A Framework for Quantifying the Temporal Visual Experience of Architecture

A Case Study of the Sheikh Lotfollah Mosque

Sayyed Amir Hossain Maghool[1], Marc Aurel Schnabel[2] and Tane Moleta[3]
[1, 2, 3] *Victoria University of Wellington, Wellington, New Zealand*
{sayyedamirhossain.maghool[1], marcaurel.schnabel[2], tane.moleta[3]}@vuw.ac.nz

Abstract: In this paper, we propose a framework for the quantification of the temporal visual experience of architecture. This framework provides quantification of low-level visual features of architectural experience in the temporal domain. It facilitates the investigation of the interrelation between architecture and automatic physiological responses, resulting in more insights about how architecture impacts emotion. Thus, we implement four computational algorithms developed upon the processing fluency theory which were initially used for the study of visual regularities of abstract artworks. Furthermore, we illustrate the potentials of this framework by applying it to data gathered from a VR simulation of an existing building. Our case study suggests that this framework can be used for systematic quantification of low-level visual features of architectural experience that account for the role of movement.

Keywords: Visual features; Virtual Reality; Architectural Experience; Fractal Dimension.

1. Introduction

Architectural experience is generated as a result of humans' perception of external information in the built environment through humans' sensory systems. Review of empirical findings from the field of environmental psychology, aesthetics, and neuroscience reveals that, among all sensory mechanisms, vision is the dominant human sense that heavily influences humans' affective system. As a result, a considerable amount of research has sought to find the interrelation between architecture and emotions evoked because of visual stimuli (Mehrabian and Russell, 1974; Bower et al., 2019). However, we still know little about this interrelation. With the recent advancement of technology such as virtual reality (VR) and photogrammetry, researchers and designers can visually simulate an experience of a building before its construction or accurately simulate the experience of existing buildings (Rushton and Schnabel, 2020) in a lab environment.

Conversely, computational methods have shown their capabilities in predicting human perception of visual stimuli in an objective way (Machado et al., 2015). To elaborate, quantification of low-level visual

Imaginable Futures: Design Thinking, and the Scientific Method. 54th International Conference of the Architectural Science Association 2020, Ali Ghaffarianhoseini, et al (eds), pp. 91–100. © 2020 and published by the Architectural Science Association (ANZAScA).

features (Mayer and Landwehr, 2018) provides potentials for decoding the link between humans' preferences and their surrounding environment. In this paper, we present a framework that combines these two recent research streams into one system that can be used for a computerised quantification of the temporal visual experience of architecture. This framework employs VR and image processing techniques for quantifying temporal low-level visual features of architectural images. To the best of our knowledge, this is the first time that the human visual experience of architecture has been investigated using a VR setup through the concept of algorithmic quantification of multiple visual features.

2. The Framework

To quantify the visual features of architectural experiences, we propose a framework comprised of two main parts. The first part includes the acquisition of visual material from an architectural experience. This part introduces simulation of architectural experiences and a mechanism for extracting sequential visual data from it. The second part includes the extraction of low-level visual features on the material provided from the last part. For the second part, we propose the adoption of four algorithms introduced by Mayer and Landwehr (2018). These two combined parts produce valuable low-level time-series data about the visual perception of a building for a moving inhabitant. Later we will illustrate the potential of this framework by applying it to data gathered from a simulation of a specific architectural experience. We expect that quantification of low-level visual features of an architectural walk-through in time domain will facilitate the investigation of interrelation between architecture and automatic physiological responses, resulting in new insights about how architecture impacts emotion.

3. Acquisition of Sequential Visual Data of Architecture

Humans are hardwired to make spontaneous unconscious reactions to their external world (Diano et al., 2017). Kandel et al. (2000) state that: 'most of our impressions about the world and our memories of it are based on sight' (cited in Hutmacher, 2019). It has been shown that even judgments about auditory information can be manipulated by exposure to different visual information (Tsay, 2013). Likewise, in most cases, architects are expected to design buildings that can be seen by humans' visual system. Thus, many times, buildings are judged based on their visual features.

Similarly, many studies conducted at the intersection of psychology and neuroscience (Mehrabian and Russell, 1974) have attempted to conduct experiments to study the visual qualities of architecture using 2D architectural images. Although these studies provide insight into the interrelation between visual features of the surrounding environment and humans' preferences, these studies are limited in terms of providing a comprehensive understanding of this enigmatic topic. It is mostly because these studies use orthogonal images as the foundational material for these investigations (Vaughan and Ostwald, 2014). Furthermore, the studies that have addressed this deficiency by using photographs or computer-generated human views of buildings (Vartanian et al., 2015; Choo et al., 2017; Jamalabadi et al., 2018) are limited in both scope and findings. To elaborate, it crucial to define the importance of movement in the perception of architecture. This is a critical component which is absent from much current literature.

As Rasmussen (1964) says, 'It is not enough to see architecture; you must experience it'. In contrast to many other types of creative practice, the user of a space exposes him or herself to the various visual characteristics of space through movement around a building. As a matter of fact, 'architecture owes its existence to form and space, whose perception owes a great deal to movement' (Ahmadi, 2019). This characteristic has been discussed in critical architectural texts. Christopher Alexander argues how movement and spatial sequence regarding the parameter of time create the fourth dimension of our perceptual realm (Alexander et al., 1977, cited in Barrie, 1996). Similarly, Barrie (1996) argues how shifting view alongside variations of physical attributes of the surrounding environment are essential components of the experience of architecture. Correspondingly, modern theories of emotion emphasise the role of regularities and patterns in the stream of sensory information on triggering human emotional responses (Fridman et al., 2019). As Barrett (2017) argues, 'the brain does not process individual stimuli—it processes events across temporal windows. Emotion perception is event perception, not object perception.' In a research study, Vaughan and Ostwald (2014) use computer-generated images of an architectural experience based on a specific path inside Frank Lloyd Wright's Robie House. In that work, they apply mathematical operations on 2D CAD images generated from a simulation of movement inside Robie House for investigation of change in the fractal dimension. However, the number of images, the method of simulation of the path of movement, and the abstract nature of the 2D perspective used for this purpose limits the findings of that piece of work. Following Vaughan and Ostwald's (2014) argument and Barrett's (2017) theory of emotion, we argue that a static perspective view is incapable of revealing the truth about architectural experiences.

A review of recent empirical literature illustrates that studies address this point by utilising in situ or VR tests that involve real movements to investigate the impact of architecture on observers (Homolja et al., 2020). Among all the presentation methods, VR can provide the richest simulation of an architectural space, because VR is effective in terms of evoking a sense of presence and is capable of conveying relatively accurate information about the scale and the size of a space (Cha et al., 2019). Additionally, VR is valuable because it provides an opportunity for users to walk inside architectural spaces naturally. To address the importance of movement in the perception of architecture in our framework, screen records of what a person is looking at during an immersive architectural experience simulation will be extracted for further analyses, as explained in the next section.

4. Visual Features Extraction

Since humans' visual perception system has evolved through the evolution process, some theories state that the presence of some visual statistical regularities can impact humans emotionally (Graham and Field, 2007). Based on the understanding of emotion and affect state explained earlier, the question here is which visual characteristics of the surrounding environmental setting can trigger unconscious affective responses? Moreover, how can we effectively decode those characteristics? In an attempt to answer these questions, a well-established body of knowledge from the fields close to architecture has already proposed a series of methods for decoding low-level visual stimuli (El-gayar et al., 2013; Lin et al. 2018). These methods shed light on the possibility of using computational power to gain a deeper understanding of architecture that accounts for the role of human visual perception as an integral parameter of the human-environment equation.

In this part, we explain four computerized algorithms that can provide objective and repeatable indicators for temporal visual regularities of interior architecture. The rationale behind how these visual features are linked to human perception and aesthetic preferences are discussed more in-depth in Mayer and Landwehr's article (2018). In that article, the authors describe how they have adopted the "processing fluency theory" to explain the psychological mechanism of these algorithms, which decode low-level visual features. Here we provide a brief explanation about each of these features and how we have utilised them for the benefit of our framework.

4.1. The Measure of Self-Similarity (Fractal Dimension)

Self-similarity can be defined as the level of the resemblance of a form to its components. It has been suggested that humans are more efficient while processing visual stimuli with fractal characteristics (Menzel et al., 2015) and show a preference for it. Also, it has been proposed that people express preferences for fractal-like patterns in the context of architecture (Sala, 2003, 2006). Likewise, Hagerhall et al. (2004), which investigated the fractal dimension of landscape silhouette as a correlate of landscape preferences, state that “fractal dimension could provide part of the explanation to the well- documented connection between preference and naturalness.” Fractal dimension can be systematically quantified using a technique named Power Spectral Analysis (PSA). It has been found that for a 2D image, the fractal dimension is a linear function of the slope of a line that is fitted to the log-log graph of spatial frequency amplitude spectrum (Graham and Field, 2007). Moreover, the visual structure of natural images computed via PSA tends to show a 1/f2 characteristic (Mayer and Landwehr, 2018). To elaborate, when the rotational average of the PSA (Ruzanski, 2020) is plotted against frequency on a log- log plane, a slope close to -2 is expected for images that have similar visual regularities to natural images.

4.2. The Measure of Visual Complexity

Simple visual data contain little information, and as a result, they need less cognitive processes. In contrast, complex images have more information and are subject to less information fluency (Reber et al., 2004). Mayer and Landwehr (2018) introduce visual complexity and visual simplicity as another low- level measure for information embedded in a visual stimulus. There are some pieces of evidence of how variation in the level of visual information rate can positively influence an observer’s preference toward a stimulus (Grütter, 1987). For instance, it has been shown that more straightforward sequences of visual stimuli are less pleasant compared to complex stimuli, as their information rate decline over time (Berlyne, 1970). In the context of architecture, visual complexity can be manipulated with different design decisions such as the amount and diversity of decoration and ornamentation contained in a space. Jang et al. (2018), which have studied the impact of visual complexity of store designs on consumer responses, argue that visual complexity of an interior form triggers higher emotional arousal in users of a space.

Furthermore, visual complexity has been quantified through the concept of algorithmic information theory. According to empirical studies, visual metrics such as edge density and the size of 2D image files after applying compression methods have been shown to be efficient indicators for the level of visual complexity (Fernandez-Lozano et al., 2019). Similarly, Mayer and Landwehr (2018) state that ‘... picture simplicity can be measured accurately by image compression rates because complex images are denser and have fewer redundancies than simple images’. They propose a standardised way of using the file size of compressed images to measure visual complexity with an algorithmic approach. Since it is difficult for a regular person to grasp the logic behind this method, we replaced this algorithm with an edge density algorithm that has also been shown as a strong predictor of human complexity perception (Machado et al., 2015).

4.3. The Measure of Symmetry

Visual symmetry can be defined as ‘the similarity of part of an image under transformations such as translation or reflection’ (Mayer and Landwehr, 2018). A picture or an image is symmetrical when it is mirrored along one axis or multiple axes. In addition to its use in architecture, symmetry plays an essential role in nature, industry, and art (Enquist and Arak, 1994). Symmetry affects aesthetic judgement (Gartus and Leder, 2013), perhaps because the presence of symmetry causes a sense of balance or equilibrium in architecture (Williams, 1999).

Humans are hardwired to react to visual symmetry; they are highly proficient at the perception and detection of symmetry (Treder, 2010). Following Mayer and Landwehr's procedure, it is possible to measure visual symmetry using computational algorithms. To achieve that an image can be split into two separate pieces along the middle vertical axis. Then, the correlation between the values of each part will be used as an indicator of vertical symmetry. Through our test, we only examined global vertical symmetry; however, other types of symmetry can be evaluated using similar algorithms.

4.4. The Measure of Contrast

According to Mayer and Landwehr (2018), the contrast of visual stimuli is not a well-defined topic in visual data quantification literature. However, it can be described as the extent to which the components of an image have a similar level of luminance. Furthermore, Näsänen et al. (2001) suggest that contrast of stimuli has a strong effect on the speed of eye movement in visual tasks, which provides evidence of the interrelation between this low-level feature and unconscious body reactions.

Mayer and Landwehr (2018) argue that measuring contrast via measuring root mean squared (RMS) of all pixels in an image provides valuable insight into the fluency of an image. Likewise, we developed an algorithm to measure the level of contrast for computing low-level visual data in our framework. We predict that the contrast feature in the immediate surroundings caused by various architectural decisions plays an essential role in the perception of architecture.

5. Case Study of the Sheikh Lotfollah Mosque

To test the computerized version of algorithms mentioned above, we conducted a case study. The building used to test this approach is the Sheikh Lotfollah Mosque constructed in the 16th century in Isfahan, Iran. We selected this building since it is rich in terms of visual elements such as the ornamentations which are inspired by Mandalas art. Another motivation for selecting this building is that it is designed in a way that there is only one way of entering and exiting the building. Therefore, the path of movement for this building is well defined.

First, to create a virtual simulation of this building, we generated a 3D model using the photogrammetry technique (Schnabel and Aydin, 2015). To achieve that, we collected 3111 images of the building. 'Meshroom' photogrammetry software has been used for generating a 3D model of the mosque based on those photos. Later, we re-scaled and cleaned up the 3D model by utilising Autodesk 3DS MAX 2018 and Autodesk Meshmixer. Finally, the model was imported to Unreal Engine 4 to generate an immersive VR experience.

To extract visual material of the field of view (FOV) through the test, we attached a virtual camera to the VR user's head location. A module was coded to store the location and rotation of that virtual camera during the testing session. Later, we used the recorded tracking data to extract a perspective view of the user during the duration of the experience. We exported the visual data presented in the user's FOV during the VR exploration to image files formatted as PNG at the temporal rate of 30Hz.

One of the authors of this paper was asked to wear an HTC VIVE PRO EYE and walk naturally through the VE. This natural movement occurred at three sub-pathways of the building (Figure 1): The entrance, hallway, and the main hall. It produced 800 distinct time-stamped PNG files for each of the three spaces (total number of 2400 images). We converted the images to the greyscale using OpenCV's "rgb2gray" function to standardise the data and make analyses more time-efficient. Alongside that, we lowered the resolution to 1920*1080 pixels. Also, since our visual similarity algorithm works better on square images, we cropped all images to a square shape (1080*1080 pixels).

To implement the second part of the framework, the four computational algorithms for quantifying low-level visual features were applied to all images. It has been achieved by using OpenCV library for Python and a series of Python modules developed by the authors of this paper based on the instructions provided in (Mayer and Landwehr, 2018) and (Machado et al., 2015).

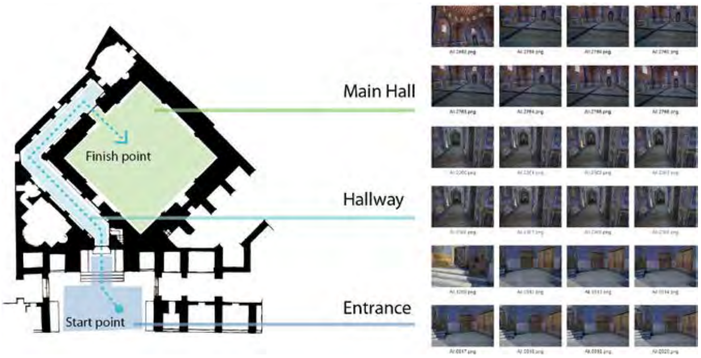

Figure 1: The path of movement.

6. Results

Figure 1 shows the schematic path of movement of the user inside the virtual simulation of the Sheikh Lotfollah Mosque. The values of each visual parameter calculated for each of the 2400 images are presented in Figure 2. To remove noise from the data, we applied a temporal noise filter with a window size of 100 frames. The data visualised in Figure 2 reveals that most of the visual features during the exploration of the Sheikh Lotfollah Mosque vary over time, especially while transitioning between different spaces (at frames 800 and 1600). The overall trend in the variations of the features alongside the data trends for each space is captured by fitting a linear regression model to the data using the "polyfit" function of the NumPy library for Python. The coefficient of the regression line indicates whether there is an overall increase or decrease associated with any of the features for the duration of the test.

In general, as illustrated in Figure 2, there is a significant increase over self-similarity characteristics from the beginning to the end of the test. The path starts with a medium degree of fractal dimension. After entering the second space, the overall value of this parameter increases slightly, but with less fluctuations compared to the previous space. Interestingly, there is a significant increase in this value when users enter the main hall. It seems that this measure is influenced by the geometry of decoration and ornamentation designed in each space. The highest points in the graph relate to the situations where the user is looking toward the decoration of the dome in the main hall.

According to Figure 2, visual complexity calculated via edge density has an overall increase. Also, a clear change in the visual complexity of the space is demonstrated while entering the main hall; A significant increase in visual complexity at the 1600th frame is noticeable. Like the self-similarity parameter, the geometry and richness of the decorations in the main hall are the primary reasons for this increase (Figure 2). Interestingly, although visual complexity and self-similarity measure different visual features, there are similar behaviours for both measures on the data analysed.

Furthermore, the building's physically symmetrical attributes are reflected through analyses of vertical symmetry on image sequences. It seems that there is no noticeable overall trend in this parameter while looking at the slope of the fitted line into all data. There is a big decrease in measure vertical symmetry around the 1500th data-point. Interestingly, this fluctuation is happening when the user enters the main hall.

An analysis of the contrast feature (Figure 2) reveals that there is a marginal decline over this parameter for the whole experience. However, the difference between the level of contrast is more apparent within adjacent spaces. To elaborate, entering the hallway decreases the level of contrast significantly. Moreover, by entering the next space, we can observe an overall increase over the same feature. The variation of contrast seems to be a function of the number and the size of openings for each space. In this building, there are 18 small shaded openings and one big opening for the main hall compared to the three small shaded openings of the whole hallway. Also, this parameter can be a function of the lightness of the materials used on the interior surface of the space.

7. Discussion and Conclusion

In this paper, we presented a framework that is designed to address the challenge of quantification of architectural experiences. The effectiveness of this framework for computing the visual aspect of the architectural experience has been demonstrated via a case study. The use of VR as a medium to conduct a simulation of movement inside a virtual building provided an opportunity for a systematic investigation of visual features associated with the experience of Sheikh Lotfollah Mosque.

Data provided from this framework reveals how low-level visual features of a building can vary because of the movement inside the building. It is noteworthy to mention that the current version of this framework is capable of capturing part of the visual features of a space. However, there are no limits to implementing more algorithms to capture other low-level visual features. Concretely, data provided via this framework can be combined with objective physiological data (bio-signals) and subjective data about affect (pleasure, dominance, and arousal) to find patterns between the sequence of visual features and corresponding emotion and affect responses in architecture (Maghool et al., 2020). This task can be done by employing machine learning algorithms that create multi-variable mathematical models.

It is noteworthy to mention that although we have used VR for collecting the sequence of visual data during an architectural experience, the same computation can be applied for real exploration of existing buildings. Therefore, a method should be implemented to record what a person is looking at during the exploration of the building. Finally, we expect that using eye-trackers will refine this framework by providing more accurate data about the exact visual stimuli at each instance of time during an architectural experience in VR or a real environment.

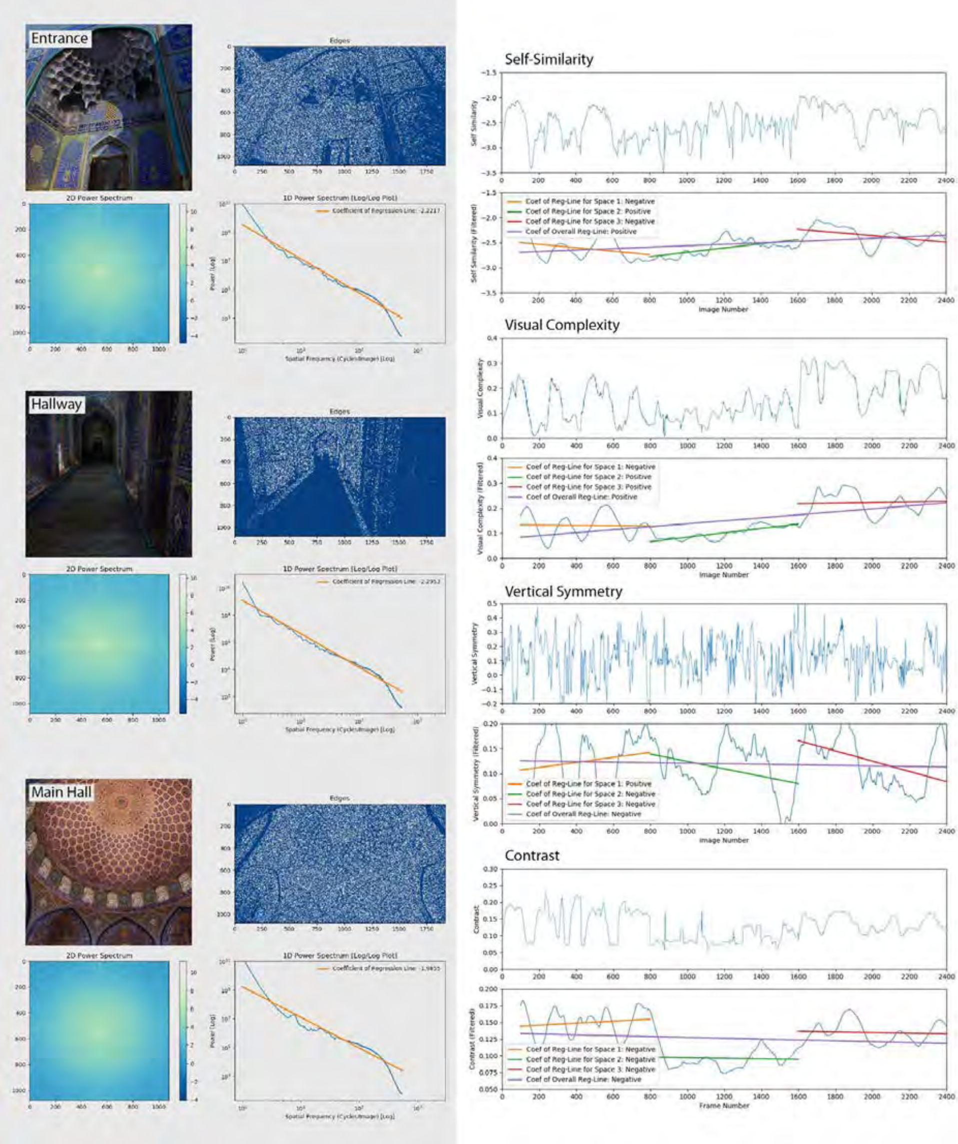

Figure 2: The edge detection and PSA algorithms applied on three images from each of the three spaces (left side). Time-series data produced after applying four algorithms on all images (right side).

Acknowledgements

We wish to thank Mr Yazdirad for his help in providing a part of the materials used in the photogrammetry process of Sheikh Lotfollah Mosque.

References

Ahmadi, M. (2019) The experience of movement in the built form and space: A framework for movement evaluation in architecture, *Cogent Arts & Humanities,* 6(1), 1588090.

Alexander, C., Ishikawa, S., Silverstein, M., Jacobson, M., Fiksdahl-King, I. and Angel, S. (1977) *A Pattern Language: Towns, Buildings, Construction,* ed., Oxford University Press, New York.

Barrett, L. F. (2017) The theory of constructed emotion: an active inference account of interoception and categorization, *Social Cognitive and Affective Neuroscience,* 12(1), 1-23.

Barrie, T. (1996) *Spiritual Path, Sacred Place: Myth, Ritual, and Meaning in Architecture,* ed., Shambhala.

Berlyne, D.E. (1970) Novelty, complexity, and hedonic value, *Perception & Psychophysics,* 8(5), 279-286.

Bower, I., Tucker, R. and Enticott, P. G. (2019) Impact of built environment design on emotion measured via neurophysiological correlates and subjective indicators: A systematic review, *Journal of Environmental Psychology,* 66.

Cha, S.H., Koo, C., Kim, T.W. and Hong, T. (2019) Spatial perception of ceiling height and type variation in immersive virtual environments, *Building and Environment,* 163, 106285.

Choo, H., Nasar, J.L., Nikrahei, B. and Walther, D.B. (2017) Neural codes of seeing architectural styles, *Scientific Reports,* 7(1), 40201.

Diano, M., Celeghin, A., Bagnis, A. and Tamietto, M. (2016) Amygdala Response to Emotional Stimuli without Awareness: Facts and Interpretations, *Frontiers in Psychology,* 7, 2029.

El-Gayar, M., Soliman, H. H. and Meky, N. (2013) A comparative study of image low level feature extraction algorithms, *Egyptian Informatics Journal,* 14(2), 175-181.

Enquist, M. and Arak, A. (1994) Symmetry, beauty and evolution, Nature, 372(6502), 169-172.

Fernandez-Lozano, C., Carballal, A., Machado, P., Santos, A. and Romero, J. (2019) Visual complexity modelling based on image features fusion of multiple kernels, *PeerJ,* 7:e7075.

Fridman, J., Barrett, L. F., Wormwood, J. B. and Quigley, K. S. (2019) Applying the Theory of Constructed Emotion to Police Decision Making, *Frontiers in Psychology,* 10, 1946.

Gartus, A. and Leder, H. (2013) The small step toward asymmetry: Aesthetic judgment of broken symmetries, *i-Perception,* 4(5), 361-364.

Graham, D. J. and Field, D. J. (2007) Statistical regularities of art images and natural scenes: spectra, sparseness and nonlinearities, *Spatial Vision,* 21(1-2), 149-164.

Grütter, J. K. (1987) *Ästhetik der Architektur: Grundlagen der Architektur-Wahrnehmung,* ed., W. Kohlhammer.

Hagerhall, C. M., Purcell, T. and Taylor, R. (2004) Fractal dimension of landscape silhouette outlines as a predictor of landscape preference, *Journal of Environmental Psychology,* 24(2), 247-255.

Homolja, M., Maghool, S. A. H. and Schnabel, M. A. (2020) The Impact of Moving through the Built Environment on Emotional and Neurophysiological State: a Systematic Literature Review, RE: Anthropocene - Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference, 643-652.

Hutmacher, F. (2019) Why Is There So Much More Research on Vision Than on Any Other Sensory Modality?, *Frontiers in Psychology,* 10, 2246.

Jamalabadi, H., Alizadeh, S., Schönauer, M., Leibold, C. and Gais, S. (2018) Multivariate classification of neuroimaging data with nested subclasses: Biased accuracy and implications for hypothesis testing, *PLOS Computational Biology,* 14(9), e1006486.

Jang, J. Y., Baek, E., Yoon, S. and Choo, H. J. (2018) Store Design: Visual Complexity and Consumer Responses, *International Journal of Design*, 12(2).

Kandel, E. R., Schwartz, J. H., Jessell, T. M., Siegelbaum, S. A. and Hudspeth, A. J. (2012) *Principles of Neural Science,* Fifth Edition, 5th Edition ed., McGraw-Hill Education / Medical.

Lin, S., Zhenguo, X., Xiangzeng, M. and Wu, A.-G. (2018) Emotional Semantic Recognition of Visual Scene in Flash Animation, *Journal of Control Science and Engineering,* 3768741*.*

Machado, P., Romero, J., Nadal, M., Santos, A., Correia, J. and Carballal, A. (2015) Computerized measures of visual complexity, *Acta Psychologica,* 160, 43-57.

Maghool, S. A. H., Homolja, M. and Schnabel, M. A. (2020) Cybernetics Approach to Virtual Emotional Spaces - An Electrodermal Activity Actuated Adaptive Space, Anthropologic: Architecture and Fabrication in the Cognitive Age (Proceedings of the 38th eCAADe Conference), 537-546.

Mayer, S. and Landwehr, J. R. (2018) Quantifying visual aesthetics based on processing fluency theory: Four algorithmic measures for antecedents of aesthetic preferences, *Psychology of Aesthetics Creativity and the Arts,* 12(4), 399-431.

Mehrabian, A. and Russell, J. A. (1980) *An Approach to Environmental Psychology,* ed., The MIT Press, Cambridge, Mass.

Menzel, C., Hayn-Leichsenring, G. U., Langner, O., Wiese, H. and Redies, C. (2015) Fourier power spectrum characteristics of face photographs: attractiveness perception depends on low-level image properties, *PloS One,* 10(4), e0122801.

Näsänen, R., Ojanpää, H. and Kojo, I. (2001) Effect of stimulus contrast on performance and eye movements in visual research, *Vision Research,* 41(14), 1817-1824.

Rasmussen, S. E. (1964) *Experiencing Architecture,* 2nd Edition ed., The MIT Press, Cambridge, Mass.

Reber, R., Schwarz, N. and Winkielman, P. (2016) Processing Fluency and Aesthetic Pleasure: Is Beauty in the Perceiver's Processing Experience?, *Personality and Social Psychology Review,* 8(4), 364-382.

Rushton, H. and Schnabel, M. A. (2020) Immersive Architectural Legacies: The Construction of Meaning in Virtual Realities, *Visual Heritage in the Digital Age,* Springer.

Ruzanski, E. (2020) Radially averaged power spectrum of 2D real-valued matrix, *MATLAB Central File Exchange,* Retrieved November 12, 2020*.*

Sala, N. (2003) Fractal Geometry And Self-Similarity In Architecture: An Overview Across The Centuries, Isama- Bridge 2003 Conference. 235–244.

Sala, N. (2006) Fractal Geometry and Architecture: Some Interesting Connections, WIT Transactions on The Built Environment, 86, 163–173.

Schnabel, M.A. and Aydin, S. (2015) Amphiboly of Digital Heritage, in G. Guidi, R. Scopigno, J.C. Torres, H. Graf (eds.), 2nd International Congress on Digital Heritage 2015, VSMM, EUROGRAPHICS, CIPA ICOMOS/ISPRS, IEEE, Granada, 2, 129–132.

Treder, M. S. (2010) Behind the Looking-Glass: A Review on Human Symmetry Perception, *Symmetry,* 2(3), 1510-1543.

Tsay, C.-J. (2013) Sight over sound in the judgment of music performance, Proceedings of the National Academy of Sciences of the United States of America, 110(36), 14580-14585.

Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Gonzalez-Mora, J. L., Leder, H., Modroño, C., Nadal, M., Rostrup, N. and 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.

Vaughan, J. and Ostwald, M. J. (2014) Quantifying the changing visual experience of architecture: combining movement with visual complexity, Across: Architectural Research through to Practice: 48th International Conference of the Architectural Science Association 2014, 557–568.

Williams, K. (1999) *Symmetry in Architecture.*