Updating of Mental Representations in Spatial Reasoning: Two pilot ERP Experiments

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Abstract. Bringing together the notions of mental impasses in problem solving and perceptual restructuring of spatial information during re-orientation the present study investigates brain activity in two real-world pilot experiments on spatial reasoning: an orientation pointing task and a Sudoku puzzle. The working hypothesis of this research is that if we approach wayfinding as an instance of problem solving we can create intellectual bridges between lab-based experimental situations and real-world scenarios and adopt new perspectives on existing findings. Two pilot ERP experiments have been conducted in an attempt to check the feasibility of mobile EEG (Emotiv) in detecting a distinct pattern of brain activity during the representational update in real-world spatial problem solving. Initial results in both cases suggest a P3-like component might be the brain's signature of a representational update.

Keywords: Spatial representation, reorientation, problem solving, representational update, EEG.

1 Introduction

The analogy between the experience of navigation -a problem of self-movement in space to achieve a certain outcome e.g. reach a goal/reward - and the general notion of problem solving seems to provide a fruitful theoretical tool to assess and control the occurrence of specific mental events in real-world complex scenarios. In favour of this view, one of the early studies investigating the neural correlation of 'insight' in problem solving has reported the involvement of the right hippocampus in insightful solutions. Researchers suggested that the contribution of the hippocampus in the reorientation of one's thinking might be similar to that of reorientation in navigation [1]. Insightful solutions involve the creation of novel associations through the integration of remote information. Researchers on problem solving, argue that adopting a process-oriented approach instead of a problem-oriented one -in studies of insightful thinking- expands the implications that can be drawn [2]. In the case of insightful problem solving, the initial mental representation can be misleading or inappropriate and may result in impasses. Mental impasses or mental fixations are experienced as a feeling of not knowing how to proceed in order to find the solution to the problem. The reorientation of one's thinking requires a perceptual restructuring of the initial representation of the problem, which allows the emergence of a successful solution path.

Similarly, to gain re-orientation one must acquire a ‘deeper understanding’ of the current location and heading direction. Since, according to recent findings [3] the neural compass is anchored to specific local spatial cues, the initial representation needs to be updated with information of locations of fixed elements within the environment. The disorientation effect [4] suggests a switch from a precise egocentric representation to an allocentric one at the moment of disorientation much like the representational change that occurs in insightful or creative problem solving. Thus, one becomes aware of the actual heading on the basis of the relation between spatial elements of the current context.

The metaphors we use when referring to problem solving such as ‘the solution path’ or ‘the problem space’ imply the deep relation between problem solving and space and underline the problem solving nature of wayfinding. Bringing together the notions of mental impasses and the representational change in problem solving the current study aimed at the investigation of brain activity during the update of the mental representation in two real-world case scenarios: an orientation pointing task and a Sudoku puzzle. Sudoku puzzles involve sequential thinking and processing of spatial relations among elements. The aim was to identify moments of mental impasses: the subjective feeling of getting stuck and not knowing how to proceed. Operationalization of the moment of reorientation was based on Wang and Brockmole’s experiment (described in the next section) and the hypothesis that we operate on distinct representations over different timescales [5], e.g. in small and large-scale environments.

2 Related Work

The process of updating the mental model has been often associated with a specific event-related potential component called the P3 or P300 [6]. Event-Related Potentials (ERP) are small changes in voltage in the signal recorded by electroencephalography (EEG), which are triggered by an internal, external or motor event. In the ERP methodology different experimental conditions may elicit distinct cognitive responses, which are reflected by differences in amplitude and latency in the respective waveforms. The signal of interest, the evoked-response, is usually obscured by the much larger EEG spontaneous activity and the averaging technique is used to cancel out this noise. The ERP components are described in terms of their polarity, latency and scalp distribution and reflect the neural responses associated with the specific event. The P3 is the third positive deflection in relation to the onset of a stimulus and usually 300ms after. It is thought to reflect stimulus evaluation processes and its amplitude has been related to the engagement of attention and task difficulty [7]. The P3 signals the occurrence of a deviation from what is expected and its relation to the hippocampal system is not unreasonable since the hippocampus seems to be sensitive to the probabilistic context in which events occur [8].

2.1 Neurophysiological studies on Insightful Problem Solving

At the beginning of the 21st century researches started studying the neural mechanism of insights using brain image techniques (fMRI, PET, ERP). According to a recent review on the neuroscientific studies on insights [9], the 'insightful brain' involves a distributed functional network of brain areas. The cingulate cortex (e.g. ACC and PCC), part of the limbic system, may signal 'early warnings' of potential impasses and is involved in detecting and monitoring cognitive conflict (old/new representations). The prefrontal cortex is activated when shifting the mind set. The medial temporal lobe (e.g. hippocampus, parahippocampus) is involved in the formation of novel and effective associations whereas the parieto-occipital region is implicated in the effective transformation of the problem's representation. Although a lot of innovative experimental tasks are employed since then, research on insight is still in its initial state.

Data from ERP studies show several inconsistencies that might reflect differences in cognitive processes [9, 10]. This is probably due to a certain degree of variability in the experimental conditions (e.g. experimental tasks, reference states and methodology). However, there are two main findings regarding brain activity elicited in the 'Aha!' conditions (insightful solutions) but not in the 'no-Aha' ones. Most of the studies have reported a negative deflection over the frontrocentral region, generated at the Anterior Cingulate Cortex (ACC) that is involved in detecting cognitive conflict and initializing the breaking of the mental set [11-14]. Furthermore, studies have also reported a positive wave at the parietoccipital electrodes generated at the parahippocampal gyrus (involved the formation of novel associations), and according to several authors this might be a P3-like component [11, 14-17]. The initial focus was on the frontal negative peak thought to be the 'Aha effect'. However, this early signal of conflict of the ACC was also present in the condition where subject fail to comprehended the provided answer [12]. Although the ACC meditates the successful restructuring of the mental representation, the effective switch of the problem's representation seem to depend on a non-verbal visuospatial information-processing network [9].

Insight-like phenomena in visual perception, like the Necker cube or the Old/Young woman elicit a similar parietal positivity (variant of the P3) at the moment of perceptual reversal. Researchers using manual responses as time reference observed a positive component between -500ms -200ms before key press, which is interpreted as indicating conscious recognition of a perceptual switch [18]. Thus positive parietal waves and the P3-like component are associated with the conscious transformation of the representation and we should expect to see such deflections, in the ERP pilot experiments, most probably in the time window of -500ms to -200ms prior to subjects' response.

2.2 Spatial Mental Representations and Their Coordinate Transformation

Mental representations of spatial information have often been described as highly organized knowledge structures [19]. Knowledge of spatial relations seems to be organized hierarchically into superordinate structures and subordinate clusters [20]. Spatial chunking or clustering into small meaningful representations allows the activation only of the task-relevant information [21], maintaining the solutions to wayfinding problems. Therefore, we seem to parcel spatial knowledge into functionally significant components and group it into bigger categories that include other similar exemplars. In a similar way, we solve problem by dividing the problem's elements into parts and group it by kinds based on similarity. Parceling and grouping information is useful because it allows inferences and predictions to be drawn [22].

The two-system model of spatial updating, proposed by Burgess, suggest the continuous translation between egocentric and allocentric representations [5]. According to this model, egocentric representations are recruited in short-term spatial memory for immediate action and mental imagery and are generated in the parietal window (posterior parietal cortex and precuneus). Coarse allocentric representations that are supported by information stored in long-term memory are generated in the hippocampus and surrounding medial temporal lobe areas (perirhinal and parahippocampal cortices) Encoding and retrieval of information requires a translation between the two representational systems and this coordinate flow of information has been associated with the theta rhythm [23]. Additionally, misaligned viewport-depended spatial representation stored in memory required a coordinate transformation into the current egocentric orientation [21, 24, 25]. Waller and Hodgson's disorientation paradigm provides evidence for the two-system model. The main finding of this study is that after disorientation variability in errors increased in the egocentric pointing task while variability in errors decreased when participants where asked to make judgment of relative direction ("Imagine your are at location X looking at Y, point at Z") [4]. This suggests that disorientation causes a switch from the use of a temporary, egocentric representation of space to a less accurate but enduring representation, most likely an allocentric one [5].

The two system-model also implies that we operate on distinct representations over different timescales, for example in small and large scale environments [5]. The Wang and Brockmole's experiment is one example that involves such transformation and integration of distinct representations [26]. 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.

2.3 Lesion studies and Lateralized cognitive processes

Relevant lesion studies may shed some light on the left/right differences that should be expected between problem solving and spatial orientation. Patients with damage in either left or right temporal and parietal regions show several lateralized differences in terms of cognitive functions. Spiers and colleagues used a virtual navigation task to test 17 patients with right temporal lobe partial removal and 13 patients with left [27]. Damage to the right temporal lobe impaired navigation whereas left temporal lobe patients did not have such difficulties in remembering locations. However, they did have difficulties in remembering the order of events and their context (episodic or context memory). Parietal lobe damage causes difficulties in wayfinding, visual attention and spatial perception. Dudchenko refers to several differences between left and right parietal damage, for example the Gerstmann syndrome, associated with damage to the left parietal lobe, includes inability to manipulate numbers and left-right confusion. Patients with left parietal lesions have difficulties on visual constructive tasks (copying drawings or arranging matches) while right parietal lobe patients have difficulties in perceiving the spatial relations among things and have a tendency to get lost [28].

2.4 Aims of the current study

The present study investigates brain activity during the representational update in spatial reasoning in real-world situations. According to Donchin's Context-Updating theory the P3 ERP component is associated with the updating of the mental representation of one's current environment to incorporate new improbable but task-related information [6]. This positive deflection should be expected around 500ms before subjects' response as indicated by experiments on perceptual reversal [18]. The temporal and parietal areas have an important role in the mental representations of spatial relations as well as in insightful problem solving being involved in the formation of novel associations and the effective transformation of the representation respectively. In addition, lesion studies predict differences between left and right hemispheres in the two tasks, implying greater involvement of the right hemisphere in the orientation task.

At the same time, we examine whether mobile electroencephalography (EEG) and the Event-Related Potential method, which is usually used in lab-based experiments, offers an appropriate methodological tool able to provide an objective indication of the occurrence of this mental event in real-world conditions. The electroencephalography (EEG) is a relatively inexpensive method for recording electrical signal of the human scalp with a very high time-resolution. The Emotiv headset is a wireless EEG system with 14 electrodes arranged in specific scalp locations (positioned according to the 10-20 international system). 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 [29]. The Emotiv Software Development Kit includes three implemented applications (the 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 in an edf format for further processing. This option offers a reliable and appropriate method of data acquisition when investigating event related brain activity.

3 Methods

Two pilot ERP experiments were conducted to investigate brain activity associated with the representational update in spatial problem solving (Figure 1). Four different subjects - two males and two females - participated in each task (eight in total). Participants were fully informed of the details of the experiment, their role in it, the kinds of data collected and that they are able to terminate it at any time if they wished. The Emotiv wireless headset was then placed on their head. 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 EPOC was recording their brain activity and saving this into a data file. Participant's data were labeled with numbers and subsequent analyses of the data used the subject number rather than the participant's name.

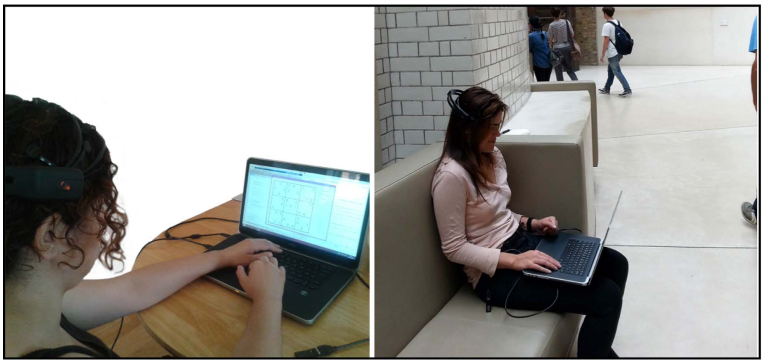

Fig. 1. Sudoku and Reorientation experiments.

3.1 Experiment I

In experiment I participants were asked to solve a Matlab-generated Sudoku puzzle of medium difficulty. Sudoku is a number placement puzzle that involves sequential thinking and calculation of spatial relations between the puzzle's elements. Each subject had to solve three puzzles with duration of less than 20 minutes each. After each game participants had a five minutes break and they were asked how many times they had the feeling of not knowing how to proceed and getting stuck before finding the next number they had to enter. In these way we were able to assess the moments that participants had the experience of mental impasses, that is when their initial representation of possible solution was misleading. Self-reports on number of answers involving impasses correlated with the number of late responses from the reaction time data. In these late correct responses with reaction times more than 50 seconds, subjects needed to break their mental 'fixation' in order to find the next entry that would constitute a valid sequences of numbers. These responses were considered as the test condition since it was hypothesised that they involved a representational update. The control condition included fast correct responses, with reaction time less than 10sec, where the next number entry was relatively obvious.

3.2 Experiment II

Experiment II was a real-world orientation experiment and took place in the halls of the V&A museum. Participants were instructed to follow the researcher in different routes through the different floors of the museum. At four different stop points along the route, they were asked to take a seat and respond to an orientation-pointing task while the Emotiv headset was recording their brain activity (Figure 2). The stimulus image presented on the laptop illustrated an arrow and the name of a specific location. Participants had to rotate the arrow using the left and right arrows (10 degrees rotational steps) in order to indicated the direction of the location in relation to their heading orientation. 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. In each stop point four test and four control target locations were presented. The control condition involved locations of the immediate environment, closely related with the route within the museum, and thus updated with self-movement. Test targets were locations of the large-scale remote environment, which are not updated with movement within an indoor environment. Representations of large-scale layouts are mostly based on survey knowledge and allocentric relations. Test condition was hypothesised to require the coordinate transformation and integration of the allocentric memory into the current egocentric representation.

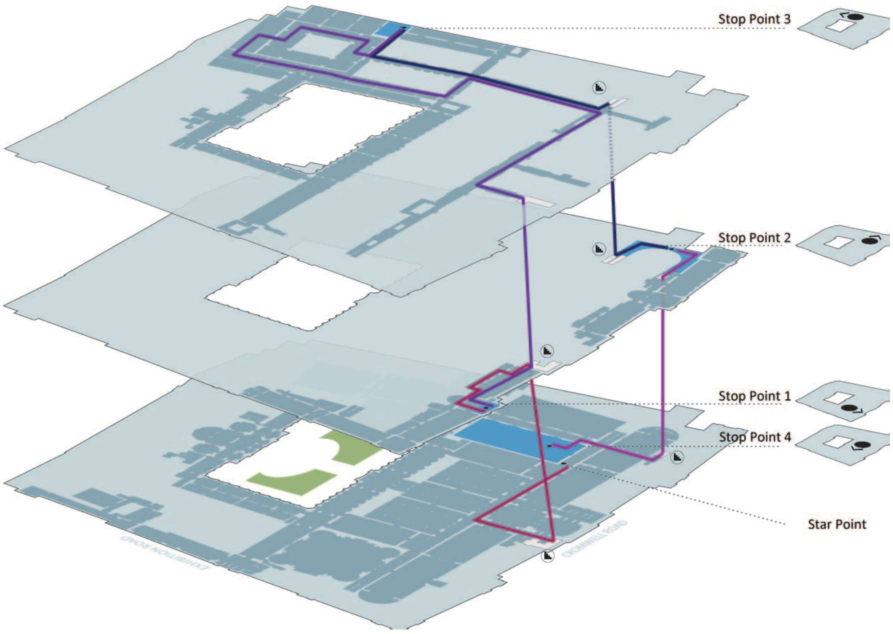

Fig. 2. Routes and Stop Points within the V&A museum.

3.3 Data Acquisition

Brain activity, for both experiments, was recorded with Emotiv Testbench software via a Bluetooth USB chip (Figure 3). 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 stream using Testbench software. For the Sudoku experiment, a different event code was generated for correct and incorrect answers. Reaction times -the duration between successive number entries- enabled the offline distinction between fast and late responses. For the Orientation experiment event codes were send to the data stream to mark subjects' responses and the presentation of the stimulus-image (a different code for test and control conditions). Event codes were differentiated offline for correct and incorrect responses.

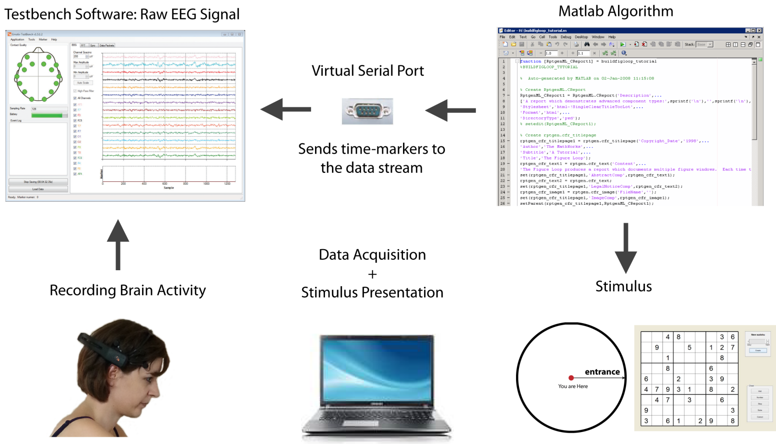

Fig. 3. Data Acquisition System: The same computer was used for recording and stimulus presentation. Recordings of the raw EEG signal were done with the Testbench software of Emotiv EPOC. Stimuli were generated by a code in Matlab and presented on the monitor. Each time subjects pressed a key as a response a time-marker was send to the EEG signal from Matlab via a virtual serial port.

3.4 Signal Processing

The EEG is sampled by the hardware at 2048Hz and then down-sampled to 128Hz (128 data points for one second). The processing steps were curried out offline using EEGLAB [30], an open-source toolbox for Matlab (Mathworks, Inc., Natick, MA, USA). Data were first pre-processed as suggested in the manual[1], 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 [31]. Event codes were extracted from the EEG data, edited and stored in an Eventlist structure. The EEG was then segmented based on subject's response. Response-locked epochs, spanning from -1000ms prior to keypress up to 200ms after and were baseline corrected based on the whole duration of 1200ms. Trials with deflections exceeding ±80 μV (peak-to-peak function) were marked and excluded from further analysis. Epochs of the test and control 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 category and each channel.

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

3.5 Results and Discussion

As shown in the grand-averaged waveforms (Figure 4) the test condition elicited greater positive deflections at the frontocentral, temporal and parietal areas in both cases. In the Sudoku task, positive deflections were observed in the left frontocentral, temporal and parietal channels (FC5, T7, P7) around -600ms before key press. The waveforms of the pointing task showed positive deflections in the time window -500ms to -200ms, greater at electrodes of the right hemisphere (FC6, T8, P8). As expected from the literature, Burgess's two-system model and the neural basis of the 'insightful brain', greater deflections in temporal and parietal lobe were elicited for both tasks with the right hemisphere being more activated in the orientation task. Increased amplitudes in the temporal lobe might reflect memory interactions underlying the updating process of the mental representation. Researchers of insight argue that memory interactions might be distinct for insight and non-insight solutions and that in this case hippocampal or parahippocampal involvement is plausible [32]. Left parietal positivity for the problem-solving task probably reflects the sudden change of problem's representation after impasses and right parietal positivity in the orientation task, the restructuring of spatial relations and the update of the current mental representation.

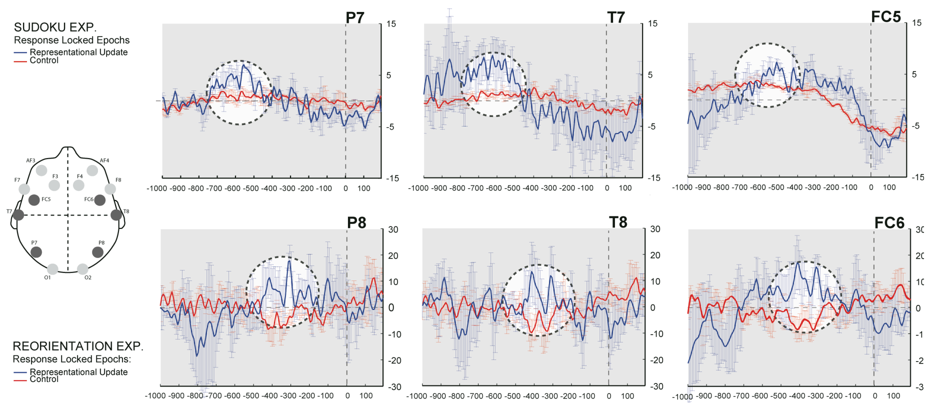

Fig. 4. Grant average of Event Related Potential waveforms of Sudoku puzzle (first row) and of Reorientation (second row) experiments.

4 Conclusions and Future Work

In the present pilot study, we tested the feasibility of mobile EEG in detecting patterns of brain activity under real-world conditions. The ERP method was used to assess cognitive components that reflect the representational switch in two cases of spatial reasoning. The first case was on spatial problem solving based on allocentric relations between elements. In this case of the Sudoku puzzle, subjects needed to break their 'fixation' after mental impasses and shift their attention to novel relations among the problem's elements. An orientation pointing-task was used for the second cases that included targets of the immediate and remote environment. Pointing to targets of the remote environment while navigating within the building required a shift of subjects' mindset: an update of their current mental representation by integrating distal information of representations from long-term memory. The initial findings of the pilot experiments are quite promising and seem to support the hypothesis that investigating wayfinding under the general concept of problem solving constitutes a fruitful theoretical tool. Designing experiments within this theoretical framework may allow researchers to adopt new perspectives on existing findings and the transition from lab-based experimental situations into real-world scenarios.

The key finding of this study is that frontocentral, temporal and parietal positivity is elicited for the Representational Update condition in both tasks. This positive deflection might be a P3-like component observed in several related studies, for example at the moment of perceptual reversal, the creation of novel associations in insightful problem solving or reflecting explicit knowledge in implicit learning paradigms. This assumption, is also supported by Donchin's Context updating theory of P3, where he suggest that deviant, unpredictable and surprising events elicit a restructuring of the mental representation and this is manifested by the P3 component [6]. Of course, several parameters could be improved in these ERP experiments and more inferences could be drawn. In particular, variables such as prior knowledge and spatial abilities could be investigated in relation to reaction time data and the latency of cognitive components. Epochs of longer duration could reveal additional patterns of brain activity present at earlier stages. Finally, data from more subjects and more trials per subject would increase further the signal-to-noise ratio.

The P3-like component might indeed reflect the update of current mental representations and hence serve as an indicator of this mental event in future real-world experimental scenarios. Future work has to focus in recording brain signals related to specific mental events while subjects navigate in real-world complex and dynamic situations in either real of virtual reality environments. Synchronized Virtual Reality/EEG systems provide the means of a real-world experience without actual movement and where different experimental conditions can be designed and compared. On the other hand, using wireless EEG while subject perform actual movement within real environment has still several limitations. The Emotiv is not stable with movement and thus wireless electrodes will need to be implement in a wearable brain cap while at the same time walking will probably produce great movement artifact in the signal. Fortunately, relevant research on whole-body movement artifacts using machine-learning algorithm (ICA) [33] is currently evolving and will hopefully soon allow researchers to conduct EEG experiments during real-world navigation.

Acknowledgments. This work has been partially supported by the Greek State Scholarship Foundation and A.G Leventis Foundation.

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