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Localization of FFA Using SSVEP-based Binocular Rivalry

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Abstract—**In binocular rivalry, a subject views two incongruent stimuli through each eye but consciously perceives only one stimulus at a time, with a switch in perceptual dominance every a few seconds. To locate the fusiform face area (FFA) which is a face-selective region, thirteen subjects are recorded with a 64-channel electroencephalograph while experiencing binocular rivalry. A face image flickering at one frequency is presented to one eye and a non-face image flickering at the same frequency is presented to the other eye. Steady state evoked potential (SSVEP) at the frequency is used as tags for the two stimuli. This paper uses an algorithm called standardized shrinking LORETA-FOCUSS (SSLOFO) to reconstruct face-selective sources from the EEG data. The sources are selected by comparing signal strength at the stimulus frequency during face dominance and face suppression. The results demonstrate that the face-selective region identified in this paper is consistent with FFA, as has been confirmed to be activated about twice as strongly in fMRI experiments when people view faces as when they view other kinds of objects. The present study also suggests that the method has the potential advantage of investigating neural correlates.**

I. INTRODUCTION

BINOCULAR rivalry provides a useful experimental paradigm with which to study the neural correlates of conscious perception[1], When dissimilar images are presented to the two eyes, they compete for perceptual dominance so that each image is visible in turn for a few seconds while the other is suppressed. Because conscious perception changes over time while the stimuli remain constant, this paradigm offers a way to distinguish between neural activity related to the physical features of the stimuli and neural activity directly related to conscious experience.

Human subjects are the referent of choice for investigating conscious perception. However, brain activity associated with rivalry is difficult to study in humans with techniques such as positron emission tomography and functional MRI because of their limited temporal resolution. Unit recordings, while offering high temporal resolution as well as neuronal specificity, are typically performed in overtrained animals and are not practical for providing global coverage of neural responses. At the expense of spatial resolution, EEGs offer the advantage of high temporal resolution and reflect the synchronous activity of large populations of neurons [2]. Visual evoked potentials (VEPs) recorded from scalp reflect the visual information processing mechanism in brain. Steady-state visual evoked potentials (SSVEPs) occur when the stimulation repetition frequency is higher than 6Hz [3]. SSVEP-based binocular rivalry is presented to study neural correlates in this paper. The two stimuli flickering at the same frequency during binocular rivalry can evoke SSVEP. The flickering frequency isn't within frequency range of the background EEG, so the SSVEP has a high signal-to-noise ratio. The subjects signal which of the two stimuli is consciously perceived by activating right or left switches. A high-resoultion distributed source imaging algorithm termed standardized shrinking LORETA-FOCUSS (SSLOFO) [4, 5] is used to analyze the SSVEP during rivalry dominance and rivalry suppression, and to localize the perception-correlative region.

Some evidences have demonstrated [6-8] that the fusiform face area (FFA) has a stronger response to face perception than to non-face perception. Therefore, face image is used as one of the two stimuli to confirm the applicability of SSVEP-based binocular rivalry in the present study of neural correlates of conscious perception.

II. METHODOLOGY

A. Subjects

Thirteen right-handed subjects (nine males and four females), with no visual or other abnormalities, aged between 21 and 30 years participated in this study. Each had a normal or correlated-to-normal vision. All subjects gave informed consent after the procedure was explained.

B. Data Acquisition

64-channel (standard 64 electrodes) EEGs were recorded with a BioSemi ActiveTwo system. Two blinking light-emitting diodes (LEDs) modulated by square wave were used as the stimulators. Two transparent images were stuck on the two stimulators. One stimulus was face image, and the other one was non-face image. Set-up for binocular rivalry could be found in [9]. Subjects reported their perceptual alternations using response keys on a keyboard. The stimulus frequency was selected for each subject according to the stability and signal-to-noise ratio of their SSVEP [10]. The stimulus frequencies for the thirteen subjects range from 30Hz to 40Hz. Four non-face images from different categories were used in each session, with the purpose of weakening the influence from source activation induced by non-face perception on FFA activation evoked by face

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perception. Details are to be described later in this paper. Fig.1. is the timing of one paradigm. There were four runs in each session. Each run corresponded to a different stimuli combination. 60-second-long data were acquired in each run. Ten seconds between runs was used for the switch of different stimuli and subject rest. Hence, 270-second-long data were acquired in each test. Signals were sampled at 512Hz and preprocessed by a 50Hz notch filter and an 8-Hz-width band-pass filter centering the stimulus frequency. The reference was chosen as the average of 64-channel EEG.

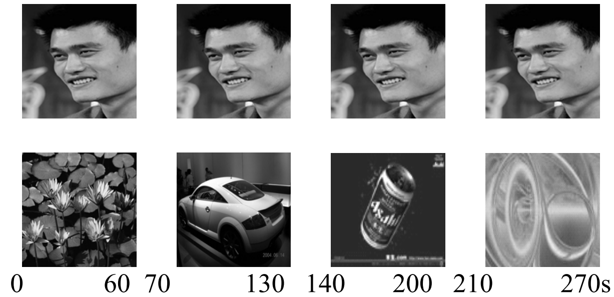

Fig. 1. Paradigm of stimuli combination

C. Localization of FFA

A high-resolution brain imaging method called SSLOFO [10], which combines two distributed source imaging methods sLORETA and FOCUSS, was used to localize the source corresponding to subjects' perception. In SSLOFO, low-resolution method and high-resolution method are combined in an automated fashion to achieve superior performance. Simulation studies carried out by Liu [4] showed that SSLOFO achieves zero localization error for single dipoles when the data are free of noise. It is also capable of recovering complex source configurations with arbitrary shapes and can produce high quality images of extended source distributions. The SSLOFO algorithm has been studied in [4, 5] in detail.

The simulations mentioned above and the later EEG data analysis were all conducted on a three-shell spherical head model [11] registered to the MNI-305 brain atlas [12] from the Brain Imaging Centre of the Montreal Neurological Institute. EEG electrode coordinates were derived using cross-registrations between spherical and realistic head geometry [13]. This head model was kindly provided by R. D. Pascual-Marqui. Computations were restricted to cortical gray matter and hippocampi using the digitized probability atlases of the Montreal Neurologic Institute. The solution space is divided in 2394 voxels of size 7×7×7 mm.

The EEG data during face dominance contain the information from FFA activation and SSVEP, and the EEG data during non-face dominance contain information from non-face stimulus-correlated region activation and SSVEP. Different non-face stimuli make different stimulus-correlated regions to be activated. Thus, averaging the information during non-face dominance can weaken the influence of non-face stimulus-correlated region activation on the localization of FFA. The two stimuli flickering at the same frequency induce the same SSVEP. Consequently, the difference between the information during face dominance and the averaged information during non-face dominance includes only the FFA activation evoked by face perception.

The detailed procedures of FFA localization are described as follows:

1) Epochs Extraction: The epochs corresponding to face dominance and non-face dominance are extracted respectively. Stimulus patterns less than 1.5 s cannot induce SSVEP well. Therefore, the corresponding epochs are deleted. Suppose there are N_{face} valid epochs for face dominance and $N_{non\text{-}face}$ valid epochs for non-face dominance after the selection of epochs.

2) Spectrum Calculation: The amplitude spectrum is calculated for these epochs by $Y(k)=|\mathrm{FFT}(x(n))|$, where $x(n)$ is the temporal EEG data of each epoch. FFT(x) is the 2^p-point fast Fourier transform (FFT) of x and p is the nearest power of two sequence length for FFT operations. x is padded with zeros if its length is shorter than 2^p. The frequency resolution is ($512/2^p$) Hz and the calculated frequency bins are $f=(512*k/2^p)$ (k=1,2,.. 2^p) for each epoch. The amplitude spectrum for the ith epoch during face dominance and the amplitude spectrum for the jth epoch during non-face dominance at the lead ch are:

$$\begin{cases} Y_{face,i}(ch,f) = \left|FFT\left(x_{face,i}(ch,n)\right)\right| \\ Y_{non-face,j}(ch,f) = \left|FFT\left(x_{non-face,j}(ch,n)\right)\right| \end{cases} \tag{1}$$

3) Spectrum Normalization: Because the data length for each epoch is different, the spectrum obtained in step 2 should be normalized. The normalized spectrum for the ith epoch during face dominance and the normalized spectrum for the jth epoch during non-face dominance at the lead ch are:

$$\begin{cases} Y_{N,face,i}(ch,f) = \dfrac{Y_{,face,i}(ch,f)}{length\left(x_{face,i}(ch,n)\right)} \\ Y_{N,non-face,j}(ch,f) = \dfrac{Y_{non-face,j}(ch,f)}{length\left(x_{non-face,j}(ch,n)\right)} \end{cases} \tag{2}$$

where $length(x)$ is the data length of x.

4) Spectrum average: The amplitude spectra at a particular stimulus frequency are averaged for the epochs during face dominance and during non-face dominance respectively.

$$\begin{cases} power_{face}(ch,f_0) = \dfrac{\sum_{i=1}^{N_{face}} Y_{N,face,i}(ch,f_0)}{N_{face}} \\ power_{non-face}(ch,f_0) = \dfrac{\sum_{j=1}^{N_{non-face}} Y_{N,non-face,j}(ch,f_0)}{N_{non-face}} \end{cases} \tag{3}$$

where f_0 is the stimulating frequency

5) FFA Localization: In this step, source distributions corresponding to subjects' perceptions are calculated by applying SSLOFO algorithms to the average amplitude spectrum at the stimulus frequency. The source distribution corresponding to face perception and SSVEP, as well as the source distribution corresponding to non-face perception and SSVEP can be described as follows:

$$\begin{cases} V_{face}(k) = SSLOFO\ (power_{face}(ch, f_0)) \\ V_{non-face}(k) = SSLOFO\ (power_{non-face}(ch, f_0)) \end{cases} \qquad (4)$$
$$k = 1, \ldots 2394$$

where k denotes the kth voxel of solution space in the head model.

$V_{face}(k)$ contains the information from SSVEP and face perception, while $V_{non-face}(k)$ contains only the information from SSVEP. Thus, the source distribution induced by face perception could be obtained as:

$$V(k) = V_{face}(k) - V_{non-face}(k) \qquad (5)$$

FFA should be those regions where the EEG induced by face perception is the strongest, which can be identified as the maximum of (5). Moreover, this study employs percentile threshold in order to suppress noise hits and other neural activity evoked by non-face perception. Hence, the threshold is set to 75% of the maximum of (5). The final source distribution evoked by face perception should be:

$$V^{'}(k) = \begin{cases} V(k) & V(k) > threshokd \\ 0 & V(k) \le threshold \end{cases} \qquad (6)$$

III. RESULTS

The source distributions $V_{face}(k)$ and $V_{non-face}(k)$ for one subject are shown in Fig.2 and Fig.3 for illustration. Because the source activation induced by SSVEP is much stronger than the one induced by stimulus image perception, the strongest region occurs in the primary visual cortex (V1) for the two source distributions. The thresholded difference $V'(k)$ between the two distributions is shown in Fig.4, which includes only the information from face perception. The three slices intersect each other at the point of maximum activity. The strongest source corresponds to face-selective region, which is close to FFA identified by fMRI experiments in the reported literatures (Fig.5.) [8].

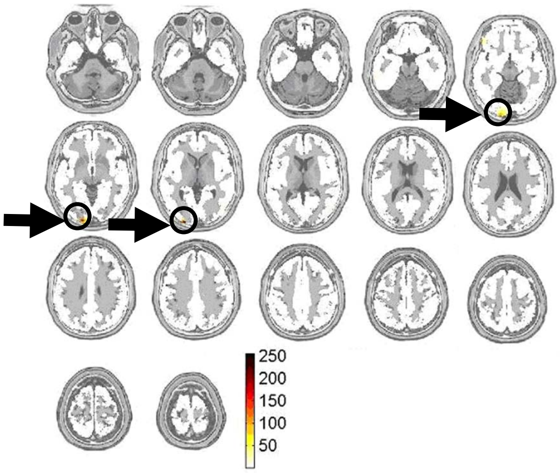

Fig2. The results of SSLOFO solution during face perception.The arrow points to the activation region (the region outlined in black)

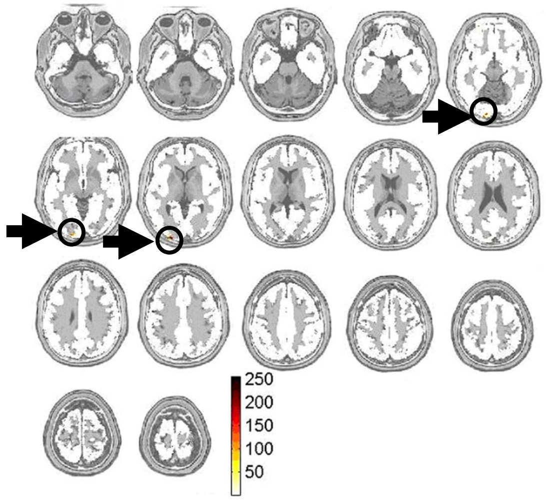

Fig.3. The results of SSLOFO solution during non-face perception.The arrow points to the activation region (the region outlined in black)

Fig.4. Orthogonal views of the difference between Fig.2 and Fig.3 The arrow points to the activation region (the region outlined in black)

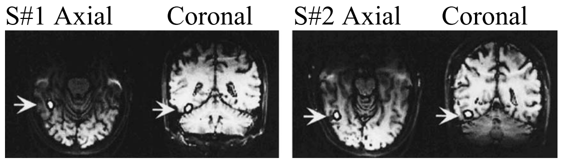

Fig.5. An axial and coronal slice showing the FFA in two subjects. The arrow points to the FFA (the white spot outlined in black) in each image.[8]

The experiments for the localization of FFA are done on thirteen subjects, with seven subjects obtaining the consistent results with FFA. The face-selective region from another two subjects is near FFA. The average source activation $mean(V(k))$ for the nine subjects is shown in Fig.6, which is very close to FFA. The source activation for other four subjects occurs in V1. One subject's result is shown in Fig.7.

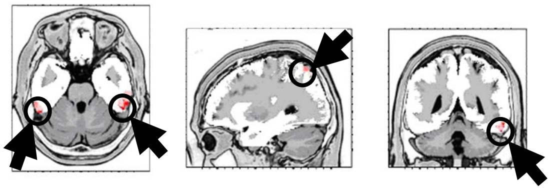

Fig.6. Orthogonal views of the average results .The arrow points to the activation region (the region outlined in black)

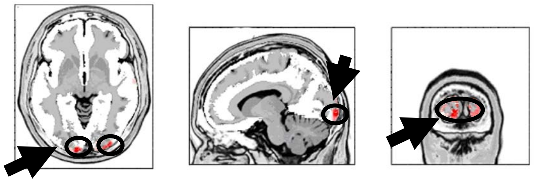

Fig.7. Orthogonal views of the results (region activation in V1) The arrow points to the activation region (the region outlined in black)

IV. CONCLUSIONS AND DISCUSSIONS

In this primary study, we have probed into the applicability of SSVEP-based binocular rivalry in the study of neural correlates of conscious perception. We analyze the EEG during SSVEP-based binocular rivalry to get the source distribution in the brain that is correlated with the stimulus and find the neural correlates of consciousness. The experiments of neural correlates of face are done on thirteen subjects, with more than half of the subjects obtaining the similar results with those obtained by fMRI in the reported literatures. However, four subjects' activation regions are in V1. The reason for this dissimilarity is still under study.

There are obvious advantages for the use of SSVEP-binocular rivalry in the study of neural correlates. Frequency tagging provides the ability to sharply distinguish stimulus-related responses from background neural activity with a high temporal resolution. It also permits the investigation of the distribution of stimulus-related signals beyond sensory projection areas with high spatial resolution by applying SSLOFO to whole-head EEG. Moreover, unlike single-unit recordings, which are not practical for global coverage of neural activity and are generally performed in overtrained animals, SSVEP-based binocular rivalry permits one to sample the synchronous activity of large populations of neurons in human subjects who are not overtrained. It is also not easy to carry out fMRI analysis for binocular rivalry to study neural correlates of consciousness perception because fMRI signal is limited by its low temporal resolution. Last but not least, SSVEP-based binocular rivalry offers great potentials for generalization, because it can be applied to any stimuli in any sensory modality. As is shown here, SSVEP-binocular rivalry can be used to study neural correlates of conscious experience in human subjects who can directly report their conscious states.

Consciousness is complicated intrinsically. The results in this paper should be further validated through more test samples. Nevertheless, the current research has established a good platform for future work.

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