NeuroImage 42 (2008) 1397–1413

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Evaluation of hierarchical Bayesian method through retinotopic brain activities reconstruction from fMRI and MEG signals

Taku Yoshioka [a,b,*], Keisuke Toyama [b], Mitsuo Kawato [b], Okito Yamashita [b], Shigeaki Nishina [c], Noriko Yamagishi [a,b], Masa-aki Sato [b]

[a] National Institute of Information and Communications Technology, Japan
[b] ATR Computational Neuroscience Laboratories, Seika, Soraku, Kyoto 619-0288, Japan
[c] Boston University, 64 Cummington, Boston, MA 02215, USA

ARTICLE INFO

Article history:
Received 10 January 2008
Revised 6 June 2008
Accepted 9 June 2008
Available online 21 June 2008

ABSTRACT

A hierarchical Bayesian method estimated current sources from MEG data, incorporating an fMRI constraint as a hierarchical prior whose strength is controlled by hyperparameters. A previous study [Sato, M., Yoshioka, T., Kajihara, S., Toyama, K., Goda, N., Doya, K., Kawato, M., 2004. Hierarchical Bayesian estimation for MEG inverse problem. Neuroimage 23, 806–826] demonstrated that fMRI information improves the localization accuracy for simulated data. The goal of the present study is to confirm the usefulness of the hierarchical Bayesian method by the real MEG and fMRI experiments using visual stimuli with a fan-shaped checkerboard pattern presented in four visual quadrants. The proper range of hyperparameters was systematically analyzed using goodness of estimate measures for the estimated currents. The robustness with respect to false-positive activities in the fMRI information was also evaluated by using noisy priors constructed by adding artificial noises to real fMRI signals. It was shown that with appropriate hyperparameter values, the retinotopic organization and temporal dynamics in the early visual area were reconstructed, which were in a close correspondence with the known brain imaging and electrophysiology of the humans and monkeys. The false-positive effects of the noisy priors were suppressed by using appropriate hyperparameter values. The hierarchical Bayesian method also was capable of reconstructing retinotopic sequential activation in V1 with fine spatiotemporal resolution, from MEG data elicited by sequential stimulation of the four visual quadrants with the fan-shaped checker board pattern at much shorter intervals (150 and 400 ms) than the temporal resolution of fMRI. These results indicate the potential capability for the hierarchical Bayesian method combining MEG with fMRI to improve the spatiotemporal resolution of noninvasive brain activity measurement.

Introduction

Magnetoencephalography (MEG) directly measures the magnetic fields caused by neural current activity, with a high temporal resolution. Its spatial resolution, however, is poor because of the ill-posed nature of the inverse problem of estimating source currents from magnetic fields (Nunez, 1981). Therefore, prior information on source currents is essential in solving the inverse problem. Different types of methods have been proposed for reconstructing source currents with prior information.

On the basis of the observation that the principal source of MEG signals is postsynaptic current flow in pyramidal cells, the source currents creating MEG signals are often modeled as current dipoles (Hamalainen et al., 1993). Inverse procedures for estimating source currents from MEG signal are classified by how the current dipoles are defined. Equivalent current dipole (ECD) methods approximate the source currents by a small number of current dipoles (Aine et al., 2000; Hari, 1991; Miltner et al., 1994; Mosher et al., 1992; Scherg et al., 1999). The positions and orientations of the current dipoles are estimated with the current amplitudes from the MEG signals. Because of the assumption of a restricted number of current dipoles, ECD methods do not provide a fine spatiotemporal pattern of neural current activity.

On the other hand, distributed source methods assume a large number of current dipoles with fixed positions and orientations. Once the positions and orientations are fixed, the current amplitudes of the dipoles and the induced magnetic fields have a linear relationship. This is referred to as the forward model. On the basis of the linear relationship of the forward model, distributed source methods estimate the

* Corresponding author. National Institute of Information and Communications Technology, 2-2-2 Hikaridai, Seika, Soraku, Kyoto 619-0288, Japan. Fax: +81 774 95 1259.
E-mail address: taku-y@atr.jp (T. Yoshioka).

1053-8119/$ – see front matter
doi:10.1016/j.neuroimage.2008.06.013

current amplitudes of the dipoles. Since the number of current dipoles in a distributed source method is often much larger than the number of MEG sensors, estimation of the dipole currents is an ill-posed problem. A number of methods such as the minimum norm method (Hamalainen and Ilmoniemi, 1994; Wang et al., 1992), the maximum smoothness method (Pascual-Marqui, 1999; Pascual-Marqui et al., 1994) and the minimum L1-norm method (Uutela et al., 1999) have been introduced to solve the ill-posed inverse problem. In addition, MRI and fMRI measurements have been used to provide anatomical and functional constraints (Dale et al., 2000; Dale and Sereno, 1993; Kajihara et al., 2004; Liu et al., 1998; Phillips et al., 2002; Schmidt et al., 1999). The anatomical constraint (MRI) provides information on the positions and orientations of the current dipoles according to the cytoarchitectonic knowledge that the cortical pyramidal cells are arranged in the gray matter perpendicular to the cortical surface (Dale and Sereno, 1993). The functional constraint (fMRI) gives information on the relative amplitudes of the dipole currents (Dale et al., 2000; Kajihara et al., 2004; Liu et al., 1998).

We previously proposed a hierarchical Bayesian framework for the distributed source method, in which fMRI information is introduced as a hierarchical prior of the variance for each dipole current (Sato et al., 2004). Since the prior current variances are estimated from MEG and fMRI data, our method is theoretically tolerant with respect to false-positive signals contained in the fMRI data. Our simulation study confirmed that the hierarchical Bayesian method gives much more precise estimation than the conventional methods, and that it is, in fact, tolerant with respect to false-positive prior information in fMRI signals.

In the hierarchical Bayesian method, the strength of the fMRI constraint can be controlled by the hyperparameters of the hierarchical prior. In the previous study, we used a non-informative prior, in which the fMRI information is incorporated only as the initial values of the prior current variances. We consider such a weak fMRI constraint to give a good estimation when all of the assumptions in hierarchical Bayesian estimation are correct and an accurate forward model is obtained. In the previous study, we actually used the same forward model for calculating the artificial MEG data and for estimating the dipole currents from those data.

The hierarchical Bayesian method is based on a number of assumptions: spatial sparseness and smoothness of the dipole currents, Gaussian observation noise, accurate cortical surface model from MRI, accurate coregistration between MEG and MRI coordinates, and so on. Since these assumptions may be violated in real data, using fMRI data for constraints would give better estimation accuracy. MEG and fMRI measurements, however, can be contradictory because of the intrinsic difference in measurement principles (Bandettini, 2000; Belliveau et al., 1991; Logothetis et al., 2001; Ogawa et al., 1990). In addition, it is practically impossible to conduct MEG and fMRI measurements under exactly the same conditions, including the experimental design and the apparatuses for the experiments. Therefore, the strength of the functional constraint must be appropriately controlled by tuning the hyperparameters. The proper range of the hyperparameters must be limited for practical application of the proposed method.

In the current study, we tested how well the hierarchical Bayesian method can estimate neural activities and evaluated the effect of the hyperparameters on estimation results with real data. To do this, we conducted MEG and fMRI experiments with visual stimuli presented in four visual quadrants. Although the true spatiotemporal pattern of the cortical activity is unknown, the functional localization and temporal patterns of neural activities have been well studied by fMRI (Dougherty et al., 2003; Tootell et al., 1997; Sereno et al., 1995). The temporal patterns of neural activities have also been investigated by ECD methods with the help of fMRI information (Ahlfors et al., 1999; Di Russo et al., 2001, 2005; Vanni et al., 2001, 2004). On the other hand, the estimation of the neural activities of early visual areas, with fine spatiotemporal resolution, is considered difficult for distributed source methods with anatomical constraints, because of the complex anatomical structure of the early visual areas. Therefore, our visual experiment provides a good testbed for evaluating our method.

To evaluate the proper range of hyperparameters, we introduced goodness measures for the spatial and temporal patterns of the estimated currents. The robustness with respect to false-positive activities in the fMRI information was also evaluated by introducing noisy priors, which were constructed from correct priors (i.e., real fMRI data) by adding artificial false-positive activities. We found the proper ranges of hyperparameters for correct and noisy priors. Our estimation results with appropriate hyperparameter values, which were in the proper range, showed the retinotopic organization and temporal dynamics in the early visual areas, consistent with previously reported physiological findings.

We further applied our method to MEG data elicited by a pseudo-rotatory visual stimulus, in which four quadrantal visual stimuli were sequentially presented with a stimulus onset asynchrony (SOA) of 400 or 150 ms, either of which is much shorter than the temporal resolution of fMRI. The estimation results showed retinotopic sequential activation in V1 with fine spatiotemporal resolution.

Materials and methods

Experiments were conducted on four healthy subjects (ages 23–30, three males and one female). All subjects gave written informed consent for the experimental procedures, approved by the ATR Human Subject Review Committee. All subjects had normal or corrected-to-normal visual acuity and normal visual fields and color vision.

Visual stimuli and apparatuses

In both the fMRI and MEG experiments, the visual stimuli had the same characteristics, in terms of shape, color, luminance and subtended angle, but the temporal sequences for stimulus presentation were optimized for each technique. The stimuli were presented in four visual quadrants: upper right (UR), lower right (LR), lower left (LL), and upper left (UL). The stimuli consisted of a physically isoluminant red and green checkerboard pattern (subtended angle, 7°; CIE coordinates, [0.346, 0.299] for red and [0.268, 0.336] for green; luminance, 26 cd/m^2) on a gray background with the same luminance (subtended angle, 10°×8°; CIE coordinate, [0.186, 0.455]; Fig. 1a). Gaps (subtended angle 1°) were inserted to facilitate separability of the cortical activities around the calcarine sulcus. A small circle was displayed on the center of the background (subtended angle, 0.1°) as a fixation point. The visual stimuli were generated using a PC and VSG2/5 (Cambridge Research Systems, UK).