A new method for simultaneous recording of EEG and fMRI

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Abstract— **A new method is proposed to perform the simultaneous recording of EEG and fMRI using dedicated EEG hardware and software specifically developed for artifact rejection. In order to test the system, 3 pilot experiments were performed. The first consisted of recording the variations in α-rhythm which were time-locked to the experimental paradigm. The second and third experiments consisted of recording the visual evoked potential (VEP) inside the scanner with and without acquiring fMRI data respectively. The corrected data of experiment 1 clearly shows the variation of the α-rhythm, time locked to the paradigm, both in the time and frequency domains. The comparison of the VEPs computed from experiments 2 and 3 clearly shows that the correction algorithm is able to efficiently remove the artifacts in such a way that the VEP can be measured.**

This work shows the ability of the proposed method to record simultaneous EEG and fMRI data, thus strongly suggesting its future application in brain imaging studies.

Keywords—**EEG, fMRI, co-registration, artifact rejection**

I. INTRODUCTION

Electroencephalography (EEG) has long been used as a standard tool to localize the sources of brain electric activity. Nevertheless, this technique shows limitations in the spatial resolution with which these sources can be localized as well as difficulties related to non-existence of a unique solution to the EEG Inverse Problem (IP) ([1]–[2]). Contrary to EEG, functional magnetic resonance imaging (fMRI) indirectly measures neuronal activity through the quantification of the variations in blood oxygen level that are coupled with this activity. When EEG and fMRI are recorded simultaneously, well known phenomena, such as the switching on and off of the α-rhythm or the presence/absence of epileptic spikes can be correlated to fMRI signals ([3]–[5]). These studies combine the high temporal resolution of EEG with the high spatial resolution of MRI. However, the recording of EEG inside the MR scanner is, in itself, a challenging task. The presence of time varying magnetic fields introduces EEG artifacts that are two orders of magnitude larger than the brain electric signal. Furthermore, smaller artifacts, time-locked to the electrocardiogram (ECG), may also appear as a consequence of wire displacement due to pulsatile vessel movement ([6]–[8]).

We propose a method to perform the simultaneous recording of EEG and fMRI using dedicated EEG hardware and software specifically developed artifact rejection.

II. METHODOLOGY

A. Data Acquisition

The EEG was recorded using hardware developed by BioSemi Inc. (http://www.biosemi.com) and having several novelties specifically introduced for artifact reduction. A special electrode set, consisting of carbon wires and 8 sintered Ag-AgCl electrodes connected to two amplifiers each, was used. The wires are twisted in order to minimize the current loops [9]. The signal is recorded using a bipolar montage in such a way that when the signals (in a total of 16) are converted to a common reference, leading to a total of 8 signals, significant artifact reduction is already obtained. The use of DC amplifiers with a very large dynamic range (24 bits, resolution of 31.2 nV), allows for full recording of the large RF artifacts without any clipping. Furthermore, they show a perfectly equal frequency response for all channels since no high-pass filtering is applied and the low-pass filtering is done digitally. A σ-δ AD converter with a 16 kHz output sample rate and 64 times oversampling is used for analogue to digital conversion. The use of such an AD converter allows the use of only one first order analogue low-pass (3 kHz) per channel.

The EEG was recorded inside a 1.5 T scanner (Siemens Sonata) during continuous acquisition of fMRI data. An EPI sequence with TR=3 s and TE=60 ms was used to collect 30 slices spaced evenly over the TR period, in a total of 90 volumes.

B. Algorithm for artifact rejection

The algorithm for artifact rejection was developed based on the assumption that the RF and gradient artifacts are highly reproducible and therefore removed, to a great extent, by averaging. Therefore, first the EEG data is aligned to the fMRI data in the time domain. This is accomplished by shifting the EEG data epochs with respect to the fMRI data. The shift is applied in the frequency domain using the Fast Fourier Transform. Then the average artifact over slices and volumes is computed and removed from the signal. The resulting corrected signal is free from the gradient artifact but still contains a reminiscent RF artifact. In particular, the signal following the latter shows an exponential decay that is removed by fitting a series of exponential functions to the data and subtracting it. For this purpose, the signal to be subtracted is written according to the following model:

$$\tilde{v}_j = b + \sum_{k=0}^{N_S-1} A_k f_{kj} \, , \qquad (1)$$

where

j is the sample index;

b is the offset;

N_S is the number of slices;

$$f_{kj} = \begin{cases} e^{-\frac{\Delta(j-kN_{samp})}{\tau}}, \text{if } j \in I_k \\ \\ 0, \text{ otherwise} \end{cases} ; \qquad (2)$$

I_k is the time window corresponding to slice k;

N_{samp} is the number of samples per slice;

Δ is the sampling time;

τ is the time constant.

The goal of the model is to fit the amplitude coefficients (A_k) for each slice whereas the offset is fitted for the entire volume in order to minimize the interference with the EEG signals to be studied. The value of τ (for each channel) is assumed to be constant over a given data set.

In order to fit these parameters, a cost function is defined in a least squares sense:

$$\text{Cost} = \sum_j \left(v_j - \tilde{v}_j\right)^2 \, . \qquad (3)$$

The parameters to be adjusted are found by minimising (3) with respect to τ, A_k and b. In this procedure, τ is varied in small steps. In each step, the corresponding A_k, b and Cost are computed, thus searching for the absolute minimum of (3). The parameters A_k and b are the solutions to the following linear system of equations (given a certain value for τ):

$$\begin{cases} \frac{\partial \text{Cost}}{\partial b} = 0 \\ \\ \frac{\partial \text{Cost}}{\partial A_k} = 0 \end{cases} \qquad (4)$$

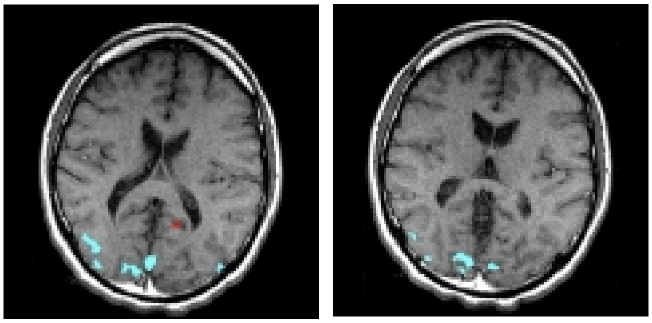
After subtracting the fitted exponential (2), the residual RF artifact is removed by linear interpolation.

Another source of interference is the ballistocardiogram artifact which is time-locked to the simultaneous ECG. It is removed by first averaging the data contained in a sliding window containing the artifact, in order to create a template. This template is afterwards removed from the data which is time-locked to the ECG.

III. RESULTS

In order to test the method, three experiments were performed. In experiment 1, the subject was instructed to keep the eyes open or closed during alternate periods of 10 volumes. The goal was to detect the variations of the α-rhythm, time-locked to the paradigm instead of its spontaneous variations. In experiments 2 and 3, the subject received a visual stimulus (checkerboard reversal pattern) during 10 volumes followed by 10 volumes of rest, and the goal was to compute the visual evoked potential (VEP) [10] with and without scanning respectively.

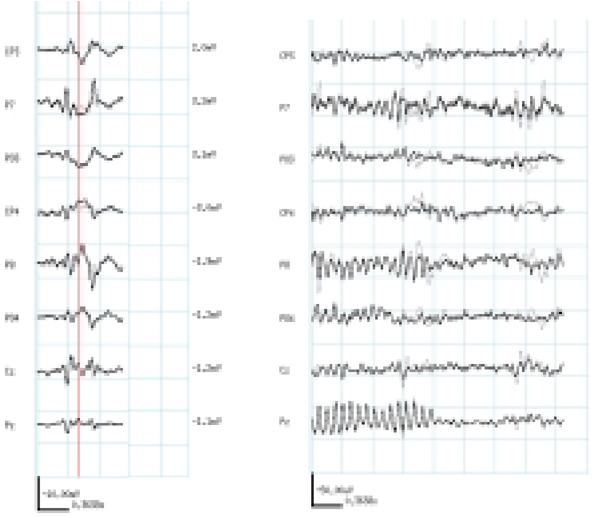
In Fig. 1 the fMRI BOLD activation maps are presented for the case of the visual stimulation experiment. They show clusters of activation mainly located in the visual cortex, thus confirming the reliability of the fMRI data recorded simultaneously with the EEG.



a) b)

Fig. 1. Regions of activation corresponding to the visual paradigm described for experiment 2. The regions in blue have a positive correlation with the stimulus whereas the region in red shows a negative correlation.

The EEG data was corrected according to the algorithm described in section II. The importance of removing the ballistocardiogram artifact is illustrated in Fig. 2.



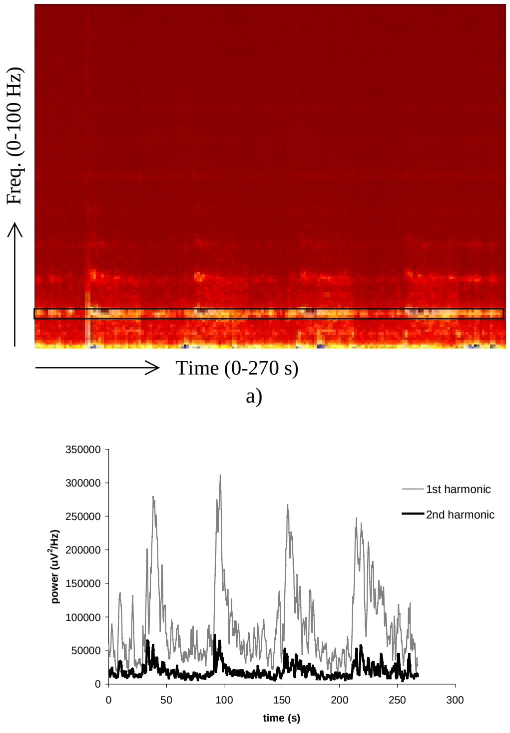
a) b)

Fig. 2. a) Average ballistocardiogram artifact. The average artifacts corresponding to experiments 1 and 2 are overlaid. b) Example of corrected EEG data. In black and grey, the data with and without correction of the ballistocardiogram artifact respectively.
Data low-pass filtered at 40 Hz.

From Fig. 2 it is seen that the amplitude of the ballistocardiogram artifact is much larger than the typical amplitudes of the EEG. Furthermore, the observation of Fig. 2.a. also suggests that the ballistocardiogram is quite reproducible from experiment to experiment, therefore likely to be removed by a simple averaging procedure. Fig. 2.b. clearly shows the time windows where the ballistocardiogram artifact was removed. The α-rhythm is clearly observable on channels Pz and P8.

The results obtained in experiment 1 are shown in Fig. 3. The spectrogram in Fig. 3.a. shows the switching on and off of the α-rhythm (and its harmonics), according to the paradigm of the experiment. Fig. 3.b. illustrates the power temporal series corresponding to the frequency band included in the rectangle of Fig. 3.a., where the variations in power, time-locked to the experiment paradigm, are presented.

The results obtained in experiments 2 and 3 are shown in Fig. 4. Since the EEG data in experiment 3 were recorded inside the scanner but without scanning, it was only corrected for the ballistocardiogram artifact. Fig. 4 shows that in both experiments, a clear response is observed in electrode PO3. The lower amplitude of the response computed from experiment 2 may be related to the lower SNR of this data, when compared to experiment 3 (where no RF nor gradient artifacts are present).



a)

b)

Fig. 3. a) Spectrogram corresponding to experiment 1 where the time points of increased and decreased power are respectively represented in yellow and dark orange. The alpha band is delimited with the rectangle. b) Plot of the power temporal series corresponding to the alpha band and to its second harmonic.

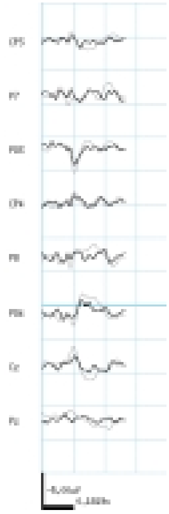


Fig. 4. VEP's computed from experiments 2 (black) and 3 (grey) by averaging 195 events (data low-pass filtered at 40 Hz).

IV. DISCUSSION

The results obtained in experiment 1 clearly show the variations in the α-rhythm, time-locked to the paradigm, both in the temporal and frequency domains, even in a worst case situation where the slice frequency (10 Hz) falls within the α-rhythm frequency band.

The comparison of the results obtained in experiments 2 and 3 clearly show that the correction algorithm is able to efficiently remove the artifacts in such a way that the VEP is measured. Furthermore, a better performance is expected if the number of events in the average is increased.

The ballistocardiogram artifact appears to be quite constant from experiment to experiment. If this finding is confirmed for more subjects, then our hardware system allows for the use of a simple averaging procedure to correct for this type of artifact.

The overall performance of the system in these studies is expected to improve when a different slice frequency is used and larger number of volumes are recorded.

V. CONCLUSION

This work shows the ability of the proposed method to obtain EEG data in the presence of a continuous fMRI induced artifact, 2 orders of magnitude larger than the EEG signal of interest. Our method allows for an optimal combination of the high spatial resolution of fMRI with the high temporal resolution of EEG, thus strongly suggesting its future application in brain imaging studies.

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