A Novel Method for Assessing Sense of Body-Ownership Using Electroencephalography

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A Novel Method for Assessing Sense of Body-Ownership Using Electroencephalography

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***Abstract*—A successful substitution of an upper limb is possible when the prosthesis is recognized by amputees as part of their body scheme. A new system alternative to fMRI for evaluating the sense of ownership during the rubber hand experiment, using non-invasive electroencephalography recordings, is described and encouraging results are presented.**

***Index Terms*— Rubber hand illusion, electroencephalography, sense of ownership, upper limb prosthetics.**

INTRODUCTION

ONE of the challenges of biomedical engineering and neuroprosthetics is to create artificial limbs that can be controlled naturally and that act and at the same time are felt like real limbs. A complete and successful substitution of an upper limb after amputation is only achieved when the prosthesis is able to generate in the amputee the sense of body ownership, i.e. when it is recognized as a part of his/her body scheme. Body ownership refers to the special perceptual status of ones own body, which makes bodily sensations seem unique to oneself [1].

A strong sense of ownership might occur with the combination of three components: (1) a dexterous, sensorized and anthropomorphic prosthesis, (2) accurate multi-DoF controllability, (3) a feedback system that delivers sensory stimulation from the artificial hand [2]. An important line of empirical research is studying bodily self-consciousness by investigating multisensory and sensorimotor body mechanisms and their relevance on how the experience of the body part as *mine* is developed, maintained or disturbed [3]. The so called 'rubber-hand' illusion is one of the most interesting multisensory paradigms used to manipulate the sense of hand ownership because it isolates the pure sense of body ownership in the absence of movement and efferent information [4].

This experiment is briefly described as follows. The subject is seated with his/her arm resting upon a small table. A standing screen is positioned beside the arm to hide it from the subject's view and a life-sized rubber model of a hand and arm is placed on the table directly in front of the subject (as per Fig. 1). The subject sits eyes fixed on the artificial hand while both the rubber hand and subject's hand are stroked with two small paintbrushes by the person carrying out the experiment (synchronising the timing of the brushing as closely as possible). With such an experiment, Botvinick and Cohen provided evidence concerning the basis of bodily self-identification showing that individuals attribute tactile sensations felt by their hand to the rubber hand that they see being stimulated synchronously [4]. Later Ehrsson and colleagues used the same protocol to investigate the neuronal counterpart of the feeling of limb ownership while brain activity was measured by functional magnetic resonance imaging (fMRI) [5]. Specifically, they investigated human multisensory brain mechanisms during the rubber hand illusion to reveal how information from different sensory modalities result in unified perceptual experiences, thus finding neural evidence concerning the basis of the body self consciousness. Ehrsson demonstrated that the feeling of hand ownership is reflected in neural activity in the premotor cortex, which suggests that self-identification of the fake hand as a part of own body results from a multisensory integration in parieto-cerebellar regions and a recalibration of proprioceptive representations within the peripersonal space (i.e. the spatial area where ones body parts are) [5].

The aim of this work is to develop a simple, low-cost, and objective system (and method) alternative to fMRI, to investigate the occurrence of illusion during the rubber hand experiment, or equivalently, the feeling of hand ownership. Such a system, based on non-invasive electroencephalogram (EEG), is intended to be exploited as a research tool for upper limb prosthetics. This is an important field of research, since hand prostheses capable of generating in the amputee sense of ownership, could be more accepted than currently available ones [6]. Although the final goal of this research is to develop a technique able to detect and assess the sense of ownership of different hand prostheses (having diverse control interfaces and/or sensory feedback systems), this letter shows the feasibility of using EEG for such purpose.

A first attempt to investigate EEG signal features during multisensory processing was carried out by Kanayama et al., focusing on spectral components analysis [7]. Specifically, they interpreted the high frequency brain activity in the gamma band as a component of multisensory perception.

Another way of studying the neuronal activity of the brain is calculating the spectral power of EEG signals at different scalp electrodes. In this study we hypothesized using the power spectrum density (PSD) as a discriminative feature to

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measure the extent of illusion during the rubber hand experiment. Specifically, we hypothesized that the multisensory perception, altered with the rubber hand illusion, is reflected in significant power fluctuations, and when strong illusion occurs, EEG power increases above the premotor cortex regions as reported in Ehrsson's fMRI studies [5]. On the contrary, with low or absent illusion, we expected no significant EEG power increases.

Materials and Methods

A. Subjects

Five unimpaired volunteers (hereafter identified with *v1..v5*), one woman and 4 men, aged 26-33, participated in the experiment. They were right-handed, claimed to have normal vision and good hand sensibility. Informed consent was obtained from each participant prior to conducting the experiment.

B. Procedure

Participants sat resting their left arm on a table, behind a standing screen in a way their arm was out of their sight throughout the entire experiment (cf. Fig. 1). A life-sized rubber model of a left arm was positioned in front of the participants, approximately 10-20 cm medial and parallel to the real arm. From the participants' perspective, the rubber limb looked like a part of their own body. The EEG cap was mounted on the scalp and connected to the recording system. The experimental procedure was adapted from [4] as in [8]. The participants were instructed to relax and fix their sight on the rubber hand while two small paintbrushes were used to stroke the rubber hand and the subject's hidden hand.

Two conditions in which we manipulated the timing of the brushstrokes on the two hands, were repeated for **three times** with no randomization. In the experimental condition for a period of 60 seconds, we exposed the participants to synchronous stimulation: concurrent brushstrokes were delivered on the real and the fake hand. In the control condition for a period of 30 seconds, we exposed the participants to asynchronous stimulation, i.e. a small asynchrony was introduced between the brushing of the two hands. As reported in previous studies, the illusion does not occur when the rubber hand is stroked asynchronously with respect to the participant's own hand [4], [8]. The mean frequency of the brushstrokes for both conditions was about 1 Hz and each stroke about 2-3 cm long. At the beginning of each trial a 15 seconds interval, during which no brushstrokes were applied was added; this *resting period* was used for calculating the PDS baseline (idle state).

When the experiment finished (after six trials), the subject filled in a questionnaire of nine statements (S1..S9), translated into Italian from those used in [4], which required the subjects to confirm or deny the occurrence of illusion, thus the extent of feeling of body ownership. Three of the statements were related to the extent of sensory transfer into the rubber hand and the feeling that it was part of their body:

- S1: It seemed as if I was feeling the touch of the paintbrush in the location where I saw the rubber hand touched.
- S2: It seemed as the touch I felt was caused by the paintbrush touching the rubber hand.
- S3: I felt as though the rubber hand was my hand.

The other six served as controls for compliance, suggestibility, and ''placebo effect'':

- S4: It felt as though if my (real) hand was drifting towards the right (towards the rubber hand).
- S5: I felt as though if I might have more than one left hand or arm.
- S6: It seemed as if the touch came somewhere between my own hand and the rubber hand.
- S7: It felt as though if my (real) hand was turning rubbery.
- S8: The rubber hand began to resemble my own hand in terms of shape, skin tone, freckles or some other visual features.
- S9: It appeared as if the rubber hand was drifting towards the left (towards my hand).

The participants were asked to rate the extent to which these statements did or did not apply, using a seven-point analogue scale. On this scale, one meant 'absolutely certain that it did not apply', four meant 'uncertain whether it applied or not', and seven meant 'absolutely certain that it applied'.

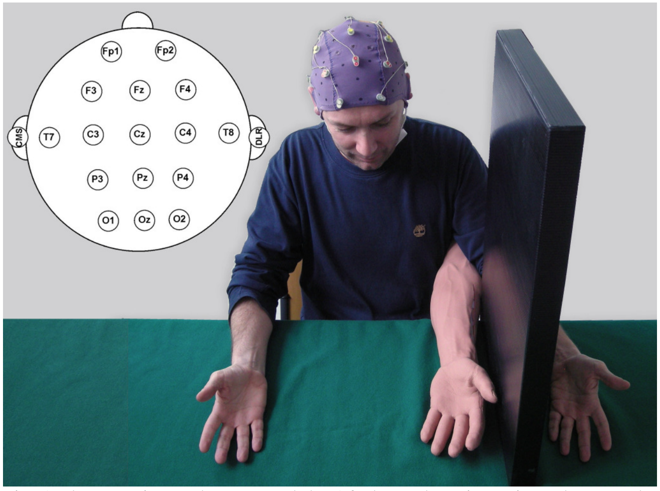

Fig. 1 The experimental set up and the 16-electrodes Biosemi cap layout. The naming scheme is taken from 10–20 international electrode placement system: Fp stands for frontal pole, F for frontal electrodes, C for central, P-parietal, and O-occipital. CMS and DLR are for the ground reference.

C. EEG Recording

EEG signals were acquired with the 16-channels Biosemi ActiveTwo system and recorded during the six trials (three experimental and three control conditions). Electrodes were placed on the scalp according to the 10–20 international electrode placement system [9]. The ground electrode was replaced by two separate electrodes (CMS/DLR) forming a feedback loop that results in a 40 dB extra common mode rejection ratio at 50 Hz when compared with normal ground electrodes [10]. EEG signals were digitized at a sampling rate of 128Hz and stored for offline analysis.

D. Data Preparation and Analysis

The processing analysis was performed using Matlab (The Mathworks, Natick, MA), using EEGlab [11], and custom scripts. The signals recorded from asynchronous trials, were concatenated to form a single trace, having as resting period the sequence of the resting periods from each trial (45 seconds), and as stimulus period the sequence of the stimulus periods (90 seconds). For the synchronous trials a similar procedure was applied but only 30 seconds of stimulus periods were concatenated in order to compare data with identical length (45 seconds of resting period and 90 seconds of stimulus period).

The EEG was re-referenced using a common average of the potentials at all electrodes. Subsequently, the signals were band pass filtered using an infinite impulse response (IIR) Butterworth filter with lower cut-off of 1 Hz and higher cut-off of 60 Hz. Artifact-free EEG signal was obtained from each scalp electrode with the fastICA algorithm. Spectral analysis was performed with Welch's power spectral density (PSD) method. Briefly, the EEG signals from each electrode were split into short segments (128 points, 1s length) and windowed with a Hamming window, with a 50% overlap between two consecutive segments. The discrete Fourier transform was then computed on the short segments, followed by computing the squared magnitude of the result.

Significant power fluctuations between stimulus and resting periods in each experimental condition were evaluated using the sign test with the *a priori* hypothesis that the difference between the power spectrum density in the stimulus (PSD_S) and in resting (PSD_R) would be positive with the occurrence of illusion ($PSD_S > PSD_R$). We performed the test for each scalp electrode considering a significant level of 5% (*p-value* < 0.05). We compared stimulus and resting periods as we assumed that only during the resting period EEG activity is in the idle state.

We evaluated the consistency of scores in the illusion (S1..S3) and control statements (S4..S9), assuming that if the illusion occurred the score of the two groups of questions would be different. In particular, from the distribution score of illusion (NS_i) and control (NS_c) statements we could discriminate between four possibilities: 1) illusion, no suggestibility ($NS_i > NS_c$), 2) illusion, suggestibility ($NS_i \approx NS_c$), 3) no illusion, no suggestibility ($NS_i < 4$ and $NS_c < 4$), 4) no illusion, suggestibility ($NS_i < NS_c$). We then compared the score distributions between the two groups of questions using the Wilcoxon rank-sum test to statistically verify differences between groups and to which condition each participant belonged.

Results

The sign test revealed on which of the scalp electrodes the power spectrum density significantly changed from the resting (PSD_r) and stimulus period (PSD_s). Results from the experimental (synchronous) and control (asynchronous) conditions are presented in Table I. In the synchronous condition four participants had significant power increase above the associative scalp regions (F-frontal, P-parietal, C-central). Only participant *v3* did not present significant PSD variation on any of the scalp electrodes. In the asynchronous condition a significant PSD decrease above the primary visual cortex (O-occipital) between stimulus and resting interval, for just two participants (*v4* and *v5*) was found. No other significant PSD changes were found in the asynchronous condition.

TABLE I
EEG POWER FLUCTUATIONS BETWEEN RESTING AND STIMULUS PERIODS

Subject	PSD fluctuation in synchronous condition	PSD fluctuation in asynchronous condition
v1	increase (F_4)	-
v2	increase (C_z)	-
v3	-	-
v4	increase (P_4)	decrease (Oz/O_2)
v5	increase (F_4)	decrease (Oz/O_2)

Statistical power fluctuations and electrodes (in parenthesis) on which PSD fluctuations were measured, for the synchronous and asynchronous conditions. Only statistically significant power fluctuations are considered ($p<0.05$). The 16 electrodes were placed on Fp-frontal pole, F-frontal, P-parietal, C-central and O-occipital scalp regions according to the 10–20 international electrode placement system.

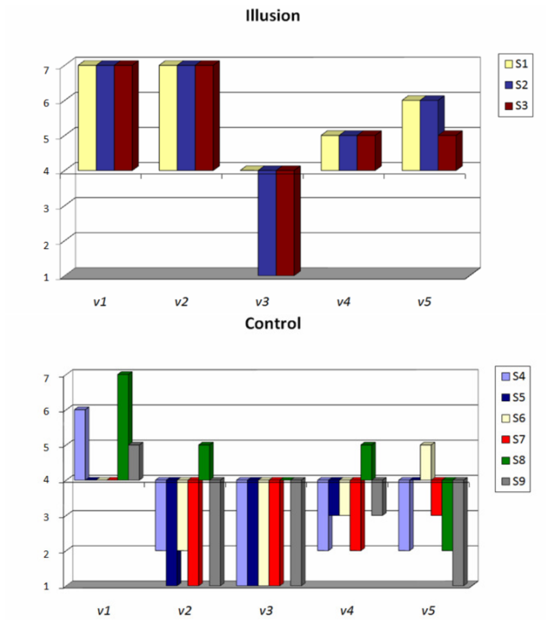

Fig. 2 Questionnaire scores. The illusion statements were related to the extent of sensory transfer into the rubber hand. The remaining six questions were used as controls for compliance, suggestibility, and ''placebo effect''. The participants had to deny (score 1-3), to confirm (score 5-7) or report that they neither could confirm nor deny (score 4) what each questions stated. The histograms highlight deviations from the "neutral" score (equal to 4).

The questionnaire results are presented in Fig. 2; deviations from the neutral score (equal to 4) are highlighted. Four subjects gave confirming scores (≥ 5) in at least two of the three illusion statements, indicating that they experienced sense of body-ownership. In particular, two participants (*v1* and *v2*) experienced a strong illusion, giving a score of 7 in all the three illusion statements, whereas only one participant (*v3*) did not experience the illusion. The scoring from the control statements, was generally low, as expected, indicating that most of the participants were not influenced by the experiment. Only participant *v1* gave high scores in three out

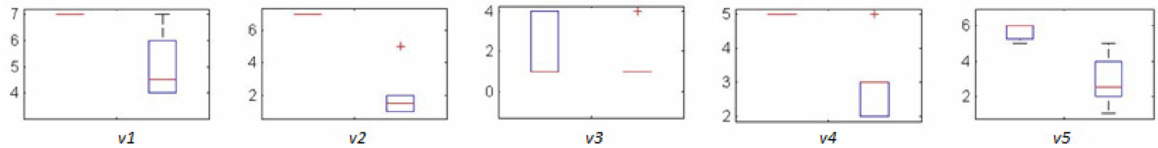

Fig.3 The boxplots summarize the Wilcoxon rank-sum test applied to the experimental and control statements. For each subject the left box refers to the illusion scores, whereas the second box refers to the control scores. The medians are shown as horizontal lines and the boxes are the interquartile ranges (IQR). The whiskers represent either the extreme data points or extend to 1.5 x IQR.

of the five control statements, indicating the possibility that he/she might be affected by placebo effect. Median scores and interquartile ranges are shown in Fig. 3. The median score of illusion statements is higher than the median score of control statements for subjects *v1*, *v2*, *v4* and *v5*, whereas it is equal for *v3*. However, scores given to the illusion and control statements are significantly different only for *v2* ($p<0.02$) and *v5* ($p<0.04$). This means that while for *v2* and *v5* we can certainly affirm the occurrence of the illusion, for *v1* and *v4* we report that the attribution of the rubber hand ownership might have been due to illusion and suggestibility, as the median score of illusion and control is "partially" different ($p<0.09$).

The test did not find any significant difference for *v3*. These results are substantially in agreement with the hypothesis on PSD changes: in participants whose score denoted the occurrence of illusion (*v1, v2, v4, v5*) we also found power increase, whereas for subject v3, that did not report illusion, no significant PSD (positive) fluctuation was found.

Discussion

Neural oscillations arise when large groups of neurons fire in synchrony. Synchronization is how the brain achieves the integration of its many parallel, and distributed neural networks, allowing the basic mechanism for representing and processing information [12]. The degree of such synchronization is measurable by means of PSD estimations, which can therefore be used as an index for assessing the extent and the neural sources of neurons oscillating synchronously during the rubber hand illusion.

The results of this work reveal for the first time that analysis of EEG signals might produce important and evident features to measure and interpret the phenomenon of sense of ownership. The illusion activates specific brain areas, and the activation has significant PSD fluctuations (as measured in the frequency domain), when compared to a resting state. To confirm our hypothesis that strong illusion reflects into positive variations of PSD, we correlated the EEG analysis with the questionnaire outputs and previous fMRI studies. It is clear that the analyses from the questionnaire and the PSD convey the same results. For those subjects that experienced illusion, as reported from the questionnaire, significant increases of PSD between the baseline and the stimulus condition were also measured. On the contrary, for the one subject that did not sense the illusion, no PSD variation was found. In addition, as a further proof of the effectiveness of this simple method, EEG power changes were measured on electrodes i.e. above the premotor cortex: F-frontal, P-parietal, C-central electrodes, accordingly to fMRI studies [5].

We completely dismiss the hypothesis of illusion in the asynchronous condition, both because the participants gave convincing remarks (denials) after that stimulus condition and because significant PSD changes were measured for just two participants over different areas (i.e. above primary visual regions) compared to those reported in [5].

Since EEG signals reflect the operation of neural network assemblies that might be characterized by different non-linear dynamics, we believe that PSD estimation has to be further investigated, also in the frequency domain. Specifically, we aim to analyze power fluctuations in subject-specific frequency bands in order to infer the size and distance of neural oscillations involved in the processing stage. We also aim to develop an EEG method capable not only of revealing the occurrence of the illusion, but also to which extent. This work opens up promising possibilities because understanding the basis of sense of body ownership may lead to the development of more acceptable hand prostheses and artificial limbs in general.

References

[1] M. Tsakiris, M. D. Hesse, C. Boy, P. Haggard, G. R. Fink, "Neural Signatures of Body Ownership: A sensory network for bodily self-consciousness", *Cerebral Cortex*, vol. 17, no. 17, pp. 2235-2244, 2007.

[2] C. Cipriani, et al., "A Novel Concept for a Prosthetic Hand with a Bidirectional Interface: A Feasibility Study", *IEEE Trans. Biomedical Engineering*, vol. 56, no. 11 (Pt 2), pp. 2739-43, 2009.

[3] M. Tsakiris, "My body in the brain: a neurocognitive model of body-ownership", *Neuropsychologia*, Vol. 48, no. 3, pp. 703-712, 2010.

[4] M. Botvinick, J. Cohen, "Rubber hands 'feel' touch that eyes see", *Nature*, Vol. 391, pp. 756, 1998.

[5] H. H. Ehrsson, et al., "That's My Hand! Activity in Premotor Cortex Reflects Feeling of Ownership of a Limb", *Science*, vol. 305, pp. 875 - 877, 2004.

[6] H. H. Ehrsson, et al., "Upper limb amputees can be induced to experience a rubber hand as their own", *Brain*, Vol. 131(Pt 12), pp. 3443-52, 2008.

[7] N. Kanayama, A. Sato, H. Ohira, "Crossmodal effect with rubber hand illusion and gamma band activity", *Psychophysiology,* Vol. 44, no. 3, pp. 392-402, 2007.

[8] B. Rosen, H. H. Erhsson, C. Antfolk, C. Cipriani, F. Sebelius, G. Lundborg, Referral of sensation to an advanced humanoid robotic hand prosthesis, *Scand J Plast Reconstr Surg Hand Surg*, vol. 43, pp. 260-266, 2009.

[9] H.H. Jasper, "The ten-twenty electrode system of the International Federation", *Electroencephalography and Clinical Neurophysiology*, No. 10, pp. 371-375, 1958.

[10] M. van Rijn, A. Peper, C.A. Grimbergen, "High quality recording of bioeletric event: Part 1 Interference reduction, theory and practice", *Med & Biol Eng. & Comput*., Vol. 28, pp. 389-397, 1990.

[11] Matlab toolbox for processing EEG, MEG and other electrophysiological data [online]. Available: https://www.sccn.ucsd.edu/eeglab.

[12] F. Varela, J-P. Lachaux, E. Rodriguez, J. Martinerie, "The brainweb: phase synchronization and large-scale integration", *Nature Reviews Neuroscience*, Vol. 2, pp. 229-239, 2001.