

Spatio-temporal source imaging of brain magnetic fields evoked by mental rotation task

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Introduction

Many psychological studies have been carried out on the mental rotation task [1] [2], which requires rotating and matching of a pair of mental imagery. These processes have been shown to activate the parietal region in positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies [3] [4]. These results show the temporal integration of brain activation during the entire mental rotation process, which requires the cooperative interaction of multiple areas in the brain. In the present study, we estimated the dynamic properties of the electrical source distribution in the human brain corresponding to the early mental rotation process based on measurements of brain magnetic fields (magnetoencephalography: MEG). To avoid difficulty in estimating the source distribution associated with higher-order brain functions, including the mental rotation process, due to the lack of detailed a priori information about the generator profile and the noisy measurement conditions, we used a multiple signal classification (MUSIC) algorithm [5], which was able to make use of the spatio-temporal properties of the measured data. Statistical analysis was carried out to detect statistically significant differences in source distribution between the mental rotation task and the control task.

Methods

Mental rotation task

The pair of simple line drawings (mental rotation stimulus) shown in Fig. 1 was presented for 1000 ms in the left and right positions, each separated by a visual angle of 1.5 degrees from a fixation point on the screen.

In the mental rotation task, the subjects were required to discriminate a symmetrical rotation pair (True: 50% probability) from a mirror-image pair (False: 50% probability), and to react by lifting the right index finger (True) or middle finger (False) as soon as possible after a reaction request stimulus that was presented 1500 ms after the onset of the mental rotation stimulus. The angles of rotation were 0, 60, 120, 180, 240, or 300 degrees, and each angle had equal probability. In the control task, subjects alternately lifted the right index or middle finger regardless of the stimulus.

During the mental rotation task and the control task, MEG signals were measured for 2700 ms, including a 200 ms pre-stimulus baseline, using a 122-channel whole-cortex-type DC-SQUID system located in a magnetically shielded room with a sampling frequency of 497 Hz. More than 100 responses were averaged for each task condition after being filtered with an analog bandpass filter (0.03-100Hz).

Subjects were six normal, right-handed volunteers (three females) from 23 to 33 years of age. All subjects had normal or corrected-to-normal vision.

Estimation of source distribution

Let us denote the primary current distribution at time t_i as $\mathbf{p}(t_i) = \{\mathbf{p}_1(t_i), \mathbf{p}_2(t_i), \dots, \mathbf{p}_N(t_i)\}^T$, and the measured brain magnetic field distribution as $\mathbf{f}(t_i) = \{\mathbf{f}_1(t_i), \mathbf{f}_2(t_i), \dots, \mathbf{f}_M(t_i)\}^T$, where N is the number of possible current source locations and M is the number of magnetic sensors. The relationship between \mathbf{f} and \mathbf{p} is described as $\mathbf{f} = \mathcal{L}\mathbf{p} + \mathbf{n}$, where \mathcal{L} is a gain matrix called the lead field matrix and \mathbf{n} is the additive measurement noise.

In the MUSIC algorithm used here, the signal and noise subspaces of the $M \times l$ spatio-temporal measured data matrix $\mathbf{F} = \{\mathbf{f}(t_1), \mathbf{f}(t_2), \dots, \mathbf{f}(t_l)\}$ are separated first using an eigendecomposition of the auto-correlation

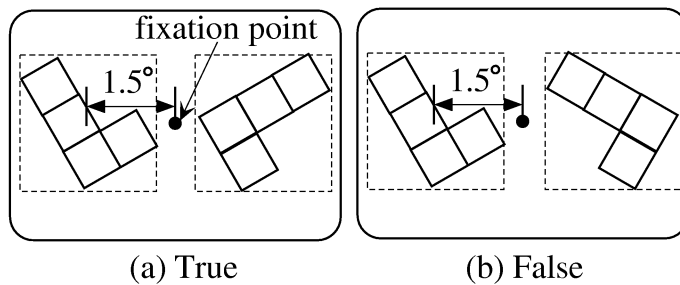


Fig. 1: Example of the visual stimulus for the mental rotation task and the control task, which was presented for 1000 ms in the left and right positions, each separated by a visual angle of 1.5 degrees from a fixation point on the screen.

matrix of \mathbf{F} , where l is the number of time slices considered for the estimation of source distribution. Here, we denote matrices containing signal and noise eigenvectors as \mathbf{V}_s and \mathbf{V}_n respectively. For each scanning grid j located in a head model, we calculated the cost value $S_j = \lambda_{\min} \left\{ \mathbf{U}_{\mathcal{L}_j}^T \mathbf{V}_n \mathbf{V}_n^T \mathbf{U}_{\mathcal{L}_j} \right\}$, where $\mathbf{U}_{\mathcal{L}_j}$ is the principal left eigenvector of \mathcal{L}_j , \mathcal{L}_j is the j -th column of matrix \mathcal{L} , and $\lambda_{\min} \{ \mathbf{A} \}$ is the minimum eigenvalue of matrix \mathbf{A} . S_j becomes 0 at the correct source location when the source is modeled as a set of current dipoles [6], and $1/S_j$ can be used as the criterion of source existence for each grid point location.

Electrical source distributions that related to the mental rotation task and the control task were estimated between the latency period from 100 to 500 ms after stimulus onset using the MUSIC algorithm with a time interval of 2ms. The number of time slices used in each MUSIC estimation (l) was set to 15[slices] (corresponding to about 30 ms in 497 Hz sampling frequency). Student's t-test (significance level: $p < 0.05$) was used to detect statistically significant differences in neural source distribution between the two task conditions at each location of the scanning grid. Grid locations were normalized between subjects in reference to the radius of the spherical volume conductor, which was determined from each subject's MR image and adopted for MEG forward calculation.

Results and Discussion

Typical waveforms of the MEG signals obtained during the mental rotation task and the control task are shown in Fig. 2. This subject showed differences in MEG waveforms between the two tasks over the latency period between 200 and 300 ms in the occipital region and right postero-temporal region.

Fig. 3 shows the estimated source distributions for subjects K.Y. and T.M. during the mental rotation task superimposed on MR images of each subject's head. The size of the dots in each MRI slice indicates the distribution of $1/S_j$, which was used as the criterion of source distribution. The left temporal region was activated during the mental rotation task in subject T.M. (latency: 230-290 ms) and the right lateral posterior region was activated in subject K.Y. (latency: 180-230 ms).

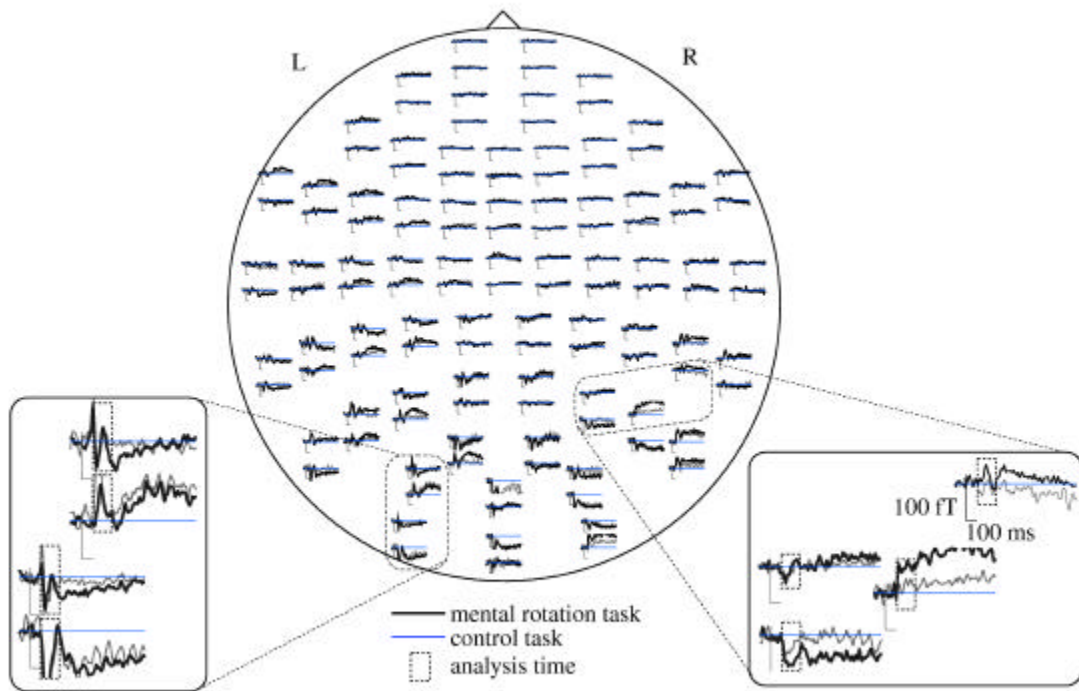
The results of statistical analysis are shown Fig. 4. Statistically significant differences in neural activation between the mental rotation task and the control task were observed in the left temporal region, right parietal region, and primary visual region in the latency period between 200 and 250 ms, as well as in the right parietal region and occipital region in the latency period between 250 and 300 ms.

Conclusion

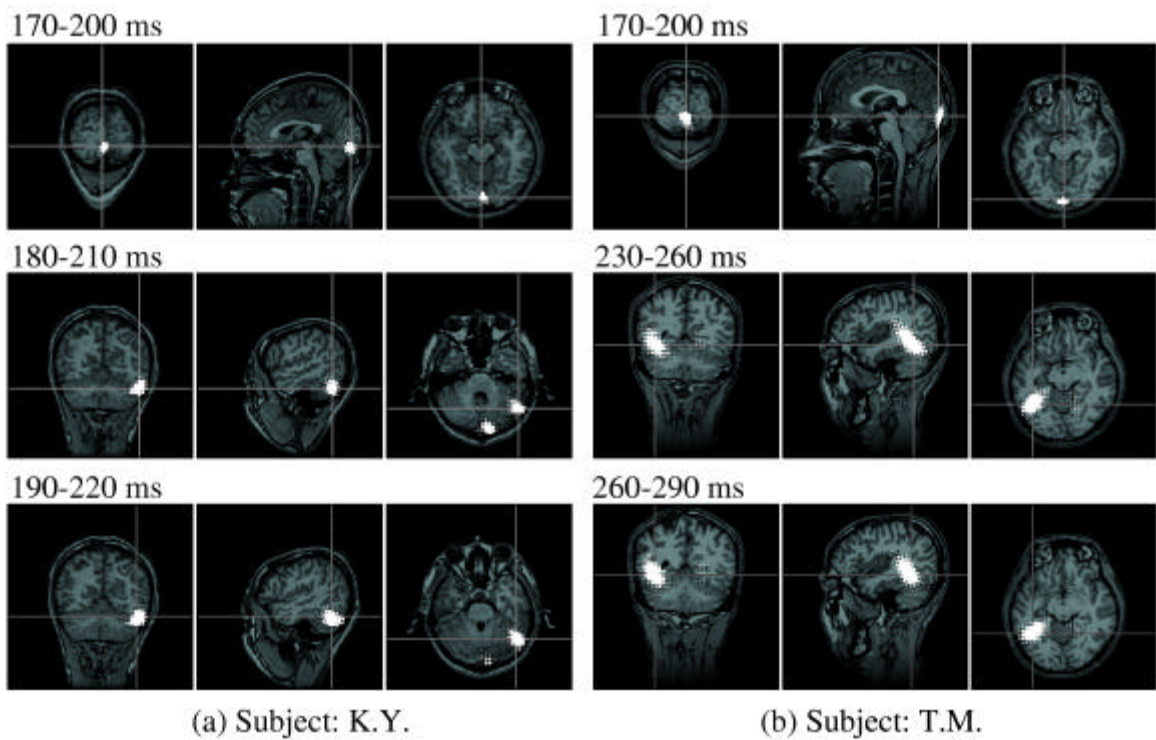
The electrical source distributions in the mental rotation task and the control task were estimated for six subjects in the latency period between 100 and 500 ms after stimulus onset, and the differences in source distribution between the two tasks was assessed by Student's t-test. Statistically significant differences between the two tasks were observed in the left temporal region, primary visual region, and right parietal region in the latency period between 200 and 250 ms, as well as in the right parietal region and occipital region in the latency period between 250 and 300 ms.

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between 200 and 300 ms in the occipital region and right postero-temporal region.



subject K.Y. and the left lateral posterior region was activated in subject T.M.

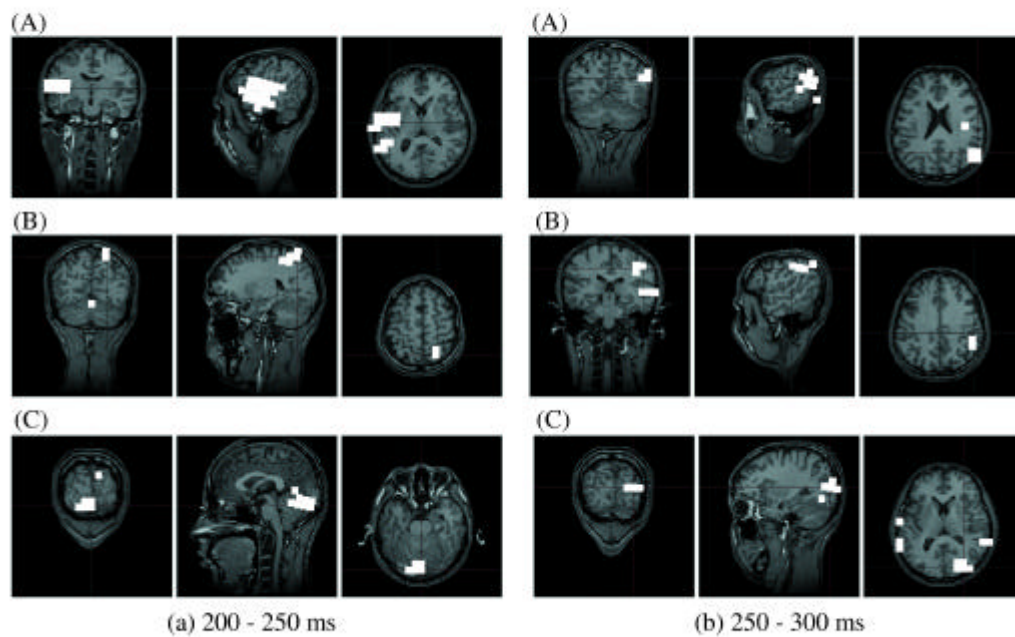


Fig. Brain activation maps for the experimental task and the control task. Statistically significant differences between the two tasks were observed in (A) left temporal region, (B) right parietal region, and (C) primary visual region over the latency range between 200 and 250 ms, as well as in (A)(B) right parietal region and (C) occipital region over the latency range between 250 to 300 ms.

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