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PINPOINT SOURCE LOCALIZATION FOR OCULAR NONSELECTIVE ATTENTION WITH COMBINATION OF ERP AND fNIRI MEASUREMENTS

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Compared with event-related potential (ERP) which is widely used in psychology research, functional near-infrared imaging (fNIRI) is a new technique providing hemodynamic information related to brain activity, except for electrophysiological signals. Here, we use both these techniques to study ocular attention. We conducted a series of experiments with a classic paradigm of ocular nonselective attention, and monitored responses with fNIRI and ERP respectively. The results showed that fNIRI measured brain activations in the left prefrontal lobe, while ERPs showed activation in frontal lobe. More importantly, only with the combination measurements of fNIRI and ERP, we were then able to find the pinpoint source of ocular nonselective attention, which is in the left and upper corner in Brodmann area 10. These results demonstrated that fNIRI is a reliable technique in psychology, and the combination of fNIRI and ERP can be promising to reveal more information in the research of brain mechanism.

Keywords: Functional near-infrared imaging (fNIRI); event-related potential (ERP); ocular nonselective attention; hemoglobin.

1. Introduction

The ocular nonselective attention, most important in the transformation of consciousness, attracted many researchers to study its mechanism in recent years.[1] The ocular nonselective attention, belonging to the advanced function of brain, occurs in the case as described below. There is an object presented in the ocular range of a subject, who was not asked to pay attention to it originally. If there is enough novelty or intensity about this object or in the case of abruptly presentation of this object, the subject will be passively attracted by this object. Here, the happening of the ocular nonselective attention, introduced by the control of brain in attention activity and the regulation of attention energy,[2] cannot be controlled by our mind. Presently, researchers widely use event-related potential technique (ERP) to

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study it and finally find P3a component in ERPs is most related with nonselective attention,[3−5] while few reports about the precise source location of nonselective attention.[6,7] The prefrontal lobe, as the area of advanced brain function, may also contain the source of nonselective attention.[8] However, this complex area cannot be well researched with ERP, for it only provides potential measurements and its spatial resolution is low especially for this region.[9]

It is necessary to use different techniques to get sufficient information within the prefrontal lobe, in the research on source location for the nonselective attention. While functional nuclear magnetic resonance technique (fMRI) is likely to solve this problem, it is easy to introduce psychological interference in the brain activity with its restraint environment. There are other techniques which hold great promise to be well utilized in the brain research, such as positron emission tomography (PET) and magnetoencephalography (MEG), but the high costs are reasons why most researchers reject these techniques. Therefore, other available techniques are highly needed.

Functional near-infrared imaging (fNIRI), as a new technique used for functional brain activity monitoring, becomes more and more canonized in brain research and clinical diagnosis presently, because of its low-cost, portability, real-time result and non-invasive measurement.[10] fNIRI can provide hemodynamic information in the functional brain activity, including the concentration change of oxy-hemoglobin ($\triangle$[oxy-Hb]), deoxy-hemoglobin ($\triangle$[deoxy-Hb]) and blood volume ($\triangle$[tot-Hb]).[11,12] The positive activation of both $\triangle$[oxy-Hb] and blood volume is always caused by the increasing supply of blood oxygenation, and positive activation of $\triangle$[deoxy-Hb] means oxygen consumption. With the measurements of three parameters, we could study the functional brain activity based on the mechanism of cerebral oxygenation metabolism.[13] We had developed a continuous-wave portable-designed fNIRI instrument, which can monitor blood activation sensitively.[14] Some meaningful results have been obtained after we applied this instrument to psycholinguistics research, such as words processing,[15,16] dyslexia[17] and working memory.[18] It is also worthwhile to mention that this instrument is specially designed to monitor the prefrontal lobe. Hence, it fits better than other technology in the research of nonselective attention.

This paper attempts to use fNIRI and ERP to study the ocular nonselective attention. In Sec. 2, we describe the experiment design, the data collection and analysis. In Sec. 3, we show the results and present how to find the source of ocular nonselective attention. In Sec. 4, we make comparisons between ERP and fNIRI on their priority and limitation; and discuss the ability of fNIRI in psychology research and the effect of this method combining ERP with fNIRI.

2. Methods

2.1. *Subjects*

Eight male and seven female subjects (of ages 22.6 ± 1.8 years, mean$\pm$SD, education degree 16.8 ± 1.2 years), all of them were healthy students in the university. In the

period of 24 hours, none of the subjects had taken any tranquilizer or psychiatrically-prescribed drugs. All subjects are right-handed and have normal or corrected-to-normal vision. Written informed consent was obtained from each subject before the experiment. In the period of experiment, blood oxygenation metabolism change of prefrontal lobe was monitored with fNIRI, and electrocortical potential waves were monitored by ERP system. All the subjects' data with fNIRI and ERP were effective, which were collected in experiment and backed up in hard disk after the experiment. The accuracy of behavior parameters from every subject is near to 100%.

2.2. *Stimuli and task design*

Stimulation was controlled with software "Presentation". The design of the experiment is shown as Fig. 1, the stimuli of this experiment is shown as a single triangle (untargeted stimulation), a single inverted triangle (targeted stimulation) or patterns with rambling lines (novel stimulation; the patterns are different from others), all stimulus are presented in the center of computers' screen with white lines and black background (the illumination is 60 cd/m^2). The side-length of every triangle is 6.7 cm in the experiment, 30 unfamiliar stimuli, 30 target stimulus and 140 untargeted stimuli are presented pseudo randomly. The times for continuously presenting unfamiliar stimulus and target stimulus should not exceed twice. The presentation time for each stimulus is 100 milliseconds. The time interval for waiting for subject's response (SOA) is randomly determined by the computer within the range from 900 to 1100 milliseconds. The subjects were asked to look at the center of screen about 1 m away. The vertical visual angle is about 3.1° and horizontal visual angle is about 3.2°. This experiment claimed that the subjects should only respond to the inverted triangle as quickly and correctly as possible, and should not respond to other stimulus. The number of right-handed subjects was equal to the number of left-handed subjects.

2.3. *Data collection of blood oxygenation change*

This study adopted the portable fNIRI instrument.[14] During the experiment, we used the instrument to collect emergent light intensity change information with 3

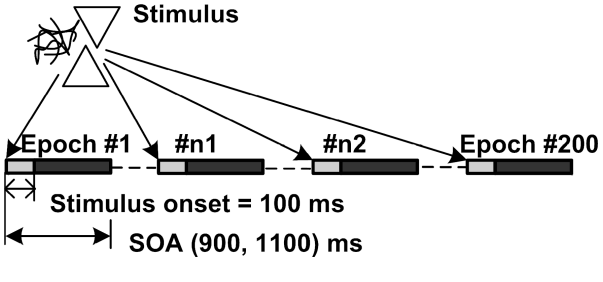

Fig. 1. The design of ocular nonselective attention experiment.

wavelength 735 nm, 805 nm and 850 nm. Before the experiment, the probe of the instrument was wired on the skin of prefrontal lobe with flexible cotton type, the down-side of the probe was just above the brow, and the mid-line of probe is placed in the sagittal plane of the brain.

2.4. *Analysis of blood oxygenation change data*

The fNIRI data are offline analyzed with the fNIRI data-processing software programmed by one member of our research group. First, the emergent light intensity data were translated into hemodynamic data, such as $\triangle$[deoxy-Hb], $\triangle$[oxy-Hb], $\triangle$[tot-Hb]. Second, the singular data in a sequence, originated from the artifact of muscle movement or system error, was balanced with the nearest data using interpolation methods. Third, different kinds of physiological noise were eliminated with PCA (principle component analysis), such as heart beat, pulse movement or breathing. Then, the baseline was corrected by subtracting the data in the rest period; and the data was smoothed with window filtering of 5-point hamming. Here, the hemodynamic change in the prefrontal lobe was extracted out. The amplitude in the stable phase of $\triangle$[deoxy-Hb], $\triangle$[oxy-Hb], $\triangle$[tot-Hb] curve for every channel and each subject was also extracted for statistical analysis. Finally, referring to the position of the measurement channels on the fNIRI probe relative to the prefrontal head, the distribution map of blood activation can be obtained with the above amplitude values for all channels.

2.5. *EEG data sampling and analysis*

The system of 72 channels Neuroscan SynAmps electrocortical potential collection and Ag/AgCl electrode cap were utilized to record EEG data. The electrodes on the cap were placed according to the international 10–20 system. The reference electrodes were the link line of papilla on both sides of the head. The horizontal and vertical ocular potentials were also recorded. The inter-electrode resistance was kept below 5 kΩ. Brain waves was recorded at bandwidth from 0.05 Hz$\sim$100 Hz and digitally sampled at 2000 Hz per channel. The EEG records and behavior data were collected synchronously. All data was offline analyzed with software "Scan 4.3". First, the data which was badly interfered by strong noise was removed, and the interference originated from ocular potentials was eliminated. Second, the data sequence was divided into epochs related with each stimulus, and the baseline was corrected. Then, the epochs with voltage values exceeding $\pm X\,\mu$v ($X \leq 100$) were rejected. No more than 15% epochs were rejected. The remaining epochs were averaged according to the stimuli type. Then, all averaged files were smoothed with zero-phase, 30 Hz, low-past digital filter. Finally, a group analysis was processed among all subjects. The ERP voltage distribution over the scalp for target stimuli and novel stimuli were obtained.

3. Results

3.1. *Frontal lobe: Activation in the ocular nonselective attention measured by ERPs*

Figure 2 shows ERPs, averaged across subjects, for novel, target, and untargeted stimuli respectively in all electrode sites. Novel stimuli cause nonselective attention in subjects' brain; and target stimuli introduce selective attention. From Fig. 2, we can see that: (1) The nonselective attention shows higher activation than the selective attention in the middle cortex, with higher peak and long time interval of P3a (300–500 milliseconds); Both types of attention activated similar shape of P3a wave, except for the contrast activity which untargeted stimuli introduced. Hence, the middle cortex is not the special area differentiating nonselective attention from common attention. (2) In the frontal lobe area (including the sites of electrodes FP1, FP2, F7, F3, F8), nonselective attention introduce positive P3a activation, while selective attention introduce low negative activation in the P3a period. The activation amplitude of selective attention in this period is near to the contrast activity in the frontal lobe. It seems that only nonselective attention can introduce a positive P3a activation in this part of the frontal lobe, compared with the selective attention and the contrast activity. (3) There is a weak lateralization of right and

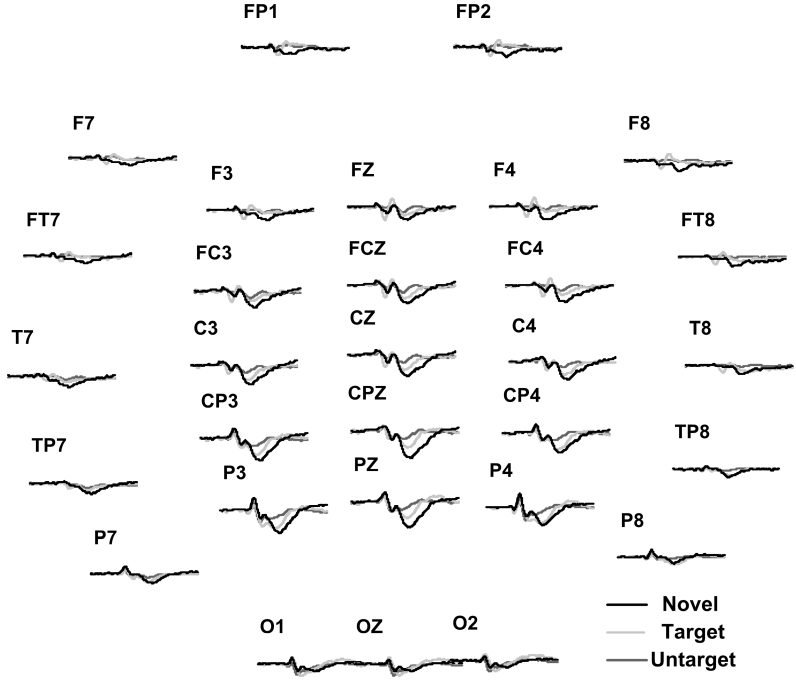

Fig. 2. Group averaged ERP waveforms superimposed for novel stimuli, target stimuli and untarget stimuli at 32 electrode sites.

left hemisphere for the nonselective attention's P3a activation in the frontal lobe. Compared with selective attention's activated region, the extensively activated area for nonselective attention is the frontal lobe with no lateralization.

As mentioned in Sec. 1, P3a component is related with the nonselective attention. In this experiment, at about 330 milliseconds after the novel stimulus presented in each epoch, the brain wave was shown to attain the peak of P3a component. For this reason, we analyzed the potential P330. Figure 3 shows the topographs of P330 component for the novel, target, and untargeted stimuli respectively. Compared with selective attention and contrast activity, nonselective attention shows a stronger P3a distribution in a larger area. In addition, only nonselective attention shows the positive P330, as shown in Fig. 3. P330 topographs also give visible evidences to the conclusion that the frontal lobe is only activated in nonselective attention.

3.2. *Left prefrontal lobe: Significant blood activation during ocular attention*

The primary curve of blood activation measured in one channel in the whole experiment, including the concentration change of oxy-, deoxy- and total hemoglobin (△[deoxy-Hb], △[oxy-Hb], △[tot-Hb] respectively), is shown in Fig. 4. In fact, most channel measurements show similar shape of blood activation with stronger positive activation of △[oxy-Hb], weak positive activation of △[tot-Hb], and weak negative activation of △[deoxy-Hb], which is the common activation pattern for most brain functional activities. In this case, the prefrontal lobe is also shown to be activated in the measurements of fNIRI. All of △[deoxy-Hb], △[oxy-Hb] and △[tot-Hb] are low signals, so there is a strong effect of the latest functional activity to the current task. Hence, it is difficult to differentiate the signal for nonselective attention and selective attention. We can only get the blood activation map for both nonselective and selective attention tasks in the whole experiment, as shown in Fig. 5.

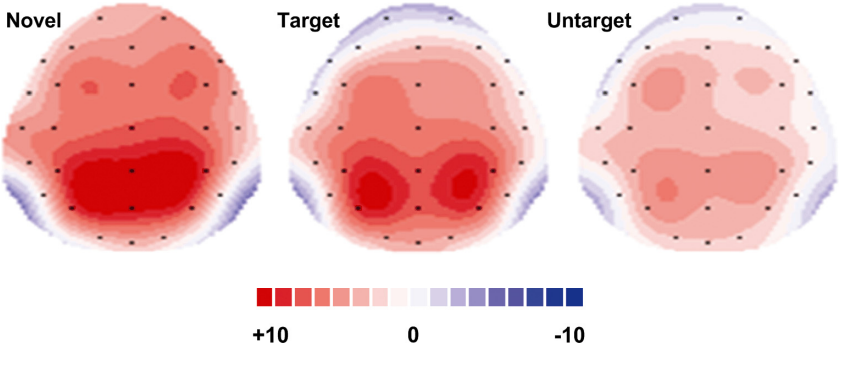

Fig. 3. Topographs of P3a components for novel stimuli, target stimuli and untarget stimuli.

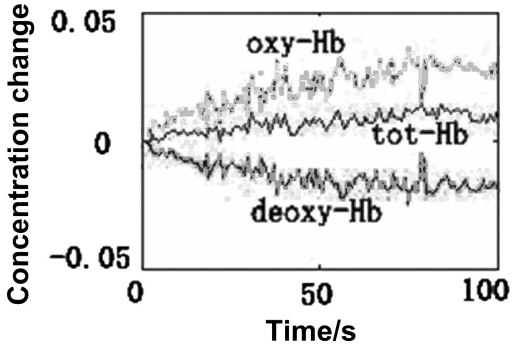

Fig. 4. The measurements of blood activation in one channel for some subject.

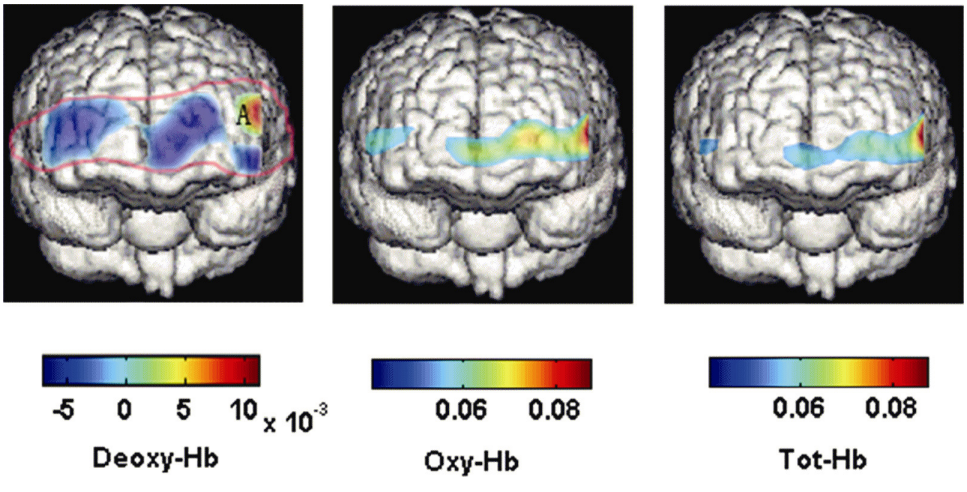

Fig. 5. Image of averaged blood activation amplitude for ocular attention task, including concentration change of deoxy-hemoglobin, oxy-hemoglobin, and blood volume.

Figure 5 describes the activation distribution of △[deoxy-Hb], △[oxy-Hb], and △[tot-Hb] in the prefrontal lobe. Compared with the sum signal of P330 components for both nonselective and selective attention, the blood activation in the prefrontal lobe measured by fNIRI agrees with the ERPs. Figure 5 shows that all △[deoxy-Hb], △[oxy-Hb] and △[tot-Hb] shows a positive activation in the left prefrontal lobe, with different intensity and size of the activated region among them. The △[oxy-Hb] map shows the largest area with positive activation. The △[tot-Hb] map shows a similar activated region as △[oxy-Hb], but with smaller area and low intensity of the activation. The △[deoxy-Hb] map shows the smallest region with positive activation. Compared with ERP, fNIRI has provided much more spatial information about brain activation in the left prefrontal lobe. In fact, the left prefrontal lobe has also been reported to be most related with attention-deficit hyperactivity disorder (ADHD).[19,20]

The small region, with a letter "A" indicated in Fig. 5, is most related with attention tasks and may be considered as one source for ocular attention. There are three reasons: (1) This region, activated strongest in the △[deoxy-Hb] measurement, also shows strongest activation in the △[oxy-Hb] and △[tot-Hb] measurements. (2) The positive activation of △[deoxy-Hb] was always used as a proof to determine the source location of brain functional activity in the fMRI technique. (3) More interestingly, the activation distribution of △[deoxy-Hb] shows a characteristic that the positively activated region is next to the most negatively activated region, which may result from deoxy-hemoglobin output which is caused by the oxygen assumption of region "A".

3.3. *Left and upper corner in Brodmann area 10: Source of the ocular nonselective attention*

With the combination of fNIRI and ERP, we can give two evidences supporting that the region "A" is the source of the ocular nonselective attention, but not the selective attention. The first evidence is shown in Fig. 6. By subtracting the P330 potential distribution of selective attention from nonselective attention's, we have obtained the most related P330 component relative to the ocular nonselective attention, as shown in Fig. 6. The ocular nonselective attention also activated with a high intensity in the region between FP1 and F7, which is near to the region "A".

The second evidence is the comparison between the blood activation caused by novel stimuli in the region "A" and the ERPs for the nonselective attention in the FP1 electrode site. The blood activation curves are shown during a period from the presentation of the final novel stimuli to the end of the experiment, as

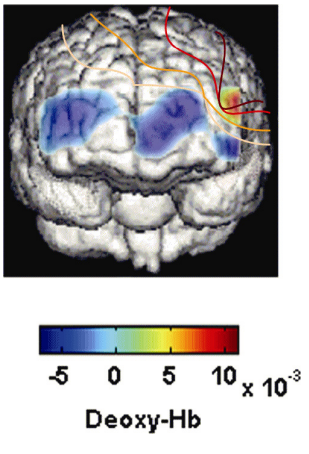

Fig. 6. Source location of ocular nonselective attention with results combination of NIRS and ERP. The stratigraphic map of ocular nonselective attention activation on prefrontal lobe is shown with lines in colors from red (high activation) to yellow (low activation).

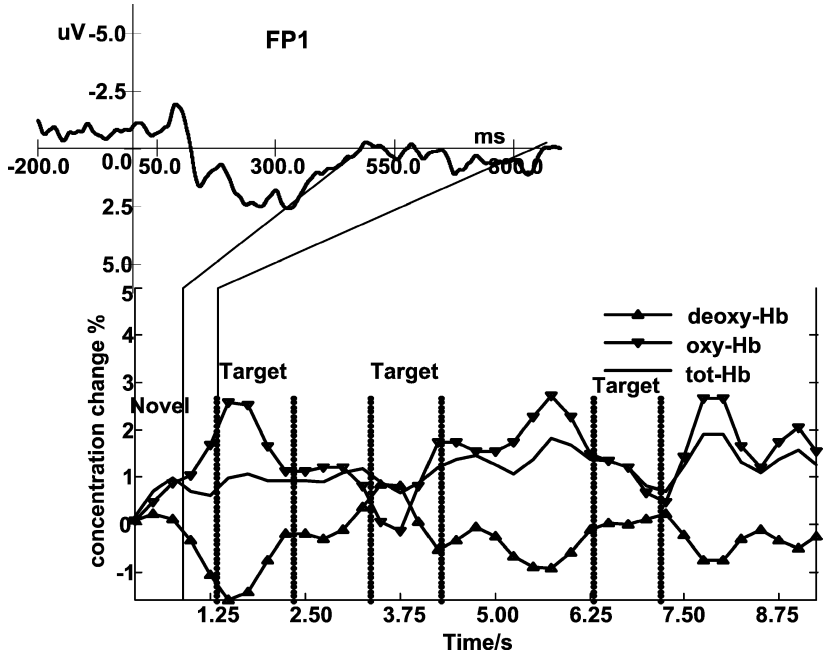

Fig. 7. Comparisons between blood activation change and brain wave for novel stimuli in the site of FP1 electrode. The blood activation change, begin from this novel stimulus to the end of the experiment, is also shown to study the effect of selective attention to the blood activation.

described in Fig. 7. At the beginning of the ocular nonselective attention, △[tot-Hb] activated most quickly until the end of the typically related P3a component measured by FP1 electrode, along with a similar but slower activation of △[oxy-Hb]. By contrast, the △[deoxy-Hb] did not change during this period. After this period, the ERPs changed to be stable and near to 0 uV. Meanwhile, the blood activation pattern also changed, with a small decrease of △[tot-Hb], sharply increasing the △[oxy-Hb], but sharply decreasing the △[deoxy-Hb]. Here, it shows an obvious correlation between blood activation and ERPs in the ocular nonselective attention task. A reasonable explanation to this relationship is that: As a response to a novel stimulus, region "A" firstly starts increasing fresh blood input to provide energy to the task-related neural discharge. Then, the neural discharge also outputs a control command to decrease the fresh blood input and increase the output of deoxy-hemoglobin. This process could control the energy waste and move the increased deoxy-hemoglobin to the heart. This explanation is based on the coupling between vascular and neuron. After the ocular nonselective attention, there are three tasks of selective attention, all of which do not show a strong and related change in blood activation as the nonselective attention. In this case, we know that it is the ocular nonselective attention that strongly activated in region "A", but not the selective attention. The region "A" is located in the left and upper corner in Brodmann area 10.

4. Discussion

Although fNIRI is a developing technique, which can only measure brain activation in the prefrontal lobe presently, the accuracy and advantage of this technique in the functional source localization has been well-demonstrated in this paper. The activations measured by fNIRI in the frontal lobe, responding to the mixed tasks including the ocular nonselective and selective attention, agrees well with those measured by ERP. Unlike ERP which subjects a drawback of low spatial resolution caused by the strong diffusion of potentials on the cortex, fNIRI shows a higher spatial resolution with the ablity in obtaining a more precise location of the source of functional activity. In addition, fNIRI can provide much richer information than ERPs on the characteristics of activation measured with three parameters, including the concentration change of oxy-, deoxy- and total hemoglobin. For this reason, the fNIRI technique can be a promising tool in the research of psychology and highy recommended to be widely used with ERP.

The method with combined utilization of fNIRI and ERP, provided as an attempt in this paper, was shown to be effective in the precise location for the source of some brain functional activity. Using this method, we finally found the source location of ocular nonselective attention, which is a small region in the left and upper corner in Brodmann area 10. With ERPs measurement, we could only know that the ocular nonselective attention activated a large area in the frontal lobe but the selective attention did not activate this area. With fNIRI which has difficulty in differentiating low signals correlated with different tasks in a mixed experiment paradigm, we could find a small region in the prefrontal lobe being activated the strongest in the complex brain activity. However, we could not decide which type of attention is the real object to activate the small region. With both techniques, we can determine that the source of nonselective attention is located in this small region, with no worry about the ambiguity between nonselective and selective attention and the possibility of another source location relative to the ocular nonselective attention.

This combination method has several advantages in the research of brain functional activities. First, for the prefrontal lobe which has become more and more important in the research of advanced brain function, the ERP's limited ability in this region can be well supplemented by fNIRI, by providing the prefrontal lobe's oxy-, deoxy- and total hemoglobin concentration changes information with high spatial resolution. Second, the activation distribution in the whole cortex, which can be monitored with ERP, could remove fNIRI's limitation in monitoring the area out of the prefrontal lobe. Third, the difficulty of fNIRI in extracting signals relative to the different tasks in a mixed paradigm, can be overcome by ERP to differentiate the fast signal ERPs responding to different tasks. In addition, because of the different mechanism and measurement parameters between these two technologies, their combination could provide more information in the further research in clinical medicine, psychology and brain function mechanism especially including the neuron vascular coupling.

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