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RESEARCH ARTICLE

Increased Sensitivity of Spatial Filters by Combining the Magnetic and Electrical Components of the Sensorimotor Cortical Beta Rhythm

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Abstract—Modulation of human magnetic or electrical sensorimotor rhythms during motor imagery is widely used in fundamental and applied neurophysiological research. To date, there is evidence of a better sensitivity of magnetic field sensors to beta-rhythm modulation; however, the potential synergistic effect of combining the two modalities has not yet been investigated. In this study, simultaneous registration of an electroencephalogram (EEG) and a magnetoencephalogram (MEG) was carried out in eight healthy volunteers during voluntary and imaginary movements as well as during electrical stimulation of the median nerve. In all subjects it was possible to identify desynchronization (suppression) of μ- and β-rhythms during the performance of sensorimotor tasks as well as β-synchronization after the end of movement or stimulation. Using the common projections of the covariance signal matrices of the electric, magnetic, and combined (MEEG) modalities, the most sensitive individual spatial filters were calculated separately for each type of reaction. Relative to the prestimulus control, the amplitude of changes in the amplitude of sensorimotor rhythm components was found to be the largest in the combined MEEG modality. At the same time, for μ-desynchronization, MEG turned out to be significantly worse than MEEG; as for β-desynchronization, MEEG was shown to be significantly better than MEG and EEG. For β-synchronization, a shift in the position of sources in the frontomedial direction was demonstrated, and there were no significant differences in amplitude between the modalities. It was also shown that, for β-desynchronization, most subjects identified MEG sources with identical EEG projections or without pronounced EEG projections, which indicated the presence of several small tangentially located cortical dipoles involved in β-rhythm desynchronization. The results suggested that the combination of MEG and EEG led to greater sensitivity in studies of modulation of sensorimotor rhythm components, in particular β-desynchronization. The multifocal nature of the magnetic β-rhythm and its different expression in EEG sources indicated the presence of independent regulatory circuits of cortical-thalamic or intracortical origin.

Keywords: sensorimotor rhythm, beta-rhythm, desynchronization, beta-rebound, MEG-EEG coregistration, spatial filter, motor imagery

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INTRODUCTION

The analysis of dynamic regulation of rhythmic brain activity is an important instrument in researching sensorimotor functions. Event-related synchronization (power increase) and desynchronization (power decrease) of rhythmic oscillations registered near the central sulcus of the brain cortex on an electroencephalogram (EEG) and a magnetoencephalogram (MEG) are widely used in the assessment of sensorimotor reactivity both in tasks with sensory stimulation and studies of voluntary movements and complex perceptual-motor states, such as motor imagery, body illusions, and simulative behavior [1]. In spite of the fact that the majority of researchers agree on the general questions of source and functional significance of α-/μ-components (~10 Hz) as idling rhythm, the discussion is still ongoing regarding the functional role and origination of sensorimotor β-waves (~20 Hz) [2]. In particular, μ- and β-desynchronizations occurring simultaneously during excitation or disinhibition of the sensorimotor cortex [3] is often followed by increased β-synchronization, also known as β-rebound, often thought of as overcompensation of earlier suppressed β-rhythm. However, with the spread of more accurate spectral power estimation techniques and high-density EEG, researchers began to observe that “rebound” occurs at lower frequencies [4, 5] and in precentral cortical areas [6, 7], as well as different drug sensitivity [8, 9], indicating a distinctive nature of β-rhythm event-related synchronization. Therefore, an alternative hypothesis emerged that there might be two sources of β-rhythm: frontal, with antikinetic function of active inhibition, and postcentral, with disinhibiting function related with attention and anticipatory behavior [10]. The registration of different components of sensorimotor rhythm is used both in fundamental research and practical applications, such as clinical diagnostics, neurocognitive training, and brain-computer interface [11, 12], where precise quantitative measurement of the reaction of EEG rhythm modulations is essential.

Currently, there is a large number of fundamental and practical researches of magnetic and electrical components of sensorimotor rhythm; however, only a few of them used MEG and EEG coregistration [13]. Apart from relatively small number of MEG facilities, a common idea that MEG is superior in localization precision and sensitivity to minor superficial tangentially oriented dipoles valuable for neurophysiological, clinical researches, and neurovisualization is a significant factor supporting the absence of such studies [14]. Indeed, studies directly comparing sensorimotor MEG and EEG rhythms [13] demonstrated higher sensitivity of magnetic gradiometers for the assessment of desynchronization and synchronization magnitudes. Nevertheless, no attempts to combine the information from two modalities for quantitative assessment of sensorimotor rhythm have yet been made.

Unlike the traditional approach to modeling of cortical sources in MEG and EEG recording by combining the physical models of electric and magnetic fields propagation [15], the signal-oriented approach is now gaining popularity [16, 17], allowing one to calculate the optimal spatial projections for expected signal dynamics based on multidimensional data acquired in the experiment. Such approaches allow to take advantages of large data dimensions without reducing the statistical power, are immune to noise and artifacts of individual sensors/modalities, and provide physiologically interpretable results, distinguishing them from similar approaches based on neural network architectures. However, there are currently not enough examples of their application for signals of different physical nature.

Therefore, the main goal of the present study was to investigate the possibility of correct calculation of interpretable spatial filters for the assessment of modulation of sensorimotor rhythm using a magnetoelectroencephalogram (MEEG) and to check for benefits of using the combined modality compared to 306-channel MEG and 64-channel EEG.

METHODS

Subjects and Study Design

The experiment included eight healthy volunteers (mean age of 24 years, four women). Seven subjects were right-handed and one was left-handed.

Three means of sensorimotor modulation were used in this research: (1) median nerve stimulation with current threshold for muscle contraction (Digitimer DS7A constant current stimulator (Digitimer Ltd., England), rectangular stimuli, 200 μs duration, 250 V maximal amplitude, 3.5–4.5 mA current, 2 s interstimulus interval); (2) single voluntary thumb movements of the right hand in response to the visual stimulus; (3) kinesthetic motor imagery of the same movements (5 s interstimulus interval). Visual counting of abstract picture elements was used as a control condition. Each subject recieved 50 nerve stimuli and made 40 attempts of imaginary and overt movements. The subjects were instructed on the technique of motor imagery in advance and previously participated in a study with the same tasks [18].

Data Collection

The encephalogram was registered simultaneously with 306-channel Neuromag Vector View magnetoencephalograph (Elekta Oy, Finland) and NVX–136 electroencephalograph (MKS, Russia) using nonmagnetic cap with 64 passive Ag/AgCl electrodes located using a 10–10 system. The recording was performed in a magnetically shielded Ak3B chamber (Vacuumschmelze GmbH, Germany) in a seated position. Additionally, electrooculography for synchronization of MEG and EEG amplifiers, electrocardiogram, and myogram of the venter of abductor pollicis brevis were registered. In addition, the subject’s head position in the MEG cap during recording was registered using special coils. Skin-electrode impedance did not exceed 15 kΩ for all encephalographic electrodes. All signals were digitized at 1000 Hz frequency.

Data Analysis

Preprocessing of the MEG signal was performed in Maxfilter v.2.2.10 software (Elekta Oy, Finland) according to a standard algorithm, including spatiotemporal tSSS filtering (time constant of 10 s and correlation limit of 0.8), elimination of head micromovements in the cap, and signal alignment to a standard head position in OX and OY axes [19]. Further analysis was conducted in MATLAB 2022b software (Mathworks, United States) using original scripts and FieldTrip and EEGLAB packages [20] for uploading and visualization of data.

Prior to further processing, the signals of all modalities were synchronized in time and filtered with a low-pass filter at a cut-off frequency of 90 Hz and moving median filter with 3 s kernel to eliminate temporal drift and other slow signal oscillations.

All signals of each sensor type were standardized to compensate for the differences in units of measure for different sensors (EEG, μV; magnetometers, fT; and planar gradiometers, fT/cm). Specifically, they were divided by the value of their total dispersion across all channels, robustly evaluated with the help of median absolute deviation [16]. For efficient usage of high-dimensional data, the spatial filters were calculated and optimized for each subject individually and for each of the time-frequency reactions separately (desynchronization in α- (8–14 Hz) and β- (14–30 Hz) ranges and synchronization in β-range). Spatial filters were calculated as common eigenvectors (W^T) of the covariance matrices of the signals in the experimental (presuming the presence of reaction of interest) and control (visual counting) conditions:

$$\Lambda = \operatorname{argmax}\left\{\frac{W^T \cdot C_{\exp} \cdot W}{W^T \cdot C_{\mathrm{ctrl}} \cdot W}\right\},$$

where W^T stands for matrix of eigenvectors (filters), Λ are eigenvalues, and $C_{\exp}$ and C_{ctrl} are covariation matrices in experimental and control conditions, respectively.

W^T vectors with the smallest eigenvalues corresponded to spatial projections with the smallest dispersion ratio in two conditions $\frac{C_{\exp}}{C_{\mathrm{ctrl}}}$, which, given the $[C_{\exp} < C_{\mathrm{ctrl}}]$ inequation, suggested the desynchronization of encephalographic signals in the experimental condition. Vectors with the largest eigenvalues, given the $[C_{\exp} > C_{\mathrm{ctrl}}]$, indicated the synchronization of encephalographic signals. The calculation algorithm for eigenvectors implied sorting W^T columns (w^T vectors) in accordance with the eigenvalues. Among all resulting filters, one w^T was selected with the smallest (for desynchronization) or largest (for synchronization) eigenvalue, where the corresponding spatial pattern calculated as $A = W^{-T}$ [21] was within the projection areas of contralateral sensorimotor cortex, i.e., frontal, central, and parietal sensors [18, 22], and had a dipole structure limited in space. This was practically implemented so that the components were chosen to correspond to one of the three marginal vector columns of the W^T matrix. If several distinct contralateral components were found, the components with more extreme eigenvalue was preferred. The correspondence of spatial projections of these modalities to the MEEG signal was an additional selection criterion for choosing EEG and MEG filters, allowing for more appropriate direct comparison of modalities.

The filters were calculated three times: for EEG, MEG, and combined MEG + EEG (MEEG) data. Prior to calculation of eigenvectors, the reduction of signal dimension was performed for MEG with the help of principal component analysis (up to 70–80 components) since the data were rank-deficient after tSSS procedure.

Selected filters were applied to the raw signal, afterwards the amplitudes of studied frequency components was estimated by signal convolution with wavelet functions with variable number of cycles, followed by combining the results as a geometric mean [23]. The resulting spectrograms were averaged for the attempts of each subject, standardized by the values of prestimulus interval [–1..0] s and converted into decibels. The mean values for rhythmic components in time-frequency sectors (Fig. 1) corresponding to the maximum of studied reactions were compared using ANOVA with subject and modality factors. Post hoc analysis with Tukey correction was performed for the modality factor.

RESULTS AND DISCUSSION

A representative spectrogram and spatial components for all sensor types in subject no. eight are illustrated in Fig 1. All subjects demonstrated desynchronization in μ (~10 Hz) and β (~20 Hz) frequency bands, typically manifesting after 500 ms from delivery of stimulus to movement or imagination and after ~200 ms from the electrical simulation of median nerve, and also typically terminating within 1–1.5 s. The delay of β-synchronization was from 2 to 4 s from command to movement or electrical stimulus (mean interval of 2.6–3.8 s) in different subjects. Interindividual variability in β-synchronization latency could be provoked by such factors as the manner of performing the movement (smoothly or with forced stops), differences in mental processing of consequences of performed movement or received stimulus, and individual features of functioning stereotypy of the sensorimotor system. Considering the potentially higher variability of β-synchronization latency between the distinct attempts, standardization of spectrograms by attempts could lower the absolute amplitude values of synchronization; however, this was not a limitation for the goals of our study. In all subjects, μ-desynchronization was within the range between 9 and 14 Hz, whereas β-desynchronization typically appeared at frequencies of doubled μ range (from 19 to 28 Hz). At the same time, β-synchronization after movement was seen at lower frequencies of β-range (from 15 to 24 Hz), which was consistent with the previous results of our research group [24] as well as other studies [4].

One filter with well comparable spatial projections of activation in the projections of all modalities was selected for each of the three encephalographic modalities (EEG, MEG, and MEEG) to compare their amplitudes of desynchronization. However, several sources of (de)synchronization in β-rhythm were found in the process of calculation of filters for the β-component in six of eight subjects with a common

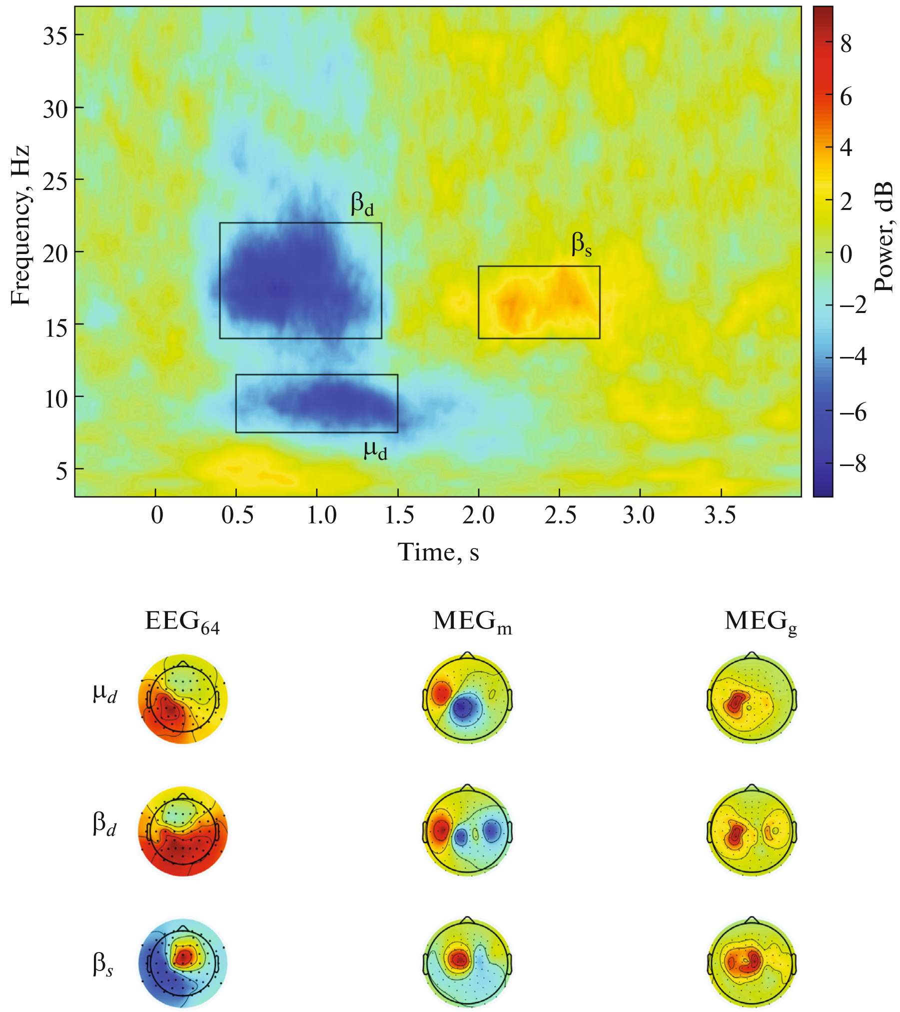

Fig. 1. Time-frequency and spatial patterns of sensorimotor rhythm modulation. The upper panel represents the averaged MEEG signal spectrogram of a contralateral source of sensorimotor rhythm in subject no. eight at a state of thumb movement (time in relation to the visual stimulus delivery for movement). The lower panel illustrates the spatial patterns corresponding to the upper spectrogram for three types of reactions (μ_d, μ-desynchronization; β_d, β-desynchronization; and β_s, β-synchronization) for three sensor types (EEG$_{64}$, 64-channel EEG; MEG$_m$, 102 magnetometers; MEG$_g$, root-mean-square of planar gradiometers); the weighting coefficient of individual sensors are marked with color.

projection in MEEG modality but differing in the polarity for magnetometers and gradiometers. Figure 2 demonstrates an example of data for subject seven, who showed two components with a single EEG projection but inverted MEG dipoles and the third source with the polarity rotated by 90° in MEG and without an EEG projection. Similar results have already been demonstrated [17] for frontal θ-rhythm using a similar algorithm of MEEG data processing. This fact might be explained by the presence of several β-components associated with the thalamic μ-rhythm as well as an intracortical component independent from μ-rhythm. This result is consistent with the modern theories of β-rhythm origin [25] as the overlap of feedforward fluctuations ~10 Hz of thalamocortical projections and feedback projections ~10 Hz of corticothalamic or intracortical connections. Nevertheless, only one projection was chosen from MEG modality because the application of all contralateral magnetic sources together would be inappropriate for comparison with EEG, characterized by a single large spatially-smoothed dipole, probably resulting from volume conduction of electric potentials. This circumstance limited the abilities for valid comparison of MEG and EEG because of the presence of individual and potentially independent sources of oscillatory activity. To determine the degree of functional and temporal connectivity of activity in spatially adjacent sources of different orientation, additional research is needed, including the anatomical localization of required dipoles.

The analysis of differences in β-synchronization sources showed the anterior and medial position of

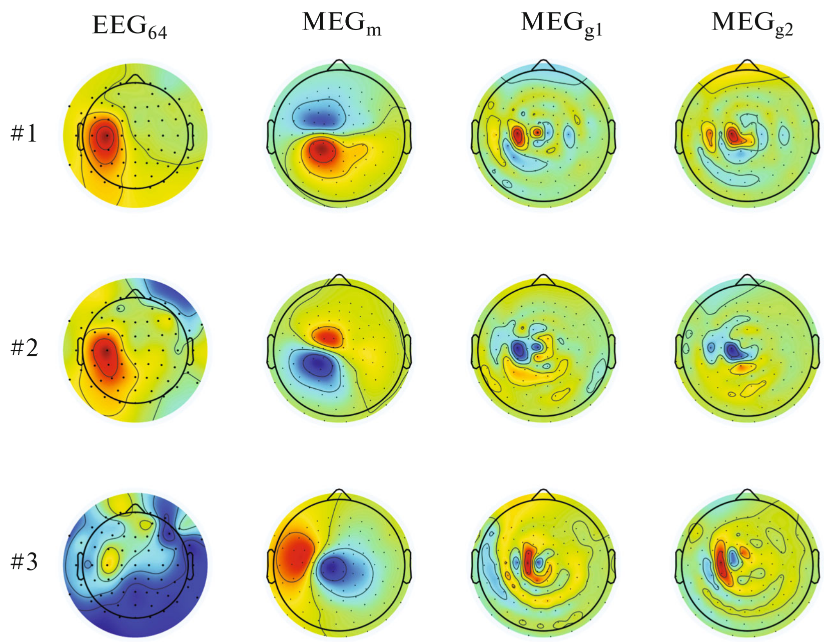

Fig. 2. Spatial filters for β-desynchronization in subject no. seven. The weighting coefficients for sensors of all modalities are marked with color (EEG_{64}, 64-channel EEG; MEG_m, 102 magnetometers; MEG_{g1} and MEG_{g2}, 102 pairs of planar gradiometers). Lines represent the three best spatial filters calculated for combined MEEG modality.

activity source from the source of β-desynchronization for all subjects with prominent short-term synchronization. This is in line with the data of few studies suggesting a similar dissociation in localization [7]. Our results are in conflict with the theory of so-called β-rebound, implying that the synchronization after movement is an overcompensation of earlier suppressed β-rhythm.

Quantitative comparison of desynchronization and synchronization was conducted for spectrograms standardized by the values of prestimulus interval [–1 0] s. The mean values for three types of rhythm modulation and three registration modalities are presented in Table 1. Combined MEEG modality had the highest amplitude of the effect among all modulation types, the differences insignificant for β-synchronization ($F(2, 38) = 0.4599$; $p = 0.8437$) and significant for μ- ($F(2, 38) = 13.6506$; $p = 0.0126$) and β-desynchronization ($F(2, 38) = 31.9386$; $p = 3.246 \times 10^{-6}$).

Pairwise comparisons with Tukey correction discovered statistical differences between MEEG and EEG for μ-desynchronization ($p = 0.0106$) and between MEEG and EEG, MEEG and EEG for β-desynchronization ($p = 1.823 \times 10^{-4}$ and $p = 4.654 \times 10^{-4}$, respectively). To summarize, substantial advantage of combined MEEG modality has been shown for the first time over MEG and EEG individually, the latter demonstrating no statistical difference from each other. In contrast to the study of Illman et al. [13], we did not observe a significant increase in sensitivity of β-synchronization evaluation, possibly due to the differences in tested tasks. In their study, only sensory stimulation was used, which was characterized by poststimulus synchronization, whereas the motor imagery used in our study, often not followed by such synchronization in some of subjects [26]. Probably, during combination of MEEG modalities in the mentioned study [13] a synergistic effect from the modality combination would also be described because of the unique information in MEG and EEG,

Table 1. Mean values of modulation amplitude for the components of sensorimotor rhythm. The mean values are given in decibels ± standard deviation

Type of reaction	MEEG	MEG	EEG
μ-desynchronization	–9.34 ± 1.74	–7.53 ± 2.11 *	–8.74 ± 2.34
β-desynchronization	–9.40 ± 1.38	–7.27 ± 1.97 **	–6.72 ±1.92 **
β-synchronization	5.07 ± 2.43	4.90 ± 2.6	4.74 ± 2.72

* Statistical difference from MEEG, $p < 0.05$; ** same for $p < 0.001$. Paired *t*-test with Tukey correction.

as demonstrated by the Spearman correlation coefficients provided by authors: $\rho = 0.77$ for β-synchronization and $\rho = 0.69$ for desynchronization. If we combine our and their results, it can be proposed that β-synchronization is relatively well presented both in MEG and EEG, while the sources of β-desynchronization have different appearances in magnetic and electric sensors.

Therefore, the results indicated a synergistic effect of the increase in sensitivity to sensorimotor rhythm amplitude modulations, particularly, β-desynchronization. The presence of multiple sources of magnetic β-rhythm and their different conjugacy with the electrical sources suggested independent cortical centers with tangential location of projection fibers. Our data also support the hypothesis of spatial and functional isolation of β-synchronization source. The study conclusions highlight the prospective use of combined MEG and EEG registration to improve the fundamental understanding of the functional role of individual components of cortical rhythms.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

Statement of compliance with standards of research involving humans as subjects. All study procedures were in accordance with the ethical standards of studies involving volunteer subjects and approved by the Ethics Committee of the Moscow State University of Psychology and Education (protocol no. 13, April 12, 2022). Informed consent was obtained from all individual participants involved in the study.

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