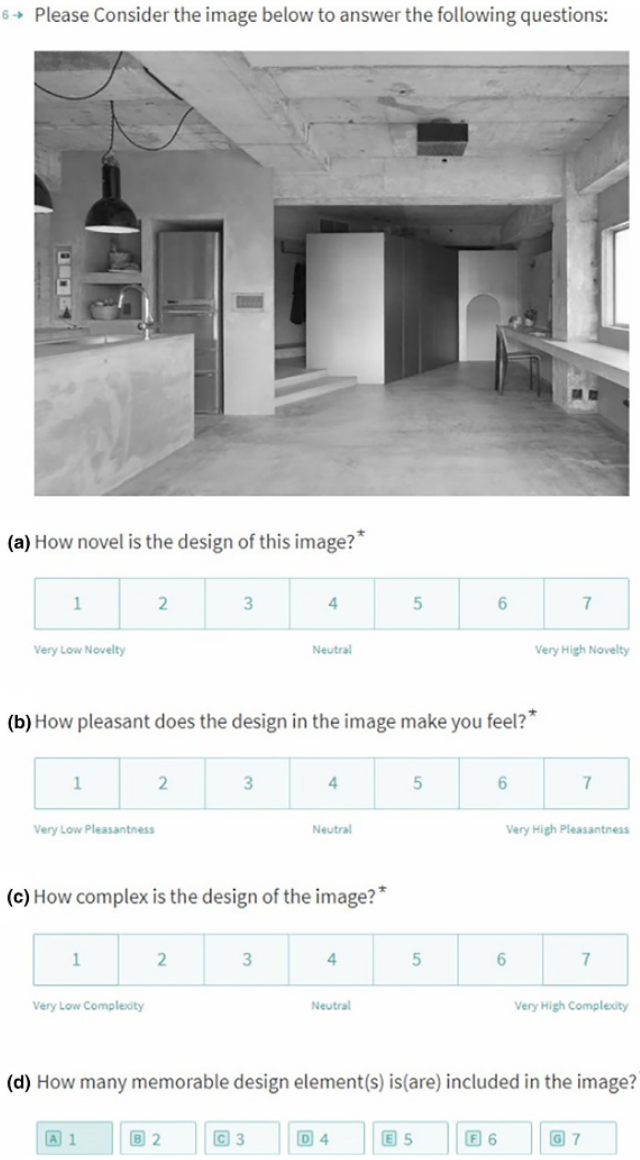


Figure 2 The interface of the online platform survey tool, Typeform, that was used for distributing the norming study survey.

presentation of the stimuli and memory testing) of the experiment (age 18–39, mean age = 25.04 years, SD = 5.90 years, and various fields of study including electrical engineering, medicine, environmental studies, anthropology, mathematics, dentistry, nursing, and social studies). As a token of appreciation, participants received a Goldy Gopher (University of Minnesota mascot) keychain.

Procedures

Data collection for examining recognition memory entailed having subjects perform tasks in three phases: *learning*, *distraction*, and *testing*. In the *learning phase*, participants were asked to view a PowerPoint slideshow containing 30 images: 15 images of interior spaces with biomorphic elements and 15 images of interior spaces with non-biomorphic elements. While viewing the images, participants' eye movements were recorded using the Eye Tribe eye-tracking

Table 1. Stimuli set dimension average and standard deviations for biomorphic and non-biomorphic interior design images, before and after eliminating outliers during the norming study

	Before				After			
	Biomorphic		Non-biomorphic		Biomorphic		Non-biomorphic	
	Avg	SD	Avg	SD	Avg	SD	Avg	SD
Complexity	4.778	0.557	3.538	0.739	4.422	0.473	4.034	0.504
Novelty	5.227	0.531	4.016	0.729	4.883	0.43	4.537	0.393
# of memorable objects	3.201	0.457	2.755	0.534	3.071	0.43	3.028	0.518
Pleasantness	4.645	0.535	3.593	0.832	4.46	0.523	4.81	0.698

Before represents the original 126 photos. After represents the 60 final photos selected to provide a normalized subset of biomorphic versus non-biomorphic interior design images.

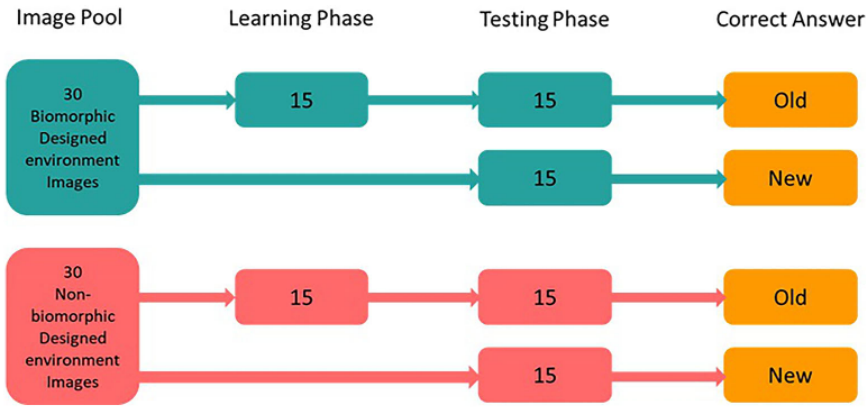


Figure 3 A number of images are shown to participants in each phase. During the learning phase, they observed 15 (of 30) biomorphic images and 15 (of 30) non-biomorphic images. During the testing phase, they were shown all 60 images and asked to identify images they recognized from the learning phase.

technology in order to know which elements of the spaces the subject was paying visual attention to. Each slide of the PowerPoint was displayed on the 23.6″ LCD monitor (resolution set to 1980 × 1080 pixels) for 2 seconds. Viewing for 2 seconds is at the top end of exposure for image memory research, and many researchers use briefer exposures measured in milliseconds (Delorme et al., 2018; Martini & Maljkovic, 2009).

In the *distraction phase*, immediately after viewing the full set of images, participants were asked to play an online puzzle for 20 minutes as a distraction, and then their general memory was tested using a standardized memory test sourced from: http://neutralx0.net/home/mini04.html. (The test was an additional distractor, and this data was not used in our study). The demographic questionnaire was collected after the memory test during the distraction phase and was another distractor.

In the *testing phase*, participants' recognition memory of old or new images was tested. The 30 images from the learning phase were combined with 30 new images, and in random order, all 60 images were shown to the participants. After viewing each image, participants were asked if they remembered having seen the image before, and then they were asked to rate the image level of spatial pleasantness (i.e., their feelings toward the biomorphic or non-biomorphic spatial design on a seven-point Likert-type scale from extremely unpleasant (1) to extremely pleasant (7)). After viewing and answering the questions for the 60 images, the participants were debriefed about the intentions of the study. Figure 3 shows a schematic process of the experiment and the number of designed images shown to the sample during the learning and testing phases. The memorability score of each image is calculated as the success rate of the participants in remembering an image as an old image, that is, the total number of participants who

recognized the old image divided by the total number of participants that the image is presented to them as an old image.

DATA ANALYSIS AND RESULTS

HYPOTHESIS 1: RECOGNITION MEMORY TASK

To investigate the relationships between interior architectural elements in two categories (biomorphic and non-biomorphic) and spatial memorability of the two semi-public settings, a linear regression analysis was conducted. In support of Hypothesis 1, greater recognition memory was observed for images with biomorphic elements compared to images with non-biomorphic elements ($b = 0.07$, $t(58) = 4.064$, $p < .001$) (Figure 4). The difference in memory for biomorphic versus non-biomorphic photographs accounted for 22% of the variance in total memory scores. Figure 4 shows that spatial memorability was higher for biomorphic elements ($M = 0.22$, SD = 0.07) than non-biomorphic ($M = 0.15$, SD = 0.05).

HYPOTHESIS 2: MEDIATION MODEL

To investigate the association between biomorphic and non-biomorphic, interior architectural elements and participants' *level of spatial pleasantness* (as a part of spatial memorability), a mediation analysis was conducted. We used Baron and Kenny's (1986) mediation analysis and non-parametric bootstrapping using R programming in four steps to test the indirect effect of spatial pleasantness (i.e., pleasantness ratings taken during the testing phase) as a mediator to the memorability of interior architectural elements (Figure 5).

It was predicted that the interior architectural elements (biomorphic and non-biomorphic) would affect spatial memorability through their effects on participants' feeling of pleasantness. Our first application of the causal step method tested whether interior architectural elements affected spatial memorability of designed environments, and if so, how. The results showed that biomorphic elements positively impacted spatial memorability. The second application of the causal step method tested the effect of interior architectural elements on participants' feeling of pleasantness. The result indicated that biomorphic elements had a positive effect on the feeling of the pleasantness construct. Step three of the method measured the positive effect of the participants' feeling of pleasantness on spatial memorability of designed environments. The final step established if there was indeed a mediating effect. In this step, the base values determined in step one were checked against the values for interior architectural elements after bringing in the feeling of

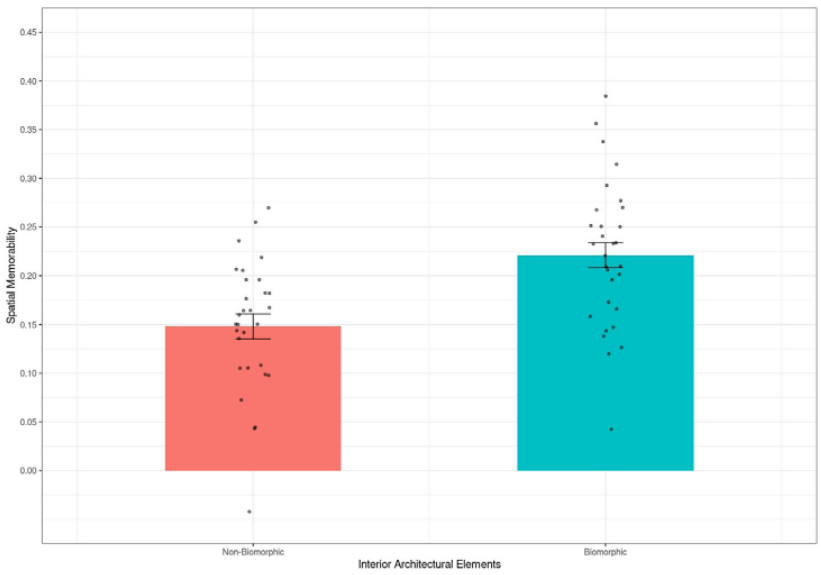


Figure 4 Spatial intrinsic memorability of design elements is significantly higher when participants looked at images with biomorphic design elements compared to images with non-biomorphic elements ($b = 0.07$, $t(58) = 4.064$, $p < .001$). The small black dots represent participants' average intrinsic memorability score per image.

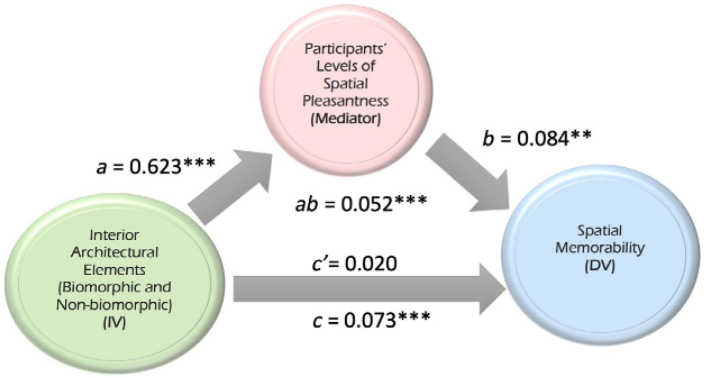


Figure 5 The mediation data analysis demonstrates how participants' feeling of pleasantness mediates the relationship between architectural elements and the intrinsic memorability of designed environments. ***$p < .001$; **$p < .01$; *$p < .05$; $^{+}p < .10$. Values are regression coefficients. Interior architectural elements coded as biomorphic [+0.5] versus non-biomorphic [−0.5].

Table 2. Mediation analysis results for the participants' feeling of pleasantness

Variable	Term	*b*	SE	*p*
Feelings of Pleasantness	*a*	0.623	0.080	<.001
	b	0.084	0.026	.004
	c'	0.020	0.023	.35
	ab	0.052	—	<.001

a, The effect of interior architectural elements on participants' level of spatial pleasantness. *b*, The effect of participants' level of spatial pleasantness on the spatial memorability, controlling for architectural design elements. *c'*, The effect of interior architectural elements on spatial memorability, controlling for the participants' level of spatial pleasantness. *ab*, The indirect effect using nonparametric bootstrapping (for more information about the mediation analysis see MacKinnon (2012).

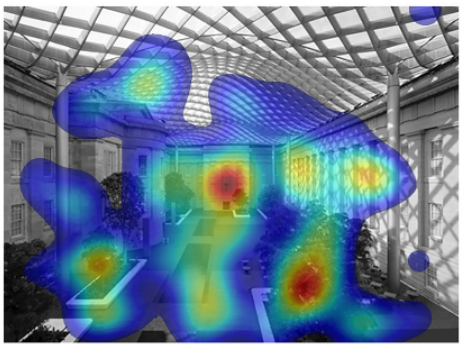
pleasantness. The effect of interior architectural elements needed to be diminished in this second step to establish a mediating effect, according to Baron and Kenny's (1986) causal step method.

In summary, the potential mediator, the feeling of pleasantness related to the interior architectural elements satisfied the conditions of mediation (Table 2) and so was indicated as a mediator. To the extent that the interior architectural elements affected the mediator, the mediator affected spatial memorability (when controlling for interior architectural elements) as the indirect effect is nonzero, and the data provided evidence for mediation. Therefore, this data is consistent with the hypothesis that a higher level of pleasantness related to the biomorphic elements increased the spatial memorability in comparison to images with non-biomorphic elements.

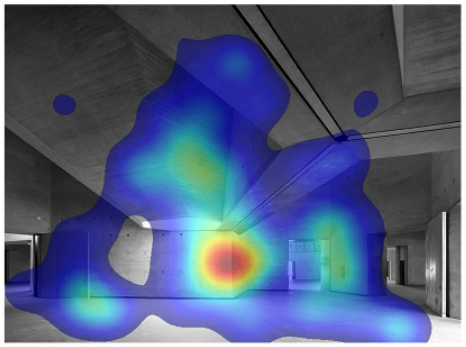
HYPOTHESIS 3: MODERATION MODEL

A moderation analysis was conducted to investigate the relationship between participants' *visual attention* to specific interior architectural elements and spatial memorability. To operationalize this construct, eye-tracker equipment was used to record participants' eye movement on the image and the duration of eye fixation on a specific spot of the image (Bojko, 2009, p. 31). An Absolute Gaze Duration Heatmap (Bojko, 2009) was used to study the correlation between the information extracted by the participant and the spatial memorability of the images that were tested during the learning phase. Color represents the amount of time that participants' eyes stayed focused on a specific area of the image. The red color areas indicate a high number of gaze points and an increased level of attention, followed by yellow, green, and blue (Figure 6).

A model on the moderating effect of visual attention on the relation between interior architectural elements and spatial memorability was tested, using the AOI (see Goldberg, 2012, for more details). In this study, AOI represents the pre-defined location of biomorphic or non-biomorphic elements in an image that are associated with the duration each participant spends looking at



An example of absolute gaze duration heatmap of a biomorphic design image



An example of absolute gaze duration heatmap of a non-biomorphic design image

Figure 6 An example of an absolute gaze duration heatmap that was used in this study. Color represents the amount of time that participants' eyes stayed focused on a specific area of the image. The red color areas indicate a high number of gaze points and increased level of attention, followed by yellow, green, and blue.

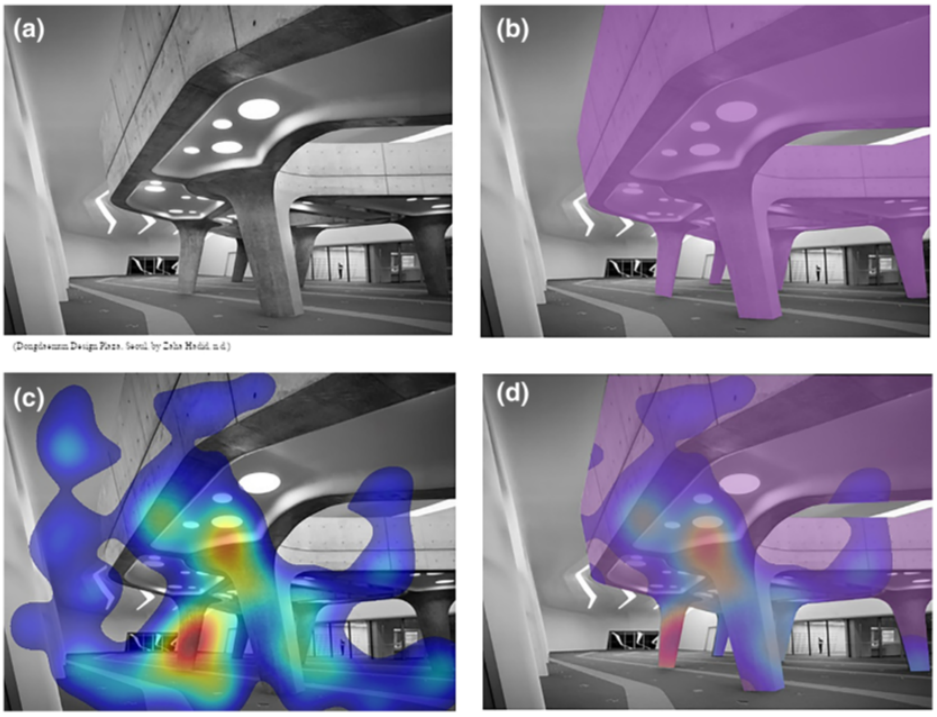


Figure 7 An example of the biomorphic mask, area of interest (AOI) was used as a quantitative measure of participant's attention to that particular object in the image. (a) Example of an entire biomorphic image. (b) Example of the biomorphic mask for the AOI. (c) Heatmap of the image. (d) Heatmap of the image that is masked by AOI.

specific elements. This AOI technique was used to measure participant's visual attention to biomorphic or non-biomorphic elements and evaluate possible relationships between interior architectural elements and spatial memorability because of participants' visual attention.

The model for quantifying visual attention to different object regions of the images is as follows:

- AOIs corresponding to biomorphic and non-biomorphic elements were defined in advance for each image (e.g., Figure 7).
- The total fixation time inside of each AOI was recorded.
- PyTribe is a python (programing language) library to connect and read data from the Eye Tribe eye-tracker. It was used to read the eye-tracker data and communicate with the Eye Tribe toolkit. This application had two different modes of operation, specifically designed for the learning and testing phases of this study.

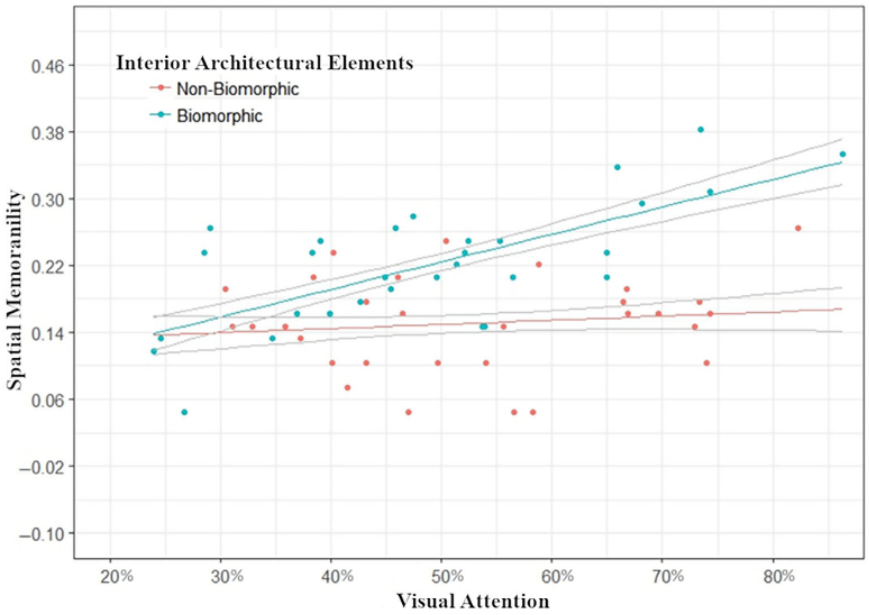


Figure 8 Visual representation of the moderation effect of architectural elements (*X*1) on spatial intrinsic memorability (*Y*) by visual attention (*X*2). The relationship between the percentage of participants' visual attention and the average spatial memorability of interior architectural design images using a recognition memory task. The red dots represent the percentage of participants' average visual attention and the average score of spatial memorability associated with non-biomorphic images. The blue dots show the percentage of participants' average visual attention and the average score of spatial memorability associated with biomorphic images.

A moderated multiple regression analysis was used to test if visual attention moderates the relationship between interior architectural elements and spatial memorability (Cohen et al., 2013), and to test if increased visual attention to specific interior architectural elements moderated spatial memorability (Cohen et al., 2013; Judd et al., 2001).

Figure 8 shows the moderation model that drives the participants' visual attention effect through observing interior architectural elements on spatial memorability of interior spaces, demonstrating a significant main effect for visual attention on spatial memorability, controlling for interior architectural elements. In other words, averaging across the interior architectural elements, a 1% increase in visual attention was associated with making 0.001-unit higher spatial memorability, $b = 0.001$, $t(56) = 3.9$, $p < .001$. This finding demonstrates that as visual attention increases, spatial memorability increases while holding the interior architectural elements constant.

Also, the simple main effect analysis suggests that a participant with the average percentage of visual attention (51%), had 0.06 units higher spatial memorability scores while looking at non-biomorphic design images than biomorphic design images ($b = -0.06$, $t(56) = -1.26$, $p = .2$). Next, the spatial memorability of each image was regressed on visual attention, the interior architectural elements, and the interaction terms for interior architectural elements and visual attention. The effect of visual attention on spatial memorability differed between the two categories of images. The slope for the relationship between visual attention and spatial memorability of images with biomorphic elements was significantly different from images with non-biomorphic elements, $b = 0.002$, $t(56) = 2.88$, $p = .005$. Therefore, as the visual attention to the interior architectural elements (specifically biomorphic) increases, the spatial memorability of those interior architectural elements also increases.

Figure 8 shows how lines associated with biomorphic images and non-biomorphic images have a positive slope. Thus, as visual attention increases through the designed images, the score of participants' spatial memorability also increases. Moreover, it is noticeable that the slope of the blue line (biomorphic) is higher than the slope of the red line (non-biomorphic). As visual attention increases, scores of biomorphic spatial memorability increase in comparison with scores of images with non-biomorphic elements.

DISCUSSION, REFLECTIONS, AND CONCLUSIONS

SUMMARY

The results suggest that interior spaces with biomorphic elements positively contribute to spatial memorability when compared to interior spaces with elements that are non-biomorphic and rectilinear. Spaces with biomorphic elements were also found to be more pleasant and increased visual attention. We measured a correlation between feelings of pleasantness and spatial memorability, as well as between designs with biomorphic elements and increased visual attention. These results should be useful to interior designers who wish to optimize the memorability of spaces.

OVERALL SPATIAL MEMORABILITY

Participants' recognition memory score related to the biomorphic elements was significantly higher than their score related to the non-biomorphic elements; a paired *t*-test and linear regression analysis supported this relationship between the biomorphic design of interior spaces and spatial memorability; the data quantitively supports the hypothesis that biomorphic elements have a positive impact on spatial memorability of semi-public interior spaces, supporting studies in perceptual psychology that have attempted to explain how *biomorphic design* impacts human recognition and memory (Feuerstein, 2001; Joye, 2007). The findings also complement studies that have predicted that people are more likely to remember biomorphic elements than non-biomorphic ones (Feuerstein, 2001; Joye, 2007).

SPATIAL PLEASANTNESS

The results suggested that an increased feeling of spatial pleasantness correlates with increased memorability of images with biomorphic elements. The findings also indicated that an increased level of pleasantness increases the likelihood of remembering interior design images in general, possibly due to a greater approach orientation toward elements found to be pleasant, as opposed to an unpleasant feeling that may prompt avoidance. These findings support the notion that human preference for pleasantness is triggered by natural shapes and forms (e.g., Kaplan & Kaplan, 1989; Vartanian et al., 2013), and that these feelings of pleasantness mediate the greater memorability of biomorphic environments.

...our findings signified that visual attention moderates the relationship between interior architectural elements and spatial memorability; participants who had a higher score of memorability of biomorphic images had a higher percentage of visual attention toward biomorphic elements.

VISUAL ATTENTION

Participants with a higher rate of visual attention toward the biomorphic elements had a higher score for spatial memorability. The findings support a portion of Attention Restoration Theory, that human connection to nature and natural forms improves concentration, decreases human mental fatigue, and enhances visual attention (Kaplan, 1995). Furthermore, our findings signified that visual attention moderates the relationship between interior architectural elements and spatial memorability; participants who had a higher score of memorability of biomorphic images had a higher percentage of visual attention toward biomorphic elements.

LIMITATIONS

The stimuli set for this study were normalized and standardized (controlling for possible influential variables such as novelty, complexity, pleasantness, and the number and density of interior architectural elements), and increasing the sample size would not appreciably increase reliability (Bridges & Holler, 2007; Piovesana & Senior, 2018). The participants were relatively diverse within their age cohort, they had a variety of backgrounds, and the sample was relatively gender balanced; this would be considered a reliable study in the milieu of Psychology. However, one could not generalize the findings to groups such as people over 30, non-students (differences in education, work experience, or social class), or non-English speakers. The sample size would need to be increased for each subgroup that might be compared within the larger sample. For instance, to

reliably measure differences between genders, the sample size would need to double. Another consideration might be creating matched samples of design students and non-design students.

In comparison with other visual short-memory research experiments such as Delorme et al. (2018), the images used in this study were more complex in their visual pattern and less distinctive from each other. For example, in the Corel dataset used in Delorme et al. (2018), there are a wide variety of subjects (ranging from fruits and animals to buildings) in colored images, but the images used in the current research were all grayscale interior images. Thus, the recognition tasks on the Corel dataset are expected to achieve a higher success rate compared with the current research. Indeed, the effect size in Hypothesis 1 ($d' = 0.14$) is rather small according to Cohen (1977). This is one of the challenges in quantifying responses to the complex stimuli sets that are experienced within interior spaces.

Other potential limitations could be the reliance on people's self-assessment for pleasurability, the use of photographs rather than physical environments, and the lack of color. Real-world environments are diverse, and it is difficult to separate the elements from the whole.

FUTURE DIRECTIONS

Adding additional parameters to this study, such as approach-avoidance decisions, could tie into overlapping research that examines other factors such as ceiling height, beauty judgments, and approach-avoidance (Vartanian et al., 2015); this would contribute to the eventual goal of assisting designers in understanding the impact of their design decisions, especially on vulnerable populations. Another modification to the research model would be to use 3D immersive environments, as that could be a better predictor of responses in real-world environments than photographs (Cha et al., 2020; Kalantari & Neo, 2020). Thinking expansively, in the not-so-distant future, it will probably be feasible to monitor subjects in real-time as they go about their daily lives; the current limitation is processing the massive amount of data that would be generated.

In another iteration of this study, the viewing time for images could be fine-tuned to get a higher number of correct responses. The dilemma with this type of sampling is that even a second or two extra viewing time can dramatically increase the number of correct responses for any stimulus set, which creates a problem with differentiating responses between the two stimulus sets. Other researchers have found that too much time for viewing the stimulus can lead to results that are not conclusive because each subject will remember an image regardless of the characteristics of the image itself.

The most direct way to improve this study would be to modify it by gathering biometric data, monitoring subjects with a portable EEG brain scanner, and measuring galvanic skin response, heart rate, and body temperature; this would assess pleasurability or other emotional reactions to the stimuli in a more precise way than asking subjects to self-assess. Broadening the scope of inquiry, a similar research design would be to isolate each of the elements of biophilic design and test which ones elicit the most pleasurable physical responses or the strongest spatial memory. Expanding even more, using environments with groups of biophilic elements as stimuli could give insights into which elements or combinations of elements produce the strongest reactions; this could have budgetary implications, allowing designers to know where to spend money to get the most effective result. This envisions a future where interior designers become like physicians, "prescribing" spaces tailored to particular users' needs.

CONFLICT OF INTEREST

We have no known conflict of interest to disclose.

ETHICS STATEMENT

Participants in this study expressed their written consent to take part in the eye-tracking experiment and the affection survey to fill in an anonymous self-reported paper and pencil questionnaire. This study was reviewed and approved by the Institutional Review Board at the University of Wisconsin-Madison.

ENDNOTE

[1]The fixation occurs when a participant's eye is fixed on a specific spot of the stimulus (Bojko, 2009).

REFERENCES

Alvares, A. (2014). *Museum of memory: An analysis of how museum circulation can help visitors remember a space*. Paper presented at ANFA Conference (pp. 8–9). https://www.brikbase.org/content/museum-memory-analysis-how-museum-circulation-can-help-visitors-remember-space.

Bainbridge, W. A. (2019). Memorability: How what we see influences what we remember. *Psychology of Learning and Motivation*, 70, 1–27.

Ballantyne, A. (Ed.). (2002). *What is architecture?* (1st ed.). Routledge.

Baron, R. M., & Kenny, D. A. (1986). The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of personality and social psychology*, 51(6), 1173.

Birren, F. (1978). *Color and human response*. Van Nostrand Reinhold Company.

Bojko, A. A. (2009). *Informative or misleading? Heatmaps deconstructed*. Paper presented at International conference on human-computer interaction, Springer, Berlin Heidelberg (pp. 30–39).

Borkin, M. A., Vo, A. A., Bylinskii, Z., Isola, P., Sunkavalli, S., Oliva, A., & Pfister, H. (2013). What makes a visualization memorable? *IEEE Transactions on Visualization and Computer Graphics*, 19(2), 2306–2315.

Bradley, M. M., Codispoti, M., Cuthbert, B. N., & Lang, P. J. (2001). Emotion and motivation I: Defensive and appetitive reactions in picture processing. *Emotion*, 1(3), 276–298.

Bradley, M. M., Greenwald, M. K., Petry, M. C., & Lang, P. J. (1992). Remembering pictures: Pleasure and arousal in memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 18(2), 379–390.

Bridges, A. J., & Holler, K. A. (2007). How many is enough? Determining optimal sample sizes for normative studies in pediatric neuropsychology. *Child Neuropsychology*, 13(6), 528–538. https://doi.org/10.1080/09297040701233875

Buchanan, T., & Adolphs, R. (2003). The role of the human amygdala in emotional modulation of long-term declarative memory. In S. Moore & M. Oaksford (Eds.), *Emotional cognition: From brain to behavior* (pp. 9–34). John Benjamins.

Bulling, A., Roggen, D., & Tröster, G. (2009). *Wearable EOG goggles: Eye-based interaction in everyday environments*. Paper presented at CHI '09 extended abstracts on human factors in computing systems (CHI EA '09). Association for Computing Machinery (pp. 3259–3264). https://doi.org/10.1145/1520340.1520468

Carlson, L., Hölscher, C., Shipley, T., & Dalton, R. (2010). Getting lost in buildings. *Current Directions in Psychological Science*, 19(5), 284–289.

Celikkale, B., Erdem, A., & Erdem, E. (2013). *Visual attention-driven spatial pooling for image memorability*. Paper presented at Proceedings of the 2013 IEEE conference on computer vision and pattern recognition workshops (CVPRW '13). IEEE Computer Society (pp. 976–983). https://doi.org/10.1109/CVPRW.2013.142

Cha, S. H., Zhang, S., & Kim, T. W. (2020). Effects of interior color schemes on emotion, task performance, and heart rate in immersive virtual environments. *Journal of Interior Design*, 45(4), 51–65. https://doi.org/10.1111/joid.12179

Cho, J. Y., & Suh, J. (2021). The architecture and interior design domain-specific spatial ability test (AISAT): Its validity and reliability. *Journal of Interior Design,* 47(2), 11–30. https://doi.org/10.1111/joid.12211

Coburn, A., Vartanian, O., & Chatterjee, A. (2017). Buildings, beauty, and the brain: A neuroscience of architectural experience. *Journal of Cognitive Neuroscience*, 29(9), 1521–1531.

Coburn, A., Vartanian, O., Kenett, Y. N., Nadal, M., Hartung, F., Hayn-Leichsenring, G., Navarette, G., González-Mora, J. L., & Chatterjee, A. (2020). Psychological and neural responses to architectural interiors. *Cortex*, 126, 217–241.

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences*. Academic Press.

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2013). *Applied multiple regression/correlationanalysis for the behavioral sciences*. Routledge.

Cupchik, G. C., & Berlyne, D. E. (1979). The perception of collative properties in visual stimuli. *Scandinavian Journal of Psychology*, 20(2), 93–104. https://doi.org/10.1111/j.1467-9450.1979.tb00688.x

Dalton, R., Hölscher, C., & Spiers, H. (2015). Navigating complex buildings: Cognition, neuroscience and architectural design. In J. Gero (Ed.), *Studying visual and spatial reasoning for design creativity* (pp. 3–22). Springer. https://doi.org/10.1007/978-94-017-9297-4_1

Delorme, A., Poncet, M., & Fabre-Thorpe, M. (2018). Briefly flashed scenes can be stored in long-term memory. *Frontiers in Neuroscience*, 12, 688. https://doi.org/10.3389/fnins.2018.00688/full

Dohr, J. H., & Portillo, M. (2011). *Design thinking for interiors: Inquiry, experience, impact*. John Wiley & Sons.

Duc, A. H., Bays, P., & Husain, M. (2008). Eye movements as a probe of attention. *Progress in Brain Research*, 171, 403–411.

Duchowski, A. T. (2003). *Eye tracking methodology – Theory and practice* (3rd ed.). Springer.

Dzulkifli, M. A., & Mustafar, M. F. (2013). The influence of colour on memory performance: A review. *The Malaysian Journal of Medical Sciences*, 20(2), 3–9.

Eberhard, J. P. (2008). *Brain landscape the coexistence of neuroscience and architecture*. Oxford University Press.

Eberhard, J. P. (2009). Applying neuroscience to architecture. *Neuron*, 62(6), 753–756. https://doi.org/10.1016/j.neuron.2009.06.001

Farley, F. H., & Grant, A. P. (1976). Arousal and cognition: Memory for color versus black and white multimedia presentation. *The Journal of Psychology*, 94(1), 147–150.

Feuerstein, G. (2001). *Biomorphic architecture: Human and animal forms in architecture*. Edition Axel Menges.

Foulsham, T., & Underwood, G. (2008). What can saliency models predict about eye movements? Spatial and sequential aspects of fixations during encoding and recognition. *Journal of Vision*, 8(2), 1–17. https://doi.org/10.1167/8.2.6

Gifford, R. (2009). Environmental psychology: Manifold visions, unity of purpose. *Journal of Environmental Psychology*, 29(3), 387–389.

Gifford, R. (2016). *Research methods for environmental psychology* (1st ed.). Wiley-Blackwell.

Goldberg, J. H. (2012). *Relating perceived web page complexity to emotional valence and eye movement metrics*. Paper presented at Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56(1), 501–505.

Higuera-Trujillo, J. L., Llinares, C., & Macagno, E. (2021). The cognitive-emotional design ad study of architectural space: A scoping review of neuroarchitecture and its precursor approaches. *Sensors*, 21, 2193. https://doi.org/10.3390/s21062193

Hu, L., & Shepley, M. M. (2022). Design meets neuroscience: A preliminary review of design research using neuroscience tools. *Journal of Interior Design*, 47(1), 31–50. https://doi.org/10.1111/joid.12213

Isola, P., Parikh, D., Torralba, A., & Oliva, A. (2011). *Understanding the intrinsic memorability of images*. Paper presented at Proceedings of the 24th international conference on neural information processing systems (NIPS'11) (pp. 2429–2437). Curran Associates Inc. https://proceedings.neurips.cc/paper/2011/file/286674e3082feb7e5afb92777e48821f-Paper.pdf.

Joye, Y. (2007). Architectural lessons from environmental psychology: The case of biophilic architecture. *Review of General Psychology*, 11(4), 305–328.

Judd, C. M., Kenny, D. A., & McClelland, G. H. (2001). Estimating and testing mediation and moderation in within-subject designs. *Psychological Methods*, 6(2), 115–134. https://doi.org/10.1037/1082-989X.6.2.115

Juliá Nehme, B., Rodríguez, E., & Yoon, S. Y. (2020). Spatial user experience: A multidisciplinary approach to assessing physical settings. *Journal of Interior Design*, 45(3), 7–25. https://doi.org/10.1111/joid.12177

Juliá Nehme, B., Torres Irribarra, D., Cumsille, P., & Yoon, S. Y. (2021). Waiting room physical environment and outpatient experience: The spatial user experience model as analytical tool. *Journal of Interior Design*, 46(4), 27–48. https://doi.org/10.1111/joid.12205

Kalantari, S., & Neo, J. R. (2020). Virtual environments for design research: Lessons learned from use of fully immersive virtual reality in interior design research. *Journal of Interior Design*, 45(3), 27–42. https://doi.org/10.1111/joid.12171

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, 15(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kellert, S. R., Heerwagen, J., & Mador, M. (2008). *Biophilic design: The theory, science, and practice of bringing buildings to life*. Wiley.

Kensinger, E. A., & Corkin, S. (2003). Effect of negative emotional content on working memory and long-term memory. *Emotion*, 3(4), 378–393. https://doi.org/10.1037/1528-3542.3.4.378

Kim, D. Y. (2010). *The interactive effects of colors on visual attention and working memory: In case of images of tourist attractions*. Paper presented at the International CHRIE Conference-Refereed Track. https://

scholarworks.umass.edu/refereed/CHRIE_2010/Saturday/1/

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1999). *International affective picture system (IAPS): Technical manual and affective ratings. The Center for Research in Psychophysiology*, University of Florida.

Levine, M. (1982). You-are-here map psychological considerations. *Environment and Behavior*, 14(2), 221–237. https://doi.org/10.1177/0013916584142006

MacKay, D. G., & Ahmetzanov, M. V. (2005). Emotion, memory, and attention in the taboo stroop paradigm an experimental analogue of flashbulb memories. *Psychological Science*, 16(1), 25–32. https://doi.org/10.1111/j.0956-7976.2005.00776.x

MacKinnon, D. P. (2012). *Introduction to statistical mediation analysis*. Routledge.

Mancas, M., & Le Meur, O. (2013). *Memorability of natural scenes: The role of attention*. Paper presented at 20th IEEE international conference on image processing (ICIP) (pp. 196–200). doi: https://doi.org/10.1109/ICIP.2013.6738041

Martini, P., & Maljkovic, V. (2009). Short-term memory for pictures seen once or twice. *Vision Research*, 49(13), 1657–1667. https://doi.org/10.1016/j.visres.2009.04.007

McGee, B., Park, N. K., Portillo, M., Bosch, S., & Swisher, M. (2019). Diy biophilia: Development of the biophilic interior design matrix as a design tool. *Journal of Interior Design*, 44(4), 201–221. https://doi.org/10.1111/joid.12159

Nadal, M., Munar, E., Marty, G., & Cela-Conde, C. J. (2010). Visual complexity and beauty appreciation: Explaining the divergence of results. *Empirical Studies of the Arts*, 28(2), 173–191. https://doi.org/10.2190/EM.28.2.d

Noton, D., & Stark, L. (1971). Eye movements and visual perception. *Scientific American*, 224(6), 34–43.

Olivers, C. (2008). Interactions between visual working memory and visual attention. *Frontiers in Bioscience: a Journal and Virtual Library*, 13(3), 1182–1191.

Pan, Y. (2010). Attentional capture by working memory contents. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, 64(2), 124–128. https://doi.org/10.1037/a0019109

Piovesana, A., & Senior, G. (2018). How small is big: Sample size and skewness. *Assessment*, 25(6), 793–800. https://doi.org/10.1177/1073191116669784

Robinson, S., & Juhani, P. (2015). *Mind in architecture: Neuroscience, embodiment, and the future of design*. The MIT Press.

Russell, J. A. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology*, 39(6), 1161–1178. https://doi.org/10.1037/h0077714

Rust, N. C., & Mherpur, V. (2020, July). Understanding image memorability. *Trends in Cognitive Sciences*, 24(7), 557–568. https://doi.org/10.1016/j.tics.2020.04.001

Shi, Y., Du, J., & Ragan, E. (2020). Review visual attention and spatial memory in building inspection: Toward a cognition-driven information system. *Advanced Engineering Informatics*, 44, 101061.

Smilek, D., Dixon, M. J., Cudahy, C., & Merikle, P. M. (2002). Synesthetic color experiences influence memory. *Psychological Science*, 13(6), 548–552. https://doi.org/10.1111/1467-9280.00496

Smith, A. P. R., Henson, R. N. A., Rugg, M. D., & Dolan, R. J. (2005). Modulation of retrieval processing reflects accuracy of emotional source memory. *Learning & Memory*, 12(5), 472–479.

Suh, J., & Cho, J. Y. (2021). A triangular relationship of visual attention, spatial ability, and creative performance in spatial design: An exploratory case study. *Journal of Interior Design*, 46(3), 11–27. https://doi.org/10.1111/joid.12194

Torralba, A., Oliva, A., Castelhano, M. S., & Henderson, J. M. (2006). Contextual guidance of eye movements and attention in real-world scenes: The role of global features in object search. *Psychological Review*, 113(4), 766–786.

Vartanian, O., Navarette, G., Chatterjee, A., Fich, L. B., Gonzalez-Mora, J. L., Leder, H., Modrono, C., Nadal, M., Rostrup, N., & Skov, M. (2015). Architectural design and the brain: Effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions. *Journal of Environmental Psychology*, 41, 10–18. https://doi.org/10.1016/j.jenvp.2014.11.006

Vartanian, O., Navarrete, G., Chatterjee, A., Brorson Fich, L., Leder, H., Mondrono, C., Nadal, M., Rostrup, N., & Skov, M. (2013). Impact of contour on aesthetic judgments and approach-avoidance decisions in architecture. *Proceedings of the National Academy of Sciences of the United States of America*, 110-(Supplement 2), 10446–10453. https://doi.org/10.1073/pnas.1301227110

Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Leder, H., Modroño, C., Rostrup, N., Skov, M., Corradi, G., & Nadal, M. (2019). Preference for curvilinear contour in interior architectural spaces: Evidence from experts and

nonexperts. *Psychology of Aesthetics, Creativity, and the Arts*, 13(1), 110–116. https://doi.org/10.1037/aca0000150

Zadra, J. R., & Clore, G. L. (2011). Emotion and perception: The role of affective information. *Wiley Interdisciplinary Reviews. Cognitive Science*, 2(6), 676–685. https://doi.org/10.1002/wcs.147

Zeisel, J., & Eberhard, J. P. (2006). *Inquiry by design: Environment/behavior/neuroscience in architecture, interiors, landscape, and planning (revised edition)*. W. W. Norton.

BIOGRAPHIES

Hasti Mirkia received her Ph.D. from the Design Studies Department at the University of Wisconsin (UW)-Madison. Her research interests are in neuroarchitecture and evidence-based design such as interdisciplinary approaches to improve health and well-being outcomes in healthcare environments.

Mark S. C. Nelson is Professor Emeritus in the Design Studies Department at UW-Madison. His research interests are in neuroarchitecture, visuality, memory, aesthetics, and material culture.

Heather Abercrombie is a Senior Scientist and Licensed Psychologist at the Center for Healthy Minds at UW-Madison. She is an expert in stress neurobiology, depression, and emotional memory formation.

Kristín Thorleifsdóttir is a former assistant professor in Design Studies and Landscape Architecture at UW-Madison. In her research, she specializes in environment and behavior studies particularly issues that relate to people's experiences in everyday environments and the influence planning and design have on health and well-being.

Arash Sangari is Senior Director of Data Science at Walmart. He has been focused on analyzing networks of dynamical systems in consumer demand, social networks, visual search, and visual attention.

Amir Assadi studied at UC Berkeley, Princeton, and the Marine Biological Laboratory. He held faculty positions at the University of Virginia and UW-Madison and retired in 2018. His research specialties are topology, symmetry, computational neuroscience, and systems biology. He also has a long-standing interest in the interface of visual arts and mathematics.