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Source Estimation of Contrast-related Perception Based on Frequency-Tagged Binocular Rivalry

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Abstract—**Binocular rivalry is a visual perceptual phenomenon which occurs when two incongruent stimuli are viewed by a subject through each eye, but only one of them is perceived at a time, with a switch in perception every few seconds, which reflects the alternation of perceptual dominance. To investigate the correlation between contrast-related perception and neural activities, the subjects' EEGs were recorded with a 64-channel electroencephalograph while experiencing binocular rivalry. A higher contrast grating flickering at one frequency was presented to one eye while a lower contrast grating flickering at a slightly different frequency was presented to the other eye. Steady-state visual evoked potentials (SSVEP) at the flickering frequencies were used to 'tag' the two stimuli. An improved inverse algorithm termed SSLOFO (Standardized Shrinking LORETA-FOCUSS) [1] was used to solve this inverse problem, which acquires the spatial distribution of neural active sources from the EEG data. The result shows that activity in primary visual cortex (V1) increased when subjects perceived the higher contrast pattern and decreased when they perceived the lower contrast pattern. This paper presents a method based on EEG to investigate neural correlates of consciousness in real-time, which provides an alternative method to achieve comparable results to those based on fMRI methods.**

I. INTRODUCTION

BINOCULAR rivalry is a visual perceptual phenomenon which occurs when dissimilar monocular patterns presented to corresponding regions of the two eyes compete for perceptual dominance, producing alternations in the visibility of one pattern and then the other over time. It is a useful experimental paradigm for identifying aspects of neural activity correlated with conscious experience, which has attracted the interest of psychologists and neuroscientists alike as a method of probing the mechanisms that underlie our visual awareness [2]. At the expense of temporal resolution, functional Magnetic Resonance Imaging (fMRI) is commonly used in investigating spatial distribution of neural activity. Magnetoencephalograms (MEGs) and Electroencephalograms (EEGs) offer the advantages of synchronization and high temporal resolution, and provide an effective method for investigating frequency-tagged binocular rivalry in real-time [3]-[5], but it was not possible to pinpoint the visual area(s) from which the signals arose.

This paper presents an alternative method to the fMRI method, combining an improved inverse solution with frequency-tagged binocular rivalry to investigate source distribution and intensity fluctuations during perceptual experience. Firstly, EEG data were classified into two groups corresponding to the left and right eye dominance, respectively, according to the subjects' manual reports on perceptual alternation. Each segment of EEG data was transformed into the frequency domain by FFT, and all segments for each group were averaged. Then, the inverse solution method was applied to the multi-channel spectral amplitude data of the two groups, respectively, to acquire the source estimation specific to the higher-contrast dominance and the lower-contrast dominance. Finally, the difference in source location and intensity between the two dominant patterns was obtained, and registered on MRI slices of a standard head model [1]. For every second long period, using processing described above, the intensity waves in real-time was obtained. The results show that the source intensities in V1 fluctuate along with the perceptual alternations between the higher and lower contrast patterns. This method based on EEG processing produces comparable results to those based on the fMRI method [6], [7], and provides potential advantages for real-time investigation.

II. METHODOLOGY

A. Data Acquisition

Six consent-informed volunteers with normal binocular vision and good visual acuity participated in the experiments. The subjects sat facing the experimental device for binocular rivalry. Two LCDs (160×128 pixels) modulated by a square wave at a range of frequencies were used as the stimulators. The experimental set-up for binocular rivalry is based on that described in [9]. The only difference is that here LCD screens are used to deliver the stimuli rather than LEDs. The optimal stimuli frequency pairs (f1 and f2) were determined for each subject according to the stability and SNR of the steady state visual evoked potential (SSVEP) [8]. The SSVEP is a component of the scalp-recorded EEG reflecting visual processing activity in the visual cortex. In this experiment, the frequencies (f1 and f2) for each subject ranged from 26 to 33 Hz. A higher contrast, horizontal, green-black grating and a lower contrast, vertical, red-black grating (see Fig.1.) were displayed on the two stimulators to the two eyes, respectively,

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restricted to a peripheral annulus (2.8–3.5°) of the visual field. The strength of stimuli was measured by a luminometer. The complete combinations of four trials (listed in Table.1) were used for each of the subjects, in order to reduce the effect of the dominant eye, i.e. the subject's normally preferred eye. Stimuli parameters were adjusted to lengthen the average duration of perceptual rivalry. 64-channel EEGs were recorded with a BioSemi Active-Two system at positions according to the extended international 10/20 system. The two flickering gratings induced binocular rivalry and the subjects reported their perceptual alternations using a lab-made button switch. They were instructed to activate neither button if neither of the two percepts was clearly dominant, i.e., when they saw a mixture of left and right images. EEG data were recorded for 120 sec in each session, and the trigger pulses of the switch were recorded by an additional channel. During 30-sec intervals, subjects were told to relax to avoid visual fatigue. Signals were sampled at 512Hz and preprocessed by a 50Hz notch filter and a 6-Hz-width band-pass filter around the tagging frequency. The reference was the common average of 64-channel EEG.

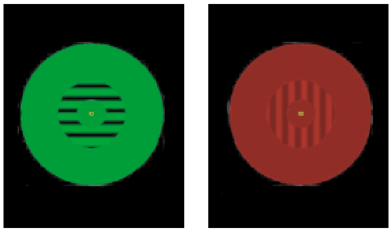

Fig.1. Visual stimuli used in the experiment (Left eye: higher contrast, horizontal, green-black grating. Right eye: lower contrast, vertical, red-black grating.)

TABLE.1

COMBINATIONS OF STIMULI USED IN THE EXPERIMENT

Combination	Stimuli
1	Green vertical f1 and red horizontal f2
2	Green vertical f2 and red horizontal f1
3	Red horizontal f1 and Green vertical f2
4	Red horizontal f2 and Green vertical f1

B. Data Analysis Procedure

Data Analysis followed four main steps.

1) Processing on perceptual reports.

Data segments less than 1.5-sec duration were discarded, as they were unlikely to evoke a reliable SSVEP. For each remaining segment the last 200 milliseconds of data was also discarded in order to eliminate the influence of the subject's reaction time. At this point, the EEG data could be classified into two groups of higher contrast duration periods and lower contrast duration periods, by the subjects' manual reports. The manual reports from subjects according to their perceptual alternations were then used to compare with the fluctuations of neural activities in the V1 area, with lower-contrast perception to red curves and higher-contrast perception to green curves.

2) Fourier Analysis of EEG data segments

For each of the 64 channels, the spectrum was calculated by using the Fast Fourier Transform algorithm for each segment. The peaks corresponding to the frequency tags (f1 and f2, ranging from 26Hz to 33Hz) were identified in the spectrum of the signals, and the presence of peaks in the EEG data at the corresponding frequencies was verified. The amplitude spectrum of each segment at the n^{th} channel was:

$$\begin{cases} \boldsymbol{X}_{higher-contrast}(n) = \left| FFT\left[\boldsymbol{x}_{higher-contrast}(n)\right]\right| \\ \boldsymbol{X}_{lower-contrast}(n) = \left| FFT\left[\boldsymbol{x}_{lower-contrast}(n)\right]\right| \end{cases} \tag{1}$$

The spectral data were then normalized by the number of data points in the original data segments. Next, the average spectrum for each group was calculated. .

Meanwhile, the amplitude spectrum of each 1-sec long segment was also calculated for real-time analysis, using the Fast Fourier Transform algorithm. The amplitude spectrum of the i^{th} second at the n^{th} channel was:

$$\boldsymbol{X}_i(n) = \left| FFT\left[\boldsymbol{x}_i(n)\right]\right| \tag{2}$$

The spectral data were then normalized by the number of data points in the original data segments.

3) Inverse Solution by SSLOFO

For each channel, spectral amplitude at the tagging frequency was used for source estimation using a 3-D source distribution inverse solution of SSLOFO (Standardized Shrinking LORETA-FOCUSS) [1]. Accordingly, we chose the standard head model as used by Liu *et al.* [1] which is based upon MRI data. We sampled equally on each of the 17 slices, with a spatial resolution of 7mm, and kept only those samples that were probable sites of source activity. We used this 3-D source distribution model with 2394 nodes in the SSLOFO approach to calculate the inverse solution.

This SSLOFO algorithm used in this study was composed of several main steps. Firstly, the standardized LORETA approach was used to estimate a solution with lower resolution, and then a standardized FOCUSS approach was taken using the estimated solution as an initial value. The effect of this was so that the estimated sources corresponding to the original source distribution were intensified while other estimated solutions decreased to zero gradually. After each cycle of iteration, the solution space was adjusted through a normalization and smoothing step. Thus, only a small number of nodes remained non-zero while the intensities of other nodes became zero by iteration. And finally the local solution was acquired with high-resolution. Sources were labeled on those nodes of non-zero intensity.

Thus, we acquired source distributions for the two dominance patterns respectively through SSLOFO. The source distributions for the two dominance patterns could be described as:

$$\begin{cases} \boldsymbol{S}_{higher}\left(k\right)=SSLOFO\left(\widehat{\boldsymbol{X}}_{higher-contrast}\right) \\ \boldsymbol{S}_{lower}\left(k\right)=SSLOFO\left(\widehat{\boldsymbol{X}}_{lower-contrast}\right) \end{cases} \tag{3}$$

where $\widehat{\boldsymbol{X}}_{higher-contrast}$ and $\widehat{\boldsymbol{X}}_{lower-contrast}$ were normalized multi-channel spectral amplitude at tagging frequency f, and k (k=1,2,…,2394) denotes the index of nodes in MRI head model.

This approach explicitly worked out the source distribution of neural activities, both in localization and in intensity, which extracted more information from signals.

The localization of contrast-related sources, calculated from the inverse solution approach, actually contained both the source of contrast-related perception and the source of the steady-state visual responses. We subtracted the source distribution of lower contrast dominance from that of the higher contrast dominance and therefore obtained the spatial source distribution of contrast-related perception as follows:

$$\boldsymbol{S}_{contrast-related}\left(k\right)=\boldsymbol{S}_{higher}\left(k\right)-\boldsymbol{S}_{lower}\left(k\right) \tag{4}$$

where k=1,2,…,2394.

4) Real-time Analysis in V1Area

To further extract the source activity fluctuations in the V1 area, the source distribution and intensity for each 1-sec long data segment was calculated. The source distribution for the i th second was:

$$\boldsymbol{S}_i\left(k\right)=SSLOFO\left(\widehat{\boldsymbol{X}}_i\right) \tag{5}$$

Then, 14 nodes within V1 area were picked out of a total of 2394 nodes in the 3-D inverse solution model, according to Brodmann areas (V1 is Area 17 in Brodmann area). For each 1-sec segment, the average intensity of the V1 area was calculated from the source intensities on the 14 nodes. Finally, intensity change data in the V1 area versus time was acquired thus:

$$I\left(i\right)=\sum_m S_i\left(m\right) \tag{6}$$

where m denotes the index of nodes within V1 area. m=384, 386, 387, 614, 615, 616, 820, 821, 822, 823, 1009, 1010, 1011, 1012.

III. RESULTS

We analyzed their EEG data using the inverse problem solution approach described above, and detailed results for subject S1 were given as below.

The result of source localization is shown as Fig.2. It shows the spatial source distribution of contrast-related neural activity. Remarkable source distribution at V1 can be seen on the 5th ~ 7th MRI slices and the common source distribution stimulated by SSVEP at occipital area is counteracted, by the processing of subtraction.

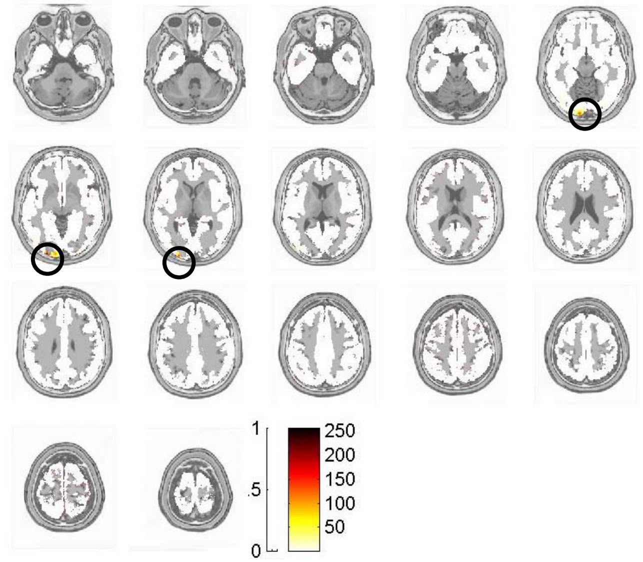

Fig.2. Source distribution of contrast-related perception (The activation region is marked in black circles)

The result of real-time V1 activity is shown in Fig.3. The blue curve is the average intensity in V1 area versus time. The green and red square wave curves are the subjects' reports of perception, indicating the time periods when the subject perceived higher contrast grating or lower contrast grating, respectively. Fig.3. shows that V1 activity tended to increase when subjects reported seeing the higher contrast grating, and tended to decrease when reporting seeing the lower-contrast one. This result is qualitatively similar to the results reported in [6], [7], as shown in Fig.4. The red and green striates in Fig.4 represent the subjects' report of lower and higher contrast percepts. And the yellow striates represent the mixed pattern of the two, corresponding to the blank segments in our result figure. The black curve is the bold signal along with the time acquired by fMRI.

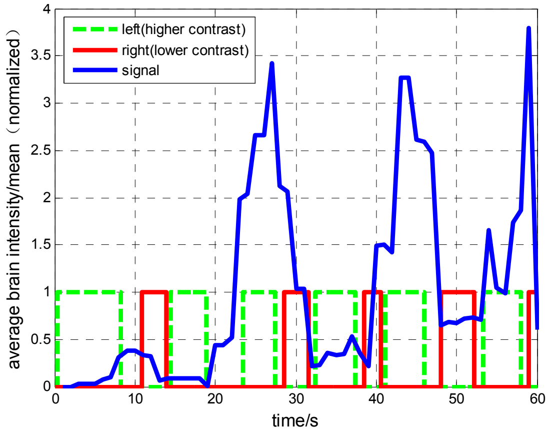

Fig.3. V1 Intensity changes versus time

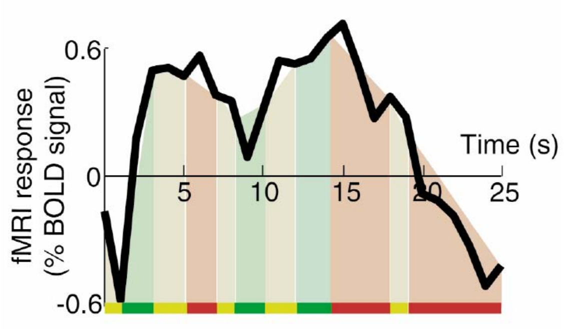

Fig.4. Result from literature [7]: fMRI response of fluctuations along with the time.

For four of the six subjects, the duration of perceptual dominance ranged from 2s to 8s, and had similar results as those shown in Fig.3. The fluctuations resulted from EEG tend to be slightly earlier than the subjective reports. This is probably due to the subject's reaction time. This indicates that EEG analysis has the advantage of a better temporal characteristic.

IV. DISCUSSION & CONCLUSION

In this study, we analyzed EEG data with SSVEP frequency-tags during a perceptual alternation task, to acquire the source distribution and real-time fluctuation of neural activities in V1 area. The results show that activity in the primary visual cortex (V1) increased when subjects perceived the higher contrast pattern and decreased when they perceived the lower contrast pattern. The results demonstrate that source estimation combined with frequency-tagged binocular rivalry is a reasonable and effective approach to estimate the source distribution of neural active sources in real-time, and the effect is comparable to the results by fMRI approach.

Three advantages are obvious in this method. Firstly, the frequency-tagging helps to extract the specific frequency component sharply for data analysis. Secondly EEG data processing provides the advantage of high temporal resolution. Finally the integrated method for source estimation analysis based on EEG data has several advantages compared with the fMRI method, such as lower cost and higher temporal resolution. To some extent, the limited spatial resolution of EEG methods is improved by the SSLOFO approach. The combination method of source estimation based on frequency-tagged binocular rivalry has potential advantages both in the investigation of high-level perception and of disease focus in brain.

Two limitations still remain to be improved in further studies. Firstly, some details related to psychological factors in the experiment design should be handled more carefully, in order to avoid the imbalance due to individual variance. Secondly, the method needs further verifications with more subjects. However, a systematic procedure of source estimation based on frequency-tagged binocular rivalry has been established, and this provides a promising tool for further studies.

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