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Affective response to architecture – investigating human reaction to spaces with different geometry

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ABSTRACT

A multidisciplinary research was carried out to reach an improved understanding of the connection between the geometry of space and human emotions. The research develops a framework and methodology to empirically examine and measure human reaction to various types of architectural space geometries. It involves two stages of investigations in which participants experience four spaces characterized by different geometries. Their reaction to the spaces was investigated by means of both qualitative and quantitative methods, which involved questionnaires in the first experiment and advanced sensors and data analysis in a second experiment. The experiments, which employ new virtual reality, electroencephalogram and data analysis methods, confirm the developed methodology. In the first stage of the investigation, participants showed different types of responses and preferences towards spaces. Results of the second stage's experiment showed a difference in our mental reaction to different geometries of space.

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Architectural space geometry; virtual environment; space perception; cognitive neuroscience; diffusion maps; affective response; emotions

1. Introduction

The search for the right way to design architectural spaces is one of the most enduring and fundamental questions in the field of architecture. Aspiring to improve the built environment, architects are continually trying to create spaces that positively affect users. Recent technological advances in architectural design and simulation methods allow architects to empirically examine and optimize numerous criteria that affect users (Grobman 2011). These criteria are primarily related to environmental aspects such as stability, light, temperature and acoustics (Hensen and Lamberts 2011). However, perceptual and cognitive criteria, which are crucial to understanding the influence of architectural space on people, are still evaluated by relying on the designer's experience or on rules-of-thumb. It thus seems that the factor of aesthetics in building project evaluation is applied as a 'best-guess' estimate (Ilozor and King 1998).

The notion of architectural space evaluation consists of three complementary realms: form, function and user. Computational tools and methods for optimizing the performance of building performance criteria are already in use in the majority of building-related disciplines and are under constant development in both research and practice. These criteria are related to the performance of the environmental and the formal aspects of space. Technologies and methods for the evaluation of user-related aspects are less advanced. These aspects can be divided into two categories, which relate to the way users 'behave' in architectural space and the way users 'feel' in space. Current research on human behaviour in a space is aimed at developing methods for computer simulation of human behaviour in

various architectural contexts (Yan and Kalay 2005; Simeone and Kalay 2012). Research in this realm has shown good potential and yielded some useful results, especially in relation to specific activities such as designing fire escapes and simulating human behaviour in building types such as hospitals where the human activity is relatively predictable (Schaumann et al. 2015).

However, understanding 'how' people behave in an architectural space does not explain 'why' they behave as they do. This aspect is related to people's emotional response to the space. Though it is possible that personality traits affect our perception of the environment (Ibrahim, Abu-Obeid, and Al-Simadi 2002), one of the fundamental aspects in relation to humans' experience in space is that the properties of the space itself may influence our mental state. Colour, contrast, motion, retinal size, location and object identity are all visual experiences, to which we respond emotionally (Baars, Ramsøy, and Laureys 2003).

The aim of the presented research is to investigate whether emotional and cognitive reactions that are generated by various types of architectural spaces can be empirically measured and quantified. The argument is that current technological advances in virtual reality (VR) tools and techniques, electroencephalogram (EEG), data analysis methods and neuroscience research may point at new ways to recognize, quantify and measure human affective response in relation to architectural space.

The argument in this paper is developed as follows: first, we critically review the current stage of knowledge in the field, define the gaps in measuring human affective response to architectural space and discuss the potential of recent technological advances to recognize different experiences in architectural

space; second, we examine human affective response to different architectural space geometries in a VR environment by traditional methods of observation and questionnaires. Third, we develop and test a framework for a research methodology and experiment setup that will enable empirical examination of human responses to architectural space geometry, based on a combination of VR and EEG data.

Undoubtedly, human reaction to space is generated by a compound response to a multiplicity of factors. The reaction to space is determined in part by its spatial context, its geographic location and in which society and culture it is embedded. The reaction is also determined by the physical dimension of the space itself: colour, light, texture, smell and sound. Methodologically, separating the contextual from the physical is challenging. Yet we argue that we can gain valuable knowledge from an initial probing into the relationship between the geometry of space and human perceptual experience. As an initial investigation, we examine basic emotional responses such as fear, interest and pleasantness, which involve aesthetic judgment. These emotions are a part of a much larger array of possible responses (Barrett and Bar 2009), yet according to earlier study, a link between the sharpness of a contour and threat perception can be recognized in brain activity (Bar and Neta 2007), as well as the feeling of pleasantness (Kringelbach et al. 2003). Since human experience consists of a much larger array of possible emotional reactions, future research will focus on mapping other types of experiences.

We begin with a literature review, which explores current knowledge on shape perception and spatial perception. Specifically, we discuss the relationship among space perception, cognition and emotions. The second part presents an experiment that examines the connection between space geometry and participants' affective response using questionnaires and a VR-based setup. Finally, we will present findings from a preliminary empirical experiment based on the combined use of a wireless EEG and a manifold learning data analysis method that shows that different types of architectural space geometry generate different brain reactions. The paper ends with a discussion of directions that are worth pursuing in the future stages of the research.

2. Literature review

This research was conducted at the intersection point of several fields: architecture, environment–behaviour studies, cognitive psychology, neuroscience and electrical engineering. The literature review starts by discussing the perception of 2D shapes in neuroscience and in cognitive psychology studies. Then it will examine similar ideas but with relation to 3D space. The review's last part concentrates on new technological possibilities for visualizing architectural space and measuring human emotions.

2.1. Perception of shapes

Perception in the context dealt with in this research is visual. Visual perception refers to different kinds of processing that allow us to see the form, colour, position and distance of objects

in the visual field and recognize objects (Rosenzweig, Leiman, and Breedlove 1999; Bar 2004). Vision plays a prominent role in the 'identification of things, to signal us whether something is indeed one thing (partly hidden by something else), a possible resource or refuge, or potentially dangerous' (Hekkert 2006). The ability to identify various objects is a necessity for survival.

According to Arnheim (1971), the physical shape of an object is determined by its boundaries. 'Perceptual shape' is the outcome of the interplay between the physical object, where the medium of light acts as the transmitter of information, and the conditions prevailing in the viewer's nervous system. Thus, a form is fundamentally determined by the way we observe it. This process of recognition does not take place in just one area in the brain (Eberhard 2007), but rather in short and long-range networks of cortical regions.

Our perception of an image is determined by the previous visual experiences we have had with that object in sight, as repeated exposure to the stimulus involves learning and associations (Reber, Schwarz, and Winkelman 2004). The brain continuously searches for analogies, linking new input with the most similar representation in memory (Bar 2009; Bar and Neta 2006). As could be expected, the process of recognition is tightly connected to our subjective response to what we observe.

Yet our preference for objects is influenced by many factors besides familiarity; according to Winkelman, Schwarz, and Nowak (2002), these include symmetry, contrast, complexity and perceptual fluency. High 'perceptual fluency', as they explain, is associated with progress towards successful recognition of the stimulus, error-free processing or the availability of appropriate knowledge structures to interpret the stimulus. The more fluently perceivers can process an object, the more positive their aesthetic response (Hekkert 2006; Zajonc 1968). Another interesting observation regarding positive response is that judgments of preference, liking and beauty are closely related (Reber et al. 2004).

Research indicates that angular contours are less pleasing than round contours (Silvia and Barona 2009; Bar and Neta 2006; Leder, Tinio, and Bar 2011). People with a low level of expertise in design prefer curved over angular shapes when they are simple, such as circles and hexagons, but those with more expertise show a preference for more complex polygons (Silvia and Barona 2009). Training in arts results in an additional increase in processing ease, which gives meaning to complex structures (Reber, Schwarz, and Winkelman 2004).

Importantly, existing literature's scope is limited in two ways: first, it focuses mainly on simplicity, symmetry or high perceptual fluency. This represents only a partial selection from the scope of possible characteristics of shapes. Complex, less clear forms might be less pleasing but can elicit very strong emotional responses, which could be as relevant to the question at hand. Second, the subject of aesthetic judgment in literature examines mostly positive responses. Negative reactions such as disliking or even intimidation are as important to improve our understanding of the entire range of human reaction to shapes. Moreover, negative reaction towards shapes may be positively appreciated. For example, Maass et al. (2000), looking at the relationship between feelings and the appearance of a building

(mainly facades), showed that participants can perceive more intimidating buildings as more beautiful.

2.2. Perception and response to space

One of the major challenges in this research is to measure mental reaction in relation to architectural space. In this section, several methods used in science literature may help us to recognize the range of emotions a person experiences in a given state. Psychophysiological parameters and measurements such as heart rate, respiration, blood pressure and galvanic skin response (GSR) can serve an indication for some human emotional experiences. Skin conductance functions as an indication of psychological or physiological arousal, which we can use to measure emotional and sympathetic responses (Carlson 2012). Physiological effects in the body vary because of the experience of different basic emotions: surprise, fear, anger, pleasure and disgust can be reflected by changes in blood pressure and finger temperature (Collet et al. 1997). Furthermore, stress can also be examined by measuring heart rate (Jovanov et al. 2003). Whether consciously felt or not, an object is said to have affective 'value' if it has the capacity to influence a person's breathing, heart rate, hormonal secretions, etc. (Barrett and Bar 2009). By measuring heart rate while directly experiencing changes in their breathing, muscle tension or stomach motility, people routinely experience more diffuse feelings, pleasure or discomfort, feeling worked up or slowed down (Barrett and Bar 2009).

As for measuring affective response in the context of environmental design practice and research, several methods that involve imaging have been used in the last decade. Chalup and Ostwald (2010) examined the potential of employing machine learning in anthropocentric biocybernetic computing for reflecting the responses of the human emotional system by using a database of facial expressions.

Another method is imaging modalities such as functional magnetic resonance imaging (fMRI) and positron emission tomography. These can help focus on the brain regions that could be involved in given responses. Vartanian et al. (2013) conducted a study using fMRI that examines how variation in contour impacts aesthetic judgments and approach-avoidance decisions. Their results demonstrated that participants were more likely to judge curvilinear than rectilinear spaces as beautiful. In another research using human neuroimaging, researchers found that the Amygdala, a brain structure that is involved in fear processing, is significantly more active for everyday sharp objects compared with their curved contour counterparts (Bar and Neta 2007). These methods are part of a neuroscientific approach to environmental design practice and research (Zeisel 2006). They do, however, limit the ability of the user to move freely through space. In addition, while using this equipment, researchers are limited in their ability to create a desirable setup and isolate the desired variables.

Zhang et al. (2011) tested cognition with a novel audiovisual CAVE-CAD tool by using a wireless EEG. The EEG detects electrical activity in the brain and its wireless version is easier to carry around, thus enhancing the user's mobility. They suggested a possible recognition of differences in brain dynamics when subjects knew their orientation versus when they were lost.

2.3. Virtual reality as a possible setup for space perception experiments

In an empiric research setup, isolating variables is crucial, and sometimes real environments contain much more information than we can handle. Virtual environments (VEs) allow researchers to manipulate variables of interest while keeping design features constant. This can help to reduce experimental noise (Heydarian et al. 2015b), which can be a burden due to the countless features we perceive in our environment. By creating new perceptual conditions for the user through introducing a practice process in the VE, researchers can analyse specific human skill components (Bergamasco, Bardy, and Gorher 2012). In this VE, different variables of a given space, such as the properties of colour, light, smell, sound and even texture, can be controlled and isolated.

Sanchez-Vives and Slater define the notion of 'presence and immersion': presence is 'the sense of being in a VE rather than the place in which the participant's body is actually located' (2005). Immersion is similar: 'A person is immersed in an environment that is realized through computer-controlled display systems, and might be able to effect changes in that environment'. Researchers compared between participants' performance, perception and sense of presence when they were in a physical office space and in a designed office space in an immersive virtual environment (IVE). The IVE was produced by an Oculus Rift DK (a VR headset). They found that participants perform similarly in both the physical and the VE (Heydarian et al. 2015b). In addition, they claim that participants feel a strong sense of presence within the IVE. A sense of presence within an IVE was also reported by Kieferle and Wossner (2001). It was also found that participants experiencing freewill exploration of VEs (produced by a Kaiser Pro-View head mounted display and a screen) can demonstrate a wide range of behaviours and responses similar to their natural exploration of real-world environments (Morie et al. 2005). IVEs have proven to be more realistic learning environments, especially for tasks related to spatial performance, such as navigation, path-finding and object perception in comparison to other mediums such as immersive workbenches, computer screens and hemispherical displays (Heydarian et al. 2015a).

The 3D feature exerts an integral influence over the VE experience. According to theories of media richness, 3D environments are objectively rich because there is synchronous contact; the visual stimuli, objects and environmental designs that offer a variety of social cues. In these VEs, communication occurs through multiple channels, including audio, visual and text (Wasko et al. 2011). Current VEs offer a good substitute for reality in terms of allowing participants to feel immersed in space while maintaining the possibility to control various parameters.

2.4. Current gaps in knowledge and the potential contribution of the proposed approach

The literature review emphasizes the existing lacunae in three main areas: (a) the ability to empirically measure the various readings of emotional reactions (traditional research is based on statistics gathered from questionnaires); (b) the level of confidence in their results (it is impossible to verify how the

participants actually reacted in relation to what they wrote on the questionnaire) and (c) the possibility of using the results in an architectural design process. According to Dosen and Ostwald (2013), only few studies genuinely investigate architectural features, as small sample sizes and unbalanced groups undermine many of the results. A novel research approach that gathers knowledge from various other research fields such as those mentioned above and exploits advances in research and technologies in visualization, physiological measurement and data analysis can potentially diminish the gap in mapping cognitive reactions towards different architectural geometries.

Although this entails some uncertainty due to the unpredictability of the results, it demonstrates the capacity of a possible instrumental setup to recognize neural response to different types of geometry. We believe that successful results can be achieved by combining qualitative and quantitative research; in fact, it is only in this way that data can be consolidated and formed so it can be implemented in practice. The results will be especially valuable in fields such as the design of educational, healthcare and detention facilities, where the influence of the design of a single space (a patient's room, a classroom, a prison cell, etc.) is crucial.

Moreover, proving that the suggested methodological model produces scientifically valid results will encourage a broad range of commercial organizations to use it for generating data on human reactions to specific types of commercial and other spaces. Having this type of data would also allow both practitioners and entrepreneurs to argue for better adaptation of their design proposals to meet human needs. In addition, a better understanding of affective response to architectural space can also contribute to better building design and better utilization of buildings by their users. Aesthetic value may be the factor that will improve traditional evaluation techniques to better determine cost-effectiveness of building projects (Ilozor and King 1998). We therefore believe that empirical data on human reactions to space holds the key to many successful applications in a wide array of domains.

3. Stage 1 – human behaviour in VE

The first stage of the research was conducted in a visualization laboratory, which contains a 3D immersive theatre consisting of a 2.4×7.0 m screen with a 75° field of view, and three high-definition projection and motion sensors. The study centred upon quantification and analysis of a participant's response to space based on observation and questionnaires. Since training in the arts should increase ease in processing (Reber, Schwarz, and Winkelman 2004), the research compared the reaction of 21 experts (design students) and 21 non-expert students (from other fields of study) to various virtual architectural spaces. The experiment employed four basic types of spaces, which were designed to be colourless (monochromatic), soundless and free of objects other than a single chair.

3.1. The process

Participants were asked to practice the system using the 3D goggles and joystick in a neutral VE, so they could gain some expertise and a sense of control over the VizTech XL software. Famous

paintings were used in the training process to set participants' minds at ease before starting the experiment. As the experiment began, the participant entered one of the four spaces by 'walking' via joystick through a standard corridor and entering a door. Participants were asked to 'walk' towards a chair after entering, explore the space and leave after they finished their exploration. The chair standing in the centre of the space provided a human scale reference. The order of spaces was changed randomly. Time was not limited, though it was measured for future comparison.

3.2. The setup

The setup consisted of four types of VEs: square symmetrical space (Sq); round-domed space or half a sphere, symmetrical (Ro); sharp-edged space, tilted surfaces (walls, ceiling), asymmetrical (Sh) and curvy-shaped space with rounded smooth surfaces (with no corners), asymmetrical (Cu). The objective was to examine two pairs of spaces: a square shape and a spherical shape were compared to complex forms that had breaks and curves. They also differ in their symmetry (two symmetrical forms vs. two unsymmetrical forms). In order to perform an optimal comparison of impact of geometry over the user, all designs had to maintain comfortable proportions and a sense of human scale. A space too small might create an instantaneous feeling of suffocation, while a space too large might create discomfort or disorientation. As such, all spaces were designed to be approximately the same size. We chose the proportions of a typical university lecture hall: a floor of 12×12 m and a ceiling over the height of 6–8 m, in order to resemble the dimensions of a university lecture hall that would be familiar to the majority of the participants (see Figure 1). In order to account for the difference between an inter-personal objective and perceived distance (Gifford 1983), we entered the reference of a chair. Volumes were designed to be colourless (monochromatic), soundless, with no objects (except for the chair). The lighting was non-directional and created equal illumination in all parts of the space (Figure 2).

The experiment began with the participant entering the space by 'walking' through a standard corridor followed by a door. This stage is important, as researchers found that entering a room or walking through doorways can facilitate forgetting or evoke one's memory (Ballard et al. 1997; Radvansky and Copeland 2006). Wang and Spelke (2000) found that human navigation through a layout in an unfamiliar environment depends on an updating representation process of targets positioning relative to the self, which occurs during movement. Therefore, participants were asked to 'walk' towards the chair after entering space, explore the space and leave (through the same door) as they finish. The order of the spaces was changed randomly.

After exploring each space, participants filled out a questionnaire regarding their experience. To collect immediate reactions, participants were first asked to indicate how much they liked the space on a 5-point Likert scale (5 refers to highest level of preference). According to research, the use of a summated multi-item scale is reliable in attempts to quantify emotions, opinions, personalities and descriptions of people's environment (Gliem and Gliem 2003; Diamantopoulos et al. 2012). Participants were later asked to characterize the space (efficient, pretty, safe, pleasant

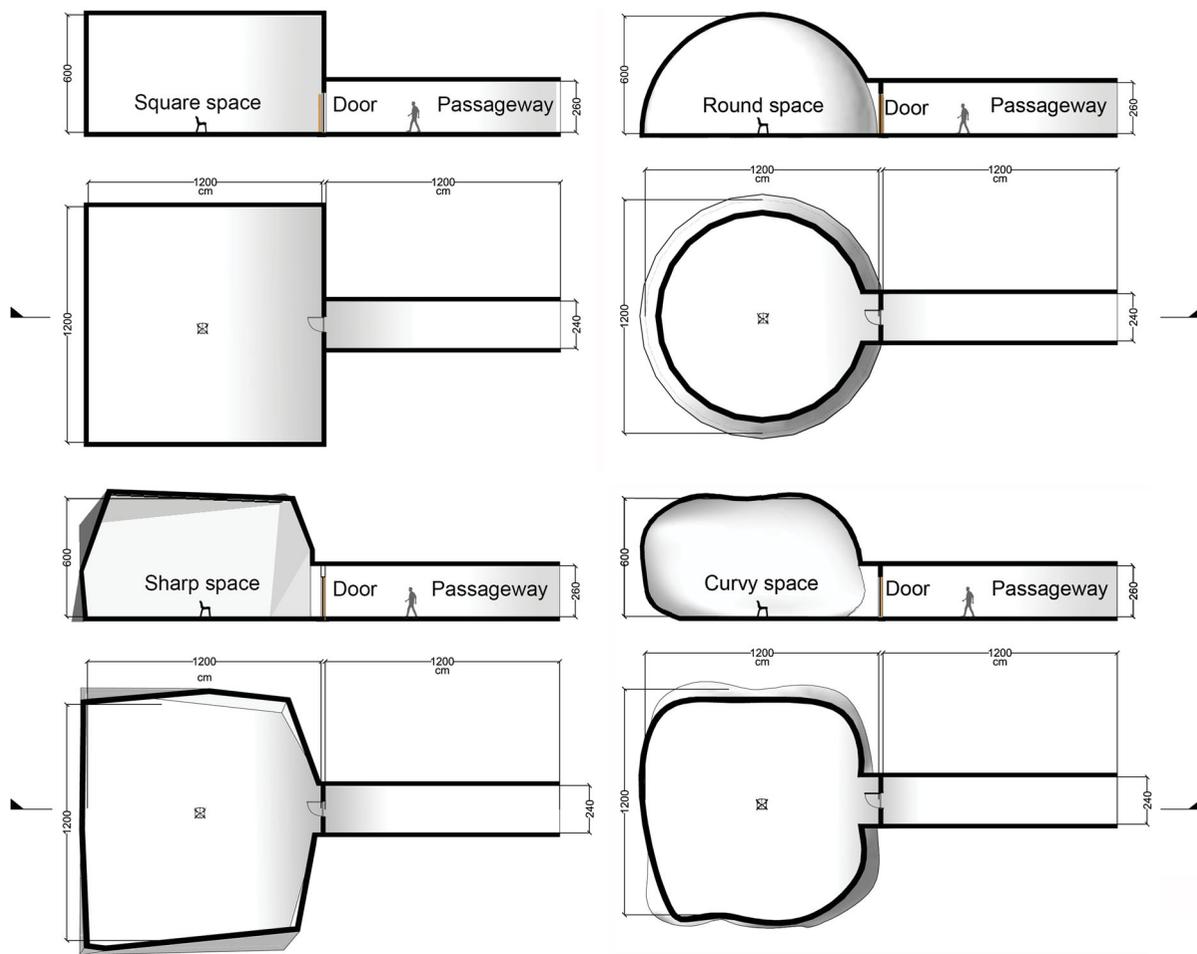


Figure 1. Plan and sections (from left to right, up to down): room no. 1, a square symmetrical space; room no. 2, a round-domed space; room no. 3, a sharp-edged space and room no. 4, a curvy-shaped space.

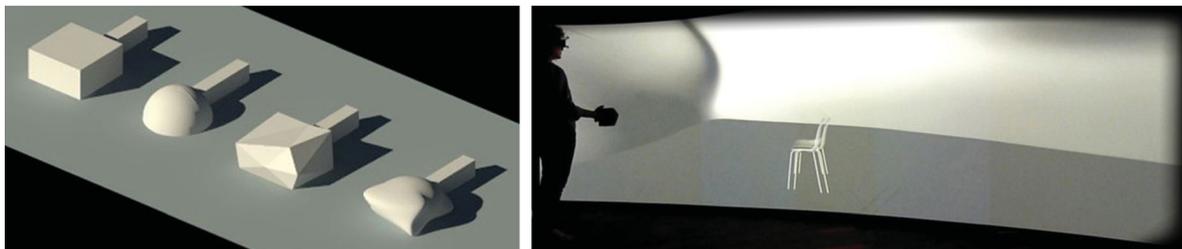


Figure 2. Upper left, external view of the four designed VR spaces. Upper right, inner view of the curvy-shaped space.

and interesting) and describe their thoughts and feeling towards the space.

3.3. Results

Results suggested a difference between the two groups of users (experts and non-experts) in terms of their various thoughts and feelings towards the spaces and their ideas regarding possible uses of the various types of space. Findings also showed a significant difference between experts and non-experts in terms of the interest triggered by a curvy-shaped space (Shemesh, Bar, and Grobman 2015) (Figure 3). Interestingly, we found no correlation between judgments of beauty and the feeling of safeness in participants' preferred spaces. This echoes findings supporting a possible difference between perceived beauty and safeness

(Maass et al. 2000; Silvia and Barona 2009; Wiener and Franz 2005). While the feature of symmetry did not seem to have influence over the user's preference, the curvature of the space was found to be influential.

4. Stage 2 – EEG measurements in human behaviour examination in a VE

In the second stage of the research, we develop and test a framework for a research methodology and experiment setup that examines human responses to architectural space geometry in VR environment, based on EEG data. The research methodology is tested in a pilot experiment. In contrast to the previous stage, which relied on questionnaires to measure human reactions to the examined spaces, in this stage, we studied the reaction to



Figure 3. Responses of experts and non-experts towards spaces: group NE (non-experts) showed great interest in the Cu space, with 90.5% of them finding this space interesting ($\chi^2(1) = 4.725, p < .05, R_{\text{crem}} = 0.335, p < .5$); (Shemesh, Bar, and Grobman 2015).

various architectural spaces geometry through a 'direct' measurement of the participants' brain activity using a wireless EEG device (Emotiv EPOC, "EMOTIV – Brainwear® Wireless EEG Technology"). Parallel to the challenge in examining space geometry through direct brain measurements, this stage also wishes to test the connection between the way people reported they reacted to space geometry in Stage 1, and the results of the direct measurements. Our assumption is based on the first experiment's findings, which indicate that a difference in the level of interest and preference towards these spaces exists. Stage 2 creates the framework to examine whether we can empirically recognize any of these differences, as we compare physical reactions to the same spaces.

Relatively easy to install, this basic device consists of 16 electrodes, which produce 14 EEG channels. The EEG data analysis method employs a manifold learning method that extracts the common source of variability from multiple measurements. The method will be further explained in Section 4.2. This unsupervised analysis specifically was not driven by hypotheses. Thus, it can be considered unbiased (Figure 4).

4.1. The recording of brain response to the virtual spaces

A well-known limitation using EEG recording that we came across during our initial setup experiments was the high background noise, which stems from muscle movement such as eye-blinking and head turning. In order to reduce the influence of noise, the experiment consists of a fixed setting, where the examined participants sit motionless in a dark visualization laboratory. The fixed setting creates, however, an inconsistency between the two experiment stages. It is clear that this inconsistency needs to be dealt with when a comparison between the two stages takes place in future stages of the research. A possible solution could be to repeat the first-stage experiment with similar fixed settings to the second



Figure 4. A person wearing the Emotiv EPOC device.

stage, or to try to find a technological solution to the background noise by increasing the number of electrodes (employing high end wireless EEG device), or changing the data analysis method.

The EEG signals from the participants are recorded while frames of different spaces (observed from the entrance) are presented to them on the visualization laboratory large screen in an arbitrary order. The simulated spaces are characterized by four different geometries, identical to the spaces designed for the first stage of the research. During these tests, the duration of the presentation of each space and the number of repetitions were adjusted: the initial 10 s of exposure to space was reduced to 6 s and the number of repetitions of one series of the four spaces was increased to two and eventually three series (a total of 12 exposures). These values were shown to empirically achieve consistency in the output signals. These data match research findings using eye-tracking in rating artworks, as emotions were measured between the second and seventh seconds (Yanulevskaya et al. 2012).

4.2. Analysing the data

The existence of any specific mental state cannot be deduced by looking at the output data. This ambiguous information calls for ‘after the act’ analysis. Our main assumption was that underlying the noisy EEG recordings, intrinsic processes exhibiting distinct patterns and structures expressing brain activity do exist. By revealing these intrinsic processes, we examined the relationship between the brain activity and the perception of space. To this end, the recorded EEG signals were analysed using manifold learning techniques (Coifman and Lafon 2006; Talmon et al. 2015), which build meaningful descriptions of data from the EEG output that initially seems to be quite scattered. Considered a relatively new approach, manifold learning has been applied successfully to problems from various fields. These include speech (Talmon, Cohen, and Gannot 2013) and audio processing (Talmon, Cohen, and Gannot 2011); anomaly detection in images (Mishne, Talmon, and Cohen 2015); analysis of EEG signals for the prediction of epileptic seizure (Talmon et al. 2015); automatic sleep stage identification (Hau-Tieng, Talmon, and Yu-Lun 2015); architecture façade and skyline detection (Chalup and Ostwald 2010) and brain–computer interface (Even-Chen, 2014).

Specifically, this study used two manifold learning techniques. In the first stage of the analysis, we applied a multichannel manifold learning method (Lederman and Talmon 2015) to identify highly coupled channels, that is, channels that carry similar information. We assumed, based on previous experience with manifold learning, that information detected consistently in more than one channel is more likely to be relevant for the purpose of recognition of the type of architectural geometry from the EEG data. Based on our algorithm, Channel P7 and Channel O2 were selected automatically. In the second stage of the analysis, we applied another manifold learning method (Talmon et al. 2015) that was specifically adapted to analyse time series and dynamic systems, to the EEG recordings from the subset of relevant channels identified in the first stage. Based on the results, we examined two of the space’s independent parameters: symmetrical (spaces number 1,2) or asymmetrical (space number 3,4) and sharp-angled (spaces number 1,3) or rounded (spaces number 2,4).

Figure 5 presents the representation of the EEG recordings obtained by the manifold learning technique. For simplicity and visualization purposes, we used a 3D description of the data. Each 3D point in the figure represents a single time frame of 1 s window that was taken in order to preform a scatter transform on the raw data, prior to the manifold analysis. These data points were taken with an overlap of 0.75 s, to insure local continuity, for better performance of the algorithm. Each of these windows was composed of 128 EEG measurements from a single channel identified as relevant in the first stage of the analysis. The three dimensions in the figure represent the three non-linear principal/dominant components (NPCs) obtained by the second stage of the analysis. Once we obtained these components, we coloured each point according to the type of space presented to the participant during that particular time frame (blue – space 1; light blue – space 2; yellow – space 3; red – space 4). We emphasize that knowledge of the type of space was not taken into account in the manifold learning analysis.

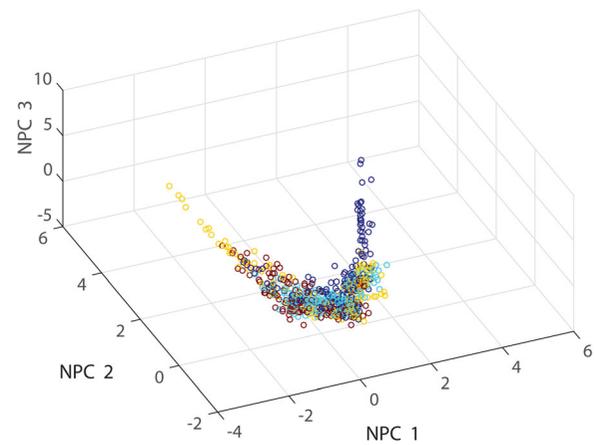


Figure 5. The NPCs computed, based on sensor p7.

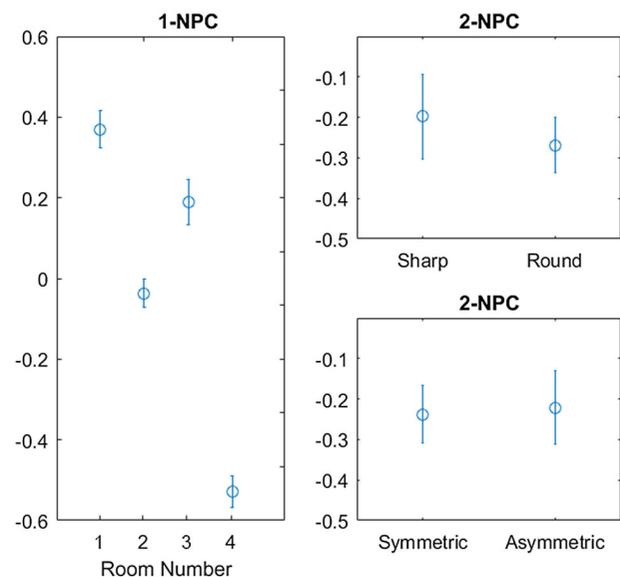


Figure 6. The median and the standard error of each room in NPC 1 (left) and NPC 2 (right) as a function of the space from Figure 5. The diagram shows that space recognition is clearly divided by the aspect of curvature.

The clustering of the points according to the different colours/spaces implies that the different spaces are substantially manifested in the EEG recordings. To demonstrate the clustering of the points in relation to the different colours for NPC 1 (the first dominant component) and NPC 2 (the second dominant component), which correspond to the x- and y- axes in Figure 5, we computed the median and standard error of the points of the same colour and presented it in Figure 6. There, we see that the mean value of NPC 1 is different for each space. It implies that the different spaces are evident in NPC 1, which was computed based solely on the EEG without taking into account the knowledge of the space. Based on NPC 2, we see that the four spaces are clustered into two groups: sharp-angled and rounded spaces.

To further demonstrate the consistency of our method, we present the analysis results of another participant (Figures 7 and 8). We see that the four different spaces are manifested in

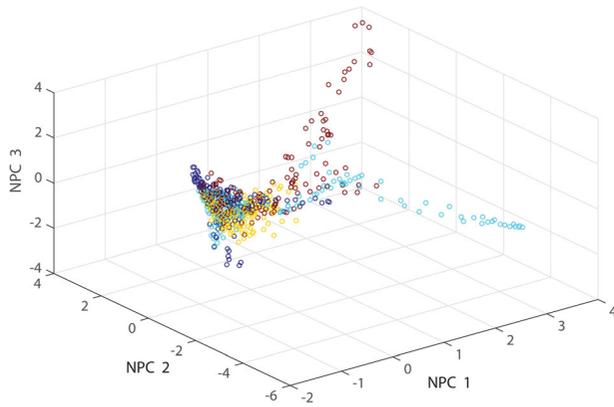


Figure 7. The NPCs computed, based on sensor O2.

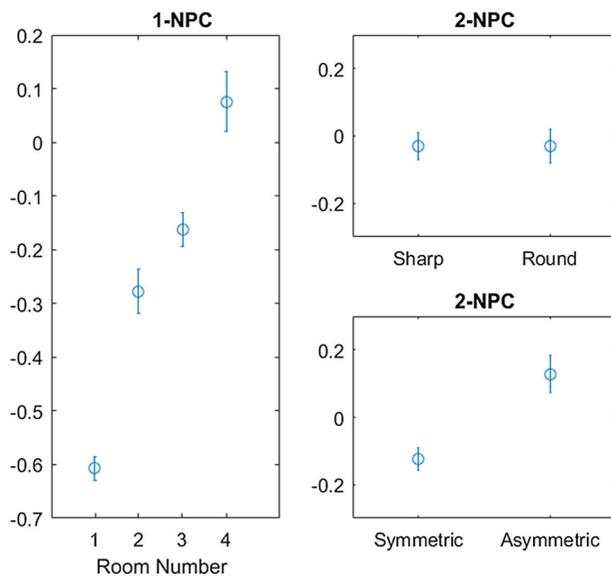


Figure 8. The median and the standard error of each room in NPC 1 (left) and NPC 2 (right) as a function of the space from Figure 7. The diagram shows that space recognition is clearly divided by the aspect of symmetry.

different brain activity, which is captured by the NPCs computed by our method. In this case, however, based on NPC2, the four spaces are clustered into two other groups: symmetrical and asymmetrical.

Analysing the output derived from our exposures to a certain space confirmed a non-coincidental response of the brain to that space. This means that we were able to distinguish between different spaces, based solely on data observation.

In Figure 9, we plot only the NPC 1 and NPC 2 of a third participant based on a 10-s EEG recording (top) and on a 2-s EEG recording (bottom). The results show that brain activity occurring in the first 2 s of exposure to a certain space is crucial since we observe a better separation according to the different spaces. This observation may imply that adaptation to a certain space occurs within this period. This finding is in line with several studies based on eye-tracking, indicating that viewers of art (no matter whether it is representational or abstract) spend the first 2 s doing a sweep of the image and analysing its 'gist'. It is only after this first explorative stage that viewers tend to focus on finer details (Locher et al. 2007; Yanulevskaya et al. 2012).

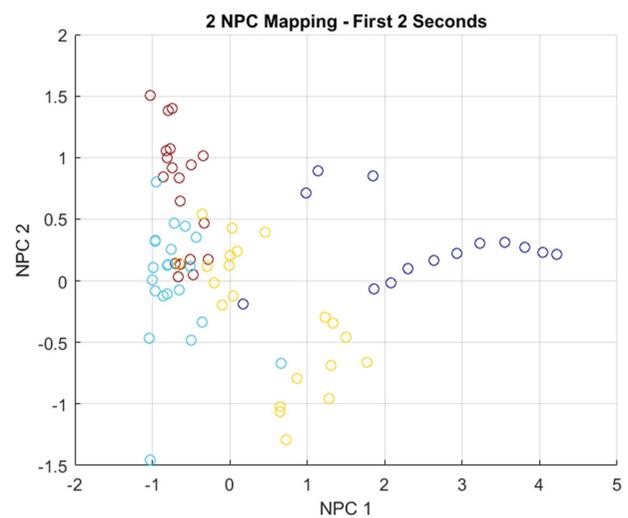
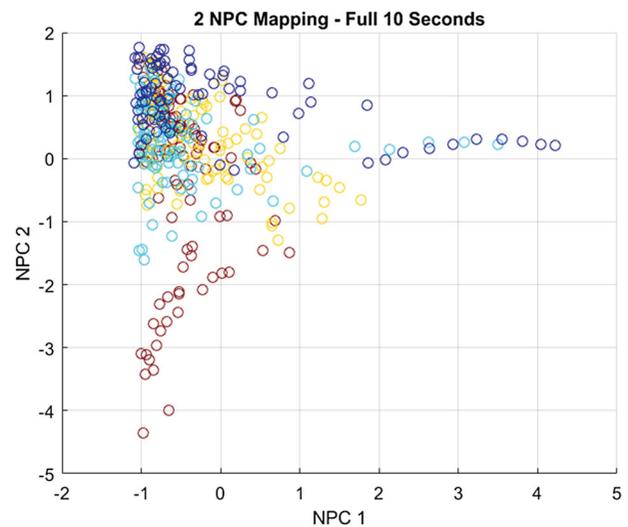


Figure 9. Brain wave activity analysed by a diffusion process technique. Analysis of data output from the first 2 s of exposure to space shows a clearer difference in brain reactions to different spaces. The graphs show the embedding of the two highest eigenvectors of the diffusion map, built with the most relevant sensor, coloured by room. The initial full 10-s exposure to the room (top) and first 2 s of exposure to the room (bottom).

5. Conclusions and future research

This research points at the gaps in our understanding of the relationship between humans' emotions and architectural space in general, and specifically architectural space geometry. We argue that this endeavour is timely, and that emerging tools of mapping such connections can be used towards that goal. The first stage of the research, which examined this connection in virtual space with traditional measuring methodology (questionnaires and observations) found that participants with no expertise in the field of design show a tendency to prefer curvy-shaped spaces and take significant interest in these spaces. Participants with a background in design displayed a tendency to prefer sharp-angled spaces. Initial results from the second stage of the research show participants' unconscious brain ability to perceive symmetrical spaces differently from asymmetric spaces. A difference between positive and negative responses was not recognized in the current setup nor any correlation between the way people reported they reacted to space geometry in Stage 1 and

the direct measurements. Findings reported here support our primary hypothesis about the possibility of differentiating the geometry of space using physiological tests. Nonetheless, further experiments with larger groups of participants are needed in order to generalize and fine-tune these results, as well as find possible explanations for this difference.

The second stage of the research, which focuses on developing a methodology and a research setup for examining mental reaction with VR and EEG, has shown in a pilot experiment a relationship between measurable brain activity and space perception. This seems to open the way for future experiments that will use this methodology and setup to examine and compare different emotions triggered by various types of architectural space geometries. Specifically, the results give rise to several hypotheses that will be the subject of a future study. For example, is the difference in the perception of space between experts and non-experts evident in the EEG measurements? Can we recognize the timeframe at which our impression of a space is determined? Can we compare the relative influence of various factors such as symmetry and curvature on our judgment of beauty? Are there other human reactions that we can map using the suggested setup and methodology?

The initial validation of the methodology and the setup in this research points at the possibility to answer at least some of these questions. The suggested setup could be enhanced by combining synchronized inputs from other physiological measures such as wireless eye-tracker (which can produce both synchronized cognitive workload data and eye-tracking information), heart rate and GSR.

Indeed, there is a great distance between mapping the connection between emotions in relation to architectural space geometry and understanding human reaction to the spatial complexity of architecture. The latter consists of many other physical, cultural and personal aspects. Nonetheless, finding ways to improve our understanding of even the most fundamental human emotional responses towards architectural space could help designers adapt their proposals to human needs, and thus contribute to creating better environments.

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