BOLD Correlates of Alpha and Beta EEG-Rhythm during a Motor Task

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Abstract— **In this study, simultaneously acquired EEG and fMRI data from a motor experiment are analyzed. The motor task consists in moving the right hand and is performed by a group of healthy volunteers. The objective is to find the most adequate way to model the movement-related blood oxygen level-dependent (BOLD) response present in the fMRI data. The analysis of the fMRI data is performed using Statistical Parametric Mapping (SPM) and estimating two different models. In the first one (*motor event* model), the BOLD response is modeled following the time instants of the motor events. The second one (*brain wave* model) incorporates the dynamics of the 5 canonical EEG rhythms (α, β, γ, δ, θ) to describe the BOLD response. From the results, it can be concluded that the motor event model better describes the BOLD response related to the movement itself, but that the brain wave model is better suited to characterize the BOLD response of complementary brain processes.**

I. Introduction

FUNCTIONAL magnetic resonance imaging (fMRI), showing the blood oxygen level-dependent (BOLD) contrast, is an established method for making inferences about regionally specific activations in the brain [1]. However, the relationship between BOLD and neuronal activity is still under debate: in particular, it is still unclear how the hemodynamic response is influenced by the temporal dynamics of the underlying neuronal activity. One of the approaches used to study this relationship is to combine information from hemodynamic measures, such as fMRI, and electrophysiological measures, such as electroencephalography (EEG). It is well known that EEG during ongoing brain activity is dominated by spontaneously occurring, spatially distributed, oscillatory rhythms in characteristic frequency bands. The utilization of frequency-specific electrophysiological information to derive regressors for the fMRI analysis has the unique advantage of being able to selectively localize the BOLD correlates to specific neuronal rhythms [2]. Whereas a huge number of studies [3]-[5] have been performed using only one band of interest as regressor, recent studies showed that changes in the BOLD signal associated with changes in the spectral profile of EEG, do not arise from a single spectral band but from the dynamics of the various frequency components together [6]. As a consequence, all frequency bands should be used in building the design matrix for predicting the BOLD response. At this regard, the work of [7] constitutes a first attempt to use the model mentioned above, however, for a better understanding, more validation is needed. In this context, we propose to study the BOLD correlates of EEG rhythms in a group of healthy subjects during the execution of a motor task. To this end, EEG regressors derived from all frequency bands are used and this model is then compared with a classical motor event model, where the design matrix is built solely using temporal information from the stimuli.
The aim of this work is to analyze the link between oscillatory EEG activity and the BOLD signal in the particular context of a motor task, to provide a better understanding of the nature of frequency-dependent neurovascular coupling.

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II. Methods and Materials

A. Subjects

Five right-handed healthy adult volunteers participated in the study performed in the "Istituto Neurologico C. Besta", Milan, Italy (2 male, 3 female, aged 29.1 ± 10 years). All subjects have normal motor ability and no history of neurological or psychiatric disorders. As the aim of our experiment was to investigate the neurovascular coupling driven by a large electrophysiological response in the sensorimotor cortex, the inter-subject variability was expected to be very low. It was therefore chosen to acquire data from a small number (five) of subjects and to summarize these results using fixed-effects (FFX) SPMs. This follows the approach of [7] where a small number of subjects (three) was used for the same reason.

B. Motor Task

The motor task assigned to the subjects was to move the right forefinger. The participants were asked to perform at least 100 brisk (lasting less than one second) and self-paced extensions of the right forefinger, with a time interval between the end of a movement and the onset of the following one of about 10 s. All subjects were in a supine position with arms relaxed and head fixed with adjustable padded restraints on both sides. They were asked to move as little as possible throughout the experiment, to avoid

blinking, and in general, to keep their eyes open.

C. Data Acquisition

For the EEG acquisition, an MR-compatible EEG amplifier (SD MRI 32, Micromed, Treviso, Italy) and a cap providing 30 Ag/AgCl electrodes positioned according to the 10-20 system, were used. An extra electrode was put on the thorax to obtain an electrocardiogram (ECG). Concurrently, the electromyogram (EMG) activity was recorded with a surface electrode placed over the right index flexor muscle. Impedances were kept below 5 kΩ. The signal was sampled at a rate of 1024 Hz using the software package provided by the manufacturer.

The fMRI data was acquired on a 1.5 T MR scanner (Magentom Avanto, Siemens AG, Erlangen, Germany). An axial gradient-echo echo-planar sequence was used to generate the functional images (TR = 2000 ms, TE = 50 ms, 21 slices, 2x2 mm^2 in-plane voxel size, 4 mm slice thickness, no gap). A T_1 - weighted scan was also acquired to have a simple anatomical image (160 slices, TR = 1640 ms, TE = 2 ms; 1 mm^3 isotropic voxels).

D. EEG Data Preprocessing

The imaging gradient artifact was digitally removed from the EEG using an adaptive filter [Laufs et al., 2008], implemented in the software provided by the manufacturer.. To remove the ballistocardiogram (BCG) artifact, its template was constructed using an optimal basis set (OBS) of principal components as to capture the most important statistical variation of the artifact [9], [10]. The removal was performed using the MATLAB toolbox EEGLAB (http://sccn.ucsd.edu/eeglab).

E. fMRI Data Preprocessing

The fMRI images were motion corrected and spatially smoothed with an 8 mm × 8 mm × 8 mm full width at half maximum Gaussian kernel using the SPM5 software package (http://www.fil.ion.ucl.ac.uk/). fMRI images were then spatially normalized to the neuroanatomical atlas of Talairach and Tournoux (using a 12 parameter affine approach and a T2* weighted template image).

F. EEG Data Analysis

A continuous wavelet transformation using the Morlet wavelet was executed with a frequency resolution of 1 Hz on the EEG data, in order to extract the brain waves α (8-12 Hz), β (12-30 Hz), γ (30-40 Hz), δ (1-4 Hz) and θ (4-8 Hz) [11]. For every frequency band the signals were squared and averaged per time instant, resulting in a time course of the power in each frequency band. Only C3 and C4 electrodes were selected since it was expected and found that these channels are most involved in modulating the oscillatory activity during motor tasks. At this regard, it is documented in literature that, during motor performance, an amplitude attenuation of specific frequency components (event-related desynchronization ERD) in the α (8-12 Hz) and β-band (12-30 Hz) precedes the voluntary movement and an increase of amplitude (event-related synchronization ERS) in the β-band occurs at the end of the movement. ERD reflects the cortical activation concurring with the motor planning, whereas ERS reflects the local inhibition of the motor cortex [12], [13].

G. fMRI Data Analysis – Motor Event Model

To investigate the effect of the experimental task, a first fMRI analysis was performed deriving regressors based on the motor events. The expected response was modeled as the convolution of the SPM canonical hemodynamic response function (HRF), including its dispersion and time derivatives, with a train of impulses synchronous with the beginning of EMG bursts. The resulting design matrix was fitted to the fMRI data from multiple subjects following a FFX approach, and inferences on the estimated EMG regressor were made using a *T*-test ($p<0.05$ corrected for multiple comparison). The FFX analysis summarizes the results over five subjects and has shown to be useful when there are few subjects and the inter-subject variability is expected to be low [7].

H. fMRI Data Analysis – Brain Wave Model

To investigate the link between oscillatory EEG activity and the BOLD signal, a second fMRI analysis for each derivation (C3 and C4) was performed. The design matrix was built using as regressors the time course of the power spectrum for the five frequency bands, convolved with the canonical HRF and its dispersion and time derivatives. As previously mentioned, we chose to use as regressors all the frequency bands, including also rhythms (γ, δ, θ) that are not directly involved in motor performance. This particular choice allows including regressors covering the entire EEG range of frequencies for predicting the fMRI response, in accordance to findings in previous studies [6]. The FFX approach was also followed, entering multi-subjects data into the general linear model (GLM) by concatenating data from all subjects into a single column vector. Inferences were made using an *F*-test on α- and β-bands derived regressors only, as these are the ones related to motor performance [12], [13].

III. Results

A. Motor Event Model

Table I and Figure 1 show the activated brain regions with their corresponding anatomical labeling, coordinates of the local maxima and volume extent. All the regions, except for the last one, are located within the left hemisphere. They have a high probability to belong to the left precentral or left postcentral gyrus [14]. Because of the correspondence of these two brain regions with motor cortex and somatosensory cortex respectively, these results are quite easy to interpret, since all normal voluntary movements should involve sensory feedback and the motor commands to the right hand originate from the left motor cortex. The activation in the left supplementary motor cortex (SMC), also called premotor cortex, can be explained from the role of SMC in the planning of motor actions and, in

particular, in the coordination of complex movement like manual control [14]. Finally a small cluster located in the right frontal pole is also found. The functions of frontopolar regions (Brodmann area 10) are nowadays yet poorly understood, but a possible explanation of these results can be found in the presumed role of frontal poles in executive function [15]. Recent studies show a possible involvement of the right frontal pole in the control (in terms of execution or inhibition) of motor response [16] and they can constitute a possible explanation of our finding.

TABLE I
SUMMARY OF THE BOLD ACTIVATION
FOR THE MOTOR EVENT MODEL

Region	x [a]	y [a]	z [a]	Volume (mm^3)
L PreCentral Gyrus	-28	-20	76	49
L PreCentral Gyrus, L PostCentral Gyrus	-42	-14	62	31
L PostCentral Gyrus	-34	-36	70	21
L PreCentral Gyrus, L Supplementary Motor Cortex	-2	-14	72	16
L Opercular Cortex	-48	-2	10	12
R Frontal Pole	40	56	20	9

[a]xyz are Tailarach coordinates of the local maxima.

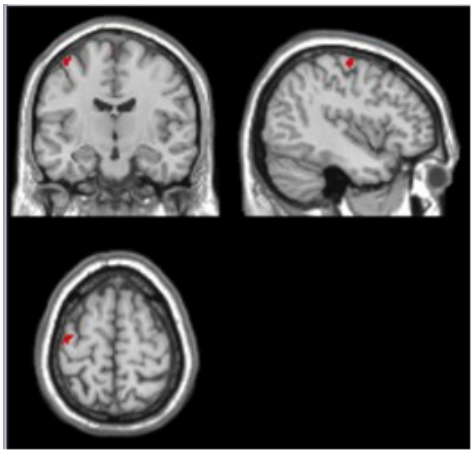


Fig. 1. fMRI findings for the motor event model shown on the MNI (Montreal Neurological Institute) atlas (the images are shown according to the neurological convention (right at the right side)).

B. Brain Wave Model

The results for α and β bands for electrode C3 are shown in Table II and Figure 2. In the case of α rhythm, as in the results of the motor event model, activations in the left postcentral gyrus (i.e. the somatosensory cortex) are found and, in addition, activation in the left superior frontal gyrus is present. However, no activation in primary motor cortex seems to be present. fMRI activations associated with EEG activity in the β band are located in the left precentral and postcentral gyri (i.e. in the primary motor cortex and in the somatosensory cortex respectively), as in the results of the motor event model. Further activations were found in the frontal region and in the supramarginal gyrus with its adjacent planum temporale. If we compare α and β rhythm areas, our results suggest that the alpha rhythm is linked predominantly to the somatosensory system, while the beta rhythm is more related to motor processing. This is a remarkable result that confirms what is hypothesized and found by [17]. The activation in extrarolandic (i.e. not adjacent to the central sulcus) regions that are visible both in the α and β wave regressors, could represent an attentional network which (at first glance rather counter-intuitively) is activated during the rest period [17]. As for the C4 results, shown in Table III and Figure 3, there are no regions with significant correlation between BOLD and C4 α rhythm. For β, it is interesting to note that in the C4 case only extrarolandic regions are activated. There is no activation in the primary motor cortex neither in the primary somatosensory cortex (i.e. in the activated areas resulting from the motor event model), but only in those brain regions that are not directly involved in motor performance.

TABLE II
SUMMARY OF THE BOLD ACTIVATION
FOR THE BRAIN WAVE MODEL FOR C3 ELECTRODE

Rhythm	Region	x [a]	y [a]	z [a]	Volume (mm^3)
Alpha	L Superior Frontal Gyrus, L Frontal Pole	-18	36	38	25
	L PostCentral Gyrus, L Superior Parietal Lobule	-34	-38	44	24
	L PostCentral Gyrus	-54	-16	38	7
Beta	L PostCentral Gyrus, L PreCentral Gyrus	-52	-16	40	157
	L PostCentral Gyrus, L PreCentral Gyrus	-56	-6	16	125
	R Middle Frontal Gyrus, R PreCentral Gyrus	50	12	38	40
	R PostCentral Gyrus, R Supramarginal Gyrus	62	-16	34	31
	L Planum Temporale, L Supramarginal Gyrus	-56	-40	20	24

[a]xyz are Tailarach coordinates of the local maxima.

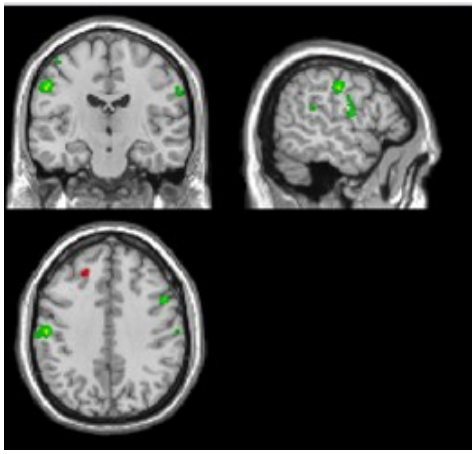


Fig. 2. fMRI findings for the brain wave model for the C3 electrode shown on the MNI (Montreal Neurological Institute) atlas. α-related activations are mapped in red, β-related activations are mapped in green and the regions common to α and β activations are mapped in yellow (the images are shown according the neurological convention (right at the right side)).

IV. DISCUSSION

In this study, we have constructed two models to describe

the BOLD response related to movement. The motor event model showed results which were prominent in the left motor cortex (precentral gyrus) and left somatosensory cortex (postcentral gyrus): two areas directly linked to the motor cortex. The brain wave model on the other hand, showed results for these two areas, but also for areas involved in concentration (frontal) and imaginary counting (supramarginal gyrus). We can conclude that the motor event model better describes the BOLD response for the performance on the motor task itself, but that the brain wave model also captures the BOLD response for brain processes complementing the execution of the motor task.

Furthermore, our results suggest that the brain wave model is very sensitive to the location of the electrodes supplying the brain waves.

TABLE III
SUMMARY OF THE BOLD ACTIVATION
FOR THE BRAIN WAVE MODEL FOR C4 ELECTRODE

Rhythm	Region	x [a]	y [a]	z [a]	Volume (mm^3)
Beta	L Parietal Operculum Cortex, L Planum Temporale R Supramarginal Gyrus	-54	-36	20	54
		62	-26	40	19

[a]xyz are Tailarach coordinates of the local maxima.

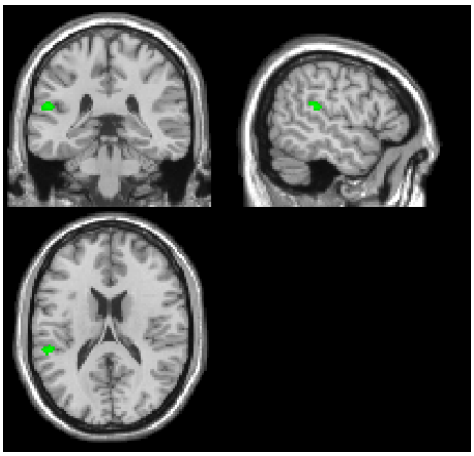


Fig. 3. fMRI findings for the brain wave model for the C4 electrode shown on the MNI (Montreal Neurological Institute) atlas. β-related activations are mapped in green (the images are shown according the neurological convention).

More specifically, the hemisphere on which the electrode was placed made a difference in the results: in fact, while C3 showed mostly activations in areas directly involved in the motor task, C4 showed no activation related to the motion of the hand, but only secondary brain processes involving concentration. This is consistent with the fact that oscillatory EEG activity strictly related to the motor task itself is recorded only by C3 because it is located essentially in the perirolandic area of the left hemisphere.

This work can be a starting point for future investigation of the alteration of the EEG oscillatory activity and of its relation with the BOLD signal in clinical populations affected by pathologies with motor impairments. The relationships between specific patterns of activation and motor deficits may help us identify targets for an improvement of the knowledge about the pathophysiological mechanisms at the basis of the diseases.

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