Cortical current sources for processing visual target motion revealed by MEG and fMRI

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Abstract

Experiments of a magnetoencephalography (MEG) and an functional magnetic resonance imaging (fMRI) were conducted to reveal the cortical mechanisms related to covert pursuit to a moving visual target. Subject was asked to gaze a fixation point at the center of screen and to track covertly a horizontally moving target. The MEG was measured when the subjects were tracking the target covertly. Current sources of about 7,000 dipoles on the cortical surface were estimated from the MEG data by a hierarchical Bayesian method incorporating the fMRI data. We investigated whether the target velocity can be reconstructed from estimated current sources. One of the datasets was used for training of the weight parameter, and validation tests were conducted using other two datasets. The result showed that target velocities could be reconstructed from the current sources in the cortical areas, related to processing target motion in eye movements, such as primary visual cortex, lateral occipito-temporal cortex, parietal cortex, and prefrontal cortex. This result suggested that these areas were responsible for tracking a moving target, in consistent with previous studies using noninvasive recording of brain function.

1 Introduction

The purpose of smooth pursuit eye movements is successively gazing on a smoothly moving object with the central fovea. It has been known that the main computational goal of smooth pursuit is to minimize the retinal slip, i.e. target velocity projected onto the retina. It has been known that eyes were able to pursue a sinusoidal target motion (its frequency up to around 1Hz) without delays in primates’ smooth pursuit (e.g., in humans [1], in monkeys [2]), whereas there is a significant delay (60ms in monkeys [3], more than 70ms in humans [4]) in the control loop of smooth pursuit. Thus, the central nervous systems of primates predict the target motion for smooth pursuit eye movements [5].

There are many reports that reveal predictive mechanisms for smooth pursuit eye movements by noninvasive functional brain imaging methods, e.g. functional magnetic resonance imaging (fMRI) [6, 7, 8, 9]. But, Cortical activity patterns with millisecond-order temporal resolution related to predictive smooth pursuit eye movements cannot be obtained by fMRI in principle. In contrast, magnetoencepharogram (MEG) can record cortical activities with high temporal resolution. Georgopoulus et al. [10] reported that trajectories controlled by joystick were predicted from signals recorded by 248 MEG channels. The result suggested that MEG signals represented information related joystick trajectories. However, it was not clear which areas were important for predicting joystick trajectory because of small number of MEG channels.

In this study, we analyzed current sources on cerebral cortex with high spatiotemporal resolution, which was estimated by hierarchical Bayesian method [11] incorporating fMRI activities. We conducted an fMRI-based MEG experiment for investigating the neural mechanisms supporting predictive smooth pursuit eye movements and for dissociating neural signals related to prediction from response signals derived from visual inputs. In this experiment, we performed Covert pursuit task in which subject was asked to orient their attention to a target and to pursue the target motion in mind because the electrooculogram (EOG) component contaminates MEG signals when subject’s eyes are moved actually. Note that there is agreement that Covert pursuit is based on common mechanisms with eye movements [12].

2 Methods

2.1 Subject

A healthy male human volunteer with normal vision participated in this study. The subject gave informed consent in writing and the study was approved by the Ethics and Safety Committee of Advanced Telecommunications

Research Institute International (ATR).

2.2 Stimuli and apparatus

MEG recorded for $4096ms$ at $1000Hz$ by 201-channel sensors of whole-head biomagnetic imaging system (Shimazu). A white target (with a diameter of $0.3deg$ and a luminance of $1.30cd/cm^2$) and a red fixation point ($0.3deg$ and $1.68cd/cm^2$) were projected by DLA-G11 (Victor) at a $60Hz$ refresh rate. The screen (a background luminance of $1.30cd/cm^2$) was placed $100cm$ in front of the subject's eyes.

Target motion patterns were generated as output signals of a second order linear system with Gaussian noise were input. The second order linear system was defined in the Laplace domain as

$$H(s) = \frac{\omega^2}{s^2 + \omega^2}, \qquad \omega = 2\pi \tag{1}$$

the pole of $H(s)$ was $s = 0 \pm \omega i$. Therefore the cycle of target motion patterns was about $1Hz$ ($2\pi/\omega$). These parameters were determined through trial and fault for that subject can perform smooth pursuit eye movements to the target. Three patterns were picked up randomly from the signals generated by the second order linear system with Gaussian noise input for our experiment.

2.3 Procedures

Subject sat in front of a projector screen. An MEG dewar was put on the subject's head. His head was held on a chin supporter. Two sessions of covert pursuit task were conducted. In each a session, each target motion pattern was presented at 30-trials respectively, and additional 30 exploratory trials were performed in random order. In each trial, the target was stationary at a center of screen for $100ms$, and moved for $3996ms$. Then, it was extinguished and subject was required their eyes blinked for about $2s$.

2.4 Current source estimation

A baseline correction, drift removal, and invalid sensors/trials removal were applied to the recorded MEG data. Surviving MEG data were collected up with respect to each session and each target pattern, and were used for current source estimation.

The three-dimensional cerebral cortex model was made from the high-resolution MRI structure image by using Brain Voyager (Brain Innovation), and used for current source estimation and result presentation. The number of vertices on the brain surface model was 27513 points.

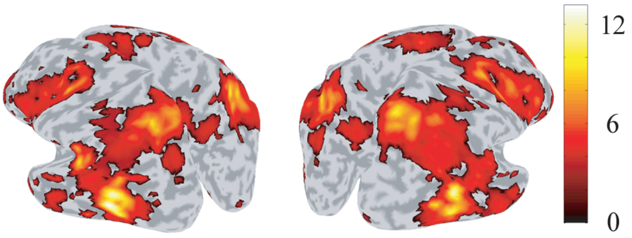

Figure 1: Result of statistical analysis of fMRI data. Color (contrasting density) bar represents magnitude of t-value.

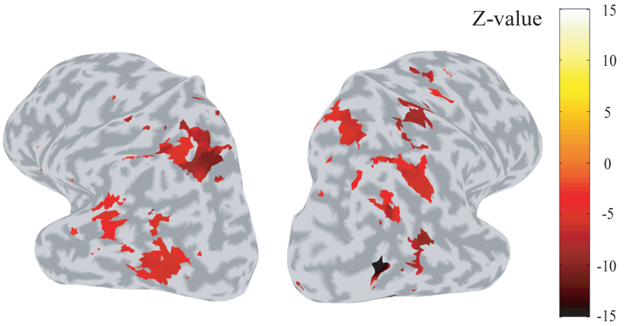

Figure 2: Colored area shows areas in which reconstruction error was significantly smaller than errors calculated from pseudo data.

Cortical areas in which current sources were assumed were decided by the statistical result of the fMRI experiment in which the same task as this MEG experiment was performed. In detail, current sources were assumed at each vertices perpendicular to cortical surface. The areas were significantly activated ($p < 0.001$, uncorrected) when subject pursued a moving target in mind with gazing a fixation point compared with when subject just gazed a fixation point. The fMRI data were analyzed by SPM5 (The Wellcome Department of Cognitive Neurology). This process limited the number of vertices on the surface of cerebral cortex to 7266 points. The statistical result of fMRI experiment was shown in figure-1.

The time courses of current sources were estimated by a hierarchical Bayesian method [11]. In order to apply this method, the leadfield was calculated by a sphere model, a Gaussian filter of 6mm FWHM was applied to spatial filtering, and the fMRI information (t-value) was used as a prior.

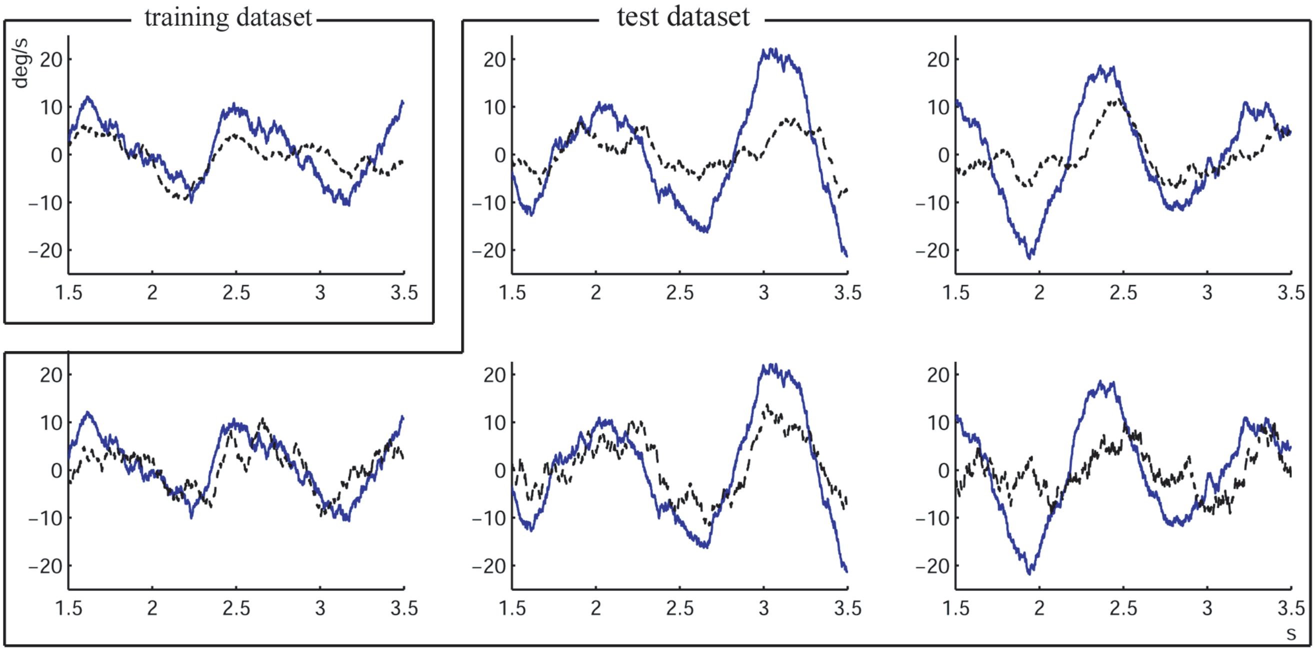

Figure 3: Results of reconstructing target velocities from current time course in right lateral occipito-temporal cortex. Solid and dashed lines denote actual and reconstructed target velocity, respectively. Weight parameters were trained with training dataset.

3 Results

We assumed that current time courses on each vertices x and target velocities y were explained by the following equation with parameter $a_\tau, (\tau = 1, 2, \cdots 150)$, and the parameter a_τ was estimated by using training dataset. The number of 150-parameters was determined through our trial and error process.

$$y_t = \sum_{\tau=1}^{150} a_\tau x_{t-\tau} + \epsilon_t \tag{2}$$

Target velocities were reconstructed from the current time course of test datasets by using the estimated parameters a_τ, and reconstruction error was calculated.

$$\hat{y}_t = \sum_{\tau=1}^{150} a_\tau x_{t-\tau} \tag{3}$$

$$e = \sqrt{\sum_t (\hat{y}_t - y_t)^2} \tag{4}$$

The error e was statistically evaluated by null hypothesis that the current sources could reconstruct any patterns of target velocity. First, fifty pseudo-datasets were prepared by the same way as presented target velocity patterns. Here, the power spectrum of the pseudo target velocities was same as the original target velocities but the patterns were different from the original velocities. Next, Parameters of the pseudo datasets were estimated by the same way as the original datasets. Finally, the reconstruction tests were performed by using the estimated parameters, and reconstruction errors were calculated. We performed statistical test whether the original reconstruction error was statistically smaller than the pseudo reconstruction errors. Here, we assumed that distribution of the pseudo reconstruction errors follows normal distribution, and the original error was transformed into Z-score using the mean and standard deviation of the pseudo-errors. Figure-2 shows areas in which the original error was statistically small [$Z < 3.09$, $p < 0.001$, one-sided, uncorrected for multiple comparison].

Figure-2 shows that the reconstruction errors were significantly small in V1 of right hemisphere, lateral occipito-temporal and intra-parietal cortex of both hemispheres, right pre-central cortex, and left supra-marginal gyrus.

Figure-3 shows reconstructed target velocities from current time course in the right lateral occipito-temporal cortex. This result showed that target velocity was able to be reconstructed from the estimated current in test dataset by using weight parameters estimated in training dataset.

4 Discussions

In this research, we recorded MEG data during covert pursuit task and estimated current sources on cerebral cortex from the MEG data by hierarchical Bayesian method [11] incorporating fMRI data recorded during the same task. We also reconstructed the target velocities from current time course and to perform statistical test for the reconstruction error. The result showed that target velocities were able to be reconstructed from the current in V1 of right hemisphere, lateral occipito-temporal and intraparietal cortex of both hemispheres, right pre-central cortex, and left supra-marginal gyrus.

Previous studies related to Brain Machine Interface (BMI) reported that actions intended by subjects were able to be reconstructed and predicted by the biomedical signals that were brought out from electrodes embedded in the brain or from EEG/MEG channels. However, global cortical activations are hard to be captured by current electrophysiology. Also, signals driven by cortical neurons are mixed and recorded by EEG/MEG channels. In contrast, this study employing a hierarchical Bayesian method showed that the current signals contributing to reconstruction of the target velocities localized in the cortical areas related to processing of target motion in eye movements. This result suggested that these areas were responsible for tracking a moving target, in consistent with previous studies using noninvasive of brain function.

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