Comparison of fMRI activation and EEG source localization using beamformers during motor response in the Stroop task: preliminary results

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***Abstract*—The simultaneous measurement of neuro-functional MRI and EEG provides the opportunity to investigate both haemodynamic and electrical activity in the human brain non-invasively. This multimodal technique makes it possible to combine the advantages of EEG (millisecond temporal resolution) with those of fMRI (millimeter spatial accuracy). However, the combination of EEG and fMRI suffers also from their limitations: there is no clear relationship between neuronal acitivity, the EEG and the fMRI signals; mismatches are observed between EEG and fMRI analyses and there are experimental limitations. In this study we present a qualitative analysis of simultaneous acquired EEG/fMRI data from a single subject performing the Stroop task. The EEG data and the fMRI time series are processed separately focused on the motor responses. We apply a beamformer spatial filter to the EEG data to localize the electrical activity corresponding to the motor responses of the right and the left hand. The areas of maximum electrical activation are compared with the fMRI activation clusters. Both analyses show activation around the primary motor cortex. These results are an indication to start with a more sophisticated and integrated analysis of simultaneous acquired EEG/fMRI data during the Stroop task.**

I. Introduction

Several imaging modalities exist to study human brain function non-invasively, i.e. to localize and determine the temporal dynamics of neural activity without involving entry into the body. Electroencephalography (EEG) allows studying brain activity on a time scale similar to specific neural events (ms) by measuring electrical potentials on the scalp. Different source localization techniques try to determine the underlying neural sources out of these potentials but are mostly unreliable by lack of a golden standard.

Neural activity is accompanied by an increased oxygen consumption. Due to the hemodynamic coupling the electrical active regions are supplied with oxygen rich blood. Neuro-functional magnetic resonance imaging (fMRI) provides the opportunity to identify the regions of local increased oxygen supply based on the different magnetic properties of oxyhemoglobin and deoxyhemoglobin. FMRI analysis obtains good spatial resolution of neural activity (mm) but the temporal resolution is limited (2-5s).

It is now generally accepted that the integration of fMRI and electromagnetic measures of brain activity has an important role in characterizing evoked brain responses [3]. EEG/fMRI analysis tries to combine the advantages of EEG (high temporal resolution) with those of fMRI (high spatial resolution). However, the combination of both modalities suffers also from their limitations[1].

First of all there is no clear relationship between neuronal activity, the EEG and the fMRI signals. The scalp topology of measured electrical potentials does not, without additional information, uniquely specify the location of underlying bioelectric activity. Conversely, even though fMRI discloses complementary features of neuronal activity, it is only an indirect measure, through metabolism, oxygenation and blood flow [5].

There are observed mismatches between EEG and fMRI. These can be interpreted as a decoupling between the electrophysiological and the hemodynamic activity or as a signal detection failure [5] .

Moreover, simultaneous EEG and fMRI suffers from experimental limitations. For the EEG signal, the signal to noise ratio (SNR) degrades due to acquisition inside the MR scanner. The biological signal of interest is obscured by different artifacts related to the MR field strength such as the image acquisition artifact and cardiac related artifact [6]. Finally, artifacts due to motion of the subject in the MR scanner can be catastrophic.

Despite these limitations, this study presents a qualitative analysis of simultaneous acquired EEG/fMRI data from a single subject performing the Stroop task. In brief, the Stroop task or test is a psychological test of our mental (attentional) vitality and flexibility [2]. The task is based on our ability to read words more quickly and automatically than we can name colors [2]. If a word is displayed in a color different from the color it actually stands for, e.g. the word ”blue” written in green ink (shown in Figure 1a), the word ”blue” is more easily read than the color in which it is displayed can be named. This kind of stimuli are called incongruent.

The paradigm we used in this study consisted of both congruent and incongruent stimuli that were presented to the subject. The subject was instructed to name either the color or the word by pressing one of four buttons, each associated with a color. We focused on the corresponding motor activity with the aim to compare the results of fMRI

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and EEG data processing and to evaluate the simultaneous acquired EEG(/fMRI) signal quality.

(a) Congruent stimulus (b) Incongruent stimulus

Fig. 1: Stroop task illustration

II. Methods

A. EEG/fMRI data aquisition

One female, age 25, participant without a history of psychopathology completed a color-word Stroop task administered during a simultaneous EEG/fMRI session. fMRI data were collected using a research-dedicated 3T Siemens (TiM TRIO) MRI scanner and an MR-compatible Brain Products EEG system. The EEG was recorded with a 32-channel cap, with Ag/AgCl electrodes spaced according to the 10-20 system and one ECG electrode to monitor the heart rate. Thirty one referenced EEG channels were used in the analyses.

The color-word Stroop task consisted of 12 blocks of alternating color naming or word naming tasks. In every block there were 12 congruent trials, 12 incongruent trials and 6 null events. For each block of trials, the sequence of the congruent or incongruent trials was randomized. Each trial consisted of one word presented in one of four ink colors (red, yellow, green and blue). The trials started with a fixation cross for 1000 ms followed by the presentation of a word. The words were presented via back projection onto a screen outside the scanner bore and a mirror fixed to the head coil.

There were four buttons, two at each side of the participant, that had to be controlled by the left middle finger (for blue responses), the left index finger (for yellow responses), the right index finger (for green responses) and the right middle finger (for red responses). Once a response was given a variable fixation cross period followed. The total length of the trials was 5000 ms on average and ranged from 3400 to 6600 ms.

Seven hundred and forty images were acquired using a gradient echo-planar imaging (EPI) sequence (TR = 2500 ms). Before the EPI sequence, a 176 slice MPRAGE structural image was acquired for registering the participant's functional data to standard space.

The EEG signals were sampled at 2000 Hz and a Brainvision syncbox (Brainproducts) was used to ensure the synchronized sampling between the EEG system and the MR scanner sequence.

B. Analysis of neuro-functional MRI

The analysis of fMRI data was performed using standard techniques in SPM 8 ("http://'www.fil.ion.ucl.ac.uk/-spm/software/spm8/"). The functional images were motion corrected, coregistered with the structural image and smoothed using a 8 mm Gaussian kernel. To determine the areas of significant BOLD contrast we used the general linear model. Therefore several regressors were calculated based on the onsets of different responses including the correct blue (left middle finger), yellow (left index finger), green (right index finger) and red (right middle finger) responses, the incorrect responses and some instructional onsets. The realignment parameters of the preprocessing were also included.

Each regressor yielded a per-voxel effect-size parameter (β) estimate map representing the magnitude of activity that was associated with the regressor. In order to examine the motor activation corresponding with the responses of the subject, the β values for the correct left hand responses were contrasted with those for the correct right hand responses. Finally, areas of significant contrast ($p < 0.05$ (FWE)) were identified in the the resulting T-statistical map.

C. EEG preprocessing and source localization using beamformers

1) Artifact removal and segmentation: Brain Vision Analyzer software (Brainproducts) was used for correction of the image acquisition artifact and cardiac related artifact (also known as the gradient and ballistocardiographic or pulse artifact respectively) as described in [6], [8].

By using the Brainvision Syncbox the EEG sections with imaging artifact were marked. To correct for the image acquisition artifact, the marked intervals were averaged, and their means were subtracted from each interval. For every interval an average of 21 marked intervals was used, incorporating the 10 earlier and the 10 subsequent intervals. In addition, a 30-Hz low-pass filter was included in the subtraction algorithm to facilitate visual inspection of the corrected EEG.

After downsampling to 500 Hz, the pulse artifact subtraction was applied with a procedure that works analogously to the imaging artifact removal by averaging the EEG signal synchronized to the ECG. By doing an independent component analysis we saw that one component was heavily related to eye movements so this component was filtered out.

A response locked segmentation (-300 ms to 300 ms around the response) of the correct left and right hand trials was performed. Afterwards baseline correction was done, taking the baseline 200 ms before each stimulus. The segments were visually inspected for eye movement. gross motion and other artifacts leaving out bad segments. Finally, event related potentials were calculated for left and right hand responses by averaging all the left hand segments (125) and right hand segments (114).

2) Source localization using beamformers: A source analysis technique that is becoming more widely used is the beamformer spatial filter [10]. It is a set of weights that are used to spatially filter the scalp-recorded data to yield an estimate of the source power for a specific location in the brain. The weights are calculated to pick up signals that originate from a specific location while simultaneously minimizing signals that originate from other locations. The beamformer technique provides independent estimates of source activities at multiple locations throughout the brain, resulting in a three-dimensional image of brain function [10] [12].

If $\mathbf{V}(t) \in \mathbb{R}^{31\times n}$ is the EEG window of interest, e.g. the ERPs for left or right hand responses, with n the number of samples and 31 referenced electrode channels, the beamformer technique used in this study can be written mathematically as [7]:

$$\min_{\mathbf{W(r)}}[\mathbf{W(r)}^T\mathbf{CW(r)} + \mu(\mathbf{W(r)}^T\mathbf{SW(r)})] \quad (1)$$

subject to

$$\mathbf{W(r)}^T\mathbf{L(r)} = \mathbf{I} \quad (2)$$

Here, $\mathbf{W(r)}$ represents the spatial filter for a specific location $\mathbf{r}$, $\mathbf{C} = \mathbf{V}(t)\mathbf{V}(t)^T \in \mathbb{R}^{31\times 31}$ represents the data covariance matrix and $\mathbf{L(r)} \in \mathbb{R}^{31\times 1}$ is called the lead field which contains the electrical fields that would be measured at each of the 31 electrodes in response to a source of unit amplitude sited at location $\mathbf{r}$ and oriented in a direction we estimated in advance according to a method described in [9].

L(r) is therefore based on an EEG forward solution, and for this purpose a dipolar model is used according to [11]. We calculated the lead fields based on a subject specific realistic head model that was constructed from the structural MR scan of the subject based on a finite difference method with reciprocity [11].

Furthermore, μ is known as the regularization parameter and $\mathbf{S} \in \mathbb{R}^{31\times 31}$ is called the resolution spread function. In this study, we selected a resolution spread function to minimize the uncorrelated noise across the electrodes. Therefore $\mathbf{S}$ was chosen as a diagonal matrix with diagonal elements equal to an estimation of the noise variance for each electrode. The latter was calculated on the EEG segment obtained by averaging the baseline periods, 200 ms before each stimulus.

Classical beamformer techniques [12] do not use the regularization term $\mu\mathbf{S}$. This term has the advantage that each matrix eigenvalue λ_j of $\mathbf{C}$ will be increased by each corresponding $\mu{\sigma_j}^2$, with ${\sigma_j}^2$ the estimated variance of the noise at electrode j and j =1 ... 31. Keeping in mind that a matrix is only invertible when its eigenvalues are different from zero, this is advantageous when $\mathbf{C}$ is singular or close to being singular. Therefore we chose the value of μ as a trade off such that the regularization term is made low enough to provide as much noise rejection as possible but also high enough to ensure stable calculations of the filter weights.

The solution to Eq. (1) and (2) becomes [7]:

$$\mathbf{W(r)}^T = [\mathbf{L(r)}^T\{\mathbf{C}+\mathbf{S}\}^{-1}\mathbf{L(r)}]^{-1}\mathbf{L(r)}\{\mathbf{C}+\mathbf{S}\}^{-1} \quad (3)$$

The main difference with the methods described in [7] is the dipole orientation calculation in advance. The dipole orientations were calculated on a grid (spacing 5 mm) where each grid point was located in soft brain tissue [9].

Having calculated the weighting parameters afterwards on the same grid, the beamformer projected power was then derived as $\mathbf{W(r)CW(r)}$. To incorporate the fact that the signal to noise ratio of source estimates declines with depth into the head, and close to the centre of the brain, source powers were normalized by an estimate of the noise power given by $\mathbf{W(r)SW(r)}$. The normalized source power estimate is therefore given by [7]:

$$Z(\mathbf{r}) = \frac{\mathbf{W(r)CW(r)}}{\mathbf{W(r)SW(r)}} \quad (4)$$

In order to measure the change in cortical power related to left and right hand responses, a pseudo T-statistic was calculated such that:

$$T(\mathbf{r}) = \frac{abs\left\{\mathbf{W}_L(\mathbf{r})\mathbf{C}_L\mathbf{W}_L(\mathbf{r}) - \mathbf{W}_R(\mathbf{r})\mathbf{C}_R\mathbf{W}_R(\mathbf{r})\right\}}{\mathbf{W}_L(\mathbf{r})\mathbf{SW}_L(\mathbf{r}) + \mathbf{W}_R(\mathbf{r})\mathbf{SW}_R(\mathbf{r})} \quad (5)$$

With index L and R representing left and right hand responses respectively.

III. Results

A. Neuro-functional MRI analysis

Figure 2 shows the results of the fMRI analysis. A contrast is defined in which the β values of the correct right hand responses are subtracted from the β values of the correct left hand responses. The areas of significant contrast ($p < 0.05$ (FWE)) are shown on the structural image of the subject and correspond with the right primary motor cortex.

B. EEG source localization

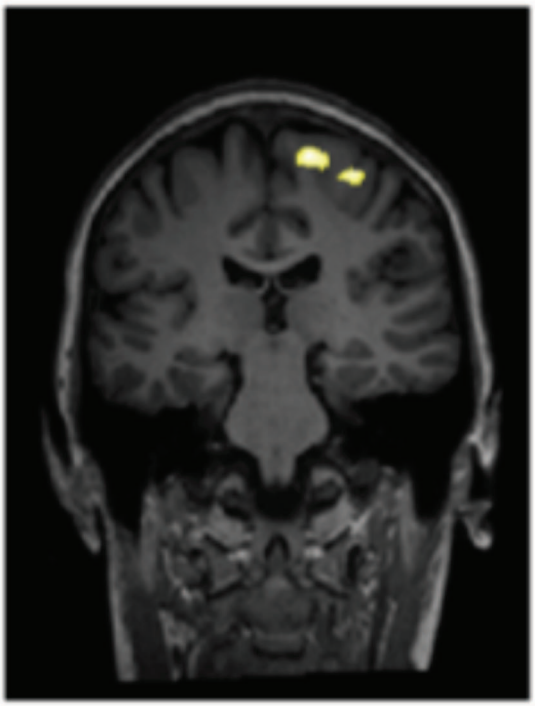
The event related potentials corresponding with the left and right hand responses are depicted in Figure 3. The black vertical line shown in the figure corresponds with the response at zero milliseconds. For completeness, the difference of both ERPs is shown in Figure 4.

With the aim to compare the fMRI analysis with the electrical source estimation we applied the beamformer spatial filter technique on both ERPs (from -300 ms before till 300 ms after the response) with a μ value set to 0.001. The source orientations were estimated in advance over the same time window. Based on Eq. (5) the sources were identified corresponding with the highest T-values. We visualized this in Figure 5 by presenting the grid points with T-values 60 $\%$ above peak T-value in red and by interpolating these values in between. These results are presented on the structural image of the subject. Again we see activation around the right primary cortex. The results also indicated a higher cortical power for right hand responses which was acceptable because the subject is right handed.

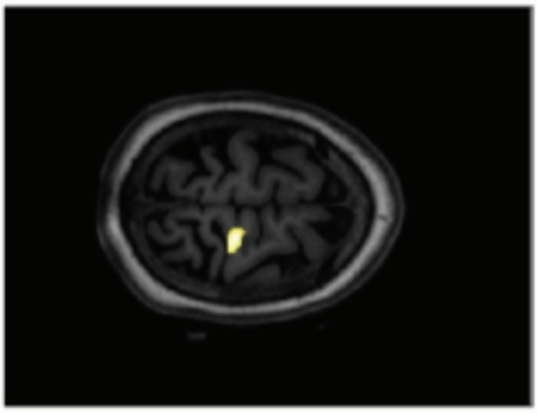
IV. Discussion

In this study, we have shown that it is appropriate to apply beamformer spatial filters to EEG data in a combined EEG/fMRI Stroop task during motor activation. Both fMRI and EEG analyses show activation of the right primary motor cortex. This indicates that the EEG artifact subtraction is acceptable regarding the identification of motor activity. The main difference between right and left hand responses was located in the right primary motor cortex.

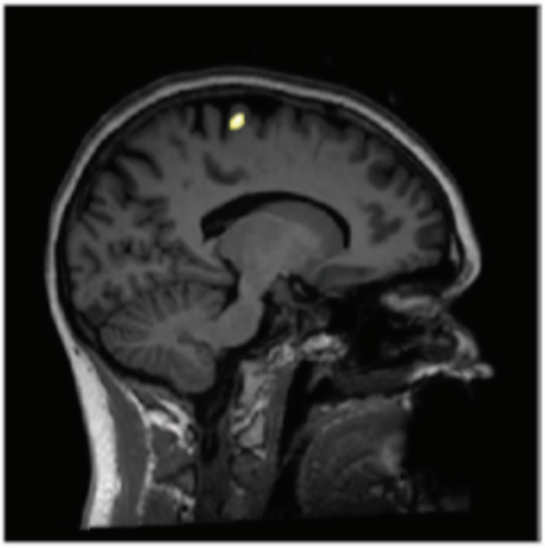
If we compare the positions of the global maximum in the T-statistical maps of the fMRI and beamformer analyses,



(a) Coronal slice

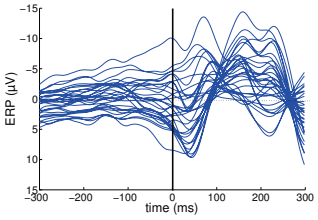


(b) Axial slice

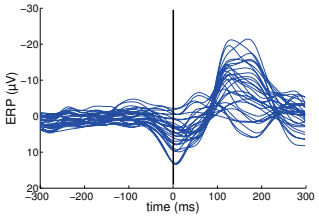


(c) Sagittal slice

Fig. 2: SPM fMRI analysis results



(a) ERP left hand trials



(b) ERP right hand trials

Fig. 3: ERP of left and right hand response locked segmented trials

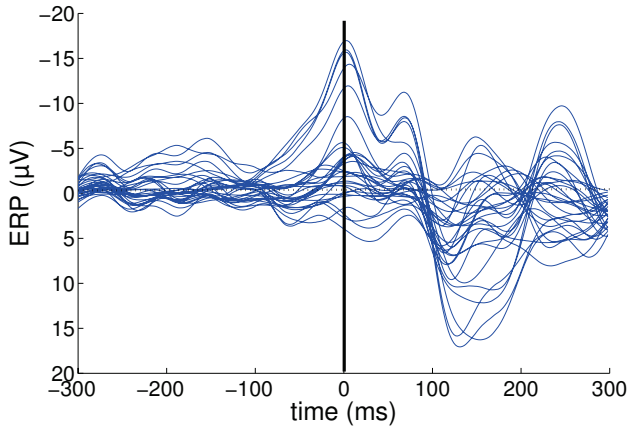


Fig. 4: Difference of ERP potentials from left and right hand trials

there is a difference of 2.3 cm. This difference may be due to incompleteness of the head model or the incomplete modeling of the electrode positions. Nevertheless, this mismatch is still within the spatial resolution of EEG source localization.

Finally, we have to note that these analyses are performed for just one subject so we should be careful with these preliminary results.

V. Conclusion

Using beamformers [7] and a subject specific realistic head model we were able to estimate the electrical sources in the brain corresponding with motor activity. We showed that the area of maximum activation could be compared with the fMRI activation cluster in order to evaluate the observed motor activation overlap in both modalities. Both fMRI and EEG analyses show an activation of the primary motor cortex. This overlap between haemodynamic and electrical activity and moreover the opportunity to measure them simultaneously are an indication to start with a more extensive integration strategy.

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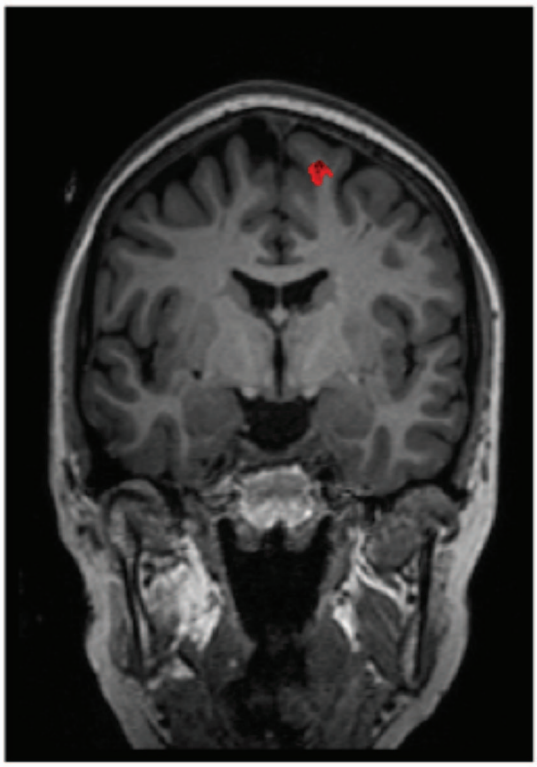
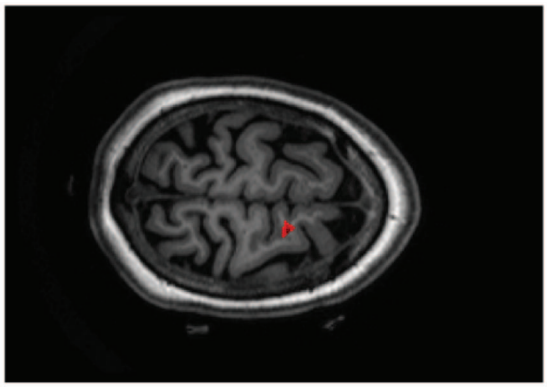
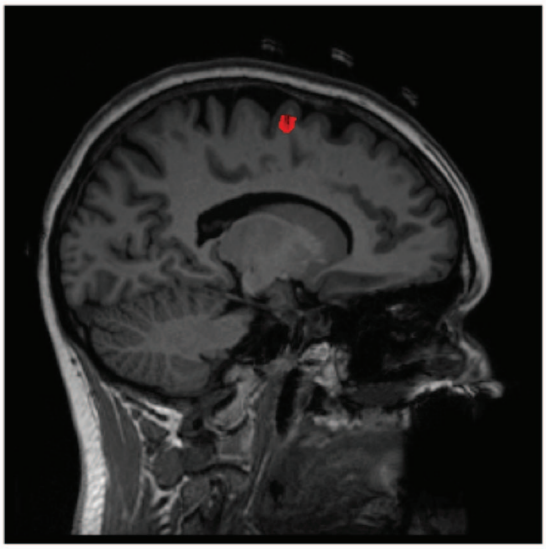


(a) Coronal slice



(b) Axial slice



(c) Sagittal slice

Fig. 5: Beamformer source localisation results

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