Brain Topogr (2008) 21:100–111
DOI 10.1007/s10548-008-0058-1

ORIGINAL PAPER

EEG and fMRI Coregistration to Investigate the Cortical Oscillatory Activities During Finger Movement

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Accepted: 3 June 2008 / Published online: 22 July 2008

Abstract Electroencephalography combined with functional magnetic resonance imaging (EEG-fMRI) may be used to identify blood oxygenation level dependent (BOLD) signal changes associated with physiological and pathological EEG event. In this study we used EEG-fMRI to determine the possible correlation between topographical movement-related EEG changes in brain oscillatory activity recorded from EEG electrodes over the scalp and fMRI-BOLD cortical responses in motor areas during finger movement. Thirty-two channels of EEG were recorded in 9 subjects during eyes-open condition inside a 1.5 T magnetic resonance (MR) scanner using a MR-compatible EEG recording system. Off-line MRI artifact subtraction software was applied to obtain continuous EEG data during fMRI acquisition. For EEG data analysis we used the event-related-synchronization/desynchronization (ERS/ERD) approach to investigate where movement-related decreases in alpha and beta power are located. For image statistical analysis we used a general linear model (GLM) approach. There was a significant correlation between the positive-negative ratio of BOLD signal peaks and ERD values in the electrodes over the region of activation. We conclude that combined EEG-fMRI may be used to investigate movement-related oscillations of the human brain inside an MRI scanner and the movement-related changes in the EMG or EEG signals are useful to identify the brain activation sources responsible for BOLD-signal changes.

Keywords EEG · BOLD · ERD · Alpha power · Beta power

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Introduction

Functional magnetic resonance imaging (fMRI) is a non-invasive method that may be used to study human brain function. Recording EEG data during fMRI identifies brain activity in motor areas and also provides information on the source of the event generator.

EEG activity recorded from the human brain at rest oscillates in various frequency bands including the theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz) and gamma (30–50 Hz) ranges. Movement preparation typically suppresses, with a decrease in power, the cortical oscillations in both alpha and beta rhythms starting more than 1 s before the onset of finger or hand movement (Erbil and Ungan 2007; Leocani et al. 1997; Pfurtscheller and Aranibar 1979; Rappelsberger et al. 1994) over sensorimotor areas.

Upon movement completion, the EEG recording shows an alpha event-related desynchronization (ERD) followed a brief "rebound" beta event-related synchronization (ERS) over different cortical regions (Salmelin and Hari 1994).

ERD indicates oscillations in cortical activation and ERS reflects a cortical idling state (Pfurtscheller 1992). These pre-movement and post-movement power changes both correspond to the somatotopic organization of the primary sensorimotor cortex (Hari and Salmelin 1997; Neuper and Pfurtscheller 1996; Stancak et al. 2000). A more recent study has described a different pattern of alpha and beta suppression band with a more persistent beta-band suppression activity during continuous fingers movement (Erbil and Ungan 2007). The regional activation of cortical areas with a decrease in power has been associated with the term 'EEG desynchronization', whereas it has been documented that brain activation produces spontaneous synchronization of fast rhythms with high amplitudes (Steriade and Amzica 1996).

The first report describing an EEG recording in an MRI scanner in humans in 1993 (Ives et al. 1993), revealed the potential for combining simultaneous neurophysiologic and imaging recordings. Subsequent studies have shown that EEG can be safely measured in a clinical MRI scanner using specially developed EEG equipment (Allen et al. 1998, 2000; Lemieux et al. 1997).

Combined recordings have the dual advantage offered by the high temporal resolution typical of neurophysiological techniques and the spatial anatomical resolution normally used in neuroradiological investigations. Earlier studies investigated the correlation between changes in oscillatory activity and blood oxygenation level-dependent (BOLD) activation during hand movement in separate recording sessions (Babiloni et al. 2005; Manganotti et al. 1998; Sadato et al. 1996). The recent development of digital recording methods compatible with the magnetic field surrounding fMRI scanners has enabled combined EEG-fMRI recording in human subjects. Few studies have investigated movement-related brain oscillatory activity during co-registered EEG-fMRI. One study observed a beta band synchronization during movement (van Duinen et al. 2005) and another analyzed the EMG activity during the coregistration EMG-fMRI (van Duinen et al. 2005).

A major problem in recording EEG during fMRI scanning is that of removing artifacts that arise from interactions between the patient, EEG electrode leads, and the magnetic fields in the scanner may result in artifacts and can obscure the EEG. Movement of the leads themselves within the static field of the magnet (not during MRI acquisition) induces an electromotive force (EMF) in a wire loop according to Faraday's law. This movement is also related to heart pulse that produces a ballistocardiographic artifact in the EEG that can be roughly the same magnitude as the EEG signals themselves (Goldman et al. 2000; Ives et al. 1993; Muri et al. 1998). The switching magnetic fields applied during image acquisition may induce an EMF in the electrode leads and in a wire loop. The resulting artefact is normally very large and completely obscures the EEG (Allen et al. 1998, 2000).

The aim of the present study was to investigate whether combined EEG and fMRI could be used to measure the correlation between topographical changes in brain oscillatory activity over the scalp and the BOLD signals from cortical motor areas. To do so we recorded EEG signals over the scalp and simultaneously acquired BOLD signals while healthy subjects inside the scanner did a hand motor task. To obtain more information on brain motor oscillations during the fMRI acquisition, we investigated the distribution of ERD for a better topographical analysis of brain motor oscillations.

Materials and Methods

Subjects

Data were recorded in nine healthy subjects (four men and five women), who age ranged from 19 to 46 years (mean: 34.11, SD: 7.94). All subjects, right-handed as established by the Edinburgh handedness inventory (Oldfield 1971), gave written informed consent for the study in accordance with the Declaration of Helsinki, which was approved by the Local Ethics Committee of the University Department and Hospital.

Experimental Paradigm

Inside the bore of the scanner subjects were laid supine on a bed with their elbows flexed at 90° and hands pronated in a relaxed position. The subject's head was stabilized with adjustable padded restraints on both sides. They were instructed to remain as still as possible throughout the experiment. While lying inside the MRI chamber the subjects did a right-hand thumb adduction. During the task they were instructed to keep their eyes open, avoid blinking, and to look at a stationary fixed point positioned at 20 cm. Attention was reinforced before each recording. During fMRI acquisition, 100 volumes of 3700 ms were acquired, alternating five activation and five control cycles (rest), resulting in 6 min of echo planar imaging (EPI) recording. The movements of the thumb of the right hand were metronome paced at 1 Hz. The metronome sound continued during activation and rest blocks; and a high-pitched sound signalled subjects to start the movement task. Each subject was trained for several minutes before the experiment to perform the task correctly at the right rate. Subjects were tested with the lights on and wearing earplugs.

Motor performance was monitored by the EMG signal recorded outside and inside the magnet.

EEG Data Acquisition

The EEG was acquired using a MR compatible EEG amplifier (SD MRI 32, Micromed, Treviso, Italy) and a cap providing 32 Ag/AgCl electrodes positioned according to a 10/20 system (impedance was kept below 10 kΩ). To remove pulse and movement artifacts during scanning two of these electrodes were used to record the electrocardiogram (ECG) and electromyogram (EMG). The EMG electrode was placed on the right abductor pollicis brevis (APB) muscle.

The reference was placed anterior to Fz, and the ground posterior to Fz as in other studies (Avesani et al. 2008; Gonçalves et al. 2006; Manganotti et al. 2008) using the same system. To ensure subjects' safety, the wires were carefully arranged to avoid loops and physical contact with the subject. To minimize the variability in the EEG artifacts due to the MR sequence and avoid wire movement caused by mechanical vibration the wires rested on foam pads.

EEG data were acquired at the rate of 1024 Hz using the software package SystemPlus (Micromed, Treviso, Italy). To avoid saturation, the EEG amplifier had a resolution of 16 bits with a range of ±25.6 mV. An anti-aliasing hardware band-pass filter was applied with a bandwidth between 0.15 and 269.5 Hz.

fMRI Data Acquisition

Functional images were acquired on a 1.5 T MR scanner (Symphony, Siemens, Erlangen, Germany) equipped with EPI capability and a standard transient/receive (TR) head coil. fMRI data were acquired with a T2* weighted EPI sequence (36 slices, TR = 3700 ms, TE = 50 ms, 64 × 64 matrix, FOV = 256 × 256, slice thickness 3 mm; voxel size = 3 × 3 × 3 mm, axial slice orientation).

At the onset of each fMRI acquisition, the scanner provided a trigger signal that was recorded by the EEG system and used as a volume marker. A T1-weighted anatomical scan (192 slices, TR = 1990 ms, TE = 3 ms; scanning matrix 512 × 512, FOV = 256 × 256; slice thickness 1 mm; sagittal slice orientation) was also acquired for each subject.

EEG Data Analysis

EEG data were analyzed with a commercial software program (Vision Analyzer, BrainVision, Munich, Germany) using an event-related approach.

The EEG artifact induced by the magnetic field gradient was digitally removed off-line using an adaptive filter (Micromed) (Fig. 1).

The EEG artifact associated with pulsatile blood flow, ballistocardiogram (BCG), was also digitally removed off-line using a simple average procedure (Allen et al. 1998).

Before segmentation into non-overlapping epochs of 2 s, a notch filter (50 Hz) was also applied to all channels. Data for electrode leads were analyzed. EEG epochs with ocular, muscular and other types of artifact were preliminarily identified and then rejected. A fast Fourier transform (FFT) was applied to non-overlapping epochs each containing 2048 data points for all electrodes and for the two experimental conditions (rest and activation), with maximum resolution (0.5 Hz) and then averaged across epochs under the same conditions. Recordings were Hamming-windowed to control spectral leakage (window length = 10%). Power spectra $P_x(f)$ (μV^2) were estimated for all frequencies between 0 and 50 Hz. Because movement preparation and execution produce ERD over the sensorimotor area at 10 and 20 Hz (Leocani et al. 1997), we analyzed only the upper alpha (10–12 Hz) and beta (13–30 Hz) frequency range.

Event-Related Synchronization/Desynchronization

To reduce the effects of inter-subject and inter-electrode variation in absolute spectral power values and to quantify the event-related relative changes of EEG power at an electrode x, an accepted ERD/ERS procedure was used (Pfurtscheller and Aranibar 1979; Pfurtscheller and Neuper 1994), according to Eq. 1.

$$\mathrm{ERD}_x = \frac{(P_{x\mathrm{activation}} - P_{x\mathrm{rest}})}{P_{x\mathrm{rest}}} \times 100 \quad (1)$$

The ERD/ERS transformation was defined as the percentage decrease/increase of instant power density at the 'event' compared with a 'pre-event' baseline value. Event-related power decreases ('cortical activation state') that implied a decrease in synchrony of the underlying neuronal populations, were therefore expressed as negative values, whereas event-related power increases ('cortical idling state') were expressed as positive values.

We computed a topographic map showing changes in ERD/ERS for each subject for the alpha and beta ranges using Matlab 7 (The MathWorks Inc., Natick, MA), and a grand mean map for the nine subjects.

Statistical Analysis

Wilcoxon's rank sum test comparing values between contralateral and ipsilateral ERD on the 5% significance level was run for alpha and beta frequency bands. For the alpha range, the electrodes providing informative data over the region of activation in the contralateral motor area were Cp5, P3, PO3, T3, T5 and Cp1; whereas in the ipsilateral area were P4, PO4, T4, T6 and Cp2. For the beta range the contralateral electrodes were C3, T3, Cp5, Cp1, P3, PO3, O1 and T5; and the ipsilateral electrodes were C4, T4, Cp2, P4, PO4, O2 and T6.

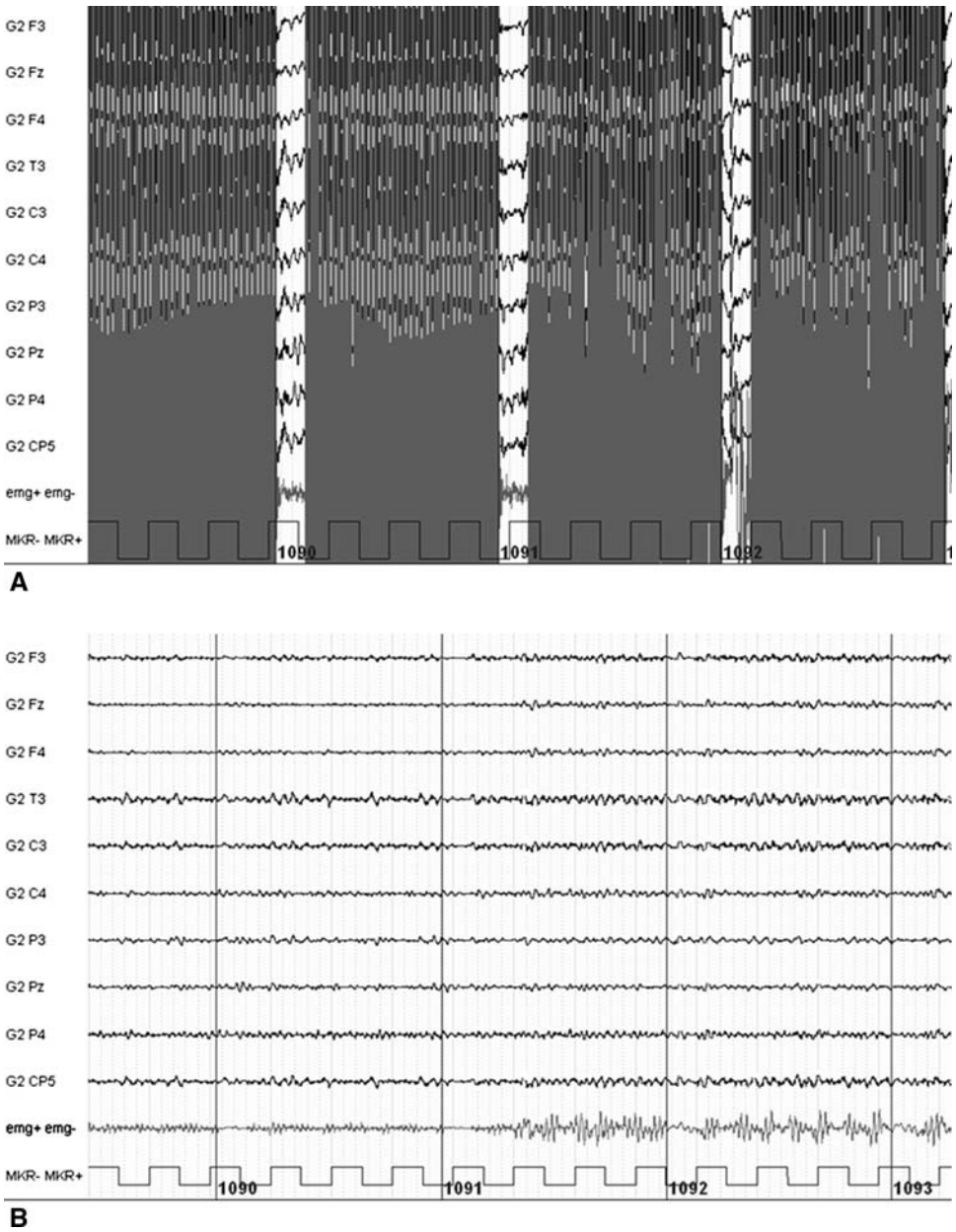


Fig. 1 (**a**) Raw EEG signal. (**b**) EEG signal corrected for gradient and ballistocardiogram artifacts

A paired sample two-tailed *t*-test was computed to compare the differences between ERD/ERS values, in alpha and beta ranges, and a reference condition to verify where desynchronization and synchronization values are significant. Two-dimensional grand mean t-maps of ERD were then computed from the *t*-values to check the topographical distribution of the significance (Celsis et al. 1999). ERD/ERS t-maps were thresholded at $P < 0.05$ ($|t| > 2.306$).

fMRI Data Analysis

The functional data were analyzed using BrainVoyager (QX 1.2, Brain Innovation, Maastricht, The Netherlands) running in windows XP environment.

Preprocessing of functional MRI included three-dimensional motion correction, slice scan time correction (sinc interpolation), linear trend removal by temporal high pass filtering (three cycles in time course) and transformation into Talairach coordinate space (Talairach and Tournoux 1998). Neither spatial nor temporal smoothing was used.

In each subject, activated voxels were identified with a single-subject general linear model (GLM) approach for time series data (Friston et al. 1995). To account for the hemodynamic delay, the boxcar waveform representing the rest and task conditions was convolved with an empirical hemodynamic response function (Boynton et al. 1996).

Brain activation was detected by comparing the signal intensity of task performance images (ON) with that of

resting images (OFF) based on the changes in local BOLD signals. Images acquired during the ON condition were compared with images acquired from the same location during the OFF condition on a pixel-to-pixel basis with Student *t*-test. *Z*-score maps representing brain activation were generated. The results were displayed on parametric statistical maps in which the pixel *Z* value is expressed on a colorimetric scale. Individual statistical maps were thresholded at $P < 0.045$ (corrected for multiple comparisons: Bonferroni). The statistical functional maps (*Z* maps) were then superimposed on the respective structural scans to localize significantly activated areas. We used the same *Z*-score range for all subjects: from 5.3 to 8, corresponding to P (Bonferroni) < 0.045.

In addition to individual subject analysis, a fixed-effect analysis was used to calculate GLM for the entire group of subjects. Group activation maps were thresholded at $P < 0.005$ (Bonferroni-corrected) and were superimposed on the (Talairach-transformed) structural scan for a representative subject.

The localizations obtained by the fMRI statistical map and the ERD values obtained by EEG are described qualitatively.

Correlation Between fMRI and EEG

For all subjects a linear correlation (Pearson's product moment correlation coefficient: r) between the positive–negative ratio of BOLD peaks (pnr) and ERD value was estimated for all recording channels. The BOLD peak in the contralateral and ipsilateral motor area was selected manually. We selected the max and min value on the ROI defined. And then we computed the pnr. The linear correlation and the correlation maps between pnr and the ERD alpha value was estimated in the electrodes providing informative data over the region of activation in the contralateral motor area (C3, T3, Cp5, P3 and PO3) and only for subjects in whom fMRI showed ipsilateral activation (C4, Cp2 and T4). Two-dimensional maps of the correlation between ERD and pnr were computed from the *r*-values to check the topographical distribution.

Results

fMRI-EEG Group Analysis

The mean alpha map showed a significant ERD decrease ($P < 0.03$) prominent over central parietal and central temporal areas contralateral to the movement; whereas the mean beta map showed an ERD decrease over the central area (Cz, Cp2) and over temporal and posterior parietal areas. T-maps showed significant changes for both desynchronization and synchronization oscillatory activity; there are significant changes in t-maps over the electrodes of interest, on which we noted the presence of ERD especially in alpha band (C3, T3, Cp5, P3 and PO3); while in beta band there are significant changes in central and posterior areas (Cz, Cp2, PO4, PO3). These maps reflect the changes obtained with mean maps (Fig. 2).

In the group analysis, fMRI showed significant BOLD activation ($P < 0.005$) in the supplementary motor area (SMA), and contralateral and ipsilateral sensorimotor area (SM1) and also in ipsilateral cerebellum (Fig. 2, Table 1). These activations were statistically consistent ($P < 0.045$) across all the subjects for the contralateral SM1 and SMA. Additional activation was observed in the ipsilateral gyrus postcentralis (GPOC) (Broadmann's area 40) in four subjects and in the ipsilateral GPOC (Broadmann's area 43) in one subject (Table 1).

Individual fMRI-EEG Analysis (Table 1 and Figs. 3–5)

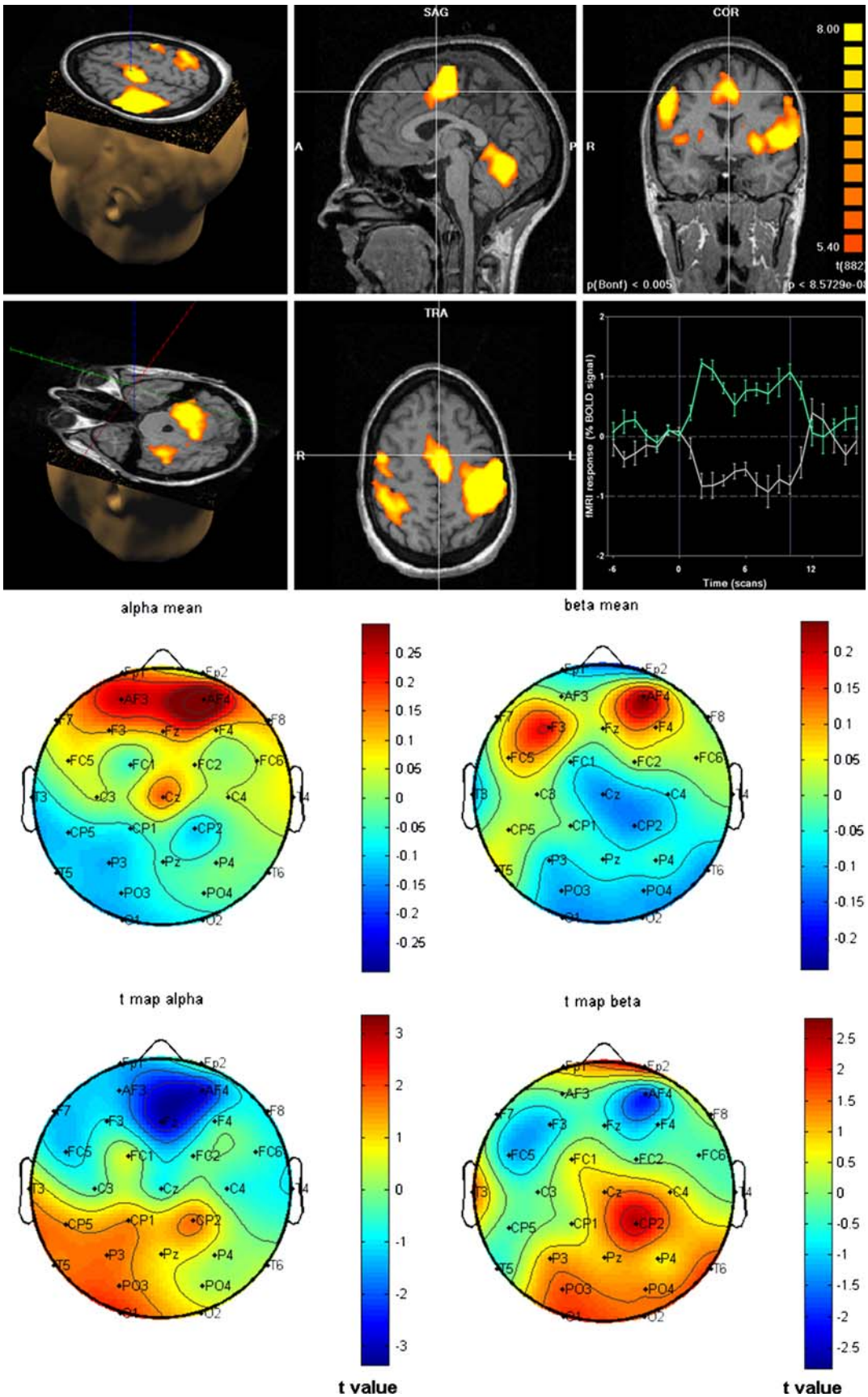
The individual data showed that the thumb abduction task invariably activated the contralateral SM1. ERD decreases in the alpha (10–12 Hz) and beta (13–30 Hz) frequency bands were prominent over the central parietal and central temporal areas contralateral to the movement. In all subjects central temporal electrodes were especially sensitive to the EEG changes and were close to the activated cortical areas corresponding to Brodmann's areas 4 and 3, 1 and 2 of the hand representation over the cortex.

In seven of the nine subjects studied, EEG recordings showed ipsilateral ERD in the alpha and beta frequency bands even in central and posterior parietal electrodes, and in all subjects midline ERD mainly for the beta band.

In brain regions contralateral to movement, individual alpha EEG power changes in all subjects correlated directly and closely with BOLD activity ($r = -0.7$, $P < 0.05$). In the five subjects for whom fMRI showed ipsilateral activation, a significant correlation was found between BOLD activation and changes in oscillatory activity over these regions ($r = 0.95$, $P < 0.05$) (Fig. 6). The correlation maps showed significant changes over the electrodes of interest: there is a negative correlation in contralateral side, whereas there is a positive correlation in ipsilateral side. The correlation maps showed significant changes for both contralateral (P3, PO3, CP1; $P < 0.05$) and ipsilateral areas (CP2, P4; $P < 0.05$) (Fig. 6).

Discussion

In this study, using combined EEG-fMRI we obtained useful new information on the description of the changes in oscillatory activity in alpha and beta bands during


SAG
COR
8.00
5.40
p(Bonf) < 0.005
TRA
fMRI response (% BOLD signal)
Time (scans)
alpha mean
beta mean
t map alpha
t map beta
t value
t value

◀**Fig. 2** (*Top*) Mean fMRI activation map during right finger movement with the functional image overlaid onto the 3D anatomical image in Talairach space in a group analysis. Color bar on the right indicates the z score of the statistical comparisons. The BOLD signal in GPRC (Brodmann's area 4) (*bottom right*) during active (*green*) and during rest condition (*gray*). The BOLD signal curve averaged across all conditions in all subject. The error bars show the standard error across all measurements. (*Centre*) Topographic maps of ERD/ERS in alpha band (*left*) and beta band (*right*), averaged of nine subjects. Blue color coding indicates maximal ERD desynchronization. (*Bottom*) T-maps of ERD/ERS mean values in alpha band (*left*) and beta band (*right*) thresholded at $P < 0.05$ ($|t| > 2.306$)

voluntary movement and on the investigation of the sites of BOLD activity as possible sources in generating these rhythms. While healthy subjects did the movement task inside the scanner, EEG recording showed a movement-related alpha and beta rhythm desynchronization over the bilateral sensorimotor area predominantly on the side contralateral to the movement. The main finding of this study was the computation of ERD maps of brain oscillatory activity recorded during fMRI scanning. Despite the technical problems related to filtering and MRI artifacts, we were able to detect oscillatory changes during thumb movements and map this activity.

We observed a significant ERD for alpha and beta bands associated with activation of the anterior and posterior central sulcus in both sensorimotor areas. The correlation between activation in motor areas and power that decreased in both bands was strongly significant. These findings are supported by studies showing that fMRI BOLD activity correlates with activity in alpha and beta bands (Babiloni et al. 2005; Brookes et al. 2005; Singh et al. 2002). Two studies combining fMRI and EEG (Parkers et al. 2006) studying the time course of this oscillatory activity during finger abduction reported that the BOLD activity in the postcentral sulcus is related to post movement beta rebound (PMBR). Only one study (Jurkiewicz et al. 2006) has described the correlation between ERD and activity over the pre- and post-rolandic areas. Our findings are in agreement with the study of Jurkiewicz that documents significant ERD at several locations in pre- and post-central sulcus. Nevertheless, our study investigated a steady state condition or task-related desynchronization (Manganotti et al. 1998, Gerloff et al. 1998), while both these previous studies examined the time course of the ERD and PMBR in finger movement. In this study, differently from Parkers et al. (2006) we could observe the reliability and the consistency of the alpha and beta suppression during the finger movements in fMRI recording. As documented by the topographical maps, we noted in most of the subjects a reliable suppression of both rhythms correlating with the BOLD activation. The novelty of the study is the individual correlation between the EEG activity of each subject with his BOLD activation. We cannot analyze the time frequency in repetitive movements, because the movement in

Table 1 Region of interest's number of voxels in each subject and in group analysis

Regions of interest	Subjects									Group analysis
	1	2	3	4	5	6	7	8	9	
GPOC (area 1)	#	#	2813	#	#	#	#	#	#	#
GPOC (area 2)	2183	#	15640	1227	#	930	6956	2474	#	6726
GPOC (area 3)	2751	2902	5413	2792	1497	872	1025	#	5877	1000
GPOC (area 3-i)	#	#	#	#	772	#	#	#	#	4951
GPRC (area 4)	3198	#	10378	2593	2528	2495	1122	9433	3259	10004
GPRC (area 4i)	#	#	#	#	#	#	#	3788	#	2146
GPOC (area 5)	#	1511	#	#	#	#	#	#	#	#
GPOCi (area 5i)	#	3005	#	#	#	#	#	#	#	#
GFM-GFS (area 6)	2589	973	3960	#	2203	853	#	3204	#	14684
GTs (area 22)	#	#	#	#	#	1134	#	#	#	#
GPOC (area 40)	#	#	#	4319	4547	#	#	#	490	26608
GPOCi (area 40i)	1305	#	9219	#	#	#	#	#	#	6825
GTs (area 42)	#	#	#	#	#	712	#	#	#	#
GPOCi (area 43i)	#	#	#	#	903	#	#	#	#	#
GFI (area 44)	#	#	1223	#	#	#	#	#	#	5460
GFIi (area 44i)	#	#	1600	#	#	#	#	#	#	3259
Right cerebellum	920	3002	21071	8568	6291	5458	8570	3212	3419	25428

Ipsilateral (i)—and contralateral refer to the hemispheric side with respect to the hand moved. The GPOC was defined as gyrus postcentralis, GPRC as gyrus precentralis (Broadmann's area 4), GFM as gyrus frontalis medius, GFS as gyrus frontalis sup, GTs as gyrus temporalis sup and GFI as gyrus frontalis inf

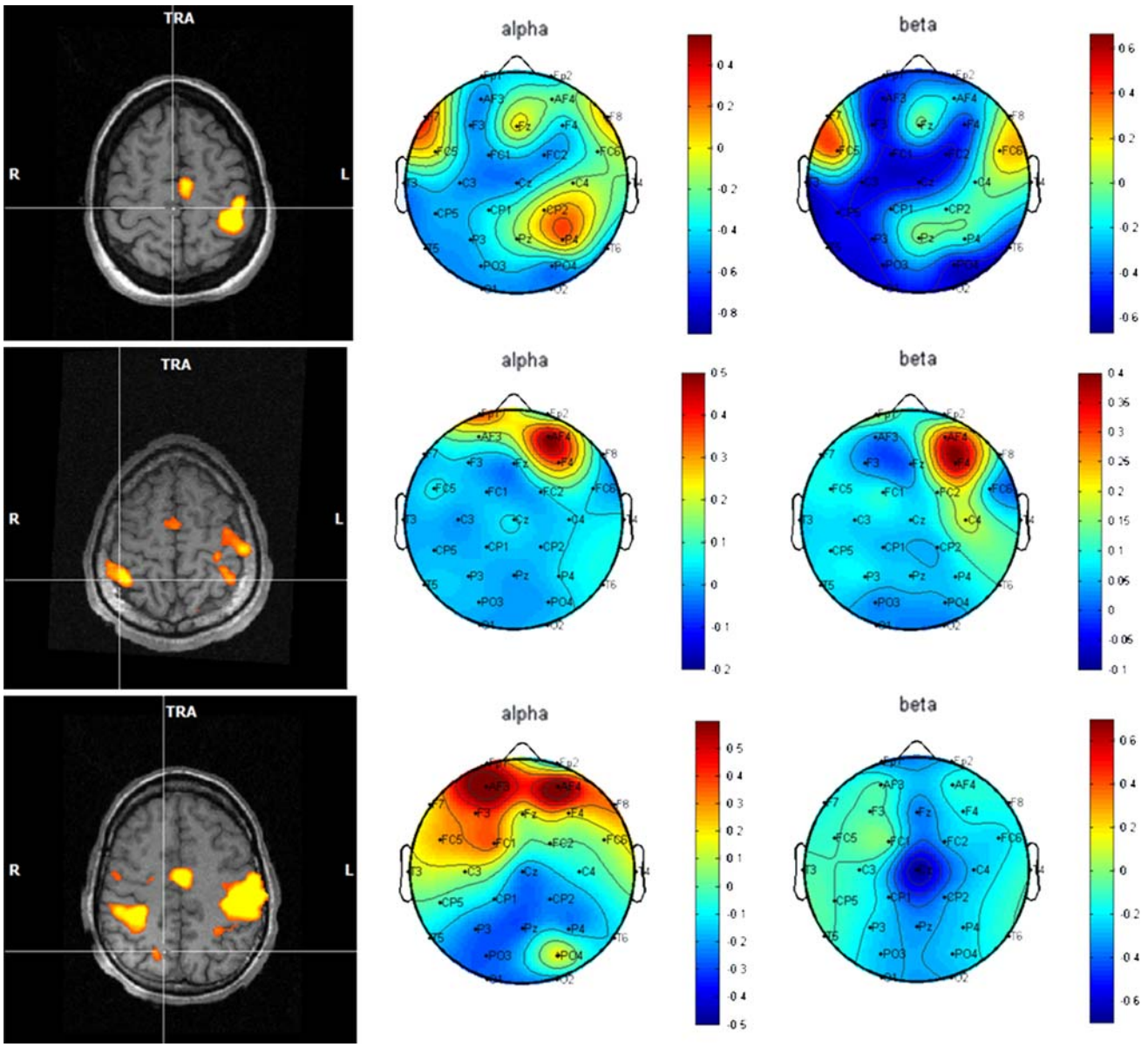


Fig. 3 (*Left*) Subject 1: SMA and contralateral SM1 activation during right finger movement with the functional image overlaid onto the 3D anatomical image of in Talairach space. Subject 2: SMA, contralateral and ipsilateral SM1 activation. Subject 3: SMA, contralateral and ipsilateral SM1. (*Right*) Topographic maps of the ERD/ERS effects for alpha and beta ranges

this study is a steady state condition as the block study in fMRI recording.

One limitation of our study is that we did not investigate alpha and beta ERD as regressor to emphasize the relative BOLD correlates within individual data sets because we did not investigate the time course of ERD. The steady state condition of finger movement can show a diffuse ERD or ERS without distinguishing the time of activation between different areas. The topographic maps of ERD/ERS are not completely typical (Gerloff et al. 1998), because there was no consistent contralateral alpha ERD at C3, and there was an unexpected strong prefrontal ERS extending to Cz and FC5. Topographic maps are probably sensitive to MRI artifacts, despite the filtering different MRI effects may affect the EEG maps. Gradient effect can induce a diffuse increase in EEG signal, which may mask slight EEG changes during motor task (Menon and Crottaz-Herbette 2005). Hand movements itself could induce a slow activity over the scalp electrodes more evident under gradient effect. Although a large proportion of the influence of the BCG was removed, the influence of fluctuation of the BCG persist in FFT analysis. Generally the BCG artifact becomes larger from occipital to the frontal sites (Allen et al. 1998); therefore, frontal regions may be affected by these BCG artifacts in most of our subjects. Despite the presence of these artifacts the linear correlation

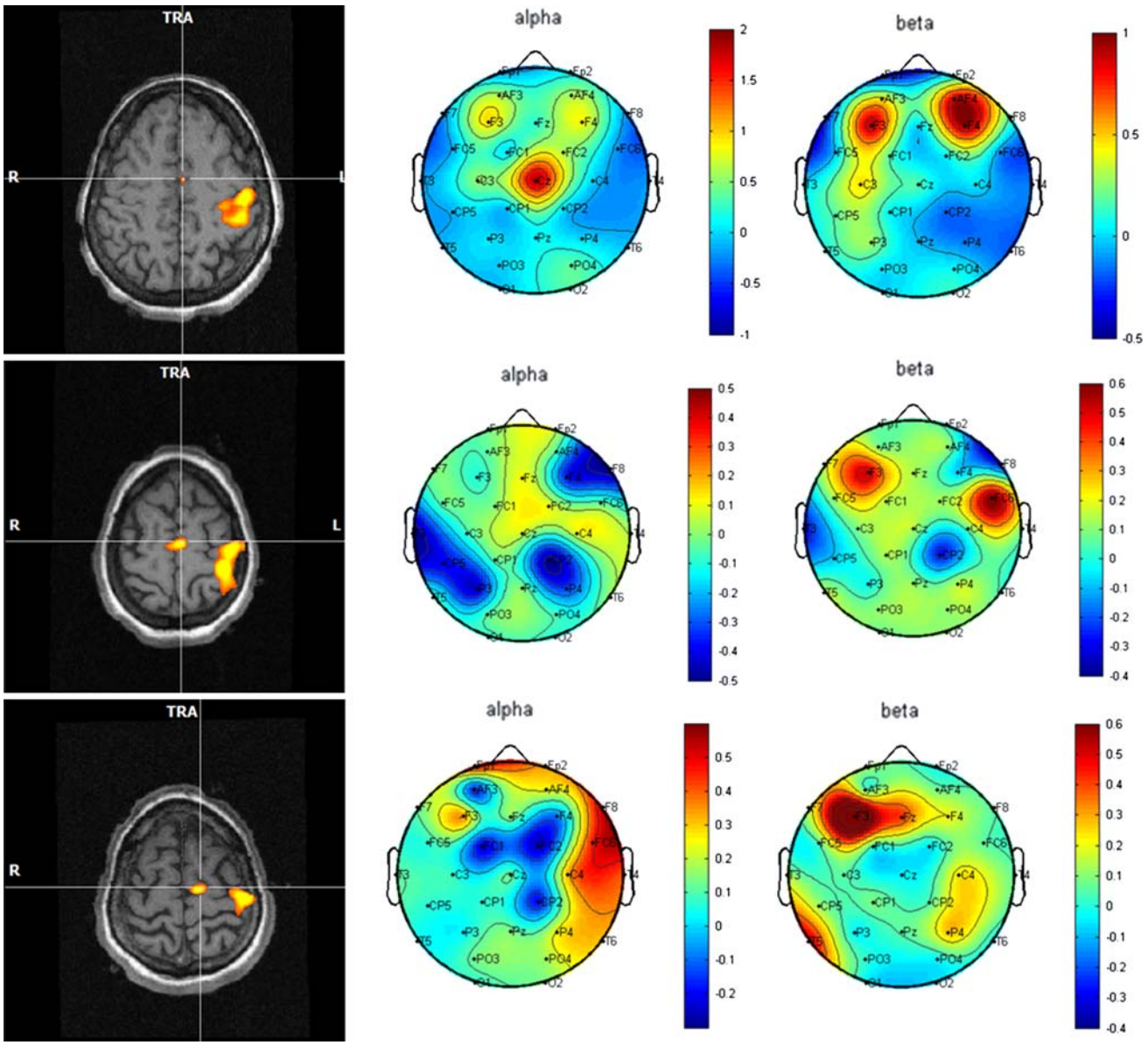


Fig. 4 (*Left*) Subject 4: SMA and contralateral SM1 activation during right finger movement with the functional image overlaid onto the 3D anatomical image in Talairach space. Subject 5: SMA and contralateral SM1 activation. Subject 6: SMA and contralateral SM1 activation. (*Right*) Topographic maps of the ERD/ERS effects for alpha and beta ranges

between ERD values and BOLD is significant in the electrodes of interest and corresponds to the motor ERD distribution. The Fz reference represents another limit of this study, because we cannot exclude the interference of active EEG recording and the presence of common diffused artefacts due to such a type of reference. Finally additional limit of the study is that we used a fixed effect analysis rather then the random analysis supposing a constant effect of simple task motor paradigm across the subjects.

However, we observed after the MRI artifact subtraction the persistence of oscillatory activity during rest and movement condition. In addition in our study under steady state condition we noted a desynchronization during movements, particularly over the bilateral sensorimotor regions. This is an important attempt to systematically relate individual EEG attenuations during motor blocks (ERD) to simultaneous fMRI effects and on an individual level. To our knowledge, this represents an attempt to reproduce ERD maps in coregistration EEG/FMRI investigations.

In our opinion, the possibility to correlate the EEG/EMG findings with BOLD activation in steady state condition represents a more suitable method to study the movement in patients with severe motor defects and who are not really able to perform a well selected movement.

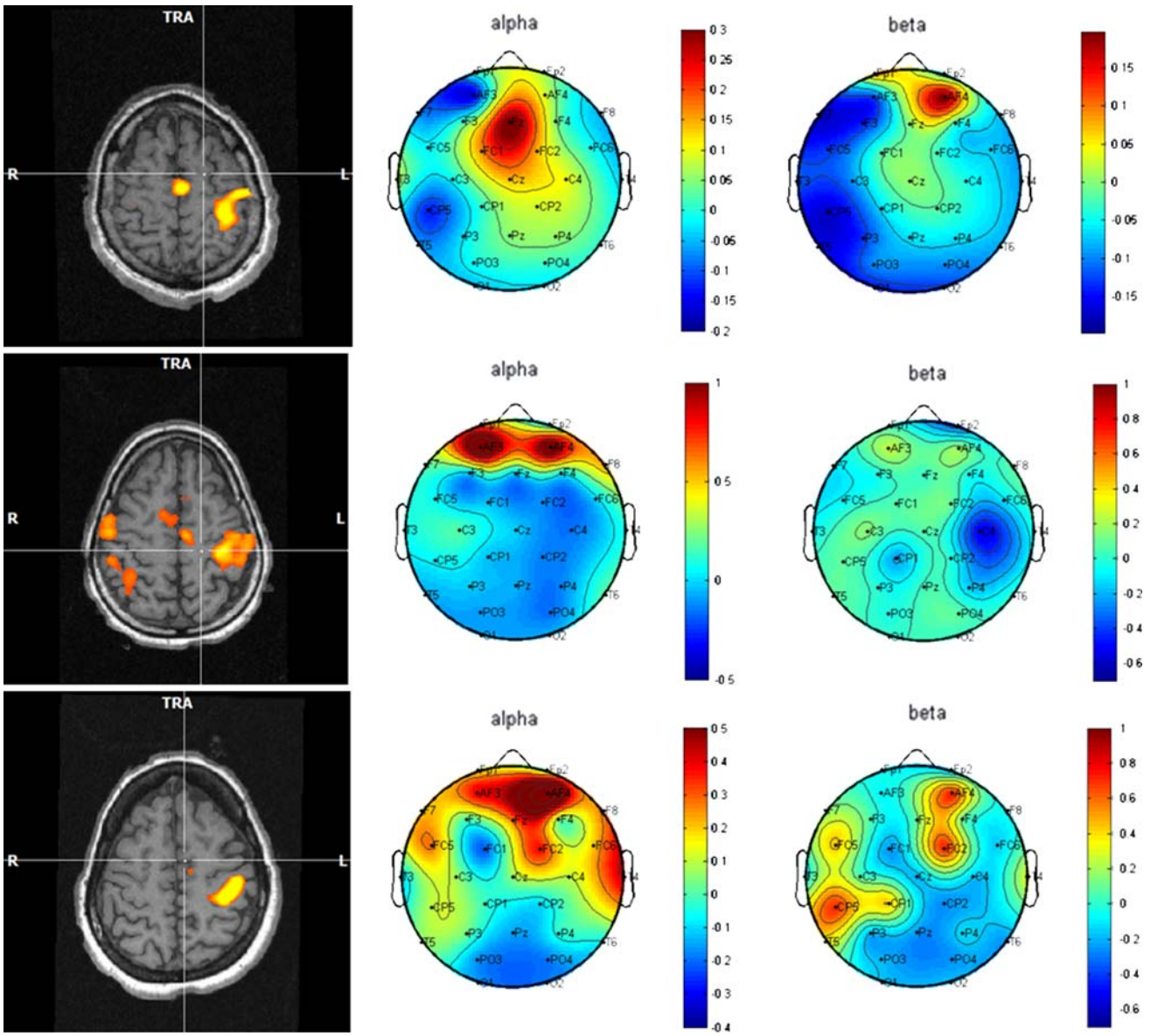


Fig. 5 (*Left*) Subject 7: SMA and contralateral SM1 activation during right finger movement with the functional image overlaid onto the 3D anatomical image in Talairach space. Subject 8: SMA, contralateral and ipsilateral SM1 activation. Subject 9: SMA and contralateral SM1 activation. (*Right*) Topographic maps of the ERD/ERS effects for alpha and beta ranges

The increase in the BOLD signal with a decrease of EEG alpha and beta power in contralateral motor areas suggests an increase in the mean rate of synaptic activity increased in the local neuronal population during the movement compared to resting baseline. Moreover, this increase correlates with the power changes in alpha and beta. This might be due to an increase in the mean rate of synaptic activity per unit volume, an increase in the amount of vasoactive substance released per synaptic event, or a combination of both.

However, EEG desynchronization identified regions that were not shown in fMRI and vice versa. It is well known that SMA activation and cerebellar BOLD activation does not correlate with the physiology of ERD. Nonetheless, it is more difficult to explain the poor correlation between ipsilateral ERD and ipsilateral activation. This might be due to signal loss caused by the lack of magnetic field homogeneities near the boundaries between tissues with very different magnetic susceptibilities, which represents a limitation of EPI-based fMRI acquisitions; alternatively this could be because the EEG is less sensitive to deep discharges or because of bilateral medial discharges that would cancel each other out. In this case, this might be the real bias of the steady state condition.

Using combined EEG-fMRI in healthy subjects represents an important tool of research and provides new

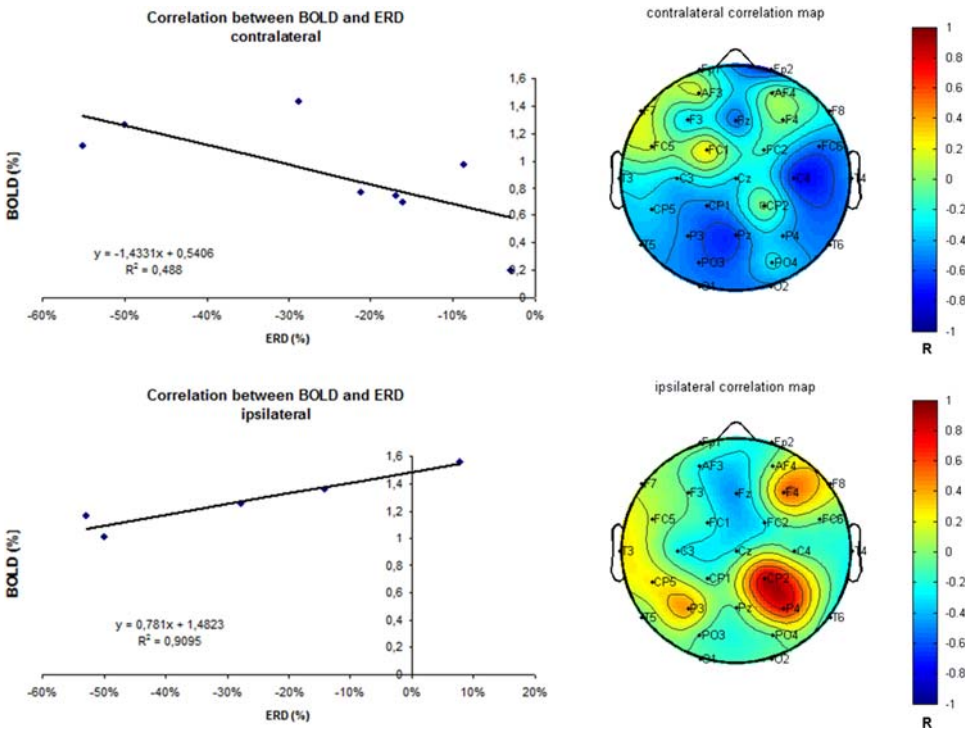


Fig. 6 (*Top*) Graphic correlation and correlation map between positive–negative ratio of BOLD's peaks and ERD values (alpha) in contralateral primary motor area. (*Bottom*) Graphic correlation and correlation map between positive–negative ratio of BOLD's peaks and ERD values (alpha) in ipsilateral primary motor area. For selected electrodes, see "Methods" section

information regarding the neural activity underlying the hemodynamic changes. Nevertheless these findings must be interpreted carefully because the fMRI signal is not a direct measure of synaptic activities or action potentials of cortical neurons; it results from the so-called BOLD effect (De Yoe et al. 1994; Kim and Ugurbil 1997; Ogawa et al. 1998), characterized by an excellent spatial resolution (1–2 mm) but limited temporal resolution (TR timing correlated).

In conclusion this study shows the possibility to investigate the map of oscillatory activity of the brain using fMRI, even under steady state motor conditions. The improvement of digital analysis in EMG or EEG signal in the fMRI protocol allows examination of possible sources of activation and review sheds light on BOLD activation. Further studies of fMRI/EEG coregistration are necessary in patients with motor disorders.

Acknowledgments The authors wish to thank Profs. Gianna Maria Toffolo and Alessandra Bertoldo (Department of Information Engineering, University of Padova) for help and advice concerning statistical analysis. This work was supported by Crediveneto, Verona, Italy.

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