Cortical Functional Connectivity Revealed by Optical Brain Imaging

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Abstract— Optical brain imaging is emerging as a novel technique for non-invasively investigating functioning brain. It uses near-infrared light to probe human cortex through intact scalp and skull, providing cerebral hemodynamic information closely associated with neuronal activity. In addition to investigating various task-related cortical activations, very recently optical brain imaging has been demonstrated to be able to assess resting state functional connectivity (RSFC) by recording and cross-correlating the cortical spontaneous fluctuations. In this work, we performed two experiments by using an optical brain imaging system to reveal cortical RSFC. In Experiment I, the cortical areas measured included bilateral temporal and adjacent inferior frontal cortices. In experiment II, we measured the prefrontal cortex. The data from Experiment I show that there are significant differences in the network between children and adults, implying the developmental differences in the language network. The data from Experiment II show significant differences between males and females in prefrontal RSFC, which may be associated with the underlying physiological basis for sex-related differences in cognitive control and emotional regulation in humans.

1. INTRODUCTION

A large amount of studies over the past twenty years have demonstrated that optical brain imaging is a useful technique for imaging functioning brain [1–5]. Due to its low cost, portability, as well as noninvasive measure on the concentration variations of hemoglobin, optical brain imaging has been increasingly used for studying healthy brain [5–7] and a variety of psychiatric disorders [8–10].

Resting state functional connectivity (RSFC) studies with functional magnetic resonance imaging (fMRI) showed that low frequency (< 0.1 HZ) fluctuations of spontaneous neural activity are temporally correlated between functional relevant regions during the resting state [11, 12]. Recent studies have also demonstrated optical brain imaging has the ability to reveal RSFC by recording cerebral spontaneous hemodynamic signals [13–16].

Very recently, optical brain imaging has been applied to quantitatively evaluating intra- and/or inter-hemispheric correlations across functional regions during resting state, such as prefrontal, sensorimotor, and visual cortices [14]. These correlations could provide useful information about cortical networks, such as network range and connectivity strength.

In this work, we performed two experiments by using a continuous-wave optical brain imaging system to identify RSFC for healthy children and adults. In Experiment I, the cortical areas measured included bilateral temporal and adjacent inferior frontal cortices. These regions are human language areas responsible for language generation and comprehension. In Experiment II we measured prefrontal cortex, the high functional area in human responsible for cognition, memory, and emotion, et al.. From Experiment I, we found significant differences in network connectivity and range between adults and children, which may reflect developmental differences in language network. Data from Experiment II showed significant differences between adult males and females in RSFC, which may shed light on the underlying physiological basis for sex-related differences in cognitive control and emotional regulation.

2. METHODS

2.1. Subjects

Experiment I was to investigate RSFC for language areas, in which twenty-two healthy subjects (11 adults and 11 children) were involved. In the adult group, there were eight males with an average age of 23.4 (± 0.9) years old. The children group consisted of eight boys with an average age of 9.0 (± 1.5) years old. Experiment II was to detect RSFC for prefrontal cortex, in which twenty-two adult healthy subjects (11 males) were included, with an average age of 23.6 (± 0.9) years old. All subjects were right handed. Before experiments, subjects were informed about the measuring procedure and written consent was obtained from adults and parents of the children. The study protocol was approved by the University's Ethical Review Board.

2.2. Experimental Setup and Experimental Protocol

Measurements were conducted with a commercial continuous-wave optical brain imaging system (FOIRE-3000, Shimadzu Corporation, Kyoto, Japan) working at three different wavelengths (780 nm, 805 nm and 830 nm). In all measurements, 8-min spontaneous cortical fluctuations were recorded. During measurements, the subject was sitting quietly on a comfortable chair in a dim room with his/her eyes closed.

The locations of the optical sensors were positioned based on the international 10/20 EEG system [17]. In Experiment I, 44 channels (22 for each hemisphere) were used to cover bilateral temporal and inferior frontal cortices, which is schematically shown in Fig. 1(a). In Experiment II, 42 channels were used to cover prefrontal cortex, as schematically shown in Fig. 1(b).

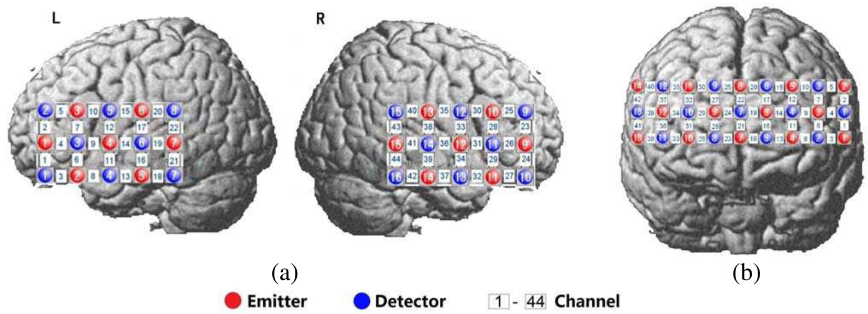


Figure 1: Experimental schematics. (a) Schematic representation of the brain showing the location of each measurement channel over bilateral temporal and inferior frontal cortices. (b) Schematic representation of the brain showing the location of each measurement channel over the prefrontal cortex.

2.3. Data Analysis

As the first step of data processing, a band pass filter (0.009–0.08 Hz) was applied to the optical data (time series of HBO, HB and HBT) [14] to reduce systemic oscillations (such as that due to cardiac cycles ~ 1 Hz, respirations ~ 0.2 Hz and blood pressure fluctuations ~ 0.1 Hz). To further remove the remaining global component which is not specific to local cortex, an ICA based algorithm [16] is used for processing data from Experiment I. While for Experiment II, a conventional regression algorithm is used [18]. The conventional regression algorithm is based on an assumption that the overall mean value for all local intrinsic signals is zero. This may be applied to the case where signals come from many functionally independent regions. Obviously, it does not hold when all signals come from functionally closely related regions such as language areas. The Pearson correlation coefficients are used for the correlation analysis. To map the correlations, a 'seed-based' approach [14] is used in which the correlations between the seed channel and all other channels are projected on the measured areas. This correlation map shows the connectivity (or synchronization) pattern of cortical spontaneous activity.

3. RESULTS

3.1. The Results for Experiment I

The connectivity (or correlation) matrices for left and right language areas are shown in Fig. 2. Each pixel value corresponds to a group average correlation value for oxygenated hemoglobin (HBO) in the 44×44 correlation matrix. From Fig. 2, one can see the adult group is stronger than the children group on both intra-hemispheric (e.g., L-L, R-R) and inter-hemispheric (e.g., L-R) correlations. Since language processing is left lateralized, relying mainly on left hemispheric networks, a seed (channel) for generating a correlation map was selected on left hemisphere. Fig. 3 gives HBO correlation maps for the adult [Fig. 3(a)] and the children [Fig. 3(b)] group. The correlation map shows correlations on the measured area between the seed and all the other channels. In comparison, within each hemisphere, the adult group shows stronger correlation and larger correlation range. Between hemispheres, the inter-hemispheric correlation is stronger for the adult group than the children group. These findings are in line with the fact that language network is developed better for adults than children who are still developing.

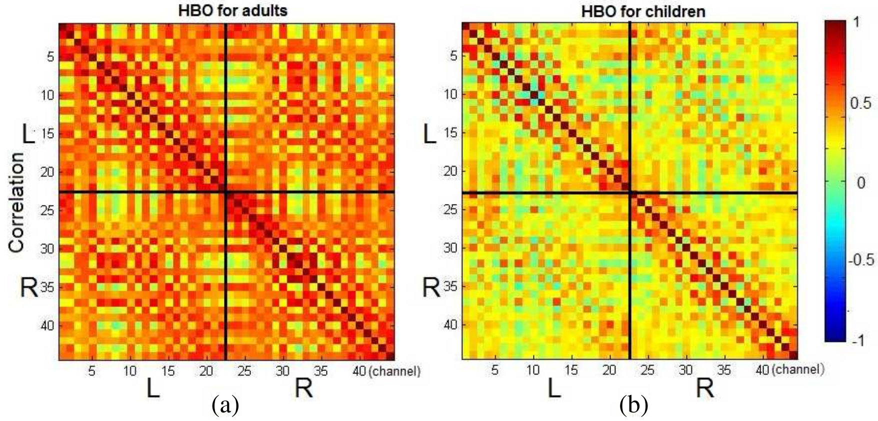


Figure 2: Group average connectivity matrices showing HBO correlations between all channels, (a) is for the adult group, and (b) for the children group.

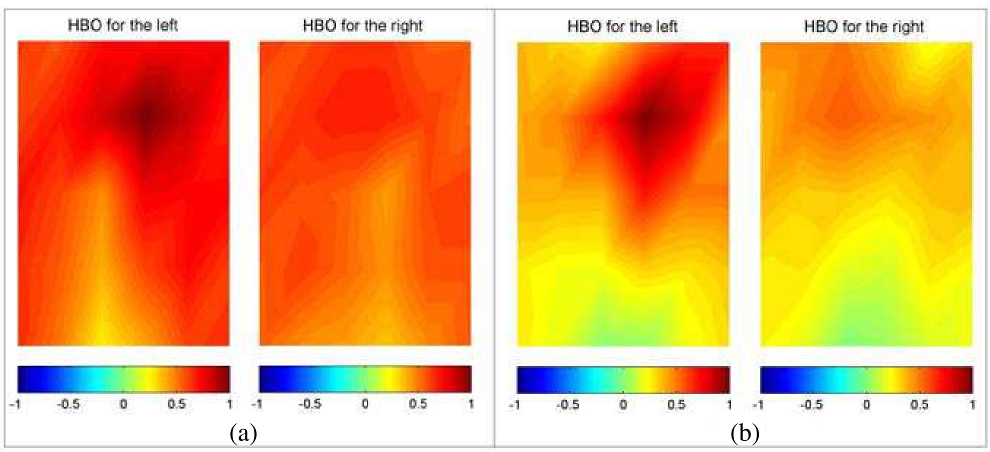


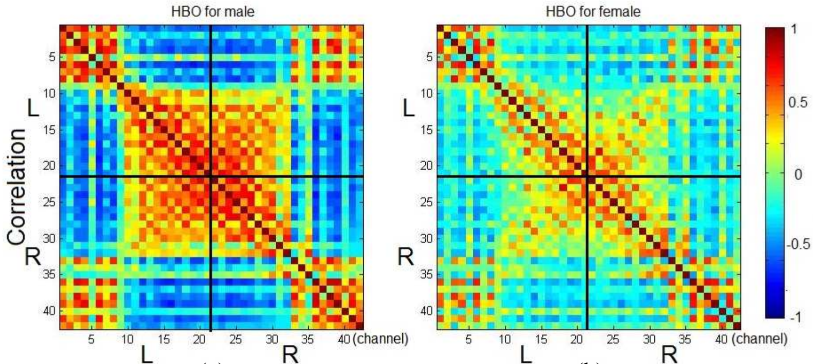
Figure 3: HBO connectivity maps showing correlations between the seed (channels 19) and all other channels, (a) is for the adult group, and (b) for the children group. The seed is located on the left hemisphere and can be visually recognized by the maximal color value in each map.

3.2. The Experiment of Prefrontal Cortex

Figure 4 illustrates prefrontal connectivity matrices for males [Fig. 4(a)] and females [Fig. 4(b)]. One can see that the male group has stronger connectivity in the anterior prefrontal cortex (BA 10) than the female group, which is revealed by the significant difference in the correlation values around the center of the figure. This finding can be also seen from the connectivity maps (Fig. 5), generated by choosing a seed (channel 19) in BA 10. Both network range and connectivity strength for males are significantly larger than females. It should be noted this finding does not depend on the selection of the seed.

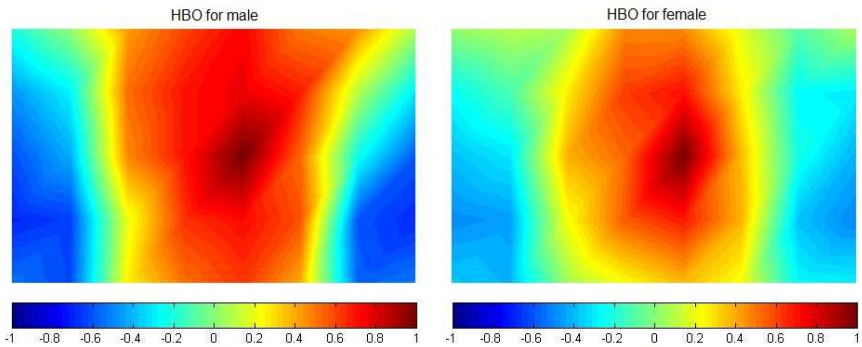
4. DISCUSSION

In this work, using optical brain imaging, we examined the resting state spatial and temporal correlations over language (bilateral temporal and adjacent inferior frontal) and prefrontal cortices on healthy children and adult subjects. In the experiment on language region, our result has shown that the local correlation range and strength in left hemisphere are larger for adults than children, which is consistent with the previous fMRI study [19]. This may reflect the differences between adults and children on language skills, provided that language skills, such as skills on language production and comprehension, are associated with the strength of the language network connectivity. For the prefrontal measurement, the male group has shown significantly larger network range and stronger connectivity strength than the female group. The significant differences between males and females in the prefrontal RSFC may shed light on the underlying physiological basis for sex-related differences in cognitive control and emotional regulation, and may also provide insight into sex-related differences in the prevalence of some neurological diseases.



(a) (b)

Figure 4: Group average connectivity matrices showing HBO correlations between all channels, (a) is for the male group, and (b) for the female group.



(a) (b)

Figure 5: The connectivity map for (a) the males and (b) the females, the seed is Ch 19 in BA 10.

5. CONCLUSION

Optical brain imaging can be used to non-invasively assess resting state functional connectivity in language and prefrontal cortices. Our data show the developmental difference in the language network and sex-related differences in prefrontal network can be reveal by optical brain imaging. This suggests that optical brain imaging is of potential applications for diagnosing neurological diseases relevant to language network development and cognitive function degeneration and defect.

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