Joint analysis of multichannel magnetoencephalogram data using multivariable autoregressive models

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1. Introduction

In this work, joint analysis of the whole-head magnetoencephalogram (MEG) measurements of subjects performing periodic finger-tapping task were conducted to investigate the effective connectivity of the different areas in the brain. Multivariable autoregressive modeling was used in the analysis. The applications of autoregressive techniques to the analysis of biological signals have been successfully demonstrated in a number of published works[1-3]. Results indicate that some regions exhibited effective connection to other areas only in a fraction of time within the cycle of the periodic tapping. The connection disappears in some other times within the tapping cycle.

2. Data analysis

The data used in the analysis were neuromagnetic fields recorded from a subject performing a periodic tapping task using a 122-channel SQUID planar gradiometer system (Neuromag 122; Neuromag, Helsinki). In this system, 122 channels are located at 61 sites with two channels each measuring the longitudinal (odd channel numbers) and the latitudinal (even channel numbers) components of the orthogonal tangential derivatives of the magnetic field. Every ground contact of the tapping finger was also recorded using photoelectric sensor (Keyence, Japan). The time of contact is used as the reference event.

In the experiment, the subject was seated in a nonmagnetic armchair in a magnetically shielded room (Amuneal Lit. USA). Following a signal cue, the subject started right-index-finger tapping in synchronous with a series of 30 auditory pulses (500 Hz tone) separated by an interval of I_p = 600 ms. This is the *paced mode* part of the experiment. At the end of the last auditory pulse, the subject was instructed to continue tapping at the established fixed rate for the *non-paced mode* part of the experiment. Two sets of MEG data were obtained, that of the paced mode and that of the non-paced mode.

In the analysis, vector autoregressive models were used. The model is given by the following equation:

$$X_n = A_1 X_{n-1} + A_2 X_{n-2} + \cdots + A_M X_{n-M} + \varepsilon_n ,$$

where X_n is a d-dimensional vector, d = 61 corresponding to the 61 sites where MEG measurements were made, the A_i's are the coefficient matrices that need to be estimated using the available data, M is the order of the model, and ε is white Gaussian noise. To estimate the coefficient matrices, the following iterative scheme[4] was used: For $m = 1,\ldots,M$ and $r = 1,\ldots,m$

$$\gamma_{mr} = \frac{1}{N}\sum_{n=1}^{N} X_{n-m} X_{n-r}^{T}$$

$$\beta_{m} = \frac{1}{N}\sum_{n=1}^{N} X_{n} X_{n-m}^{T}$$

$$\alpha_{mr} = \left[\sum_{j=1}^{r-1} \alpha_{mj}\alpha_{rj}^{T} - \gamma_{mr}\right] N_r^{-T}$$

$$B_{m} = \left[\beta_m + \sum_{r=1}^{m-1} B_r \alpha_{mr}^{T}\right] N_m^{-T}$$

$$N_m N_m^{T} = \gamma_{mm} - \sum_{r=1}^{m-1} \alpha_{mr}\alpha_{mr}^{T}$$

The original coefficient matrices A_m can be computed using the relation:

$$A_m = \sum_{r=m}^{M} B_r N_r^{-1} W_r$$

where

$$W_m = 1$$

$$W_r = \sum_{i=m}^{r-1} \alpha_{ri} N_i^{-1} W_i$$

for $r = m + 1, \ldots, M$.

The MEG data were pre-processed as outlined in Fig. 1. The whole data set is therefore composed of 145 realizations (segments) for each of the 122 channels with an effective length of 2401 data points. Autoregressive analyses were carried out on a sliding time window 100 points in width and with a 50-point overlap.

3. Results and Discussion

To obtain the order of the model, we used Akaike's information criterion (AIC) [5]. Figure 2 shows the AIC as a function of model order. The AIC is minimum when the order is equal to 3. Multivariable autoregressive models of order 3 were then used in the succeeding analyses.

To investigate the effective connectivity of the different sites, the estimated coefficient matrices for each time window were examined. In particular, we looked at the effective connection of site 31 in terms of the values of the estimated coefficient matrices. The significance of the connection of other sites to site 31 can be inferred from the values of the 31st row of the coefficient matrix. On the other hand, the significance of the connection from site 31 to the other sites is given by the values of the 31st column of the coefficient matrix. The absolute values of these quantities as functions of time are shown in the color-coded Fig. 3. The x-axis represents the site number while the y-axis is the time axis. The color code represents the absolute value of each element in the 31st row and column of the coefficient matrix. From the figure, it can be observed that there are only few sites that interact with site 31. Moreover, the interactions are functions of time, that is, a strong interaction can be observed only in a fraction of the tapping cycle. Figure 4 shows the different sites affecting site 31. The encircled sites are those affected by site 31 while the sites with squares are those affecting site 31.

Although the results obtained are based only on a linear model, these results can unravel how the different areas in the brain interact to achieve a specific task, in this case, the index finger tapping. The results can also serve as a starting point to further analyse the effective connection of the different areas in the brain.

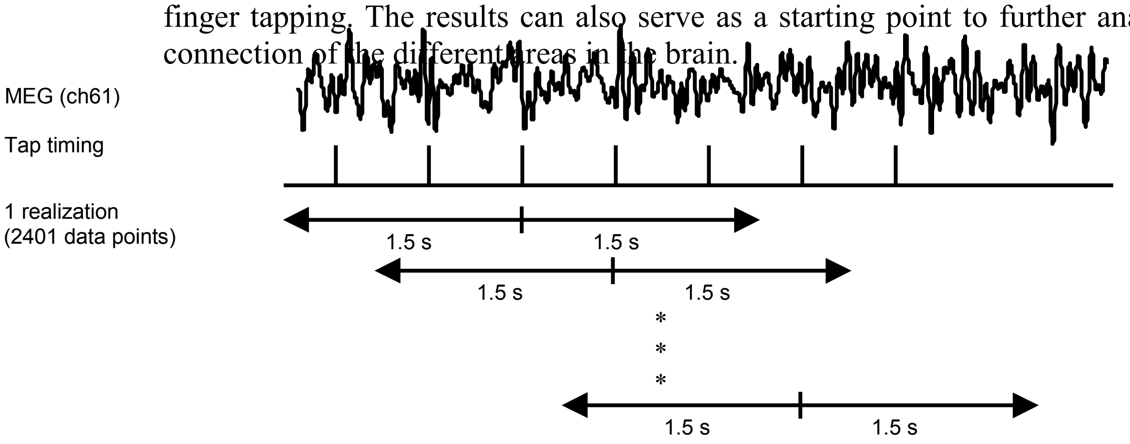

Fig. 1. Preprocessing of the MEG data. The whole-head MEG data was divided into segments 3 s long, 1.5 s before and 1.5 s after each tap. Each segment is composed of 2401 data points and is considered as one realization of a random process. This gives a total 145 segments (realization).

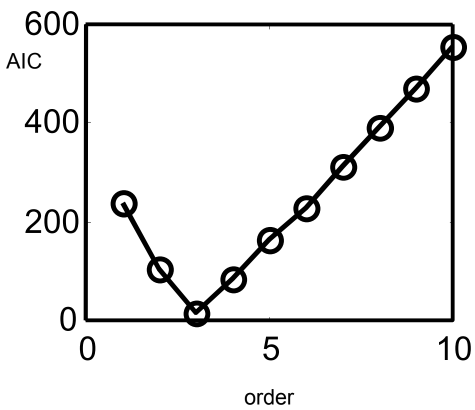

Fig. 2. The AIC, as a function of the model order, is minimum when the order is 3.

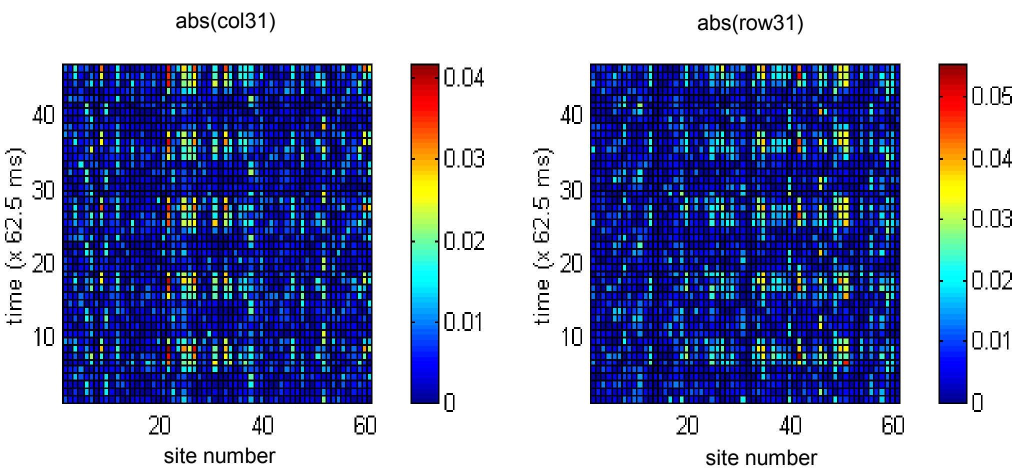

Fig. 3. The absolute values of the elements of column 31 and row 31 of the estimated coefficient matrix A_1. The x-axis represents the column (row) number and the y-axis is the time axis. See text for a detailed discussion.

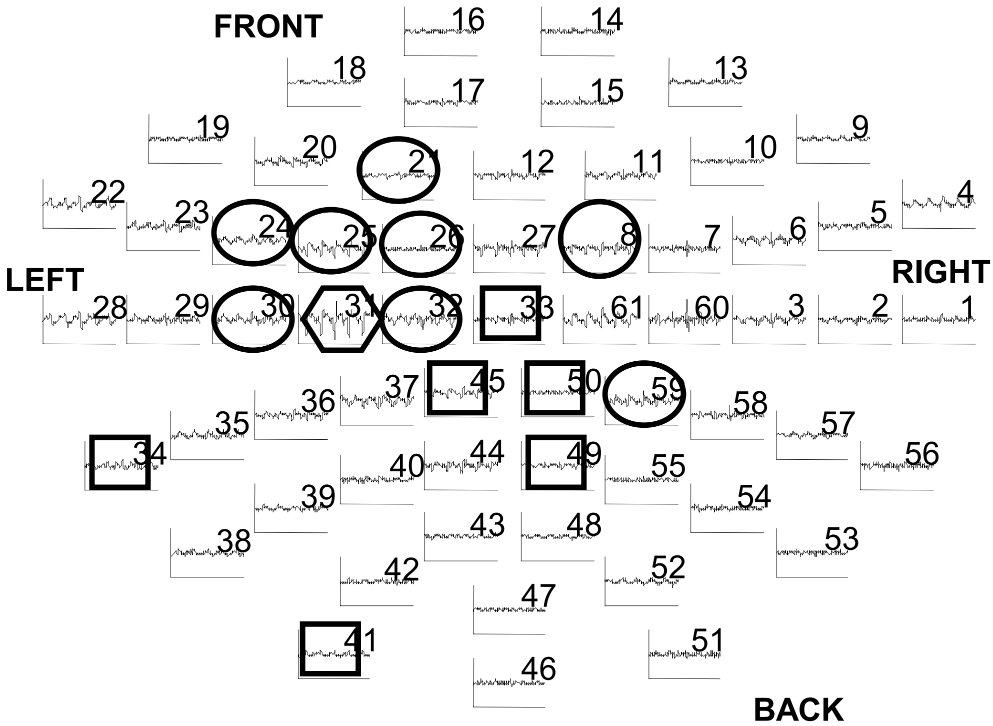

Fig. 4. Sites affecting site 31. The sites with circles are the sites influenced by site 31. The sites with squares are those affecting site 31.

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