International Journal of Bioelectromagnetism *www.ijbem.org*
Vol. 11, No. 4, pp.150-154, 2009

Reconstruction of Time Correlations among Multiple Oscillatory Neural Activitiesby Beamformer Analysis to MEG

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Abstract. We studied the applicability of Beamformer analysis to MEG to estimate multiple sources and to reconstruct their time correlations to determine coordinated multiple signal sources during higher brain activities such as working memory acquisition. We conducted a simulation study to reconstruct source positions and time correlations of alpha-band oscillations in three different regions of the brain. Our result showed that Beamformer analysis can estimate positions of dipole sources with an error of less than 2 cm and reconstruct their time correlations with a difference of less than 9.4% at a typical experimental signal-to-noise ratio (5.0), when all the time correlations among three sources are different from each other. Even when time correlations are identical in two of the three sources, Beamformer analysis can reconstruct the time correlations of dipoles with a difference of less than 23.7%, however, the error of the estimated source positions will exceed 2 cm. These results suggest that Beamformer analysis is a useful tool in reconstructing varieties of time correlations among multiple sources. The Beamformer estimation on MEG might provide unique information about time correlations among multiple neuronal sources, which is not available in other brain imaging modalities such as fMRI and PET.

Keywords: MEG, Beamformer Analysis, Working Memory, Alpha Band Oscillation, TIme Correlation

1. Introduction

Many researches use different brain imaging modalities to elucidate the information processing flow of the brain. Working memory (WM) is a type of memory activity, which is an active short-term memory associated with neural activity in multiple regions of the brain for object-based tasks and performance of work. Recent experimental work on WM-related neural activity has focused on alpha-band oscillations in specific regions of the brain. An electroencephalogram (EEG) study has shown that alpha-band oscillations increase in the posterior and bilateral central regions of the brain [Jensen et al., 2002]. A magnetoencephalogram (MEG) study has shown that alpha-band oscillations increase in the occipital, right temporal, left prefrontal regions of the brain [Dowaki et al., 2008]. This evidence shows that alpha-band oscillations in specific regions of the brain play an important role in working memory processing. It also suggests that coordinating activities of those oscillations might be another important function for WM processing. To observe the neural activity associated with coordinated multiple signal sources, their time correlations need to be determined. However, time correlations among alpha-band oscillations in different regions of the brain have not been examined yet. A Beamformer analysis will make possible accurate estimations of dipole positions, from which we will be able to deduce time correlations among multiple sources.

Beamformer analysis has already been applied to various types of MEG reconstruction problems, even in applications in which sources are temporally correlated. For more accurate spatio-temporal estimation of correlated sources, an eigenspace-projection Beamformer analysis has been developed from Borgiotti-Kaplan Beamformer, which produces better source reconstructions than the ordinary minimum-variance Beamformer analysis. [Sekihara et al., 2001]

The purpose of our research is to test the concept that the eigenspace-projection Beamformer analysis can also be applied to MEG during WM task, such as Sternberg task, since MEG has an advantage of good temporal resolution to provide information on the time-courses of dipoles in detail. We therefore have conducted a simulation study of WM-related MEG models to test the applicability of Beamformer analysis for estimating multiple sources and reconstructing their time correlations to determine coordinated multiple signal sources in experimental MEG during WM task.

2. Method

We applied the eigenspace-projection Beamformer analysis [Sekihara et al., 2001] to 2 models of WM-related MEG that assume dipole-like signal sources in different locations of the brain (Fig. 1). We set four different conditions of time correlation among the sources in each model (Fig. 2) The sensor geometry was the same as the whole-head MEG system with a 204-ch. gradiometer (Vectorview; Elekta Neuromag). Three sources are assumed. They are located in the right prefrontal lobe, the left temporal lobe, and the left occipital lobe in model 1 and in the left prefrontal lobe, the left temporal lobe, and the right occipital lobe in model 2 (see Fig. 1 (a) and (b)). All the correlations among the three time correlations of the sources were assumed to be different under conditions 1 and 2, and two of the three correlations were assumed to be identical under conditions 3 and 4 (See Fig. 2 (a), (b), (c) and (d)). As relatedness of alpha-band oscillations in different regions of the brain during WM-related neural activity is still unknown, we produced 4 different conditions of relatedness. We assumed dipole 1 was either strongly or weakly correlated with dipole 2 and we independently assumed it was either strongly or weakly correlated with dipole 3. MEG signals were multiplied by a sinusoidal wave with frequency of 0.33 Hz, and random noise of 20 percent was added to the signals.

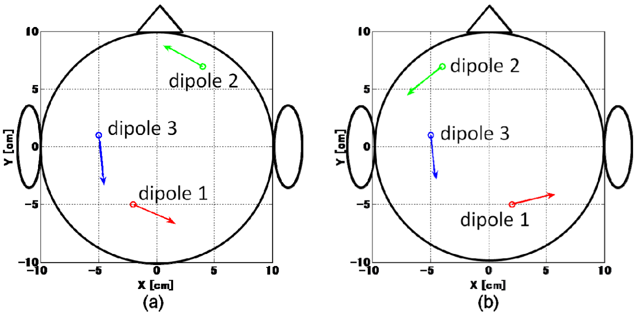

Figure 1. *Positions of signal sources used in the simulation. Dots and arrows show locations and moments, respectively. (a) Assumed dipole moments of simulation model 1. (b) Assumed dipole moments of simulation model 2.*

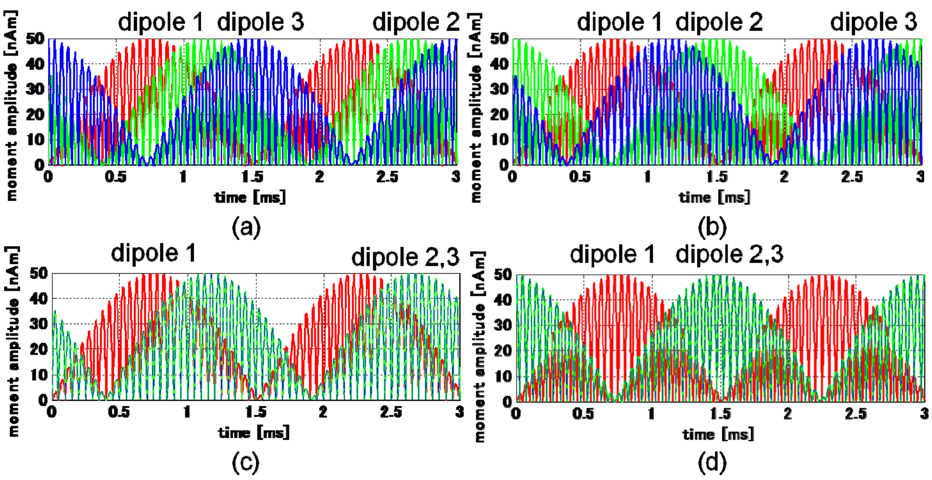

Figure 2 . *Representation of assumed time correlation among signal sources. (a) The time courses of assumed dipole strength under condition 1 (All the time correlations are different). (b)The time courses of assumed dipole strength under condition 2 (All the time correlations are different). (c) The time courses of assumed dipole strengths under condition 3 (Two of the time correlations are identical). (d) The time courses of assumed dipole strengths under condition 4 (Two of time correlations are identical).*

We used Eq. 1 to calculate time correlation between two signal sources (source ***a*** and source ***b***), and used Eq. 2 to evaluate the accuracy on the estimation of position.

$$\boldsymbol{Corr}.\left(s^{a}(t), s^{b}(t)\right)\ [\%] = \frac{100 * \sum_{i} s^{a}(t_i) \cdot s^{b}(t_i)}{\sqrt{\sum_{i}\left(s^{a}(t_i)\right)^2} \cdot \sqrt{\sum_{i}\left(s^{b}(t_i)\right)^2}} \tag{1}$$

where

$\mathbf{s}^{a}(\mathbf{t}_i)$ = signal of source a at $\mathbf{t}_i$
$\mathbf{s}^{b}(\mathbf{t}_i)$ = signal of source b at $\mathbf{t}_i$

$$\Delta r_i^{est} = \left\| r_i^{simu} - r_i^{est} \right\|_2 \tag{2}$$

where

$\Delta\, \mathbf{r}_i^{est}$ = error of estimated position of dipole i
$\mathbf{r}_i^{simu}$ = position of dipole i in the simulation model ($\mathbf{r}_i^{simu}$=[x_i^{simu}, y_i^{simu} ,z_i^{simu}])
$\mathbf{r}_i^{est}$ = position of dipole i in the estimated result ($\mathbf{r}_i^{est}$=[x_i^{est}, y_i^{est} ,z_i^{est}])

3. Results

Here, we present the results of simulation model 1. Fig. 3 shows the estimated sources at t = 1.5 (s) under condition 2 (Fig. 3 (a)) and 4 (Fig. 3 (b)). When two identical time correlations did not exist, all the dipoles were estimated correctly. However, if two identical time correlations existed, one source was estimated correctly but positions of the other two sources were distorted and could not be estimated.

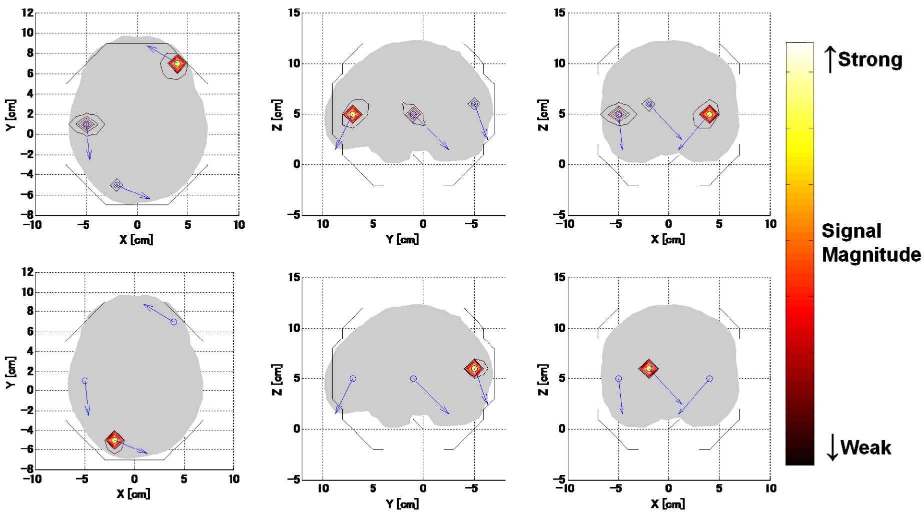

Figure 3. *Source localization results of time-correlated sources using Beamformer analysis. Dots and arrows show assumed locations and moments of sources, respectively. (a) Estimated sources at t = 1.5(s) when two identical time correlations did not exist. (b) Estimated sources at t = 1.5(s) when two identical time correlations existed.*

Table 1 shows the assumed and estimated time correlations among three sources and Fig. 4 shows the time-courses of assumed and estimated strengths of the dipoles under conditions 2 (Fig. 4 (a)) and 4 (Fig. 4 (b)). As positions of dipoles 2 and 3 were not estimated when two identical time correlations existed, we used dipole strengths at assumed positions of dipoles 2 and 3 to calculate temporal correlation among sources for condition 4. The amplitudes of dipole signals were normalized as the Beamformer analysis normalizes the lead field vector and does not reconstruct the strength of the original dipoles. [Sekihara et al., 2001]

Table 1. Assumed and estimated time correlations among three sources

Identical Time Correlations	*Dipole Pair*	*Assumed(%)*	*Estimated(%)*	*Difference(%)*
Do not exist.(condition 2)	(dip.1, dip.2)	40.59	48.74	+8.15
Do not exist. (condition 2)	(dip.1, dip.3)	79.25	81.28	+2.03
Do not exist. (condition 2)	(dip.2, dip.3)	53.04	59.33	+6.29
Exist. (condition 4)	(dip.1, dip.2)	40.59	60.01	+19.42
Exist. (condition 4)	(dip.1, dip.3)	40.59	63.02	+22.43
Exist. (condition 4)	(dip.2, dip.3)	100.00	88.79	-11.21

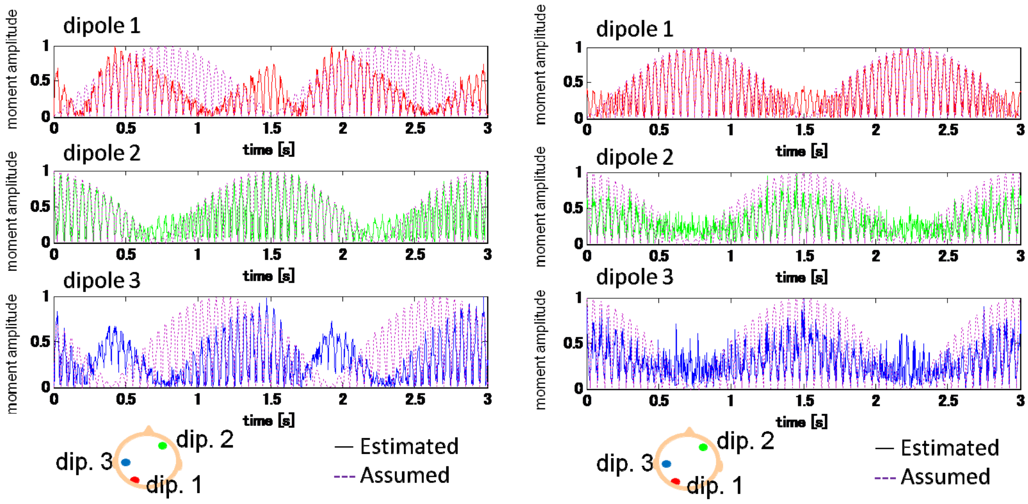

Figure 4. *Reconstruction of time courses of time-correlated sources using Beamformer analysis. (a) The time-courses of assumed and estimated dipoles strengths when two identical correlations do not exist. (b) The time-courses of assumed and estimated dipoles strengths when two identical correlations exist.*

The results showed that time correlations among sources could be reconstructed with the maximum error of 22.43% even if two identical temporal correlations existed.

Through all the simulation results, the maximum error of source position was 2 cm and the maximum difference of temporal correlation was 9.4% when two identical temporal correlations did not exist (condition 1 and 2). The difference between the two different conditions was small. The maximum difference under condition 1 was 9.4% whereas that of condition 2 was 8.15%. However, two of three source positions were distorted and the maximum difference of temporal correlation was 23.71% when two identical temporal correlations existed (condition 3 and 4). The difference between the two different conditions was large. The maximum difference under condition 3 was 5.34% whereas that of condition 4 was 23.71%.

4. Discussion

We found that positions of multiple sources were estimated properly and their time correlations were reconstructed reasonably by the eigenspace-projection Beamformer analysis when all the time correlations were different. Even when time correlations of some of the sources are identical, Beamformer analysis can estimate correlations of the sources, but in that case the estimated positions of sources are distorted. If identical time correlations among sources exist, combining MEG and other brain-imaging modalities with higher spatial resolution, such as fMRI, would be appropriate to accurately reconstruct both time correlations and locations of multiple sources.

5. Conclusions

We have examined the applicability of Beamformer analysis for the estimation of multiple sources and the reconstruction of their time correlations by conducting a simulation study to determine coordinated multiple signal sources during higher brain activities such as working memory acquisition. The estimation of sources and the reconstruction of their time correlations are in sufficient agreement with the simulation model when all the time correlations are different. However, both of them, especially the estimation of multiple sources, are not in sufficient with the simulation model when two of the time correlations are identical.

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