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A neurocognitive study of the emotional impact of geometrical criteria of architectural space

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ABSTRACT

The paper presents a new approach to examining the connection between human emotions and architectural space, focusing on the aspect of geometry. It examines how emotional reactions to geometrical manipulations within architectural space can be empirically measured and quantified. By using physiological sensors, such as EEG (Electroencephalography), GSR (Galvanic Skin Response), and eye-tracking (ET), we were able to collect data from participants experiencing virtual environments, differentiated by criteria of scale, proportion, protrusion and curvature. Findings suggest that these criteria influence the user's emotional state. The developed methodology, which combines both qualitative and quantitative measurements, shows changes of interest, both 'positive' and 'negative', suspected to indicate different emotional states.

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Virtual environment; space perception; affective response; parametric design; evidence-based design; space geometry; neuroaesthetics; neuroarchitecture

1. Introduction

With recent advances in virtual reality (VR. For a full list of acronyms and their definition see the Appendix) technologies and an increase in interoperability between tools and software in various fields, scientists and designers are seeking to understand the possible emotional reactions which architectural spaces generate. The connection between architecture and emotional reaction is complex since the number of variables which spaces contain is immense. They comprise parameters related to geometry, colour, material, illumination and other environmental conditions. Moreover, emotional reactions consisting of various human body reactions need to be defined. Measurement strategies should be developed or adapted (Zeng et al. 2009; Lettieri et al. 2019). The following research aims to decrease the lacunae in this field. It bridges the perception of architectural spaces and human reaction by empirical means. It employs a VR research setup and develops both quantitative and qualitative data collection techniques, via analytical methods. The paper starts by mapping geometrical criteria of space suspected of evoking emotional response, focusing on scale, proportion, curvature and protrusion. Later, an account is presented of recent work linking architecture and neuroscience, as a means to understand mental processes in environmental evaluation. The use of virtual environments (VEs) as a relatively new way to investigate architecture and its implications is also discussed.

The second segment presents methods and results that show how types of architectural space geometry generate different emotional and cognitive reactions. The paper ends with discussion of the possible meanings of these results, as well as applications and directions worth pursuing in future research.

1.1. Criteria involved in the visual perception of virtual space-geometry

Emotional reaction is a cognitive action, or a process of acquiring knowledge and understanding through thought, experience, and the senses (Leisman, Moustafa, and Shafir 2016). The main assumption in this research is that humans are emotionally affected by the space they perceive. In comparison to the abundance of research on the emotional effect of two-dimensional (2D) characteristics of space, the impact of three-dimensional (3D) space geometry on human emotional response has seldom been examined. Shape characteristics, considered to evoke affective emotions, commonly used in the visual domain of 2D perception, need reevaluation and investigation in the 3D domain. In this paper, we focus on two main gaps in the literature, which encourage us to investigate the connection between geometrical criteria of space and emotional response. The first relates to the isolation of the space variables, as spaces of investigation in the literature usually contain too many variables, and lack variables differentiation (Banaei, Ahmadi, and Yazdanfar 2017; Uttley, Simpson, and Qasem 2018). With the growing use of VR, this gap appears to be diminishing. The second relates to the absence of measurement of the variable of space geometry (Nanda, Pati, and McCurry 2009).

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

The second gap may be explained by the assumption that the spatial properties of an object are more complex to investigate. According to researchers, they include perceived position and orientation, and must contain at least three dimensions fully to represent the object's physical position and orientation in the 3D environment (Palmer 1999; Welchman et al. 2005). Preference for objects has been shown to be influenced by many factors, including mere exposure, familiarity, symmetry, contrast, complexity, and perceptual fluency (Zajonc 1968; Winkielman, Schwarz, and Nowak 2002; Hekkert 2006). Form, colour, position, and distance of objects in the visual field are responsible for different kinds of objects recognition (Palmer 1999). In this process, the boundaries of a shape are involved (Arnheim 1971). It seems necessary to study which features exist in space, and whether they are known to be involved in spatial perception processes as well.

In this section we will investigate scientific literature where geometrical criteria of space were mentioned in a context of emotional response.

1.1.1. Scale and proportion

Similarly to the ability to recognize potentially 'harmful shapes' (Bar and Neta 2008) as is important to our survival, we expect that the actual consequences of perceiving a potentially harmful physical environment would be just as alarming. Researchers deal with the notion of peri-personal space (Gifford 1983; Legrand et al. 2007) as they try to address agoraphobia and claustrophobia (Botella et al. 1998; Lourenco, Longo, and Pathman 2011; Hunley, Marker, and Lourenco 2017). In this sense, the ability to investigate the effect of interior design must take into considerations criteria of geometry in relation to our body (Li et al. 2020) (in contrast to observation of a photo, for example).

Palmer (1999) claims that the visual cortex contains cells sensitive to a range of different sizes or scales, that is, 'spatial'. Considering a basic square space viewed in three dimensions: Height, width and depth, the distance between one, or all of these dimensions, to the body should be taken into account. To this day, it is still unclear which dimension of space is most dominant, since most of the literature is related to just one, such as ceiling height (Fischl and Gärling 2008; Erkan 2018; Cha et al. 2019) or, to use more general definitions, 'spaciousness' (Stamps III 2011). Others compare multiple variables, such as the openness ratio, two-room proportions, room area, and balustrade height (Franz, von der Heyde, and Bülthoff 2005). These studies occasionally use spaces with openings and other interior design elements, basing their findings on questionnaires. From our architectural practice, we suspect that large-scale spaces are often created to leave stronger impact on users. We therefore seek empirical evidence for impact, possibly generated by a change of scale and of proportions of space.

The idea of 'human scale' is worth exploring in that sense. Another criterion which might have an influence on our body is often mentioned in the context of aesthetics. It is that of proportion, popularly known in the design domain. According to the Cambridge Academic Content Dictionary, proportion is 'a part or share of the whole, or the relationship between one thing and another in size, amount, or degree'. We can explain proportion in its general meaning, as 'the number, amount, or level of one thing when compared with another' in art, proportion refers to 'the correct relationship of the parts of a work of art to each other, especially in their size'. In mathematics, a proportion is also 'an equation (= mathematical statement) that shows that two ratios (= comparisons) are equal'.[1] It is claimed that the degree of similarity among the proportion of object in three view angles sums up the ideal proportion sequence (Rimmer 1997; Livio 2008; Lo, Ko, and Hsiao 2015). Franz, von der Heyde, and Bülthoff (2005) argue that participants prefer room ratios 'near to the golden section'. This concept dates back to ancient periods, yet an empirical validation of the notion of 'pleasant proportions' in architecture is missing, to this day, in literature.

1.1.2. Protrusion and curvature

We recognize two additional geometric criteria which could influence our emotional state. The first relates to the type of the boundary of space – either curvy or sharp angled; The second to our ability to recognize this typicality of that boundary. Kennedy (1988) described eschatology as a phenomenon in which the eye creates an 'ending' for 'unfinished shapes'. He created an experiment showing participants' line endings and subjective contours – gradient in contour. The gradient Kennedy observed was of lines which ended with a sharp, curved, and rough cuts (no ending). Researchers found curvature was preferred over angularity even for simple elements, such as lines (by observers liking-scores) (Bertamini et al. 2016). We believe these studies indicate the presence of two important criteria: protrusion and curvature.

This need for 'the eye' to complete an 'unfinished shape', which could easily be read, is connected to the assumption that the moment of completing and understanding the form is pleasant, in a sense. A peak shift effect was explained by Purtle (1973a), who found that a rat learns not a prototype of a rectangle, but a rule, i.e. rectangularity. This assumption was made, since that rat chose an extreme shape of a rectangle over an identical form of a rectangle, which was supposed to be associated with a reward he had received in a past exposure. Ramachandran and Hirstein (1999) argued that this principle holds the key to understanding the evocativeness of much of visual art, since attention exists mainly in regions of change – e.g. edges that would be more interesting than homogeneous areas. They claim that 'interesting' in some circumstances, translates into 'pleasing'. It happens when the peak of the gradient response reaches a point beyond the value of the stimulus associated with reinforcement (Purtle 1973b; MacKinnon, Gross, and Bender 1976; Blanco et al. 2006; Ramachandran and Hirstein 2011).

We suspect this phenomenon could also occur in the context of space, and can be investigated using appropriate methods and new tools of parametric design, which enable control in contour and shading of space, and manipulating the criterion of protrusion. Forms, both curved and sharp, can to some extent obtain protrusion on its facets, and therefore, a gradient more, or less, pleasing to the eye (Palumbo and Bertamini 2016). Protrusion (P) means an extension beyond the normal line or surface.[2] When a basic square shape is protruded, it means that a point chosen from a presentation of intersecting coordinates on a flat surface of each of its facets is protruded in random directions on each side. Protrusion basically manifests the level of complexity of an object's shape, and is claimed to be separate from the aspect of curvature (Palumbo and Bertamini 2016).

In a research study aimed to investigate Fencher's theory regarding the beauty of rectangles, participants were asked to rate preferences for curved 3D objects that use various types of object complexity as metrics. Findings revealed that participants preferred either very simple or very complex objects, according to liking scale (Phillips, Farley Norman, and Beers 2011). The spikiest object was selected as the most attractive (Friedenberg and Bertamini 2015). These findings may also indicate that curvature, as well as the smoothness of a shape, are two important criteria, which are different from one another. This research aims to apply and investigate these concepts in a context of space, manipulate and measure them.

Curvature by itself is a criterion suspected to generate emotional influence. Several research studies deal with the impact of curvature on our visual perception (Bar and Neta 2008; Nanda et al. 2013; Vartanian et al. 2013; Nasr, Echavarria, and Tootell 2014; Palumbo and Bertamini 2016). Researchers investigated a tendency to prefer curved shapes over sharp shapes in the context of space as well, as we further describe in the following Section 1.2.

We may see that direct empirical studies focusing on the connection between the geometry of space and an emotional response are rare, with the exception of the criterion of curvature. For that reason, we chose to conduct a study which takes into consideration several geometrical criteria, as we will describe in Section 1.2.

1.2. Architecture and neuroscience

An empirical approach to studying the way the environment affects us began over a decade ago, when researchers claimed that environment-behaviour studies combining neuroscience are essential (Sternberg and Wilson 2006; Zeisel 2006; Eberhard 2007; Mallgrave 2010; Edelstein and Macagno 2012; Dougherty and Arbib 2013; Pallasmaa, Mallgrave, and Arbib 2013; Jelić 2015; Robinson and Pallasmaa 2015; Jelić et al. 2016; Papale et al. 2016; Coburn, Vartanian, and Chatterjee 2017). This connection is increasingly possible using different scientific techniques, such as the observation of responses, physiological measures, psychological analysis and functional mapping of different regions of the brain (Eberhard 2009; Goldhagen 2017; Karakas and Yildiz 2020; Coburn et al. 2020).

In the field of neuroscience, devices such as electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI) are used to investigate brain response to various environments. Essawy, Kamel, and Elsawy (2014) used an EEG device to test participants' response to spiritual spaces defined as ones exhibiting. Using fMRI, Kirk et al. (2009) found that the brains of experts and non-experts in the arts respond differently during aesthetic judgment. Vartanian et al. (2013) and Pati et al. (2016) also used fMRI for comparing rectilinear and curvilinear interior spaces. They reported that images containing curvilinear spaces activated the aesthetic processing part of participants' brains. Yanulevskaya et al. (2012) found that smooth lines are generally considered positive by the beholder. Choo et al. (2017) claimed to have found patterns of neural activity associated with specific architectural styles. Marchette et al. (2015) used fMRI to understand how landmarks are coded in the human brain. Coburn et al. (2020) claim to recognize brain neural response to properties of coherence (the ease with which one organizes and comprehends a scene), fascination (a scene's informational richness and generated interest), and 'hominess' (extent to which a scene reflects a personal space) of interior design images.

This study offers the possibility to broaden the neuroscience-architecture connection, and to better examine theoretical knowledge in an empiric manner. It also reinforces the need for combined technological solutions which could allow resear chers to conduct these types of research, which to this day are rare in this field.

1.3. Using VR for neuro-architectural research

The ability of the virtual environment (VE) to be immersive is very much dependent upon its ability to supply a realistic (yet not necessarily familiar) environment. Virtualization is defined as the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists (Sanchez-Vives and Slater 2005). Achieving both realism and isolation of variables of interest is an important task for the designer-researcher. In this way, researchers can achieve both experimental noise reduction (Heydarian et al. 2015) and a sense of immersion (Kieferle and Wössner 2001; Sanchez-Vives and Slater 2005; Morie et al. 2005; Rodríguez Ortega, Rey Solaz, and Alcañiz Raya 2011; Zhang et al. 2011).

Research using VR while combining noninvasive body area sensor networks (BSNs) has the potential to set a base for empirical investigation of physiological and mental phenomena. Edelstein et al. (2008) have shown the ability to reflect a cognitive state of disorientation in a featureless VE, obtained by a Cave-Cad tool (an interactive virtual environment which presents scaled renderings of architectural environments) and the use of EEG. Dias et al. (2014) argue that, by using electromyography (EMG) and electrodermal activity (EDA), they were able objectively to discriminate arousal responses from the neutral condition related to 'positive' or 'negative' emotions in users confronted with architectural spaces in VR. Thanks to VR technology, more realistic representations involving multiple coordinated sensory modalities enable the study of spatial cognition, using more natural experimental conditions (Bhatt, Hölscher, and Shipley 2011; Vecchiato et al. 2015). For example, Banaei et al. (2017) recorded the EEG of participants while they walked through different interior forms in VR. Ergan et al. (2019) have quantified the sense of stress and anxiety in relation to a set of architectural design features using the combination of VEs and a set of biometric sensors. This approach could also contribute to research aimed at treating certain physical skeletal impairments. A detailed understanding of the neural mechanisms guiding human perception and action during locomotion (Vecchiato et al. 2015) could lead to VR-based paradigms for enhancing safe, accurate mobility (e.g. reducing falls) in normal and impaired individuals (Porras et al. 2020). Certain conditions such as claustrophobia and agoraphobia might be treated by employing VR (Botella et al. 1999). Researchers even claim that VR could reduce anxiety (Tarrant, Viczko, and Cope 2018).

These studies, however, run into an existing methodological problem, in that most of the neuroscientific devices require the tested participant to be still. Movement while exploring 3D space increases data noise which disturbs the actual perceptual or cognitive activity mapping (Olbrich et al. 2011; Islam, Rastegarnia, and Yang 2016).

1.4. Review conclusions

We witness an increase in the amount of research into the connection between architecture and neuroscience, neurobiology and neuropsychology in recent years. The emotional influence of different environments, both at a small and at an urban scale have been investigated (Geiser and Walla 2011; Aspinall et al. 2015; Hollander and Foster 2016; Mavros, Austwick, and Smith 2016; Karandinou and Turner 2017; Neale et al. 2017; Tang et al. 2017; Yates et al. 2017). Researchers are dealing with the benefits society can gain by using such interdisciplinary research (Sussman and Hollander 2014; Pykett 2015). This increase can be attributed, among other things, to the accessibility of VR technologies, 3D design tools and the interoperability among tools in different disciplines. Further development of a methodological approach could contribute to a maturation of the neuroarchitecture field into an experimental science (Coburn, Vartanian, and Chatterjee 2017; Bower, Tucker, and Enticott 2019). In this study, we have taken an experimental approach, based on theoretical knowledge collected in multidisciplinary areas, and used a combination of several measures, both quantitative (physiological sensing) and qualitative ('real time' questionnaires) to investigate the emotional impact. To our knowledge, this is the first investigation using these combined methods to find out the emotional impact of the geometry of space, recognizing a combination of several measured geometrical features (Table 1).

2. Methods and methodology

To pursue the project's central question, that is what is the effect of geometry of space on emotional reactivity, a combination of quantitative and qualitative data were required to relate neuroscientific measurements with emotional responses. The experiment collected several human-centred operational measures, indicators of an emotional response: the length of stay a participant chooses to stay in the virtual space (VS) (presence in sec. (PIS) – a behavioural measure); two questions questionnaire (liking score (LS) and chosen use – a self-reporting measure). Physiological measures included: Beta (Waves) Band Power Ratio (βBPR), mean pupil diameter (PD), maximal pupil diameter (MPD), rate of fixations (FR), duration of fixations (FD), maximal GSR amplitude peak (MGSR), rate of GSR peaks (GSRR). These measures are taken during and right after presence in VSs, which differentiate in geometrical criteria as we further describe. They indicate the level of interest, as well as the polarity of the emotional response (positive/negative) according to the model we have developed (Figure 1).

2.1. Designing the main experiment's virtual set up

This section describes the method of quantifying geometrical criteria of spaces, using controlled manipulations. Spaces with a different scale (S) or proportions (P height (H) or P width (W)) were designed using relatively simple modeling software – Google Sketchup© or Rhinoceros (Copyright©, Robert McNeel & Associates). Spaces which differ in protrusion (P) or curvature (C) were constructed using parametric computer software. These criteria required a more complex modeling technique, to create a gradient change. Grasshopper software was used to create a gradual and equal change between spaces, using a code, built for this research in python. Every space could be given a statistically valid level representing how 'curvy-sharp edged', 'bumpy-smooth', 'large-small', 'high-low', 'narrow-wide', it was (Table 2). In the manipulations of P and C, we focused on spaces of a typical scale and the proportion of a standard public scale, similar to the one used in the preliminary experiment (Shemesh, Bar, and Grobman 2015), in order to eliminate other criteria of scale and proportions. We also checked volume, scale, and relative cartography, to ensure that the spaces were identical in every other aspect. The spaces maintain a proportion of 2w/2d/2h, which was chosen as the basic proportion for this research, mimicking a square shaped public space. To create a gradient and equal change between spaces in terms of scale, proportion, curvature and protrusion, twenty-seven virtual 3D models (Figure 2) were exported to the Unity real time engine to be implemented in the experiment file.

2.2. Apparatus

The following noninvasive wireless sensors were used to collect physiological measures from participants, while experiencing different virtual environments (VE's) (Figure 3):

- Emotive insight – A five channel, wireless headset that records EEG signals.
- Shimmer 3 GSR (Galvanic skin response) – A sensor that monitors skin conductivity between two reusable electrodes attached to two fingers of one hand.
- Pupil Labs Binocular 200 Hz eye tracking (ET) cameras – An add-on to the HTC-Vive virtual reality headset.

'Emotive Insight'[3] includes five EEG sensors and two reference sensors, which cover sites around the cerebral cortex: The frontal cortex (executive functions), parieto-temporal (auditory, spatial/co-ordination), and occipital (visual). The device was used with designated software, which displayed the brain waves and the levels of connectivity of the sensors in real-time (Zabcikova 2019). The EEG signal, captured by the non-invasive method from the surface of the head, is formed by the activity of neurons and its level of voltage is low (5–300 uV). The processing is integrated in the Emotive app. The Emotive Insight system (Model 1) employed in our experiment recorded data directly received from the headset. This simple system has a significant amount of filtering and signal processing capability in order to remove mains noise and harmonic frequencies. The system sampling rate was performed at 2048 Hz, with a dual notch filter at 50 Hz and a low pass filter at 64 Hz, with data filtration reduced to 128 Hz or 256 Hz for transmission. Reports in the literature indicate that the system output is roughly equivalent to developed EEG systems (Pratama et al. 2020).

Table 1. A comparison of studies based on the intersection of neuroscience and architecture (The table is based on Bower, Tucker, and Enticott 2019; Karakas and Yildiz 2020; Azzazy et al. 2020).

Human experience	Built environment features	Measurement techniques	References
Restorative and stress reduction effects of environments. Well-being, stress.	Natural environment and built environment without nature, building-integrated vegetation, stimulus in interior spaces (vegetation, music, and visual features), bed positions, and orientations.	fMRI, EEG, VR, EDA, HRV, questionnaire, self-report, and post-test measurements.	Martínez-Soto et al. (2013);Hekmatmanesh et al. (2019); Higuera-Trujillo et al. (2020).
Aesthetic judgment/appreciation.Pleasure, familiarity, novelty, comfort, and pleasantness.	Arrangements of furniture, windows, and doors, visual complexity, architectural decorum, typicality, and ambiances of interior spaces.	EEG (BEMicro, EBNeuro wth EEGLAB), VR, aesthetic judgment tasks, and rankings.∗3D Virtual CAVE using 3DS Max 2011.	Murcia et al. (2019); Vannucci, Gori, and Kojima (2014); ∗Vecchiato et al. (2015).
Pedestrian experience, navigation, and wayfinding. Mediation, attention, anxiety, displeasure, pleasant and unpleasant, directional behaviour, familiarity, and fear.	Urban characteristics of a place (edges, patterns, shapes, and narrative), urban spaces and forms (building shapes, textures, isovist parameters, visual entropy, visual fractals), physical characteristics of routes, and ceiling height.	EEG, VR, GIS, GPS, body sensors, self-report, and video recording.	Li et al. (2016); Erkan (2018).
Visual engagement, visual attention, and imageability. Visual attention, avoidance behaviour, conscious and unconscious attention.	Spatial characteristics of urban streets (street edges, ground, sky, existence of people and objects, and adjacent realms), characteristics of civic monuments (front facades).	EEG (EASYCAP with EEGLAB toolbox, Emotive), VR Eye tracker, MoBI, video recording, questionnaire, self-report, and scorecards.∗3D Virtual HTC-Vive (head mounted)Unity Game software.	Simpson et al. (2019); Sussman and Ward (2019); ∗Banaei et al. (2017); Hollander et al. (2019).
Aesthetic processing. Efficiency, beauty, safety, pleasantness, and interest assessment.	Comparing rectilinear and curvilinear interior spaces. Architectural space geometry (square, round, sharp, and curvy).	2D image in fMRI Signa Excite HD.3D Virtual CAVE VizTech XL software, EEG (Emotive-EPOC).	Vartanian et al. (2013), Vartanian et al. (2015), Shemesh, Bar, and Grobman (2015); Shemesh et al. (2017).
Phenomenological experiences, experiential intensity, positive/negative user experience, multisensory experience, and natural experience of architectural spaces. Relaxation, excitement, engagement, stress, focus, interest, attention, appreciation, peace, beauty, connectedness, anxiety, pleasure, motivation, pleasant, and frustration.	Characteristics of religious spaces, mosques, and spirituality of the built environment, ordinary and contemplative architectures, presence and size of windows, spatial alignment, contours of objects, natural daylight, exposure to nature, density, height of ceiling, flexibility in isolation/socialization, openness of space, colour, artificial lighting, visual cue and landmark, shape layout, texture material, ease of access, and symmetry/asymmetry, design features of interior spaces as levels of luminance, colour of the surfaces, openness in space, natural daylight, and visual cues.	fMRI, EEG, VR, EDA, HRV, questionnaire, self-report, post-test measurements, crowdsourcing, and semantic differential scale.	Vijayan and Embi (2019); Bermúdez (2017); Ergan, Shi, and Yu (2018, 2019); Higuera-Trujillo et al. (2020).
Presence levels with stereoscopic vision.	Residential spaces, and a 'work' office.	3D Virtual CAVE-like (Stereoscopic), questionnaire.	Rodríguez Ortega, Rey Solaz, and Alcañiz Raya (2011).
Stress and tension.	Materiality and texture.	Autonomic nervous activity (pulse rate, blood pressure and regional cerebral blood flow). Questionnaire. A Physical room.	Tsunetsugu, Miyazaki, and Sato (2005); Zhang, Lian, and Wu (2017).
Engagement and excitement (Betta waves)Levels of frustrations (upper Theta range).	Compare the Urban vs. natural environment.	EEG and Interviews.	Tilley et al. (2017).
Brain activity.	Navigation in different urban roots.	EEG.	Karandinou and Turner (2018).
Comfort.	Walking within two different neighbourhoods; residential vs. business.	EEG.	Hollander and Foster (2016).
Arousal levels, anxiety excitement.	Walking on two different trails; park vs. commercial.	EEG.	Banaei et al. (2015).
Excitement. meditation state, engagement.	Comparing green park, urban shopping areas and commercially crowded spaces.	EEG.	Aspinall et al. (2015).
Relaxation and calm awareness (Alpha waves).	The impact of spiritual buildings on the human brain.	EEG.	Essawy, Kamel, and Elsawy (2014).
Right cingulate gyrus and left precuneus were activation.	Comparing urban, mountain, forest, and water environments.	fMRI and Questionnaires.	Tang et al. (2017).

The wireless system was necessitated for a number of reasons. First, we needed significantly to reduce cable interference and practical function for free head mobility in a VR environment, as well as limiting preparation time prior to experiments, since the procedure involved wearing and calibrating several sensors. Second, the dry electrodes were critical

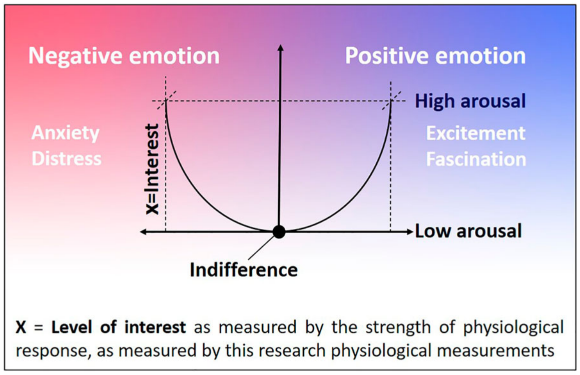

Figure 1. Methodological model indicating emotional response. X = Strength of physiological response as measured by physiological measures of this study, indicating level of interest. 'Positivity' or 'negativity' of interest, based on the overall Human-centred operational measures in this study.

to maintaining signal consistency in longer periods of brainwave acquisition. Third, since we had not intended at this time to perform EEG studies or more advanced electrophysiological analyses, such as coherence and power spectrum analyses, the five-electrode system was ample for the job at hand.

The Shimmer 3 GSR sensor system allowed us to monitor skin conductivity between two reusable electrodes attached to two fingers of one hand. With stimulation, the sweat glands become more active, increasing moisture on the skin and allowing the current to flow more readily by changing the balance of positive and negative ions in the secreted fluid, thereby increasing skin conductivity. Signals could be captured with this unit for further analysis, because all signals were measured and recorded simultaneously and in real-time. The raw data was logged onto an SD card for ease of access. We employed this GSR system, since it was capable of both hard-coded and manually selected gain control, provided pre-amplification of the GSR signal, convertible to digital format, and most importantly, the system was capable of streaming directly to a host device without the need for an intermediate receiving unit. This system's real-time LabVIEW drivers and support library allowed us ease in interface development with other monitoring devices used in this study. The equipment was also wearable, addressing our challenges of mobility, and provided high-quality, reliable data from wireless transmitters.

The binocular 200 Hz eye tracking cameras of the Pupil Labs ET device are located inside the VR headset, very close to the eye itself (clip-on attachment rings with IR illuminators and USB

Table 2. A keynote geometrical criteria.

Geometrical criteria	Setup implementation – a description of the virtual space (VS)
Scale	A square and a sphere gradually become larger or smaller by a factor of three:(1) Small – 4m width/4m depth/2m height (*C0P0S1H1*); (2) Medium, identical to the basic space of a square in the first stage, at the same scale as other criteria of *P* investigated in this stage: 12m/12m/6m (*C0P0S2*); and (3) Large – 36m/36m/18m (*C0P0S3*). The dimensions of a dome (half a sphere) in different scales are: 4m (diameter) (*C4P0S1)*; 12m (*C4P0S2)*, 36m (*C4P0S3)*. The spaces maintain a proportion of 2w/2d/2h.
Proportion	Changes in ceiling height: Low = 4m/4m/2m (C0P0S1H1); Medium = 4m/4m/2.6m (H1b); High = 4m /4m/6m (H2); Very high = 4m/4m/18m (H3).Changes in virtual space width: Narrow = 2m/4m/4m (W1); Standard = 2.6m/4m/4m (W1b); Wide = 6m/4m/4m (W2); and Very wide = 18m/4m/4m (W3).
Protrusion	Defined as an extension beyond the normal line or surface (Miriam Webster Dictionary 2020). When a basic square shape protrudes, it means that a point chosen from a presentation of intersecting coordinates on a flat surface of each of its facets protrude in random directions on each side. Changes according to a Grasshopper algorithm – Orthogonal to Sharp (two parts) (C0,P0–4,S2); Round to Curvy (C4,P0–4,S2). Each transformation is 'baked' five times along each process. Measured on the basis of a scale between 0–4. When a VS has no protrusion (*P* = 0) it is simple and symmetrical.
Curvature	Changes according to a Grasshopper algorithm – Orthogonal to Round (C0–4,P0,S2); Sharp to Curvy (C0–4,P4,S2). Each transformation is 'baked' five times along each process. Measured on the basis of a scale between 0–4.

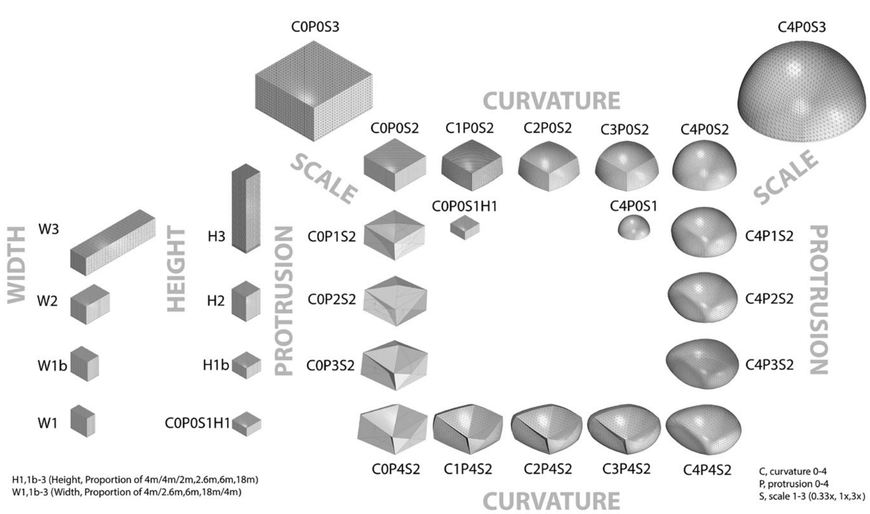

Figure 2. (Above): twenty-seven 3D models of the Virtual spaces that were exported from the Grasshopper + Rhino software, which examined the various criteria measured – protrusion, curvature, scale, proportion (height and width) in VR.

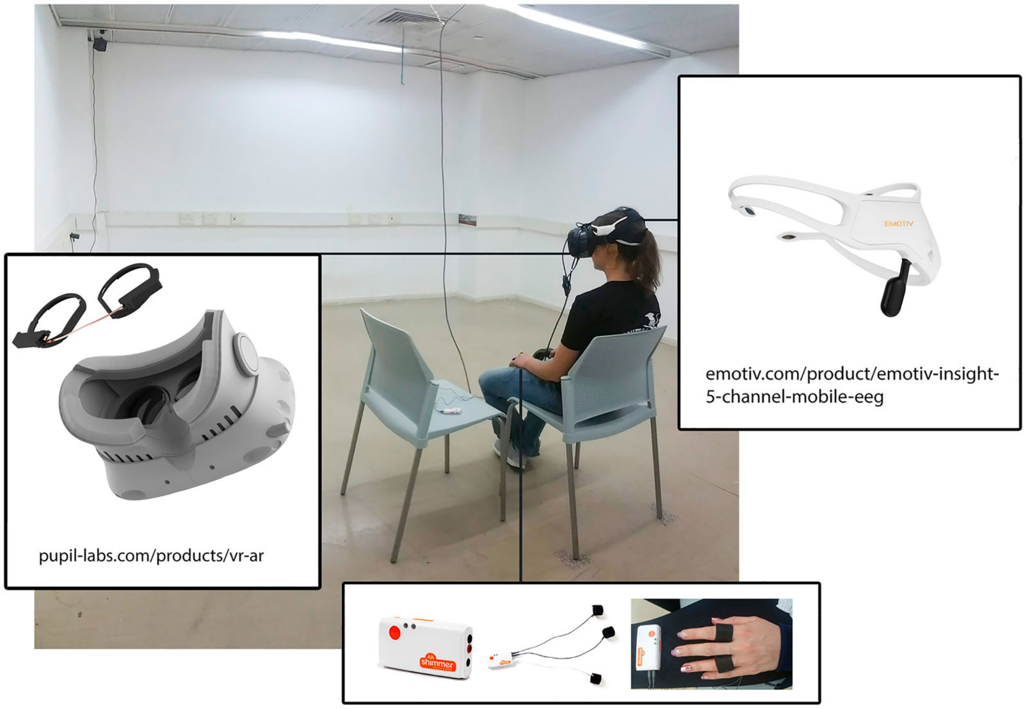

Figure 3. Middle: a participant sitting in the laboratory, experiencing virtual reality with the HTC-Vive system installed. Left: The Pupil-Labs ET fixture, located inside the HTC-Vive – VR headset. Right: The Emotive Insight, containing five dry electrodes at 10–20 locations AF3, AF4, T7, T8, and Pz. 14 bit ADC resolution, transmit data over Bluetooth Low-energy 4.0 at 128 samples/second/channel by the device. Below: The Shimmer GSR device – the placement of the sensors on the fingers.

connector clip).[4] In both real and virtual environments, we move our eyes frequently (several times per second) back and forth over the visual field, to acquire useful information about the parts of the environment that we find most relevant and/or interesting. The visual field maps a large portion of the region in front of the observer, subtending approximately 130° vertically and 180° horizontally (Palmer 1999). The HTC-Vive VR headset has a field of view (FOV) of about 145 diagonal degrees when the eyes are about 10 mm away from the lenses, as the actual FOV perceived is about 100 horizontal degrees and about 110 vertical degrees.[5] Although the FOV is slightly smaller in the VR of a headset, emergence is far greater than with a large screen, and the movement of the head compensates for this FOV reduction to a certain extent. We can then record the focus points and diameter behaviour along a Unix time (a computational system for describing a point in time) as we track spatial coordinates and export them, in addition to the data mentioned above.

2.3. Procedure

112 participants included designers (Ds) and non-designers (NDs) (Table 3) who declared to have no ADHD, visual deficits other than corrected vision, heart disease, pregnancy, vertigo or claustrophobia were invited into the laboratory room. Ds defined as individuals with a professional or academic background in art and design, including architecture. Both groups of participants went through the same experience, and wore virtual 3D goggles manufactured by HTC-Vive (Figure 3). The experiment was conducted in a VR environment generated by Unity's real time engine. The total time, including electrode placement stimulus presentation and data acquisition, took about 40 min;

Table 3. Demographic variables of participants in this study.

	freq	Group	M	σ
	12	D	33.8	5.72
	100	ND	26.24	4.73
sum	112			
	freq	Gender	M	σ
	45	M	27.82	5.46
	67	F	26.53	5.27
sum	112			
Group		Gender		
	M	**F**	**Sum**	
D	8	4	12	
ND	37	63	100	
sum	45	67	112	
Group		Dominant hand		
	R	**L**	**Sum**	
D	8	4	12	
ND	92	8	100	
sum	100	12	112	
D.Hand		Dominant eye		
	R	**L**	**unclear**	**Sum**
R	50	48	2	100
L	4	8	0	12
sum	54	56	2	112
Group		VR experience		
	Yes	**No**	**Sum**	
D	2	10	12	
ND	21	79	100	
sum	23	89	112	
VR experience		Computer games experience		
	Yes	**No**	**Sum**	
Yes	19	4	23	
No	54	35	89	
Sum	73	39	112	

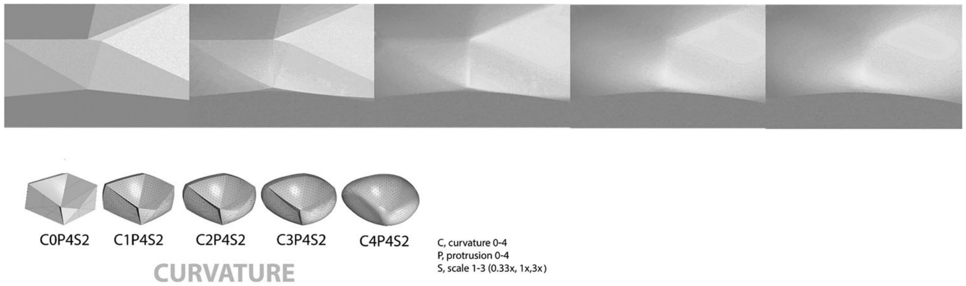

Figure 4. From left to right, an inner view of the same corner in spaces C0P4S2; C1P4S2; C2P4S2; C3P4S2; C4P4S2, which differ in their level of C (curvature).

pilot experiments indicated that a longer duration might be too exhausting. The experiment room was empty, colourless, without windows, containing only the VR equipment of the setup and a computer which collected the different signals and ran the software. The room temperature was held constant for all participants. The setup included physiological sensing devices that included GSR (Shimmer), eye tracking (Pupil Labs) and EEG (E-motive insight). Each participant was required to wander in a virtual urban park environment especially designed using the Twinmotion© real-time program, so he or she would possibly experience a neutral to positive meditative mental state (Hollander and Foster 2016) prior to the measurements taking place.

Participants were shown, in random order, virtual scenes of 27 spaces, with varying degrees of scale, proportion, protrusion and curvature. Geometrical VS Criteria, which were the measurable environmental variables (MEV), are detailed in Table 2. Participants were immersed inside these spaces, and were allowed to move their heads to see the space that surrounded them (Figure 4). Nevertheless, they were asked to be seated and move the body as little as possible during the observation process, in order to diminish EEG noise and Bluetooth signal interruptions. After each scene, they were presented with two questions through the VR system. 'How much did you like this space' (ranking with the controller in a choice between 1–7) (Tinio Pablo, Leder, and Strasser 2011) and 'what kind of an activity fits this space' (seven positive vs. negative uses, concluded from data gathered in our previous work (Shemesh, Bar, and Grobman 2015)). This repetitive process occurred twenty-seven times per participant.

2.4. Data analyses

Data analysis posed a challenge in this research. Measurements taken with different sampling rates that varied across the three physiological measurement devices had to be synchronized. There was difficulty in the use of various statistical methods employed to extract significant data from relatively large and diverse datasets. Additionally, variability involved physiological differences among participants. Each of these issues was addressed in the analysis.

Handling raw data included three phases. During the first, data were collected from each sensor. The second involved organizing, screening and removing flawed data. The third involved filtering and down-sampling analysis for statistical manipulations. Then, several statistical analyses were performed over the human-centred operational measures.

Knowing the sensitivity of these devices, and anticipating movement and ambient noise, we screened out flawed recordings and included data which met pre-set standards (high Bluetooth reception, minimal recording continuity, supervision for no perceptive distractions, device detachments or extreme movements). Data were later analysed by the statistical tests. We argue that greater validation of the results can be achieved through the combined use of different sensors. Nevertheless, to bridge between different measures and frequencies, several tests were needed: Statistical analysis of self-ranks, The regression tree technique, An univariant analysis, Analysis based on ranks, Multivariate analysis of physiological measures of every sensor in the univariant test, and Diffusion Map Algorithm.

3. Results and discussion

This study sought to examine the emotional response of humans to the geometrical criteria of scale, proportion, protrusion and curvature of space, by examining designers' (Ds) and non-designers' (NDs) physiological responses, as well as their behavioural responses to virtual spaces. Results demonstrated that physiological reactions of NDs towards virtual spaces (VSs) characterized by different geometries were significantly stronger than those of Ds, regardless of the investigated criteria (P: $F = 16.164515$; *df*, 88; $p < 0.0001$, C: $F = 16.247940$; *df*, 88; $p < 0.0001$, S: $F = 14.295772$; *df*, 88, $p < 0.0003$, P(W) and P(H): $F = 9.762352$; *df*, 88, $p < 0.0024$). In addition, it was found that designers fixate significantly longer in the space observation (P: $F = 3.2590$; df, 107; $p < 0.0738$; C: $F = 3.2601$; df, 107; $p < 0.0738$; S: $F = 3.9695$; df, 107; $p < 0.0489$), as found in an earlier study (Kirk et al. 2009). No evidence was found of correlation between the physiological measures and other human-centred operational measures, that included: dwell time/presence in sec. (PIS – a behavioural measure) and liking score (LS – a self-report measure). Having said that, the relationship between these geometrical environmental variables and human-centred operational measures taken has yielded some interesting results.

3.1. Scale

Large VSs showed significantly higher PIS measurement compared with small ones ($F = 6.3602$; *df*, 325; $p < 0.0121$). High LS was evident in both groups of participants regarding large VSs. Significantly high LS was received among NDs, when viewed between the 4th and the 27th scenes (an average satisfaction score of 3.8). These VSs produced significantly larger pupillary diameter measurements (F = 96.903; *df*, 325; $p < 0.0001$). They also produced significantly fewer and shorter fixations (FR: S1 > S3; SE = 0.04175817; z-value 4.018549 Pr(>|z|) 5.855769e-05; FD: S1 > S3; F = 6.6165; *df*, 754; $p < 0.0106$). Small VSs were correlated with low PIS, compared with high VSs, as well as smaller PD. Respectively, the amount and the duration of fixations was larger in these spaces. We therefore recognize the existence of positive interest – meaning, a positive emotional response.

3.2. Proportions

Measures obtained during presence in spaces differed in their proportions and produced more statistical differences in the different methods of analysis. The more extreme the proportion, the stronger was the recognized measured response. Longer PIS was measured in high VSs, compared with PIS in low VSs. Ds, in contradiction to NDs, tended to like the ceiling as it got higher. Moreover, a smaller PD was recognized in high VSs, compared with low spaces. The lower the space was, the larger the pupil dilated (SE = 0.223; t = −4.190; *df*, 757, $p < 0.0002$). Larger FR was recognized in low spaces compared with high spaces (H1 > H3; SE 0.0393; z.ratio −3.109; $p < 0.0101$).

Looking at the overall human-centred measurable variables, VS differing in width showed an even stronger effect on the participant. The wider the space, the longer was the PIS which was measured. Narrow proportions received a high percentage of low LS, with greater significance among NDs, if PIS was less than ten secs. Large PD and MPD were more recognized in narrow than in wide spaces (PD: F = 103.171; *df*, 757; $p < 0.0001$; MPD: SE = 0.223; t = 5.013; *df*, 757; $p < 0.0001$). We also recognize a tendency to a higher beta ratio in the narrow VSs (F = 6.24984; df, 86; $p < 0.0143$). A larger FR, parallel to the gradient change of width (W1 > W3; SE = 0.0415; z.ratio 7.124; $p < 0.0001$), as well as longer FD (W1 > W3; SE = 0.812; *df*, 754; t.ratio 8.233; $p < 0.0001$), was noted in narrow VSs. The measure of FD was found to be highly correlated with the criterion of space width. We therefore suggest the existence of negative interest – meaning, a negative emotional response.

3.3. Protrusion and curvature

The combination between criteria of zero curvature (C = 0) and asymmetry ($P = 1$–4) produced several correlated human-centred operational measures. For the measured variable of MPD, a repeated measures mixed effects model analysis showed significant differences (MPD: P4 > P0, F = 18.287; *df*, 325, $p < 0.0001$; C0 > C4, F = 131.067; *df*, 325, $p < 0.0001$). The regression tree technique used to predict a response variable using a set of predictor variables resulted in significantly high LS of Ds and NDs towards these spaces. Physiologically, the stronger the protrusion was in non-curved asymmetric VSs, the larger was the PD in medium scale spaces (F = 273.823; *df*, 325; $p < 0.0001$). The lower the curvature, the larger was the PD (F = 131.067; *df*, 325, $p < 0.0001$). The pupillary dilation increased significantly (according to ranked analysis) as the scale increased. A larger MPD was evidenced in asymmetrical when compared with symmetrical spaces (F = 49.251; *df*, 325; $p < 0.0001$).

Tests showed a significantly high contribution of pupillary measurements compared with other types of measurements. More research is needed to confirm this observation and exclude any other unnecessary factors, such as luminance, which remained steady in the virtual design process.

The combination of criteria of high curvature (C = 4) and asymmetry ($P = 1$–4) showed less correlation between measures than expected, since it produced positive evaluation among NDs according to previous report's questionnaires (Shemesh, Bar, and Grobman 2015). Space C4P4S2 did, however, receive, a relatively positive use score, in that 27.1% of NDs chose a 'creative use' as most suitable for it, compared with 33.3% of the D group. Half of the D group gave it a 'social use', which should be considered positive. High curvature, regardless of the amount of protrusion/symmetry, also produces significantly high MGSR measurements, which are assumed to be related to an aesthetic emotional response (Blood and Zatorre 2001).

Interestingly, a VS characterized by medium curvature plus maximal protrusion (C2P4S2) produced the largest PD, MPD, the highest PIS, and a high LS in both groups. Protrusion appears to be a significant factor in asymmetry as a criterion of influence, for a sharp contour appears to trigger pupillary dilation, perhaps contributing a peak shift effect climax, lacking in curvature and asymmetrical amorphic spaces.

PD and MPD are efficient indicators for the interest produced by the sharpness (no curvature) and asymmetry ($C = 0+P = 4$) of the spaces (MPD: SE = 0.0723; *df*, 1625; t.ratio −6.444, $p < 0.0001$). The combination between criteria of high curvature (C = 4) and low curvature (C = 0) in symmetrical space ($P = 0$) shows interesting findings. We suspect these shapes (a complete square – C0P0S2 and a complete sphere – C4P0S2) produced a unique impact, since significant differences in GSR, independent of scale, were observed. In addition to higher PD and MPD for sharp rectangle spaces, a higher β ratio was recognized – as we compare this measurement with that of a sphere. Researchers claimed that the parahippocampal area in our brain initially responds selectively to images of place, but is actually responding selectively to rectilinear features, a lower-level stimulus property (Nasr, Echavarria, and Tootell 2014). Earlier research dealing with 2D patterns suggest that the effects of complexity on aesthetic judgment are sensitive to familiarity, while the effects of symmetry are not (Tinio Pablo and Leder 2009). Therefore, it is possible that these effects, as well as a momentary peak shift, were involved in the process of these VSs observation and in response to aesthetics in VSs.

3.4. Effects of geometrical criteria over affective responses to virtual spaces

Sharp VS's containing a curvature of 0 (C = 0) which were also asymmetrical, were characterized by a gradual change in PD and MPD, which indicated interest as the protrusion of the space increased. It seems that sharpness plus asymmetry ($C = 0+P = 4$) are criteria responsible for positive interest, as we observe all human-centred measurable variables.

Hubel and Wiesel (1979) originally noted that edges stimulate cells in the visual pathways, because they are indifferent to homogeneous regions. This observation could explain the reason why curved (C = 4) asymmetrical VS was not positively perceived. Another possible explanation is related to the absence of a peak shift affect, since curvature, when non-symmetric, lacks contour and has no visually clear 'ending'. This effect absence might possibly be related to the amount of protrusion, which is 'restrained'. Possibly, other renderings of light and shadow could have achieved different perceived contrast effects (Oberfeld and Hecht 2011). Another explanation why this space did not produce any recognizable physiological evidence of possible significant interest may indicate different cognitive processes involved in its evaluation. A metaphor describing a 'warm womb-like space' in earlier research, which collected qualitative data, was expressed after the actual act of observation, happening in a non-immediate way (Shemesh, Bar, and Grobman 2015).

Another important finding is related to proportion. This criterion achieved significant results in all human-centred measurable variables, both physiological and non-physiological (PIS and LS). The findings demonstrated that certain geometries in general, and in proportion in particular, have significant emotional impact possibly related to protrusions into personal space and boundaries (Lloyd 2009), and are less related to aesthetics. The threat seems to be the strongest in changes of VS width measures. The narrower the space, the more discomfort can be recognized. Distress emerges based on all human-centred operational measures taken (short dwell time, low LS, high level of arousal as recorded by EEG and GSR measurements). In addition, the narrowest space was (as opposed to the lowest perceived room height) (Vartanian et al. 2015; Cha et al. 2019), the more coherent and significant measure in both groups of participants. Similar effects were noted in lower spaces. We suspect the reason is that (a) high ceilings remain outside one's useful field-of-view (compared with the wide VS) and low space is more easily perceived in our normal vision field (similarly to narrow), and (b) narrow VS is characterized by vertical lines (compared with low VS). Therefore, only those who lifted their heads could react to this dimension of height. We contend that further research related to simultaneity of physiological peaks should concentrate on this measure, since it could demonstrate a process of space perception which potentially produces significant arousal at a certain point in the process.

It terms of scale, the results demonstrated that long dwell-time inside a VS correlated with large spaces (as compared with small spaces). The same held true for PD, and LS (high values in large VSs), while having fewer and shorter eye movement fixations in these VSs. The results supported the notion that participants had a positive interest in large spaces, and a negative one in small spaces.

4. Conclusions and future research

In response to a research question which asked, what is the effect of geometry of space on emotional reactivity, this study has examined the connection between the properties of space and human emotions. It measured changes in the geometry of space, specifically related to the criteria of scale, proportion, protrusion and curvature. It developed a novel methodology, in which different physiological responses to visual 3D stimuli were simultaneously recorded and analysed. Conclusions regarding the physiological effects produce a basis for further investigation regarding the suspected connection of different physiological measures involved in the visual perception-emotional response process, occurring in the 3D environment.

This research produced several headline results. Firstly, emotional reaction to space, both positive and negative can be measured by changes of curvature (C), protrusion (P), scale (S), change of proportion in height P(H) or width P(W) of virtual spaces. More specifically, large symmetrical spaces affect positively users. The more extreme the proportion, the stronger the measured response, especially in narrow spaces, in which distress is recognized. The higher the criterion of protrusion in a complex asymmetrical VS – the stronger the emotional response. All physiological measurements are significantly more intense among non-designers, which indicates they experience a stronger reaction towards manipulations in the geometry of the virtual space, than those of designers.

Additionally, the study attempted to find and apply methods from the cognitive neurosciences in order to design more effectively sympathetic spaces with potential applications that vary from special-needs children and educational structures (Franz 2019) to geriatric and rehabilitation spaces (Edelstein 2008; Devlin and Andrade 2017), and public and living spaces. An inductive approach towards future research that will add a single criterion in each stage/examination will help produce valid data for the mapping process of the connection between human conscious experience and architectural space. Increasing our understanding of the connections between each one of the examined criteria, as well as a combination of them, both geometric and other, could help architects and designers better appreciate the impact of design on its user, thus leading to better design.

At this stage, we can produce several design recommendations which focus on the shape of space by adding 'humane conditions', such as presence of windows, daylighting (Ergan et al. 2019) and different materials (Zhang, Lian, and Wu 2017). For instance: in symmetrical spaces, if proportions and scale (as well as other criteria such as temperature, light and colour) are not distressing (Choi, Kim, and Chun 2015; Li et al. 2020), they can benefit activities of concentration and rest. In correlation, complexity or asymmetry produce different measures which indicate a higher level of interest – and even positive interest, in the case of non-curved asymmetry. Architectural spaces of the sort could be suitable for uses which benefit from this reaction, yet it may also be distracting, and not recommended for specific task-oriented uses. Large symmetrical spaces are suitable for multitude users, not only due to their large capacity (a large volume can contain more people), but also due to their tendency to attract participants to stay in them longer. This suggestion, however, applies solely to simply-shaped spaces, as the effect of complex shapes of large spaces is still unknown. Extreme proportions have the potential negatively to influence wellbeing. If we wish to design spaces which create a high level of excitement, we could use extreme proportions. For the experienced users (designers, or people who experience terrifying spaces in games, for example), we suspect that these proportions are actually more enjoyable. However, narrow spaces should be experienced as distressing, regardless of expertise or advanced familiarity. Assuming that the 'right' design is usually user-oriented (Tvedebrink and Jelić 2018), additional research is required to understand the gap between an aesthetic emotional reaction and a later cognitive interpretation, as well as the impact of additional environmental and personal criteria involved.

The results demonstrate a relationship between the properties of space and human emotions. The main realization regarding this challenge lies in our ability to discover levels of interest and compare them to other behavioural and self-reported measures. By being able to do so, we can recognize an emotional response. The fact that no evidence was found of correlation between the physiological measures and other human-centred operational measures (There is a gap between what we think about VSs and the way we react to them), indicates the importance of using this combined experimental method of investigation. To some degree, we believe a measurement of the nature of interest (polarity) will be possible according to physiological measurements alone in future research. We suspect, according to this study, that a negative interest response is easier to depict. We also assess that emotional response is gradient by its nature, yet this assessment calls for further research (Duque, Sanchez, and Vazquez 2014; Lettieri et al. 2019). Additionally, the presence of emotions associated with aesthetics in general and in relation to positive/negative interest in specific terms, calls for further research. We expect that the interconnectivities between the cognitive neurosciences and architectural design will continue to flourish, as this research-developed methodology can contribute to the maturation of the neuro-architecture field into an experimental science. We suspect findings regarding the criteria of geometry would soon be possible to apply in the practice of architecture and design.

Notes

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Appendix. A table of acronyms found in this article

ADHD	Attention-Deficit Hyperactivity Disorder
AR	Augmented Reality
BSN	Noninvasive Body Area Sensor Networks
βBPR	Beta (Waves) Band Power Ratio (physiological measure)
C	Curvature (VS geometrical criterion)
2D	Two Dimensions
3D	Three Dimensions
D	Designers
d	Depth
EEG	Electroencephalography
FD	Fixation Duration (physiological measure)
FR	Fixation Rate (physiological measure)
GSR	Galvanic Skin Response
h	Height
HRV	Heart Rate Variability
EDA	Electrodermal Activity
EMG	Electromyography
ET	Eye Tracking
fMRI	Functional magnetic resonance imaging
FOV	Field of View
GIS	Geographic Information System
GPS	Global Positioning System
GSRR	Rate of GSR peaks
IR	Infrared
LS	Liking Score (self-report measure)
m	Meters
MEV	Measurable Environmental Variables – Which are the geometrical VS Criteria: Curvature (C), protrusion (P), scale (S), proportional change in height P(H), or width P(W).
MGSR	Maximal Galvanic Skin Response Amplitude Peak (physiological measure)
MPD	Maximal Pupil Diameter (physiological measure)
ND	Non-Designers
P	Protrusion (VS geometrical criterion)
PD	Mean Pupil Diameter (physiological measure)
P(H)	Proportion (Height) (VS geometrical criterion)
PIS	Presence In Seconds (behavioural measure)
P(W)	Proportion (Width) (VS geometrical criterion)
S	Scale (VS geometrical criterion)
USB	Universal Serial Bus
VR	Virtual Reality
VS	Virtual Space
VE	Virtual Environment
W	Width