2004 International Symposium on Nonlinear
Theory and its Applications (NOLTA2004)
Fukuoka, Japan, Nov. 29 - Dec. 3, 2004

Neocortical dynamics detected by steady-state multisensory evoked neuromagnetic fields

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Abstract–Steady-state evoked neuromagnetic fields (SSEFs) obtained by visual, auditory and somatosensory stimuli presented simultaneously were measured and analyzed to study human neocortical dynamics related to perceptual dominance among different sensory stimuli. The SSEFs could be extracted with a combination of principal component analysis and band-pass filtering. The time-frequency/scale structures of the extracted SSEFs were analyzed by short-time Fourier transform and continuous wavelet transform. It was found that the amount of power at the presented frequency for each sensory stimulus was unstable and relatively large while the other was small. The results demonstrate that analysis of the temporal structure of SSEFs may be a promising approach to reveal human neocortical dynamics.

1. Introduction

How does the brain work? What mechanisms in the brain are associated with mind? Are the human brains special? These questions have long attracted our attention over many centuries. An important step to answer these questions is obtaining knowledge about dynamic processes underlying certain brain activities such as perceptions, cognitive behaviors and movements. Recent advances in functional neuroimaging techniques made its study possible.

Magnetoencephalography (MEG) is a useful noninvasive functional neuroimaging technique for investigating human brain neocortical activities. In MEG, very weak cerebral magnetic fields generated by ionic currents flowing inside dendrites of neocortical neurons can be detected by a SQUID (superconducting quantum interference device) system.

A rapid change in a sensory stimulus evokes transient electro/magnetic physiological responses. If this change occurs repetitively at a frequency high enough to prevent the transient response from returning to a baseline state, an oscillatory response, known as a steady-state response, is evoked [1-3]. To investigate brain mechnisms of sensory awareness, we have measured and analyzed the oscillatory steady-state evoked neuromagnetic fields (SSEFs) when multimodal sensory stimuli were presented simultaneously.

2. Measurements

A 68-channel whole-cortex MEG system (CTF Systems, Inc.), with 68 first-order gradiometers, was used. The MEG system measures the normal component of the neuromagnetic field to the sensing coil plane. Using the reference system and a software, the sensor outputs were translated into the ones measured by the third-order gradiometers [4]. Each gradiometer had a baseline of 5 cm and a coil diameter of 2 cm.

Visual, auditory and somatosensory stimuli were presented simultaneously to obtain SSEFs as shown in Fig. 1. Flickering light was presented to the left and right eyes. Click noise sound was presented to the left ear vir air tube. Mechanical vibration was presented to the tip of the right index finger.

The SSEFs over the whole cortex of four healthy male subjects were measured in an unshielded. Flickering light, click noise sound and vibrating mechanical stimuli were presented at 7, 17 and 22 Hz, respectively. Presented frequency in each modality was determined in a preliminary experiment in a subject.

The MEG data of 60 s were recorded by on-line analogue filtering with a bandwidth of 0-300 Hz. The sampling frequency of the data acquisitions was 1250 Hz.

Fig.1 Steady-state multisensory evoked neuromagnetic fields were measured simultaneously by a whole-cortex MEG system.

3. Analytical Methods

In order to extract oscillatory SSEFs, principal component analysis (PCA) [5] was employed in this study. Eigenvector of each PC could be interpreted as representing spatial distribution of independent neuromagnetic fields [6]. PCA could be replaced with independent component analysis (ICA), since general principle of the extraction is utilization of coherence among measured fields at all sensing coil locations.

3.1. Extraction of SSEFs

The neuromagnetic fields measured by a whole-cortex MEG system in each measurement trial are expressed by a matrix **B**, which consists of the components of (the number of sampled latency k) x (channel number p), as follows:

$$\mathbf{B} = \begin{bmatrix} B_{11}, B_{12}, \cdots, B_{1p} \\ B_{21}, B_{22}, \cdots, B_{2p} \\ \vdots \quad \vdots \quad \vdots \\ B_{k1}, B_{k2}, \cdots, B_{kp} \end{bmatrix} = \begin{bmatrix} \mathbf{b}_1' \\ \mathbf{b}_2' \\ \vdots \\ \mathbf{b}_k' \end{bmatrix}, \tag{1}$$

where ' denotes transpose.

When **B** in each trial is analyzed by PCA, a series of eigenvectors

$$\mathbf{A} = \left[\, \mathbf{a}_1, \mathbf{a}_2, \cdots, \mathbf{a}_j, \cdots, \mathbf{a}_p \right], \tag{2}$$

are yielded, where $\mathbf{a}_j$ is an eigenvector of the j-th eigenvalue λ_j and consists of p vector components as

$$\mathbf{a}_j' = \left[\, a_{j1}, a_{j2}, \cdots, a_{jj}, \cdots, a_{jp} \right], \tag{3}$$

The scalar products of the eigenvectors and the original variables at successive times,

$$\mathbf{a}_j'\mathbf{b}_t = a_{j1}B_{t1} + a_{j2}B_{t2} + \ldots + a_{jp}B_{tp} = \sum_{i=1}^{p} a_{ji}B_{ti}\ , \tag{4}$$

are defined as the principal components (PCs). The PCs are orthogonal, so that measures on one PC are guaranteed to provide independent information from measures on another. In addition, when the original variables are correlated, a small number of PCs can account for a large proportion of the original variance.

$$\frac{\lambda_j}{\lambda_1 + \lambda_2 + \ldots + \lambda_p} \times 100\ [\%]\ , \tag{5}$$

is defined as proportion for the j-th PC. The vector of the PC score of the j-th PC $\mathbf{S}_j$ is expressed as follows:

$$\mathbf{S}_j = \mathbf{a}_j'\,\mathbf{B}' = \left[S_{j1}, S_{j1}, \ldots, S_{jk} \right], \tag{6}$$

PC score could be interpreted as representing temporal characteristics of independent neuromagnetic fields.

We applied PCA to raw data to extract SSEFs in single trial data (e.g., Fig. 2, upper). However, it was not very successful because of low signal to noise ratios. In some time window, we could extract SSEFs with no a prioli selection of particular frequency band but not all of the duration. Next approach we tried was the combination of band-pass filtering and PCA. First of all, band-pass filtered data centered at each tagged frequency were obtained (e.g., Fig.2, lower). From these band-passed data, we could extract each SSEFs as the dominant, mostly as the first principal component. However, there is a problem in this approach. We lose most of the temporal information by applying narrow band-pass filtering. To dissolve this problem, we tried to calculate PC score by the product of the extracted eigenvector and original raw data before filtering instead of filtered data [7, 8]. By this procedure, PC score may show more realistic temporal characteristics.

3.2. Nonstationary analyses

Short time Fourier transform (STFT) and continuous wavelet transform (CWT) were applied to the PC score to analyze nonstationary characteristics of extracted oscillatory activities. The STFT represents a sort of compromise between time- and frequency-based views of signals. It provides information on both when and at what frequencies a signal event occurs.

In recent years, the wavelet transform (WT) has been widely used for nonstationary signal analysis. The fundamental idea is to replace the frequency shifting operation that occurs in the STFT by a time (or frequency) scaling operation. This makes the WT a time-scale representation rather than a time-frequency one.

Mathematically, CWT is defined as the sum over all time of the signal multiplied by scales, or shifted versions of the wavelet function ψ [9]. The result of CWT is many wavelet coefficients, which are a function of scale and position. The wavelet coefficient $C_{a,b}$ of signal $s(t)$ at scale a and position b is defined as

$$C_{a,b} = \int_{-\infty}^{\infty} s\,(t)\,\frac{1}{\sqrt{a}}\,\psi\!\left(\frac{t-b}{a}\right) dt. \tag{7}$$

Symlet wavelets with the order 5 (i.e., sym5) were used in this study.

4. Results and discussions

Fig. 3(A) is eigenvector of the first PC for the data filtered centered at 22 Hz corresponding steady-state somatosensory evoked field. Eigenvector is represented as a field distribution in this figure. The isocontour lines are drawn by 0.05 steps with the points of 68 locations in the coil plane. The solid and dotted lines are positive and negative values of eigenvector components, respectively. Fig. 3(C) is the PC score obtained by the inner product of the eigenvector shown in Fig. 3(A) and original raw data. Figs. 3(D) and 3(E) are the results of time-frequency analysis based on STFT (spectrogram) and time-scale analysis based on CWT. The spectrogram represents the magnitude of STFT normalized by the maximum value. Wavelet coefficients were also normalized by the maximum value.

Temporal characteristics of the oscillatory activity could be detected clearly by the STFT and CWT. As can be seen in this figure, 22 Hz activity is extracted. The change in amplitude of the 22 Hz activity is clearly detected by STFT. Furthermore, lower frequency activities are superimposed. The proportion of the first PC was 70.4 %. By stretching out the middle of the SSEF, we could observe details of the time-frequency and time-scale characteristics.

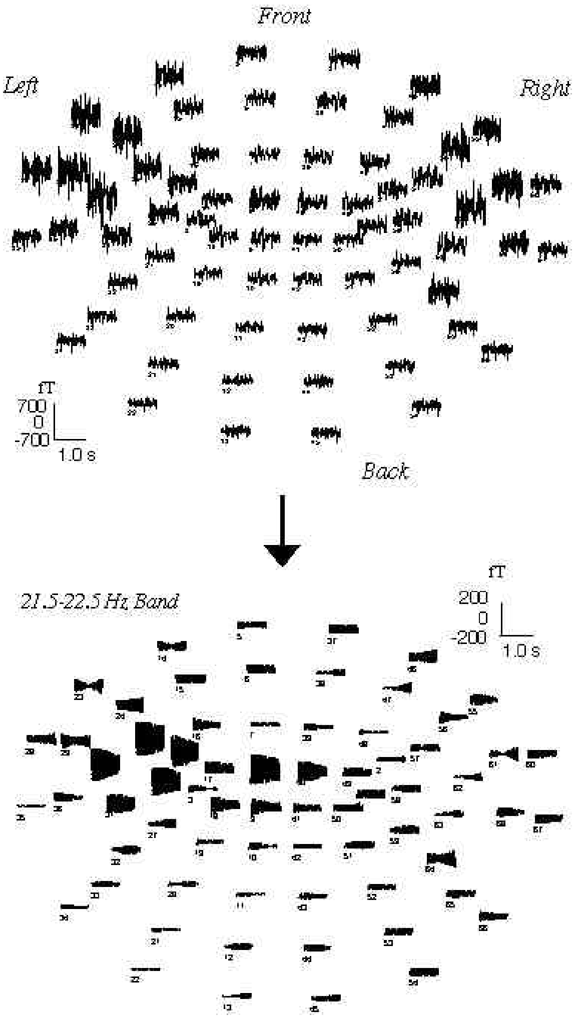

Fig. 2. Measured neuromagnetic fields (upper) and those processed by a band-pass filter (21.5-22.5 Hz) (lower) in subject 1.

Time-scale analysis detect the temporal characteristics of shift of the low frequency peak which superposed on the dominant 22 Hz oscillation.

Fig. 4 shows representative spectograms of retrieved PC scores for steady-state multisensory evoked fields. The amount of power at the presented frequency for each

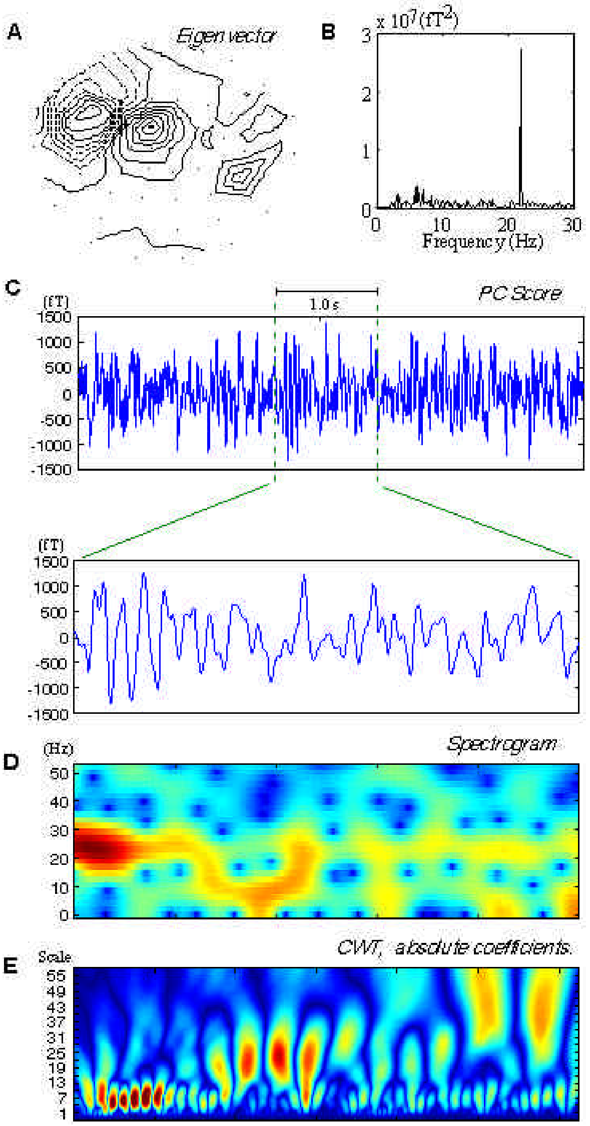

Fig. 3. A) Eigenvector of the first PC for the data filtered centered at 22 Hz corresponding SS somatosensory evoked field (subject 1). Isocontour lines are drawn by 0.05 steps. The PC score vector of the first PC is represented as a waveform (C). The power spectrum of the PC score is shown on the top (B). A spectrogram (D) and absolute wavelet coefficients obtained by CWT (E) of the PC score for the first PC are also shown.

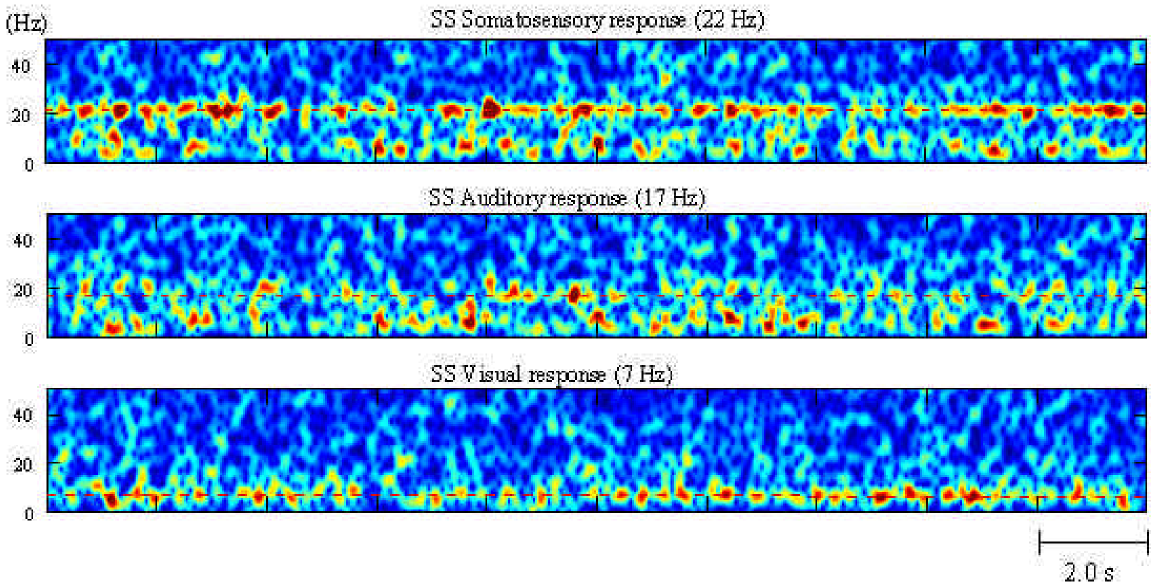

Fig. 4. Representative spectrograms of PC scores for steady-state (SS) evoked somatosensory, auditory and visual fields (Subject 1).

sensory stimulus was unstable and relatively large while the other was small.

5. Conclusion

Coherent oscillatory evoked neuromagnetic fields reflecting synchronous activity of neurons involved in the presented sensory stimuli could be extracted as eigenvectors in single trial data using principal component analysis after applying band-pass filters tuned for each presented frequency. The time-frequency/scale structures of the retrieved temporal data were analyzed by short-time Fourier transform and continuous wavelet transform. It was found that the amount of power at the presented frequency for each sensory stimulus was unstable and relatively large while the other was small. The results demonstrate that analysis of the temporal structure of coherent oscillatory evoked neuromagnetic fields may be a promising approach to understanding neural correlates of sensory awareness.

Acknowledgments

The author would like to thank Dr. M. B. Burbank, Dr. D. Cheyne and Dr. S. E. Robinson of CTF systems, Inc. for their cooperation during MEG measurements.

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