

Electrophysiological Source Analysis of Passive Self-Motion

Hugh Nolan, John S. Butler, Robert Whelan, John J. Foxe, Heinrich H. Bülthoff, Richard B. Reilly

Abstract—The neural processes underlying perception of motion are relatively unknown. In this study Electroencephalography (EEG) is used to investigate the neural responses to passive self-motion. A Stewart platform was employed to translate subjects forwards and backwards while high-density EEG data was recorded. Modern source modeling methods were combined with classical waveform and topographic analyses to determine the electrophysiological correlates of motion processing.

I. INTRODUCTION

The effective processing of vestibular and multisensory self-motion information is a vital component of numerous everyday tasks. Driving a car, walking down a road, even maintaining balance – these are tasks that rely upon the continuous proper detection and integration of self-motion information. Multisensory integration has been seen to change with age [1], and in particular it has recently been seen that inefficient audio-visual integration in the over-65 population has a positive correlation with an increased risk of falls (A. Setti *et al.*, under review). This stands to reason as balance and self-motion processing are finely-tuned processes involving integrating vestibular, visual, somatosensory, proprioception and, to a lesser degree, auditory information from the environment [2-4] – if integration is compromised, it can quickly lead to dysfunction [5, 6].

The neural processes involved in the processing of self-motion have remained less studied than visual or auditory processing, for example, due in part to technical challenges involved in acquisition of neuroimaging data during motion. Previously we have shown that it is possible to acquire electroencephalographic (EEG) data without interference

during passive self-motion on a Stewart platform [7], which opens up numerous new avenues of the study of self-motion. Furthermore we have shown that vestibular self-motion, presented in an oddball fashion, evokes a P3 waveform like other sensory systems, and thus we can conclude that vestibular information is integrated on a cognitive level in a similar manner to other senses (under preparation).

In this study we use advanced methods of source modeling of EEG to investigate the neural processes underlying the perception of passive self-motion. Data from a motion-based EEG experiment are analysed. Subjects were seated in a Stewart platform and translated forwards and backwards in a passive vestibular motion task, while 128-channel EEG was recorded.

II. METHODS

A. Subjects

Sixteen subjects with normal or corrected-to-normal vision participated in the experiment. The age range was 22 – 35 (mean $28.1 \pm$ standard deviation 3.9). Subjects gave their informed consent before taking part in the experiment, which was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. One subject's data was particularly noise-contaminated and was removed from the study.

B. Apparatus

A Maxcue 600 platform manufactured by Motion-Base PLC [8] was employed. This is a 6-legged Stewart platform with 6 degrees of freedom, which are rotation and translation about 3 axes. A fixation cross was displayed on a projection screen, with a field of view of $86^\circ \times 65^\circ$, a resolution of 1400×1050 and a refresh rate of 60 frames per second. Subjects wore Sennheiser HD600 headphones with one-way

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Hugh Nolan*, Robert Whelan and Richard B. Reilly are with the Trinity Center for Bioengineering, Trinity College Dublin, Dublin 2, Ireland (*corresponding author, e-mail: nolanhu@tcd.ie, robert.whelan@tcd.ie, richard.reilly@tcd.ie; phone: +353-1-8961580; fax: +353-1-6772442).

John S. Butler and John J. Foxe are with the Cognitive Neurophysiology Laboratory, Children's Evaluation and Rehabilitation Center (CERC), Departments of Pediatrics and Neuroscience, Albert Einstein College of Medicine, Bronx, New York, United States (e-mail: john.butler@einstein.yu.edu, john.foxe@einstein.yu.edu).

Heinrich H. Bülthoff is with Department Bülthoff, Max Planck Institute for Biological Cybernetics, Tübingen, Germany, and the Department of Brain and Cognitive Engineering, Korea University, Seoul, South Korea (e-mail: heinrich.buelthoff@tuebingen.mpg.de).



Figure 1. (Left) The outside of the Stewart platform. (Right) A subject with EEG electrodes in place, ready to perform the task. During this study, a cloth sheet covered the platform to mask visual motion cues, and a Biosemi ActiveTwo EEG system was installed to record EEG data.

communication capability while white noise was played to mask the sound of the platform. EEG data were recorded at 512Hz using a Biosemi ActiveTwo™ 128 channel EEG system with 7 supplementary electrodes recording EOG and reference channels. Data were referenced to the average reference.

C. Motion Paradigm

Subjects were presented with sequential forwards and backwards motions. A random interval of 1.5 – 2.5 s separated the stimuli. There were a total of 6 blocks, each consisting of 100 trials – 50 forwards and 50 backwards – yielding a total of 300 forward stimuli and 300 backward stimuli per subject. Each block lasted approximately 5 minutes. All subjects were given two breaks lasting 5-10 minutes.

The ideal motion displacement profile was:

$$s(t) = 0.49 \frac{(2\pi t - \sin(2\pi t))}{4\pi^2} \quad 0 < t \leq 1s$$

where t is time. It had a maximum displacement, velocity and acceleration of 0.078 m, 0.156 ms^{-1} and 0.49 ms^{-2} respectively, lasting 1s, which are above the detection thresholds reported in [9]. During testing it was noted that due to mechanical limitation the Stewart platform, the acceleration profile had a total time closer to 1.25s, and so the recorded acceleration profile rather than the ideal profile was used for analysis. Accelerometer data was aligned to EEG data using common parallel port triggers.

D. Data Processing

All data were high-pass filtered at 1 Hz and low-pass filtered at 95 Hz for processing, with a bandstop filter at 47 - 53 Hz. The FASTER processing method [10] was used to preprocess data and remove artifacts. Epochs of 1500ms with 500ms pre-stimulus baseline were extracted from the continuous data; there was a mechanical delay of approximately 200ms from the trigger onset to the onset of the motion.

After pre-processing, the data were analysed using exact low resolution brain electromagnetic tomography (eLORETA) software (publicly available free academic software at <http://www.uzh.ch/keyinst/loreta.htm>). This method gives an exact solution to the inverse problem of EEG [11, 12]. It is based upon LORETA [13], which has received considerable validation from studies combining LORETA with other more established localization methods, such as functional Magnetic Resonance Imaging (fMRI) [14] and [15], structural MRI [16], and Positron Emission Tomography (PET) [17] and [18]. Classical EEG features (ERP waveforms and scalp topographies) were also analyzed to provide more information about the results and to provide a solid methodological basis upon which to build.

E. Analysis

The goal of this study was to identify neural correlates of self-motion. Temporal regions of interest were pre-identified as the peaks of the acceleration profile, which were seen to be at 500ms and 1000ms.

To maximize the effect of the acceleration-based ERP components, the *difference* of the forwards and backwards ERPs calculated – as the acceleration profiles were inverse, the response to acceleration is summed while any common components (such as the transient onset potentials) were cancelled by subtraction.

III. RESULTS

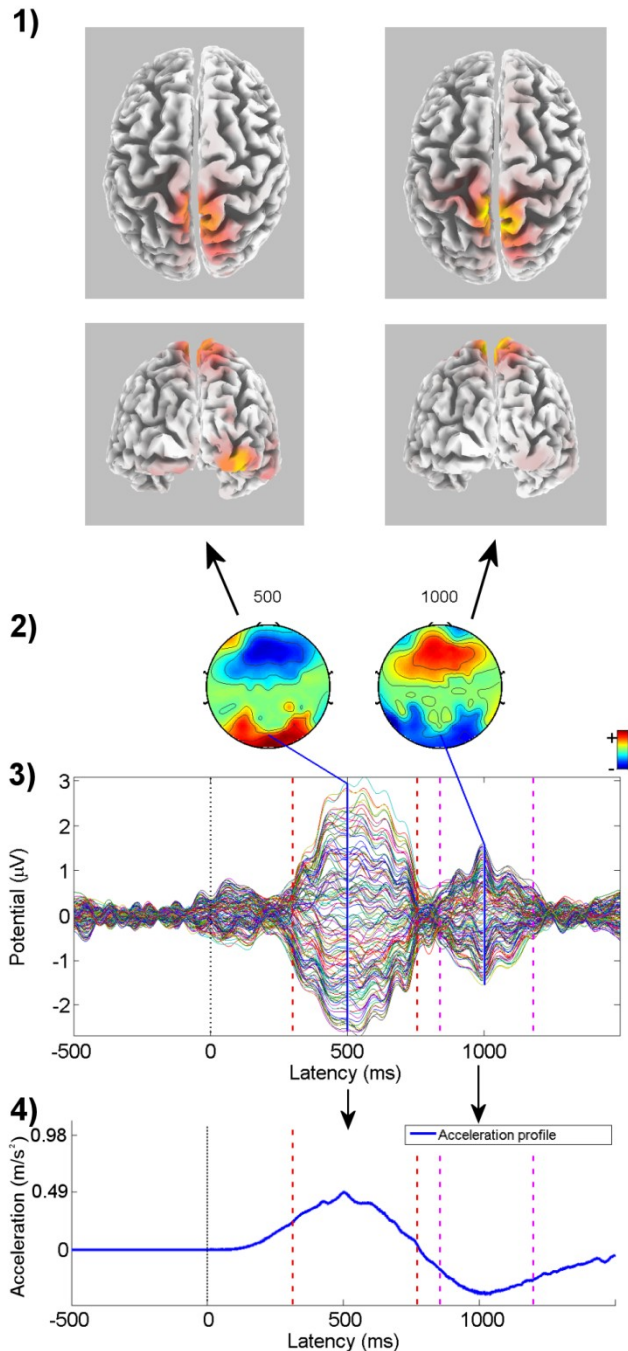


Figure 2. Results from the difference of Forwards and Backwards conditions.

Fig. 2 displays the results from the difference ERP computed from the Forwards – Backwards condition. Starting from the top, the figure displays:

- 1) Output from eLORETA at 500ms and 1000ms (showing an average activity over 50ms). This is a current source density (CSD) map, showing the localisation of the recorded EEG activity on a typical cortex. The first viewpoint is from the top of the brain. The activity shown is over the parietal cortex, reported in the eLORETA software to best approximate in the postcentral gyrus and the superior parietal lobule. The second viewpoint is from the back of the brain, and the activity in the occipital cortex was reported to best approximate to the central / inferior occipital gyrus.
- 2) Topographic maps computed from the ERPs at 500ms and 1000ms (showing an average activity over 50ms). The non-green areas are those statistically different from zero ($p < 0.05$, tested using per-electrode t-tests and limiting false positives by considering only significant electrodes with at least 3 of 4 neighbouring electrodes also being significant). These reveal that the activity displayed in the CSD maps has opposite polarities at 500ms and 1000ms, a distinction which the CSD maps lack.
- 3) Butterfly plot of the ERPs. This plot shows the ERP traces from each channel overlaid. Here we can see clearly that the peak amplitudes at 500ms are significantly higher than those at 1000ms ($p < 0.05$ in 70% of the significant topographic areas), which is not evident in the CSD or topographic maps. The Dashed lines are displayed for visual delimiting of the two peaks.
- 4) Acceleration profile, for temporal reference. The acceleration profile is displayed here to allow for visual comparison between the butterfly plots and the acceleration profile.

IV. DISCUSSION

In this study we sought to elucidate the neural underpinnings of motion perception using EEG and source analysis. Using a combination of waveform, topographic and source analysis, Fig. 2 displays a comprehensive breakdown of the response to a sinusoidal acceleration. One striking comparison is between the pattern of activity in the butterfly plots and the acceleration profile – there is a correspondence between the shape of the ERP traces and the acceleration profile. Taking the topographies into consideration, the pattern of activation is inverted between 500ms and 1000ms, as is the acceleration profile. This indicates that the ERPs represent a neural process linearly processing acceleration. The use of eLORETA also enabled cortical localization of this process. The question of validity arises with any source modeling technique, and so we will consider whether the source modeling output is sensible in the context.

The area shown to be most strongly activated at both 500 and 1000ms is the in the superior parietal cortex, approximately in the postcentral gyrus and extending posteriorly into the superior parietal lobule. The parietal

cortex is well known to be associated with spatial awareness, particularly in the superior aspects. The areas shown here are quite central, particularly at 1000ms where activity is approaching the central sulcus. This implies there is a strong somatosensory component contributing – the postcentral gyrus contains the primary somatosensory cortex [19]. This is sensible given there will be constant differential somatosensory stimulation on the back and legs from the seat on the motion platform. The back and legs are represented on the superior aspect of the cortex in the traditional somatosensory homunculus [20], which fits well with the observed activity.

The activation also extends posteriorly into the superior parietal lobule. There has been a number of studies showing a range of functions involving the superior parietal lobule – projections to the frontal cortex are implied a number of times [21, 22], as are somatosensory, visual and auditory connectivity [23, 24] and spatial localization [25]. This visual connectivity could explain the activation in the occipital cortex, approximately located in the middle/inferior occipital gyrus, which is an area associated with visual spatial processing [26]. It has also been shown the middle occipital gyrus is still active in spatial processing in the early blind, implying a non-visual specific activation [27] – this is an interesting finding to compare, as the present experimental setup removes any visual motion cues, rendering the subjects effectively blind to motion. It is interesting that the occipital activation at 1000ms appears diminished compared to that at 500ms, and that the waveform amplitudes are significantly different between times – is the discrepancy in amplitudes due to deactivation of the middle occipital gyrus during the deceleration phase of the motion? It has been seen that the expectation of sensory stimulation during visual motion paradigms modulates brain activity [28] and that crossmodal spatial attention modulates visual cortex activity [29], so it is possible that the implicit expectation of a visual motion component produces an initial activation of visual spatial areas which are then deactivated as there is no visual motion information. Further analysis of this question using a combination of visual and true motion would allow this hypothesis to be tested.

It is interesting to note that while spatial processing areas near somatosensory and visual areas have been identified, no areas which have been seen to relate solely to vestibular processing are identified. As the task was initially considered to be primarily vestibular, this could be interpreted as a strange result. However, the localization of the human vestibular cortex is under debate – for example, three separate structures are proposed in [30-32]. The results of this study provide evidence that vestibular information is represented and processed in a distributed, multisensory manner in multiple cortical areas - this is in accordance with current primate research in vestibular processing [33], and there is abundant literature showing that the vestibular, visual and somatosensory have strong multisensory links – for example, [34, 35]. This observation draws the question of how much of the observed activity in the identified parietal and occipital regions are vestibular-guided rather

than somatosensory and visual, respectively. It may be possible to draw some inference from studies such as [4], [34] and [35], but whether the behavioral data reported in these studies map directly to the neural activity seen here is as yet uncertain.

In summary, the results show that the electrophysiological correlates of passive self-motion involve centro-parietal areas associated with spatial, somatosensory and kinaesthetic processing, as well as occipital areas associated with visual spatial processing. The localizations were produced by using eLORETA for source analysis. They are results are sensible in this context, which also further validates the use of the method. There is a clear linear relationship between the ERP waveform and the acceleration profile, which demonstrates constant motion processing in the parietal cortex. Amplitude modulation during the deceleration phase can also be seen, and this is perhaps related to the absence of visual motion cues.

Further work on this topic could investigate the amplitude modulation effects observed in the deceleration phase, investigate the forwards and backwards (and other) motion directions separately or investigate the differences between active and passive motion processing.

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