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VISIBILITY ANALYSIS, SPATIAL EXPERIENCE AND EEG RECORDINGS IN VIRTUAL REALITY ENVIRONMENTS:

The experience of 'knowing where one is' and isovist properties as a means to assess the related brain activity.

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ABSTRACT

Research suggests that isovist properties can be employed to describe certain situations within the built environment that are related to human spatial behaviour and experience. Visibility analysis might be also employed in empirical studies that focus on the neuronal dynamics during navigation. We propose that isovist measurements may provide the means to identify the moment that specific 'mental events' arise along with our spatial experience. The paper discusses briefly the need of such behaviourally relevant quantitative spatial descriptors when studying neural dynamics in complex spatial setting as well as the importance of a principle consideration of the subjective lived experience. This study explores the experiential event of 'knowing where one is' during navigation while taking into consideration similar cases of sudden knowledge acquisition in the areas of sequential and implicit learning. A pilot virtual reality experiment is presented to illustrate how the experience of suddenly 'knowing where one is' can be investigated using visibility analysis. In this case the isovist measurements of area and revelation along participants' paths offer a useful tool that allows us to isolate and study with further analysis of the EEG signal, the moment that this experience is manifested as neuronal firing patterns in the human brain.

KEYWORDS

Visibility Analysis, Virtual Reality, Spatial Cognition, EEG, Isovist properties

INTRODUCTION

Human spatial experience and behaviour are influenced at a great degree by properties of the spatial context and different events that take place within this context. Isovist analysis, a quantitative description of such properties, can be employed to capture the relation between visuo-spatial properties and human behaviour and experience. Empirical studies, that have focused on this relationship, have reported the relevance of visibility measurands to experiential spatial qualities (Franz & Wiener, 2005), to wayfinding behaviour (Conroy, 2001; Wiener et al., 2007), gaze behaviour during space perception (Wiener, Hölscher, Büchner, & Konieczny, 2012) and gaze fixation and decision making at street corners (Emo, 2014). This paper explores how behaviourally relevant isovist properties can describe spatial situations that trigger the emergence of specific mental and experiential events which in turn can be studied using neuroscientific methods.

The experiential event, explored in this study, is the moment of 'knowing where one is' during navigation in relatively unfamiliar environments. The feeling of 'knowing where one is' is akin to an internal 'you are here' sign. The 'you are here' sign or in other words 'spatial presence' can be understood as a " *'gut' feeling of being in a specific spatial context, and intuitively and spontaneously knowing where one is with respect to the immediate surround"* (Riecke & von der Heyde, 2002). In order to get a greater understanding of what kind of spatial situations may trigger the sudden experience of 'knowing where one is', cases of similar lived experiences from the wider field of cognitive sciences are taken into consideration. For example, research on sudden knowledge acquisition in cases of incidental sequence learning and implicit learning are of great interest. These cases share similarities with navigation, since self-movement within an environmental context involves the registration of sequences of point locations and related events. The focus of these studies (Frensch et al., 2003; Rünger & Frensch, 2008) lies on the conditions under which humans acquire explicit reportable knowledge. The relevant findings suggest that this experiential event is closely related to the occurrence of unexpected or deviant events. Therefore, it is reasonable to assume that sudden knowledge acquisition during navigation might be related with the sudden and unexpected revelation of large amounts of new visual information. Consequently, if visibility analysis provides the means to pin point the exact moment that this experiential event takes place then this will allow us to take the investigation one step further and study how this particular event is manifested as neural firings in the embodied mind.

Pioneering studies on the neural dynamics and human behaviour in spatial settings within the field of behavioural neuroscience illustrate the importance of taking into account the subjective lived experience as well as the distribution of the contextual spatial information. Such inventive approaches of 'real-world' experimental designs can be found in the work from the Institute of Behavioural Neuroscience at University College London. Spiers and Maguire (Spiers & Maguire, 2006) investigated the neural dynamics associated with the experience of driving a taxi cab in London, by unfolding the process of navigation based on the content of participants' thoughts. The assessment of participants' thoughts was done using retrospective verbal protocols; that is, after the experiment (fMRI scans) participants were asked to describe their thoughts while watching a video recording of their previous routes. These content-based mental events were then used to isolate and study the linked neural activity. This experimental paradigm illustrates the need to take into account first-person perspectives in order to understand how brain activity is related to the human experience. In another real-world experiment on navigation, researchers used video recordings of routes from a recently learned urban area in Soho, London. They employed different tasks to trigger the mental events of planning and re-planning the route to a certain location in order to assess the neural representation of distance during periods of movement and at street junctions (Howard et al., 2014). A subsequent study explored the correlations between spatial properties at street junctions, or more precisely before entering new street segments, and the representation of this information in the hippocampus using the same paradigm (Javadi et al., 2017) . Three graph theoretic measures of centrality (degree centrality, closeness centrality, betweenness centrality) were used to investigate whether the hippocampus represents information of the topological structure of the environment. Right posterior hippocampus appears to be sensitive to fine-grain spatial information, tracking changes in local path connections, that is number of connecting street segments to any street segment measured by degree centrality. Global properties of space that reflect how 'important' the street is within the network such as "*how central it is in the network both in relation to all streets (closeness), the edge of the space (step depth to boundary) and what can be seen from the street (line of sight)*" are indexed by activity in the anterior hippocampus (Javadi et al., 2017). Formal descriptions of properties of the spatial context -that guides movement- are, therefore, valuable tools that can facilitate research on brain dynamics in complex experimental settings.

In a similar way, visibility analysis may guide the process of signal analysis of the recorded EEG during navigation in Virtual Reality environments.

2. DATASETS AND METHODS

The focus of the pilot Virtual Reality experiment presented in this section is on the moment that people are able to make a button press response based on a feeling of suddenly knowing where they are. In order to investigate the conditions that engender this experience - and in turn facilitate the assessment of the neural dynamics associated to that experience - we first need to understand how this experience is related to properties of the spatial layout and what other similar experiential events may we find if we look closer at the knowledge offered by cognitive neuroscience.

2.1 THE DISTRIBUTION OF CONTEXTUAL INFORMATION: SIMILARITY AND CHANGE

Mental representations of the spatial information seem to be "highly organized knowledge structures processed according to cognitive principles" (Klippel, Knuf, & Hommel, 2005) rather than exact map-like copies of the external environment, as the word 'cognitive maps' misleadingly implies (Barbara Tversky, 1993). Research in spatial cognition suggests that information of spatial relations is structured into superordinate units and subordinate clusters (Hommel & Knuf, 2000). Spatial chunking or clustering into smaller representations allows us to operate within the capacity limits of working memory activating only the spatial information that is needed to guide our action within the specific immediate context (Avraamides, Adamou, Galati, & Kelly, 2012). Mental simplification mechanisms of the representation of spatial knowledge appear to follow laws and principles that are also present in visual perception. Perceptual processes actively organize the visual (and spatial) information into part-whole relations following Gestalt principles of perceptual organization such as similarity, proximity, closure etc. (Barbara Tversky, 1981; B. Tversky & Schiano, 1989). Similarity and change, are important factors in the creation of these spatial clusters. Individuals possibly integrate contextual information from movement in two stages: discrete locations encountered through movement are aggregated based on their "*informational similarity* " which implies a relative stability or a relative invariance while the identification of relations between these aggregates probably occurs at point locations where "*substantially new information is revealed*", for example at street junctions (Penn, 2003).

The temporal regularity of events encountered through movement within a sequence of a route in a spatial context is an important factor that influences how learnable or legible a certain spatial layout is. The ability of the mind to be receptive to the predictability of events is closely related to what memory researchers call episodic memory. Episodic memory is sensitive to the order of events and their context since it constructs association of location and other elements of experience in memory structures (Spiers et al., 2001). Therefore, it is not unreasonable to imagine that the sudden revelation of substantially new visual information at a certain location may activate such memory structures and the update of the mental representation.

Evidence of how the process of navigation is affected by such events and properties of space can be found in studies that explore the relation between isovist properties and human behaviour. For instance, Conroy-Dalton observed that during navigation in virtual environments individual behaviour changes at street junction, where a large amount of new visual information becomes available (Conroy, 2001). People pause and turn their heads to capture the new information, to re-evaluate the environmental information and make new decisions on movement and direction. These vital decision points were locations that correlated with high values of isovist area (and were configurationally integrated as well). Furthermore, Franz and Weiner provide evidence that isovist measures capture properties of space that are related to locomotion and experiential qualities (Franz & Wiener, 2005). Their research offers a translation of several spatial qualities such as spaciousness, enclosure and openness, complexity and order into quantitative isovist measurements. In addition, they propose a new isovist measurement that is related to visual stability and the changes in the amount of the available visual information.

Revelation coefficient, as proposed by Franz and Weiner, is the "*relative difference between current neighbourhood size [isovist area] and the collective neighbourhood size of its directly adjacent nodes*" (Franz & Wiener, 2005). High revelation indicates low visual stability and thus a spatial experience that involves the element of surprise (related with predictability and mystery) , 'promising' gain of new visual information through movement (Franz and Weiner 2008). Nick Dalton explores this new measurement of 'revelation' in relation to the notion of 'place' and he suggest that the total revelation of an area "*serves as a powerful measure of the local heterogeneity of a location and hence a place's identity*" (Dalton, 2011). Consequently, the isovist properties of area and revelation seem to be quite adequate in capturing the context-events of interest. In other words, the moment when unexpected new large amounts of visual information becomes available is hypothesised to be related to the experience of sudden knowledge acquisition.

2.2 SIMILAR EXPERIENTIAL EVENTS: INCIDENTAL SEQUENCE LEARNING

The experience of suddenly knowing where one is, requires a mental representation of space which includes a representation of one's body in that space. Therefore, this spatial experience is assumed to be related with an update of the mental spatial representation with new information and the transition from implicit knowledge into explicit reportable knowledge.

Spatial learning, such as route learning in unfamiliar environments, seems to involve cognitive processes that are also present in sequential and implicit learning; that is sequences of events and knowledge of their implicit underlying rules. Implicit learning of sequential structures is usually based on the presence of an underlying rule. Similarly, in spatial learning the order that stimuli are encounter within an environment, that has been designed and built, is inherently structured following certain rules. Research on incidental sequence learning usually investigates the conditions under which humans acquire explicit reportable knowledge through implicit or non-conscious learning (Rünger & Frensch, 2008). According to the Unexpected Event Hypothesis (Frensch et al., 2003), insights into an implicit regularity and thus a switch from implicit to explicit knowledge occurs when one experiences a deviation from what is expected or predicted.

Unexpected or deviant events have been studied thoroughly within the field of cognitive neuroscience. Donchin argues that such events, which are unexpected but task-related elicit an update of the current mental representation to incorporate the new deviating information and according to his Context Updating Theory "*events are remembered if they require, upon their occurrence, a restructuring of our mental models which is presumably what happens when we are surprised*" (Donchin, 1981). His research and theory suggests that these processes are manifested by a specific component found in the EEG recording, the P300 component. The P300 component, a well studied event related component, is the third positive deflection in the recorded waveform and is elicited around 300 ms after the presentation of a task-related but unexpected stimulus.

The P300 signals the occurrence of a deviation from what is expected and its relation to the hippocampal system is conceivable since the hippocampus seems to be sensitive to the contextual uncertainty of the environment (Harrison, Duggins, & Friston, 2006). Navigation, especially in unfamiliar environments, involves processing of information that is perceived sequentially, and thus requires some form of learning of the temporal order of contextual events, their similarities and especially their deviations. The integration of deviant events within the spatial mental representations is fundamental since it is linked to the experience of surprise and cognitive processes related to decision making.

2.3 REQUIREMENTS AND LIMITATION OF EEG EXPERIMENTS

Different conditions within an experiment may elicit distinct cognitive responses. These responses are reflected by different patterns in the electric signal that is recorded from the human scalp using electroencephalography (EEG) headsets with multiple sensors. The high time-resolution EEG signal of different conditions may have differences in amplitude and latency and polarity (Event Related Potentials, ERPs) in the respective waveforms or differences in terms of frequency bands (e.g. delta, theta. alpha, beta, gamma). When the objective of the investigation is the neural response associated with a specific event, the focus of the analysis is on the EEG signal that is before or after the event of interest (Luck 2005). In a typical EEG experiment, the continuous EEG signal is marked with event-codes and is segmented into epochs that are time-locked in relation to the specific event such as a presentation of an image in the computer monitor. Since, Event Related Potentials are small changes in voltage that are triggered by an event, the signal of interest is usually obscured by the much larger EEG spontaneous activity. The averaging technique is, therefore, used to cancel out this noise. That means that in order to be able to get significant results we need to average together a big number of trials of the same experimental condition that is hypothesised to involve the same cognitive processes. Therefore, in order to analyse the signal based on specific spatial situations that engender specific mental events we need to use environmental modelling systems that describes these situations in comparable quantitative measurands in combination with self - reports on the subjective experience e.g. button press responses.

2.4 THE VIRTUAL REALITY EXPERIMENT

The game environment of this pilot virtual reality experiment was created and developed by the first author of this paper, in the game engine Unity3D (C#) following guidelines from other VR experiments done at the Institute of Cognitive Neuroscience at UCL and the Department of Biomedical Engineering at Columbia University (Jangraw, Johri, Gribetz, & Sajda, 2014). The 3D environment represents a real urban region of a south European city that was slightly changed and mirrored in order to prevent variability of the degree of familiarity with the environment among participants (figure 2). The selection of this urban region was based on Lynch's five elements - district, edges, pathways, landmarks and nodes - which are considered as important factors of the city's imageability (Lynch, 1960). The specific area seemed to have all of these elements - and thus a sufficient degree of imageability - and was considered as being able to evoke with certain ease a mental image.

The twenty participants that took part in this study, were first asked to study a map of the urban environment. Then, the instruction was to start exploring the 3D environment and press a button when they had a feeling of knowing where they were. In order to get a significant number of trials per subject each participant was asked to take the same task 8 times, starting each time from a different location (figure 1). During the whole duration of the task the Emotiv EEG was recording their brain activity and event-codes were sent from the game engine to the recording software of the Emotiv (Techbench) via virtual serial ports. The event-codes were sent when there was a significant change in the amount of the available visual information (based on isovist area and revelation), for example when passing from a small street to a large square, and when landmarks became visible. This experimental design offers the possibility to further process the recorded EEG signal and analyse the data in relation to subjects' button-press responses as well as in relation to the environmental stimulus. In this way we will be able to assess the neural signature of the specific experience, which in this case, is likely to be triggered when new visual information becomes suddenly available.

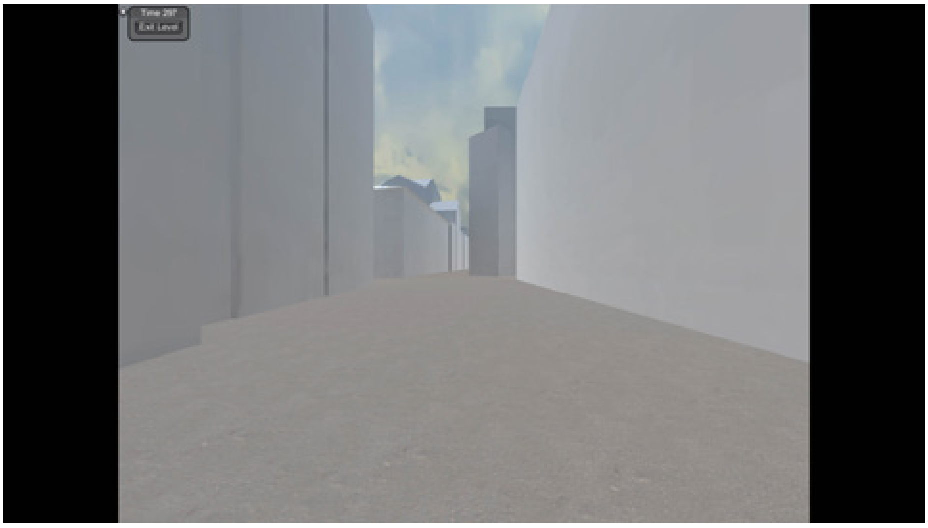

Figure 1 - Snapshot from starting location in the virtual reality urban environment

3. RESULTS AND DISCUSSION

In this paper our aim is to present how isovist measurements may allow to pin point the moment that certain mental events arise along with our spatial experience. If we are able to identify such moments based on specific context-events then we can analyse the recorded EEG signal not only in relation to subject's responses but also based on the occurrences of certain visual or geometrical cues. Using the ERP method we can study averaged EEG waveforms that are time-locked to the specific event of interest e.g. subject's response or the presentation of a visual/spatial cue.

Preliminary results from the exploratory behaviour of participants in the Virtual Reality urban environment (figure 2) allows us to draw some initial inferences upon the relation of crossing spatial thresholds that reveal new large amounts of visual information and the behavioural effect of pressing the response button. Twenty participants were asked to explore the virtual city region - after studying the map- and report by pressing a button on the keyboard whenever they had a feeling of knowing where they were. Each participant had eight trials, starting each time from a different location as shown in figure 2.

The total number of button-press responses was 155; 44% where after seeing a specific landmark; 43% after entering urban squares or street junctions with isovist area more than 85% of the highest value; 2% were after passing through junctions of distinctive configuration -where more than four streets intersected-; and 11% were after junctions that did not fall in the category of 85% of highest isovist area (figure 3). However, 12 out of the 17 responses that occurred after crossing these junctions with lower isovist area where after seeing a nearby landmark. From the 43% of the responses that where related to high isovist area (67 in total) 8 were at points where isovist revelation was more that 90% of the highest values (usually occurring at thresholds of passing from narrow small streets to the main streets of the area).

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Figure 2 - Exploratory behaviour of participants from each starting point. Square symbols indicate each starting location and circle symbols the button-press response . The paths from each different starting point (8 in total) are illustrated with different colours. However, the order of each trial was different for every participant.

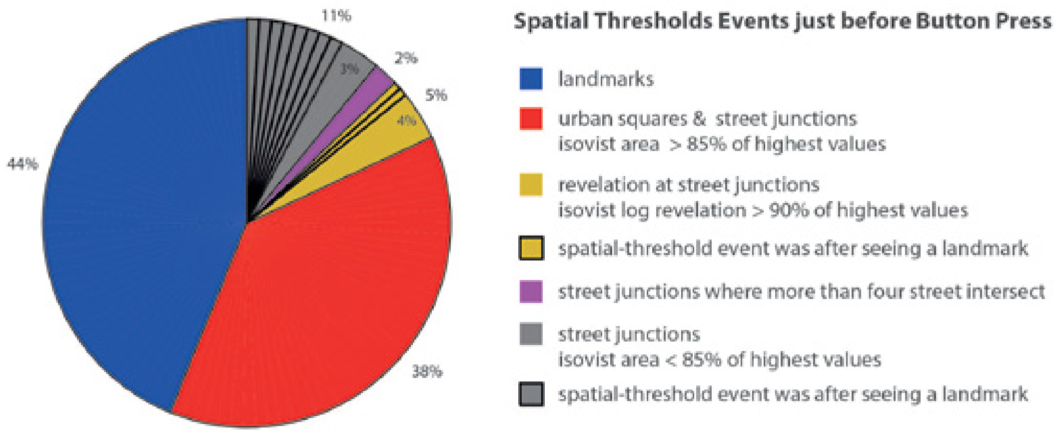

Figure 3 - Pie chart illustrates percentages of number of times each spatial threshold event was encountered just before participants pressed the button to indicate their response. From a total of 155 button press response 68 were after a landmark became visible (44%); 59 after passing from locations with isovist area higher than 85% of the total (38%); 8 after locations with revelation greater than 90% of the higher value (5%); and 17 after junction with isovist area lower than 85% (11%, 12 out of 17 were after seeing a nearby landmark).

The cases in which responses were after changes in the distribution of visual information are of great interest here. In particular, the moments when large amounts of new visual information becomes available, which are followed by a response, provide the opportunity to relate the specific response of first-person experience to a quantitative spatial measurement. Participants' exploratory paths can be characterised in terms of their 'visual rhythm' looking for patterns of "*crescendo effect due to the increasing visual openness*" (Morello & Ratti, 2009). This can be expressed by unfolding the isovist values of area and revelation along each path. In order to illustrate how the button-press response can be investigated in relation to the 'visual rhythm' of the participant's path, we present here the trials of one participant (figure 4) , whose responses were mainly based on the distribution of visual information. The '*crescendo effect*' in both measurements of area and revelation is present before the button press in all the trials of this participant (figure 5).

Figure 4 - Exploratory behaviour of participant 5 from the 8 starting locations.

The '*crescendo effect*' in isovist paths is one of the tools - one example of spatial thresholds - that enables the 'synchronisation' of the time-depended EEG with quantitative environmental modelling properties. The continuous EEG signal is marked with event-codes when participants cross these spatial thresholds. The analysis can be then based on the segmentation of the EEG stream into epochs of a fixed duration that are time-locked in relation to the specific context-event. The unrelated noise in the EEG is cancel out by averaging together a big number of epochs that contain the event-related signal of interest. The final ERP waveforms are a result of a grand average of epochs across subjects, one for each electrode and each experimental condition. Therefore, isovist paths of area and revelation can be used to pin point the moment when there might be a change in the pattern of the recorded neural activity that is related to the specific experience.

The relation between local visual cues and the global spatial structures is of course a significant factor that highly contributes to this experience. The notion of intelligibility and its relation to spatial cognition is a popular area of interest in the space syntax literature (Conroy

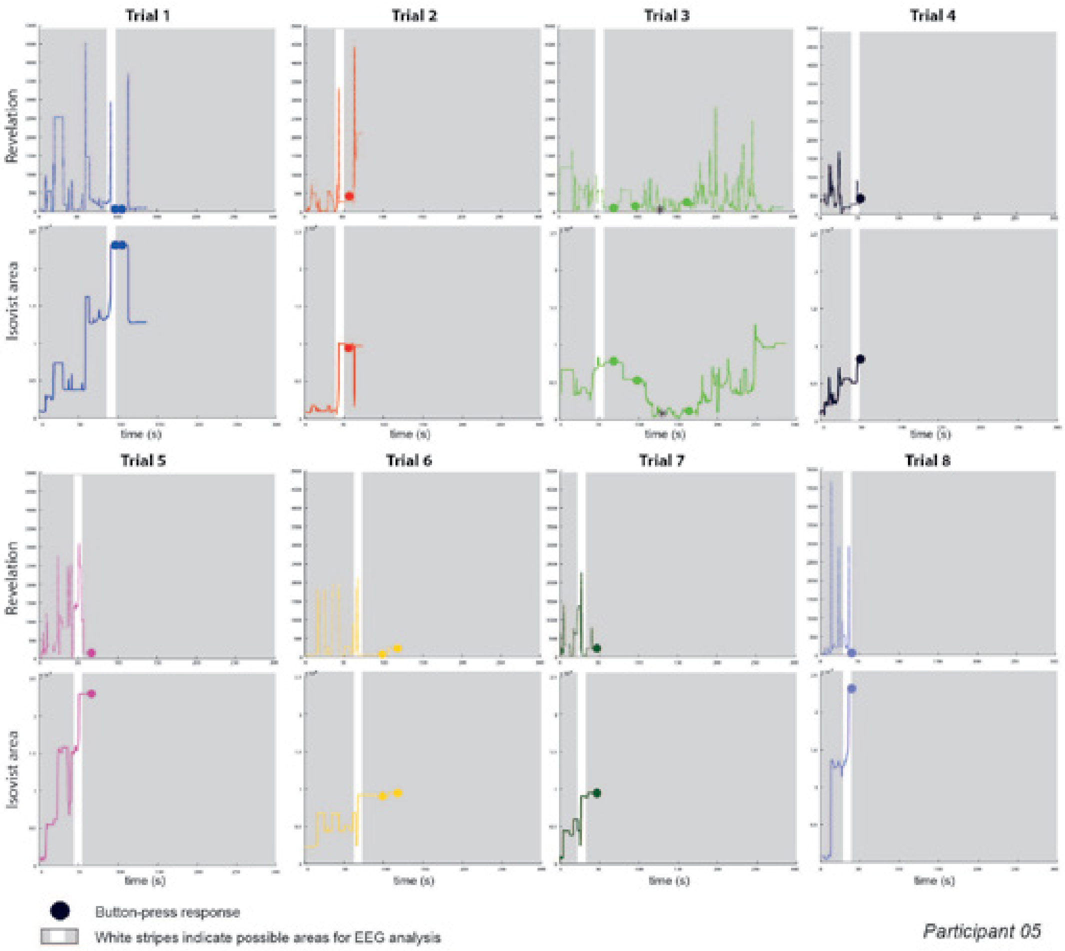

Figure 5 - Isovist values of Area and Revelation as they unfold along participant's path for each trial. The '*crescendo effect*', before button press response, is highlighted in white stripes indicating the area of interest for the analysis of the EEG signal.

Dalton, Hölscher, & Spiers, 2011; Penn, 2003). The concept of intelligibility (Hillier, 1998) is fundamentally related to our ability to make inferences at strategic location about the global spatial structure that lies beyond our immediate visual local cues. However, humans seem to acquire knowledge of global properties of the spatial layout after a certain degree of familiarity with the environment and recent evidence indicate that the hippocampus (posterior hippocampus) tracks changes of such global properties only during retrieval of information from long-term memory (Javadi et al., 2017). In this pilot case study we investigated navigation in relatively unfamiliar environments and therefore the focus was on the sequences of local visual information along participants paths.

4. CONCLUSIONS

The experience of 'knowing where one is' is important for successful wayfinding and seems to be related with an update of the mental spatial representations with new information. Although, spatial updating occurs constantly during navigation (Burgess, 2006), the specific reportable spatial experience seems to also involve cognitive process that result in explicit knowledge of the 'you are here sign' or the 'gut' feeling of spatial presence (Riecke & von der Heyde, 2002). The '*crescendo effect*', before button press response, in isovist measurements of area and revelation along participants' paths most probably indicates the moment that this experiential event is manifested in the brain. Future work will be focused in averaging epochs of the EEG signal time-locked to this moment and we expect that these grand averaged waveforms will reveal the P300 component, which according to Donchin's Context Updating Theory (Donchin, 1981) reflects cognitive processes related to memory and the affective experience of surprise.

A recognizable change or pattern in the EEG signal, present at the moment that specific visuo-spatial situations are encountered through movement, provides objective evidence that reflect a specific subjective individual spatial experience. A recent qualitative study of the orientation experiences and design preferences of UK older adults living in a communal retirement development reports that having 'memorable and meaningful' spaces was more favoured among participants, 'than signage as an orientation aid' (O'Malley, Innes, Muir, & Wiener, 2017). Neurophysiological evidence, such as the P300 component, coupled with environmental modelling techniques can provide quantitative descriptors that can help us clarify what sort of spaces are memorable and meaningful. Our design decisions can be then based on such neurophysiological findings that are related to our cognitive and emotional responses to the built environment. This kind of evidence can be valuable when designing for example retirement facilities for older adults since it can have a great impact on the wellbeing of people who often experience memory difficulties. Gaining a deeper understanding of how the visual and spatial context affects our navigation performance can be obviously fruitful; it may even result in a valuable toolbox of spatial parameters or spatial thresholds which can be used to control the experimental conditions of future investigation within the field of behavioural neuroscience.

The environmental context is undoubtedly a significant factor that affects the embodied experience. Experimental designs that aim to unfold the neural dynamics of the embodied mind during real-world situations should give special attention to the conditions under which spatial properties correlate with specific mental events of the lived embodied experience. Environmental modelling, such as visibility analysis, offers a quantitative technique that can be used to formally describe these conditions and identify experientially relevant spatial thresholds. Such empirical evidence may allow a greater understanding of what sort of visuo-spatial conditions are more important in the spatial knowledge acquisition processes or more salient in our mental representations of the spatial information of the built environment.

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