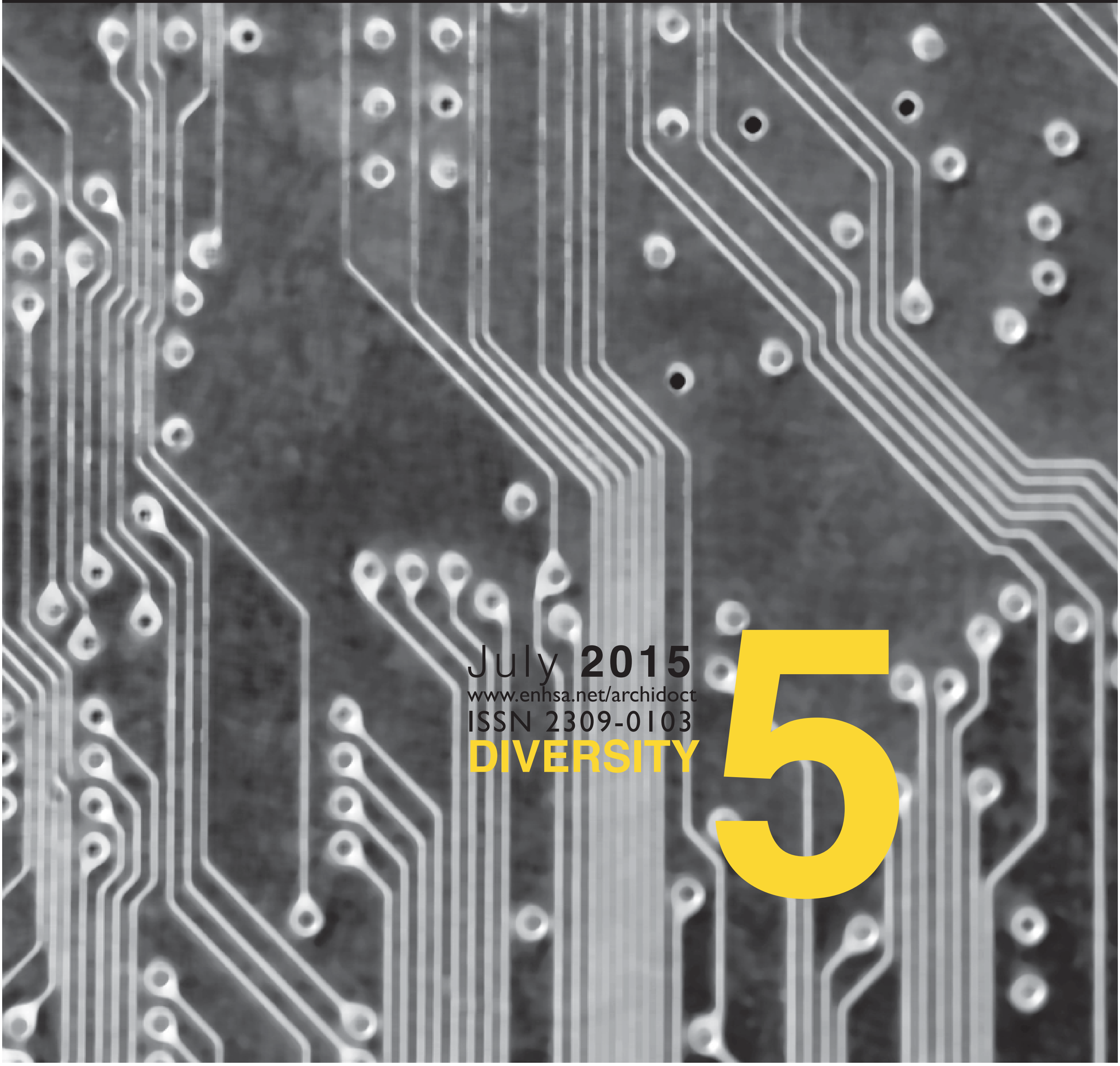
archi DOCT

The e-journal for the dissemination of doctoral research in architecture.

Supported by the ENHSA Network | *Fueled by the* ENHSA Observatory



July **2015**
www.enhsa.net/archidoct
ISSN 2309-0103

DIVERSITY

5

Lifelong Learning Programme

european network enhsa of heads of schools of architecture

European Observatory of Doctoral Research in Architecture

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 3 (1) / July 2015

A pilot study on Spatial Cognition: Brain activity during the integration of distinct Spatial Representations

Efrosini Charalambous

Abstract

In recent years, there is growing interest in the common ground, between the disciplines of spatial cognition, neuroscience and architecture. Research in cognitive neuroscience offers a deeper understanding of how we perceive and experience our environment. The objective is to find a way to 'transfer' the knowledge offered by the cognitive sciences, from lab experimental conditions into to real world dynamic and complex situations. Such an attempt requires adopting a new perspective and approaching the notion of wayfinding as 'a continuous problem solving situation under uncertainty'. This will allow us to study specific mental events in real-world scenarios and collect data using neuroscientific methods, such as EEG (electroencephalography). This paper departs from exploring how the human brain structures the information of environmental stimuli and how we use different reference frames to represent spatial relations and store them in memory. The main focus of this study is to explore the differences in brain activity when orienting in relation to locations of a small-scale indoor environment in comparison to a large-scale surrounding environment. Some initial findings of a pilot experiment on orientation that introduces the use of EEG recordings in real-world situations will be presented.

Keywords

Spatial cognition; spatial representations; orientation; allocentric; egocentric; EEG; spatial reference frames;

Introduction

To orient ourselves while navigating we must be able to recognize our surroundings, use stable landmarks to make decisions and maintain our orientation while keeping track of our movement. Evidence from rat experiments shows that the sense of direction relies on an orienting mechanism based on the integration of an internal sense of movement and information from head direction cells, which are specific neural cells that fire if the heading is oriented in a certain direction (Dudchenko, 2010). The ability to update the mental representation of our current position and stay oriented within our immediate surroundings is called spatial updating. Of course, spatial updating involves an additional intuitive ability of self-localization, a 'you are here' internal sign. For Riecke and Von der Heyde (2002), 'spatial presence' can be understood as '*the consistent 'gut' feeling of being in a specific spatial context, and intuitively and spontaneously knowing where one is with respect to the immediate surround*'.

The brain provides the 'you are here' information through a set of neurons called the 'place cells'. In 1971, John O'Keefe and colleagues conducted electrophysiological recordings of individual neurons, within a specific brain region called the hippocampus and reported that certain neurons fired when a rat was in a specific location in its environment while a different set of neuronal cells were activated when the rat was in a different location (Keefe and Dostrovsky, 1971). For the discovery of these cells, that constitute the brain's positioning system, John O'Keefe was recently awarded the Nobel Prize for Physiology or Medicine in 2014 (jointly with May-Britt Moser and Edvard Moser). In 1978, John O'Keefe and Lynn Nadel published an influential book called 'T*he Hippocampus as a Cognitive Map*' where, after reviewing studies on rats with lesions in the hippocampus and along with the discovery of place cells, they concluded that these cells form the neural bases of spatial cognition (Keefe and Nadel, 1978). Furthermore, they argued that the function of hippocampus provides the substrate for the construction of a mental representation of the spatial environment, which they called a 'cognitive map', borrowing a concept that was first introduced by Edward Tolman in (1948).

On spatial problem solving

Evidence from several experimental tasks on spatial cognition illustrates the consistent distortions of our mental spatial representations. These distortions occur at the level of perception as well as during encoding and retrieving information from memory. The way we shape and distort our cognitive representations is greatly influenced on how we perceive the environmental stimuli. These mental simplification mechanisms seem to follow laws and principles that are also present in visual perception. Perceptual processes actively organize the spatial information into part-whole relations following Gestalt principles of perceptual organization (Tversky, 1981, Tversky and Schiano, 1989). According to the Gestalists' view, the information of a stimulus is grouped together following principles such as similarity, proximity, symmetry and closure forming part-whole relations.

Research suggests that knowledge of spatial relations is organized hierarchically into superordinate structures and subordinate clusters (Hommel and Knuf, 2000, McNamara, 1986, Meilinger and Vosgerau, 2010). When learning target locations in a new environment, people tend to group the acquired information into clusters that share similar spatial (e.g. distance, perceptually salient features) and non-spatial properties such as functions or semantic relations (places and objects associated with same action). At the same time, these clusters are also grouped together forming higher-order structures (McNamara, 1986, Tversky, 1981). Spatial chunking or clustering into small meaningful representations "*allows us to activate only the spatial information that is needed in a* given *moment enabling us to operate within the capacity limits of working memory*" (Avraamides et al., 2012). Chunking seems to occur where there are salient discontinuities or discrete changes (Klippel et al., 2012). For Barbara Tversky, the way the mind transforms and organizes knowledge is similar to that of solving problems; we parcel information into functionally significant components and group it into bigger categories that include other similar exemplars. Parceling and grouping information is useful when organizing knowledge and solving problems, because it '*allows inferences or predictions*' (Tversky, 2005).

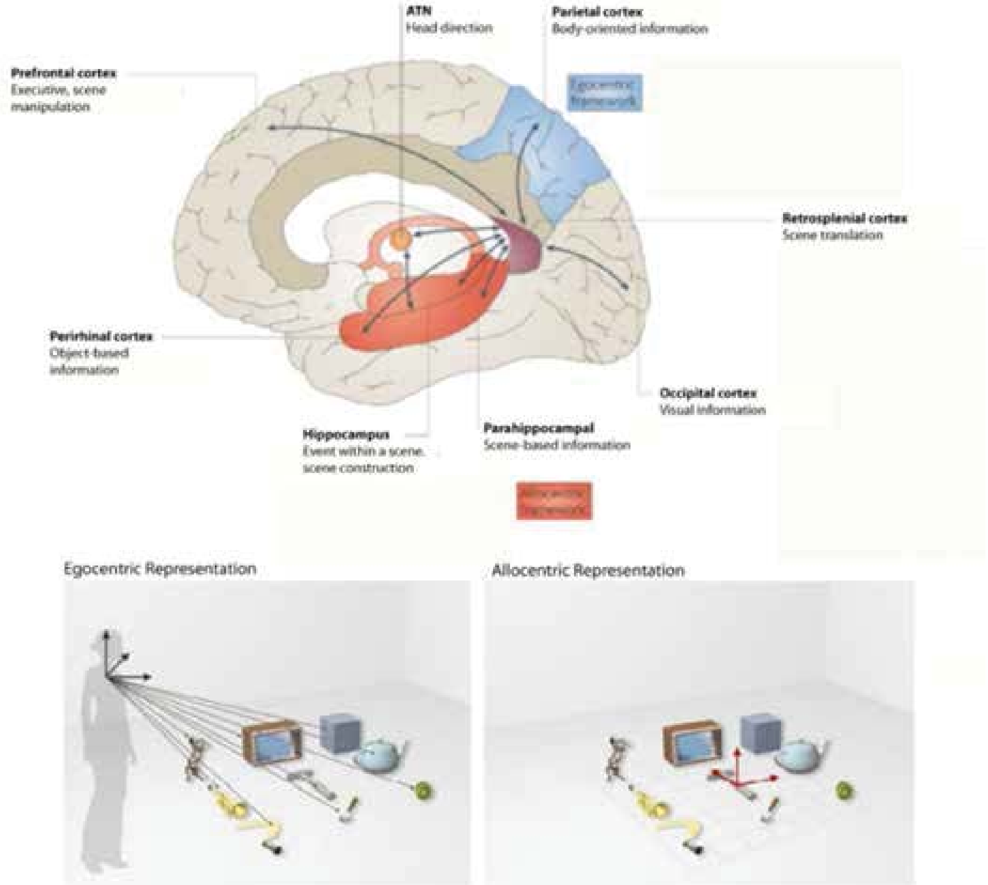


Figure 1. The two-system model: The coordinate transformation of egocentric and allocentric representations (Images adapted from: Seralynne D. Vann, John P. Aggleton & Eleanor A. Maguire, 2009 What does the retrosplenial cortex do? Nature Reviews Neuroscience and Meilinger and Vosgerau, 2010, Putting Egocentric and Allocentric into Perspective. In Spatial Cognition VII)

Therefore, mental spatial representations are not exact maplike copies of the external environment, as the word '*cognitive maps*' implies, but rather "*integrated and highly organized knowledge structures processed according to cognitive principles*" (Klippel et al., 2005). The human brain seems to encode spatial information using several heuristic that aim to anchor object to a certain location in space and thus minimize the information needed to be stored in memory. Shelton and McNamara (2001), among others, propose that the process of learning and remembering the structure of the environment involves an interpretation of the spatial information on the basis of a spatial reference frame. Spatial reference frames are usually divided into two categories: the *egocentric* and *allocentric* (Klatzky, 1998). The Egocentric is an action-related reference frame, which represents self-to-object relations and the specific orientation and location of the observer, whereas the *Allocentric* is an orientation-free reference frame and encodes object-to-object relations. Humans represent the spatial relations using both coordinate systems (**figure 1**). However, depending on the circumstances

However, depending on the circumstances (Mou and McNamara, 2002) or individual differences (Gramann, 2005) people seem to prefer the use of one to the other. For instance, several researchers suggest that spatial memories of small layouts are represented in terms of egocentric reference systems while the lack of influence of movement-related spatial updating in large-scale navigation, implies the use of a more stable allocentric system (Burgess, 2006).

Spatial Mental Representations and Their Coordinate Transformation

Neuroscientific studies on spatial memory suggest that the representation of spatial information occurs at two different interrelated neural networks that correspond to the two reference frames. The translation from one network, or reference frame, to the other requires information from the head direction cells which are responsible for the orientation of the observer. Neil Burgess (2006) proposes that spatial updating can be seen as a two-system model of a continuous translation between egocentric and allocentric representations. According to this model, transient egocentric representations are recruited in short-term spatial memory for immediate action and mental imagery and generated in the parietal window (posterior parietal cortex and precuneus). Coarse allocentric representations that are supported by information store in long-term memory are generated in the hippocampus and surrounding medial temporal lobe areas. Encoding and retrieval of information requires a translation between the two representational systems.

Waller and Hodgson's (2006) disorientation paradigm provides evidence for the two-system theory. In their experiment, subjects first learned the locations of objects positioned in a room. They then entered into a rectangular opaque chamber in the middle of the room and sat on a rotating stool. Participants were asked to point to different objects in the room and conduct a task called Judgment of Relative Direction ('Imagine you are at the X, facing the Y. Point to Z'). Their performance was tested with eyes-open, eyes-closed and after rotating the stool they were sitting on which caused a certain degree of disorientation. The main finding of this study is that after disorientation variability in errors increased in the egocentric pointing task and decreased in the allocentric JRD task (Judgment of Relative Direction). This suggests that disorientation causes a switch from the use of a temporary, egocentric representation of space to a more stable allocentric representation of relations between landmarks.

The two-system-model also implies that we operate on distinct representations over different timescales, for example in small and large scale environments (Burgess, 2006). Additionally, spatial representations stored in memory are viewport-depended (Basten et al., 2012, Meilinger and Vosgerau, 2010, Avraamides et al., 2012), and when there is a misalignment with the current heading '*a differently oriented egocentric or allocentric memory requires a coordinate transformation into the current egocentric orientation*' (Meilinger and Vosgerau, 2010). The Wang and Brockmole's experiment (2003) is one example that involves such transformation and integration of distinct representations. Blindfolded subjects were asked to point to objects inside the room and outside locations of the campus. When participant's heading was aligned with indoor objects they were faster at pointing to other indoor location than to campus landmarks but when they where aligned with outdoor locations they were equally fast. The main conclusion was that the representation of the campus included that of the room but not the other way around. When oriented in relation to the immediate environment (room), switching to large-scale representation of the surrounding environment is cognitively demanding because it involves transformation of allocentric information and updating of one's current egocentric representation. I have therefore used a similar experimental situation in order to investigate if differences in recorded brain activity reflect the process of updating and integrating information from distinct spatial representations.

Methodology

Recent developments in sensor technology and wireless communication provide a means to test scientifically derived hypotheses in real-world situations using wearable monitoring devices. A relatively inexpensive method for recording electrical signal of the human brain activity with a very high time-resolution is the electroencephalography (EEG). The Emotiv headset is a wireless EEG system with 14 electrodes arranged in specific scalp locations (**figure 2**). Even though, this affordable Brain Computer Interface (BCI) system is often used to enhance user's gaming experience, the device has been also reliably used for scientific explorations (Badcock et al., 2013). The Emotiv Software Development Kit includes three implemented applications (Expressiv, Affectiv and Cognitiv Suite) which process on-line information from brain activity, as well as muscle movement artifacts in some cases, using machine-learning algorithms. Even though these Suites provide the means for a good gaming experience, the exact details of the underlying algorithms are not available to the user. Thus, their ambiguous "black box" nature makes them unreliable for scientific research. However, the Research SDK package includes the Emotiv Testbench, a software tool that allows researchers to access and record the raw EEG signal, insert time-markers in the data stream and export the data for further processing. This option offers a reliable and appropriate method of data acquisition.

The EEG is a time-dependent signal and can be processed and analyzed in the time-domain or in terms of frequency bands (e.g. delta, theta. alpha, beta, gamma). When the EEG data is used to assess the neural responses associated with a specific internal (cognitive task), external (stimuli) or motor event, the focus is on the prior or post-event signal. In this case researchers analyze the Event-Related Potentials (ERP). ERPs are small changes in voltage that are triggered by an event and are described in terms of their polarity, latency and scalp distribution. Positive (P) and negative (N) deflections in the waveforms reflect the flow of information through the brain. (Luck 2005). Different conditions within an experiment may elicit distinct cognitive responses that are reflected by differences in amplitude and latency in the respective waveforms.

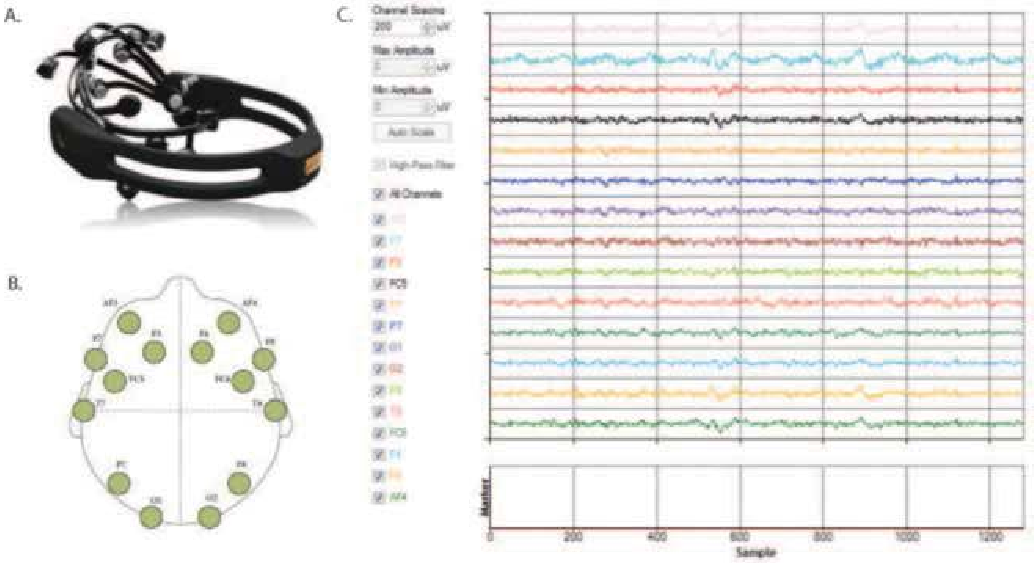


Figure 2.
A) The Emotiv EPOC headset B) Scalp positions of the 14 electrodes C) The Testbecnh software and the raw EEG signal

The continuous EEG signal is marked with event-codes and is segmented into epochs of a fixed duration that are time-locked in relation to the specific event. Random bio-signals such as eye-blinks and muscle artifacts can be detected by visual inspection or by using artifact detection algorithms. Trials contaminated with artifacts are usually either rejected or marked and excluded from further processing. However, a more effective alternative is the use of artifact correction procedures that minimize the rejection of valuable trials. ICA-based (Independent Component Analysis) artifact correction can be applied to the data in order to decompose the data into a set of underlying components, remove certain components that correspond to artifacts and then recompose the data without those artifacts (Lopez-Calderon and Luck, 2014). The event-unrelated noise is cancel out by averaging together a 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.

The orientation experiment

The aim of this study is first to check the feasibility of the Emotiv Epoc and the ERP methodology in detecting differences in brain activity in real world situations and second to examine if the integration of information from distinct spatial representation is reflected in the recorded brain activity. The underlying hypothesis is that spatial locations within an indoor small-scale environment are mainly based on an egocentric coordinate system. Therefore, the mental representation of locations of the immediate environment is relatively updated with self-movement and thus more easily accessible, even if one follows a complicated route. On the other hand, as shown in the Wang and Brockmole's experiment mentioned earlier, the representation of the surrounding large scale environement requires a translation of the spatial knowledge and its integration with the current representation. Such cognitive process would be more demanding, since updating of the spatial information of the surrounding outdoor environment does not occur automatically with self-movement. In this case spatial knowledge from long-term memory requires a transformation from an allocentric coordinate system into the current egocentric coordinate system. For that reason, recorded brain activity, during tasks that require such a translation, should reflect this cognitive prosseses. To test this hypothesis an orientation experiment was desinged and an egocentric pointing task was used in order to assess these differences.

The experiment took place in the halls of the V&A museum. The intention was to simulate the experience of maze navigation and disorient the participants by following complicated routes through the different floors of this over-stimulating environment (**figure3**). Four subjects, two male and two female, participated in the experiment. Participants were fully informed about the details of the experiment, their role in it, the kinds of data collected. The Emotiv wireless headset was then placed on their head. At four different stop points along the route, participants were asked to respond to an orientation-pointing task. Participants were first familiarized with the procedure and then instructed to sit comfortably, move and blink as little as possible in order to reduce artifacts. They were asked to take a task presented on the laptop and press the appropriate key of the keyboard as a response. While participants were conducting the tasks the Emotiv was recording their brain activity and saving this data into a file.

The orientation task was divided into two sets of four trials for each stop point (**figure 4**). In the 'outdoor' set, target locations of the large-scale surrounding environment were presented (e.g. South Kensington Station, the Marble Arch Station, Bayswater etc). Locations presented in the second set, the 'indoor' set, were closely related with the route within the museum (e.g. the entrance, the previous stop point, the shop) and thus based on a more easily accessible egocentric representation. In both conditions, participants were asked to rotate an image indicating these target locations in order to align it with their heading orientation. The image was rotate clockwise or anticlockwise 10 degrees by pressing respectively right and left arrows. Subjects were asked to start pressing the response keys, only when they had calculated the correct answer. Responses with a deviation up to 30 degrees from the correct orientation were considered as correct.

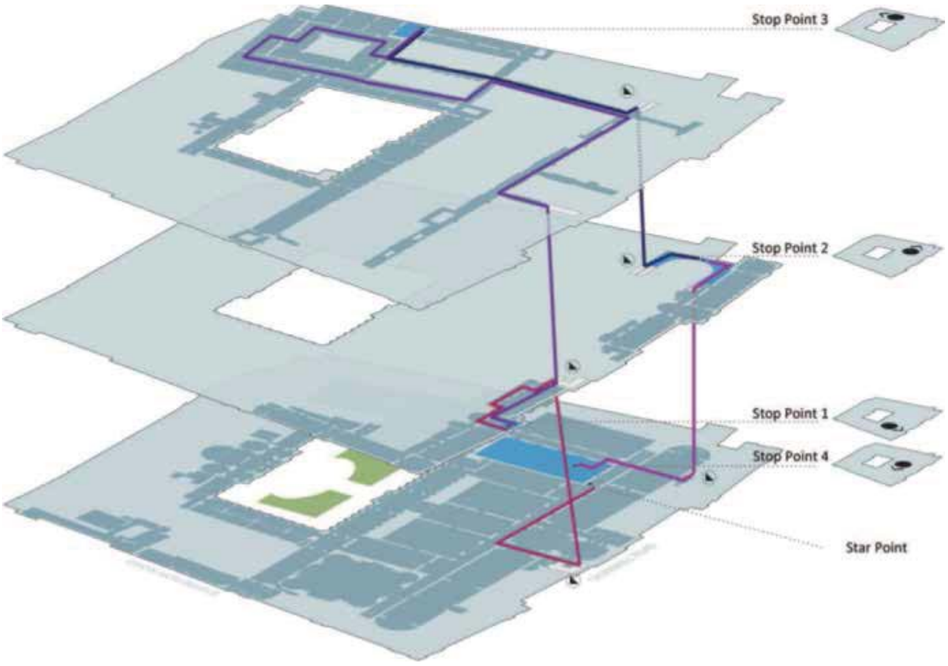


Figure 3. Route and Stop Points in the V&A museum

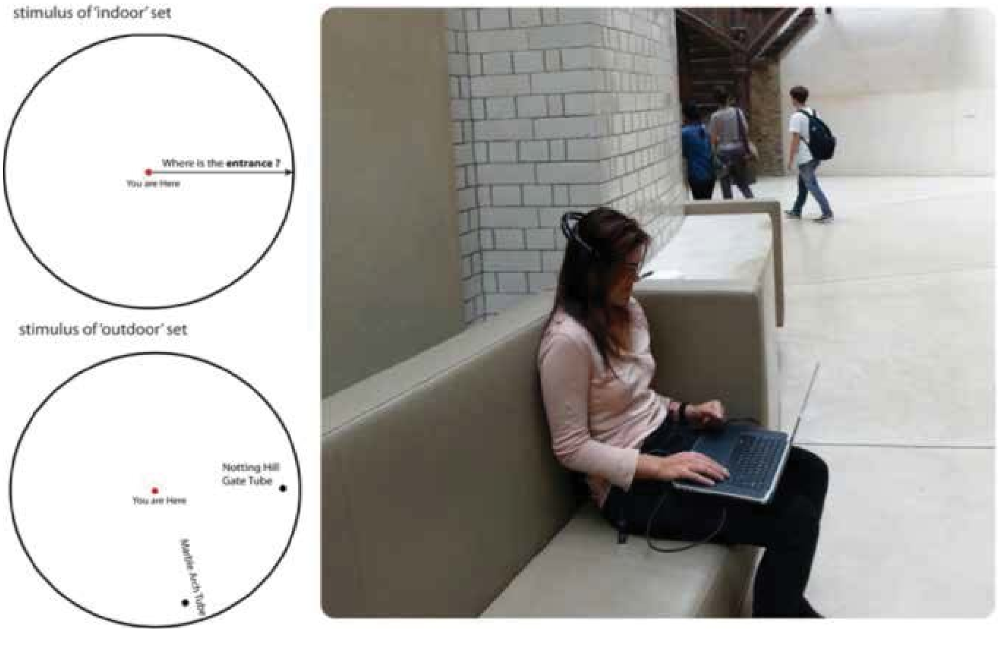


Figure 4. Left: Experimental stimulus Right: Subject conducting the task in the V&A museum

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 3 (1) / July 2015

Data Acquisition and Processing

Brain activity was recorded with Emotiv Testbench software via a Bluetooth USB chip[1]. The same computer was used for stimulus presentation and recordings in order to have more accurate timing of the keystrokes, as event-markers in the recorded data stream. Markers were sent from Matlab through a virtual serial port, to the raw EEG data using the Testbench software (**figure5**). Additional markers were sent for the onset and end of each new trial. A different event-code was sent to the data stream to mark subjects' responses for the two different sets, which made possible the distinction between 'indoor' and 'outdoor' responses. Event codes were differentiated offline for correct and incorrect answers.

The processing steps were carried out using EEGLAB (Delorme and Makeig, 2004), an open-source toolbox for Matlab (Mathworks, Inc., Natick, MA, USA). Data were first preprocessed as suggested in the manual[2], using a high-pass filter at 0.2 Hz and a low pass filter at 40Hz to remove high frequency noise. An Independent component analysis (ICA 'runica' function) was applied to the continuous data. Stereotyped artifacts such as eye-blinks and eye-movement were detected and removed by the algorithm. The corrected data were then processed using ERPLAB (Lopez-Calderon and Luck, 2014). Event codes were extracted from the EEG data, edited and stored in an Eventlist structure. With the Binlister routine, events corresponding to the different experimental conditions were assigned to different bins (categories). The EEG was then segmented based on the time-locking event. Response-locked epochs, spanning from -1000ms prior to key-press up to 200ms after and were baseline corrected[3] based on the whole duration of 1200ms. Artifacts were detected using the peak-to-peak function and trials with deflections exceeding ±80 μV were marked and excluded from further analysis. Epochs of the two different conditions were averaged separately. A low-pass filter with a cut-off at 30 Hz was applied to the epoched data to remove further noise, following the recommendation of the toolbox's manual. Finally a grand-averaged waveform across subject was produced for each bin and each electrode.

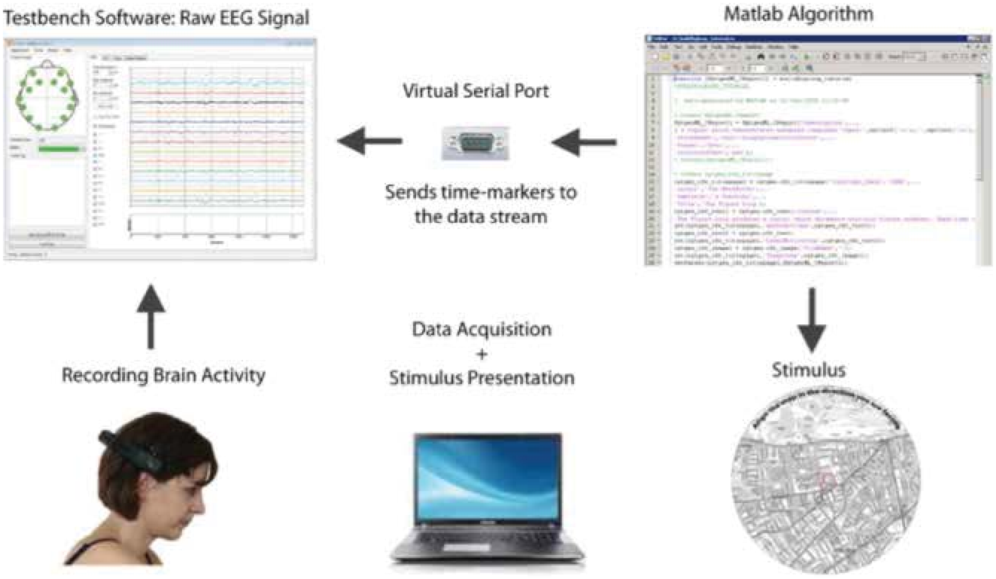


Figure 5.
Data Acquisition System

1. The EEG is sampled by the hardware at 2048Hz and then down-sampled to 128Hz (128 data points for one second). The device applies a pass-band filter to the signal to remove frequencies below 0.16Hz and above 85Hz and a notch filter at 50hz and 60hz to remove artifacts produce from the power line.

Results

The different coordinate systems of the spatial representations of the two conditions, the 'indoor' and 'outdoor' sets, are reflected in a within-trial comparison of angular deviation errors. Lines representing each subject's response at each stop point have less variation for the 'outdoor' set compared to the 'indoor' set. This tendency probably reflects a more stable representation of the locations of the surrounding environment. Whereas, in the 'indoor' set, variation of errors results in more sharp peaks, suggesting that the representation of the locations presented in each trial are independent of each other and thus revealing the egocentric nature of the 'indoor' spatial model (**figure6**).

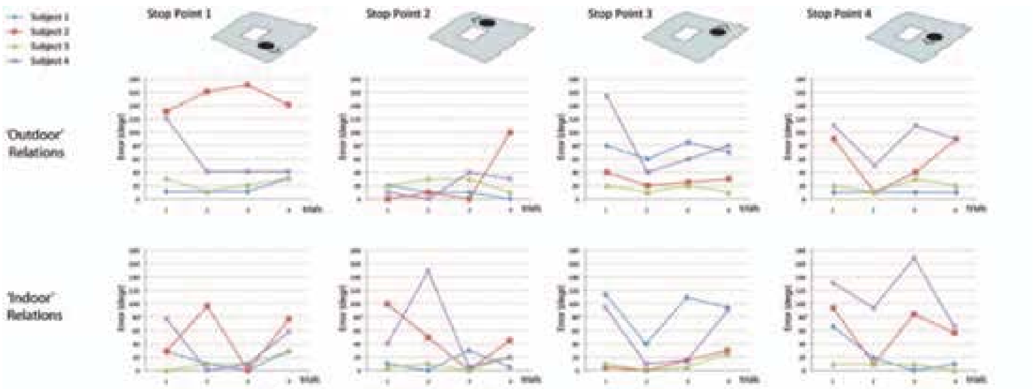


Figure 6. Error of angular deviation of each subject at each stop point for each task: Lines representing each subject's response have less variation for the 'Outdoor' task compared to the 'Indoor'. The Y-axis represents the error of angular deviation in degrees and the X-axis the number of trials.

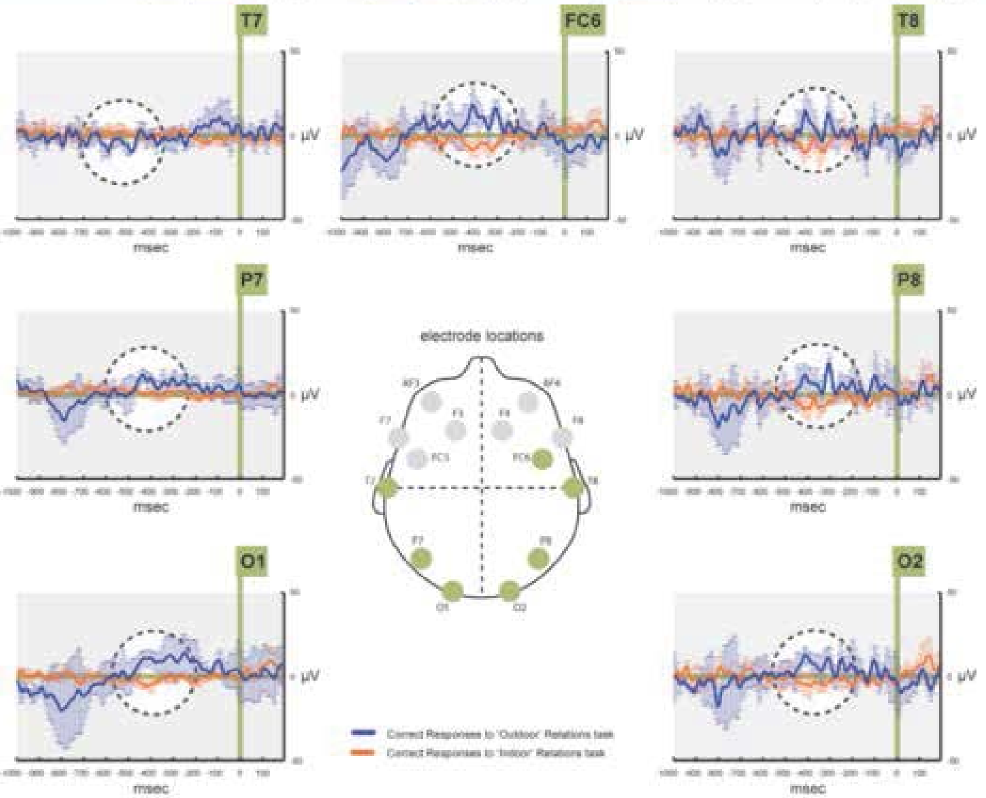


Figure 6. Orientation Experiment Aha Vs NoAha. ERP waveforms show positive amplitudes for the 'Outdoor' Relations Set condition Vs the 'Indoor' Relations Set in temporal, parietal and occipital areas in left hemisphere but right areas as well, as expected form the literature. Positive deflection occur in the time window of 500 to 200 ms before key press .

---

[2] http://erpinfo.org/erplab/erplab-documentation/tutorial_4/Filtering.html

[3] Subtracting the mean value (the DC offset) of the waveform.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 3 (1) / July 2015

The event-related waveforms of the recorded brain activity reveal the differences between correct responses of the two conditions. In the 'outdoor' task deflections are greater than in the 'indoor' task in almost all electrodes reflecting increased cognitive load. More specifically in the right frontal (FC6), temporal (T8), parietal (P8) and occipital (O2) channels the 'outdoor' condition elicited more positive deflections in the time window of 500 to 200 ms before key press, whereas the 'indoor' set shows more negative peaks at the same time window. These differences imply the occurrence of different cognitive processes in each condition. Additionally, the recorded EEG data provide some preliminary evidence that the updating of the current mental spatial representation with information from long-term memory becomes conscious around 500 to 200ms before subjects indicated their answer (**figure7**).

Conclusions

In the present study, the aim was to explore the differences in brain activity between the mental model of an interior spatial layout and the spatial representation of the exterior surrounding environment. Behavioral results show that there is a tendency in forming allocentric spatial representation for large-scale environments with more stable relations between locations. On the other hand, route knowledge is based on transient egocentric representations that are independently related to the observer's location. Thus people tend to maintain separate spatial representation for different spatial experiences. This clustering of representations respects the capacity limits of the working memory since it permits only the activation -from long-term memory- of the necessary spatial information that is needed for immediate action.

Integration of separate spatial representations is possible but requires a translation of spatial information between the two reference frames. The EEG recordings of this study support the hypothesis that the mental model of the surrounding environment is based on a distinct spatial representation. Additionally the positive deflections in the waveforms that are elicited in this condition reflect the cognitive processes that underlie this coordinate transformation. As expected from the literature (e.g. Burgess's two-system model) greater deflections in temporal and parietal-occipital lobe are elicited in the case where transformation of the allocentric representation is needed. Increased amplitudes in the temporal lobe might be related with memory interactions underlying the updating process of the mental representation and parietal positivity might reflect the restructuring of spatial relations in the current mental representation.

The attempt to study brain activity in real-world environmental interaction is non trivial and requires an appropriate methodology. The findings from this experiment are quite promising regarding the feasibility of the EEG/ERP methodology. The EEG methodology expands the space of possible research questions that might be investigated in relation to spatial representations, environmental psychology and spatial perception and cognition. The subjective experience of the built environment might be in a certain degree objectively measurable when collecting data using such neuroscientific methods. Simple experimental laboratory conditions are not necessarily representative of what actually occurs in real complex situations. Our understanding of space, as architects, may contribute in a fruitful way in the recent attempts to investigate the neural responses that are associated with real-world spatial experience and the perception of the built environment. Research in this emerging interdisciplinary field could provide new guidelines that would also shift the architectural research towards a more mind-oriented exploration.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 3 (1) / July 2015

References

Avramides, M., Adamou, C., Galati, A. & Kelly, J. (2012). Integration of Spatial Relations across Perceptual Experiences. In: Stachniss, C., Schill, K. & Uttal, D. (eds.) Spatial Cognition VIII. Springer Berlin Heidelberg

Badcock, N. A., Mousikou, P., Mahajan, Y., De Lissa, P., Thie, J. & Mcarthur, G. (2013). Validation of the Emotiv EPOC((R)) EEG gaming system for measuring research quality auditory ERPs. PeerJ, 1, e38

Basten, K., Meilinger, T. & Mallot, H. (2012). Mental Travel Primes Place Orientation in Spatial Recall. In: Stachniss, C., Schill, K. & Uttal, D. (eds.) Spatial Cognition VIII. Springer Berlin Heidelberg

Burgess, N. (2006). Spatial memory: how egocentric and allocentric combine. Trends in Cognitive Sciences, 10, 551-557

Byrne, P., Becher, S. & Burgess, N. (2007). Remembering the Past and Imagining the Future: A Neural Model of Spatial Memory and Imagery. Psychological Review, 114, 340-375

Delorme, A. & Makeig, S. (2004). Eeglab: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of Neuroscience Methods, 134, 9-21

Duduchenko, P. A. (2010). Why People Get Lost, Oxford : Oxford University Press

Gramann, K. (2005). Evidence of Separable Spatial Representations in a Virtual Navigation Task. Journal of experimental psychology. Human perception and performance, 31, 1199

Hommel, B. & Knuf, L. (2000). Action Related Determinants of Spatial Coding in Perception and Memory. In: Freksa, C., Habel, C., Brauer, W. & Wender, K. (eds.) Spatial Cognition II. Springer Berlin Heidelberg

Keefe, J. & Dostrovsky, J. (1971). The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. Brain Research, 34, 171-175

Keefe, J. & Nadel, L. (1978). The hippocampus as a cognitive map, Oxford, Oxford : Clarendon

Klatzky, R. (1998). Allocentric and Egocentric Spatial Representations: Definitions, Distinctions, and Interconnections. In: Freksa, C., Habel, C. & Wender, K. (eds.) Spatial Cognition. Springer Berlin Heidelberg

Klippel, A., Knuf L. & Hommel, B. (2005). Perceptually Induced Distortions in Cognitive Maps. In: Freksa, C., Knauff, M., Krief-Bruckner, B., Nebel, B. & Barkowsky, T. (eds.) Spatial Cognition IV. Reasoning, Action, Interaction. Springer Berlin Heidelberg

Klippel, A., Yang, J., Wallgrun, J., Dylla, F. & Li, R. (2012). Assessing Similarities of Qualitative Spatio-temporal Relations. In: Stachniss, C., Schill, K. & Uttal, D. (eds.) Spatial Cognition VIII. Springer Berlin Heidelberg

Lopez-Calderon, J. & Luck, S. J. (2014). ERPLAB: an open- source toolbox for the analysis of event-

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 3 (1) / July 2015

related potentials. 8

Luck , S. J. 2005. An introduction to the event-related potential technique, Cambridge, Mass. ; London, Cambridge, Mass. ; London : MIT Press

Mcnamara, T. P. 1986. Mental representations of spatial relations. Cognitive Psychology, 18, 87-121

Meilinger, T. & Vosgerau, G. (2010). Putting Egocentric and Allocentric into Perspective. In: Holscher, C., Shipley, T., Olivetti Belardinelli, M., Bateman, J. & Newcombe, N. (eds.) Spatial Cognition VII. Springer Berlin Heidelberg

Mou, W. & Mcnamara, T. (2002). Intrinsic frames of reference in spatial memory. Journal of experimental psychology. Learning, memory, and cognition, 28, 162-170

Riecke, B. E. & Von Der Heyde, M. 2002. Qualitative Modeling of Spatial Orientation Processes using Logical Propositions

Shelton, A. L. & Mcnamara, T. P. (2001). Systems of Spatial Reference in Human Memory. Cognitive Psychology, 43, 274-310

Tolman, E. C. 1948. Cognitive maps in rats and men. Psychological Review, 55, 189-208

Tversky, B. (1981). Distortions in memory for maps. Cognitive Psychology, 13, 407-433

Tversky, B. (2005). On Exploring Parts and Wholes. In: Gero, J. S. & Maher, M. L. (eds.) Computational and Cognitive Models of Creative Design VI. Sydney

Tversky, B. & Schiano, D. J. (1989). Perceptual and conceptual factors in distortions in memory for graphs and maps. J Exp Psychol Gen, 118, 387-98

Waller, D. & Hodgson, E. (2006). Transient and Enduring Spatial Representations under Disorientation and Self-Rotation. Journal of Experimental Psychology: Learning, Memory, and Cognition, 32, 867-882

Wang, R. F. & Brockmole, J. R. (2003). Simultaneous spatial updating in nested environments. Psychon Bull Rev, 10, 981-6