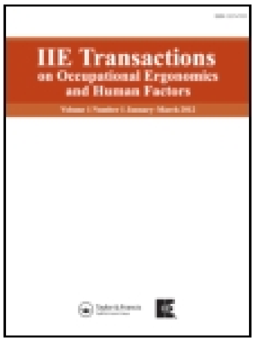

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Functional Connectivity and Activation of Motor Cortex during Preparation for Hand Movement

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Occupational Applications

Our results illustrate the enhanced functional connectivity (FC) between motor-related brain regions and high-level cognitive brain regions during the transition period between rest and hand movements. These results suggest that the sensorimotor network is interacting with prefrontal areas during the transition period to maintain the preparation state. Both actual movement and the transition period without actual movement modulate brain activities. Capturing the detailed relationship of movement intention could be utilized to improve precision and latency of anticipation-based brain-computer interfaces (BCI). Furthermore, consistent with the neuroergonomic approach, this study demonstrates that functional near infrared spectroscopy is a

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suitable tool for region-specific, task-related, and resting-state FC analysis. Our findings could enhance the development of more intuitive and natural interfaces between human and machine systems in diverse areas. The approach presented here could help create assistive devices that perceive and predict operator's intention of movements.

Technical Abstract

Introduction: Traditional and new generations of neuroimaging techniques allow observing the modulation of brain activities during transition periods between rest and physical movement execution. A thorough understanding of the brain activity and FC changes during these transitions could contribute to increasing the precision and decreasing the latency of anticipation-based brain-computer interfaces, and improving human-system integration in general. Consistent with the neuroergonomic approach, functional near infrared spectroscopy (fNIRS) can monitor the outer cortex during extensive physical movement and in realistic settings using wearable and portable sensors.

Methods: In this study, 19 healthy subjects were monitored with fNIRS during rest, a fist opening and closing task, and the transition period preceding the task. FC analysis was used to evaluate how the transition period preceding the task modulated the brain activities.

Results: There were several increases in FC during the transition period, especially between the right dorsolateral prefrontal cortex and the contralateral primary somatosensory and primary motor cortices, as well as the FC connecting the contralateral primary somatosensory cortex with the ipsilateral primary somatosensory cortex and the primary motor cortex. Regions located in

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the sensorimotor networks and right dorsolateral prefrontal cortex were also found to be activated during the transition period.

Conclusions: These results demonstrate that the sensorimotor network was interacting with the high-level cognitive brain network during the transition period to maintain the preparation state. Furthermore, fNIRS is an emerging tool well-suited for region specific task-related and resting-state FC analysis. The results and the approach presented here suggests that operators’ intention to move can be detected before the actual movement, and that could be employed for development of more intuitive and natural interfaces between human and machine systems.

Keywords

Functional near infrared spectroscopy; fNIRS; Functional connectivity; FC; Movement preparation; Neuroergonomics;

1. Introduction

Understanding the relationship between cognitive processes and the underlying patterns of brain activity has been a fundamental goal for cognitive neuroscience research (J. Trevena & Miller, 2010) and for applications of neuroscience to work and everyday activities, or neuroergonomics (Ayaz et al., 2013; Mehta & Parasuraman, 2013; Parasuraman, 2011). Unlike the explicit cognitive processes during rest and movement, the cognitive process during transition period between rest and movement, which usually corresponds to the preparation period preceding movement, is implicit (J. A. Trevena & Miller, 2002). Although there is no actual movement in the transition period, modulation of brain activity has been observed, such as the Readiness Potential recorded by scalp electrodes around 500 milliseconds before a movement (Brunia, 1988; Deecke, Scheid, & Kornhuber, 1969; Libet, 1993; Libet, Gleason, Wright, & Pearl, 1983). However, detailed information of brain activities during the transition period, such as how brain regions interact with each other to establish the motor preparation through FC, is still a pending question (Treserras et al., 2009). Thorough understanding of it would help with the investigation of the adaptation of brain networks for upcoming movement, and would have implications for improving the precision and latency of anticipation-based brain-computer interfaces (Deng, Yao, & Dewald, 2005; Gangadhar, Chavarriaga, & del R Millán, 2009; Williams, Rouse, Thongpang, Williams, & Moran, 2013), for neuroergonomic research related to human system integration and automation (Ayaz, Shewokis, Bunce, Schultheis, & Onaral, 2009; Parasuraman & Wilson, 2008), and various neurorehabilitation approaches such as neurofeedback-based motor function rehabilitation (Niazi et al., 2011; D. Zhang, Liu, Huan, Liu, & Zhu, 2009).

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Several recent functional magnetic resonance imaging (fMRI) studies have utilized FC analysis to investigate brain dynamics during preparation of movement. Newton and colleagues found that correlations increased within the sensorimotor network during transition from rest to finger tapping (Newton, Morgan, & Gore, 2007). In addition, Treserras and colleagues found that the default-mode network and sensorimotor network were functionally correlated through an interaction between the posterior cingulate cortex, and precuneus and the medial superior parietal cortex in the upper precuneus during transition period between resting and motor task state (Treserras et al., 2009). Also, a positive relationship between default-mode network and right sensorimotor cortex while a negative relationship of default-mode network with left sensorimotor cortex during transition period were also reported (Newton et al., 2007). Other than the FC-based analysis, a TMS-based study found that the excitability of the motor cortex contralateral to the moving hand increased, whereas the excitability of the ipsilateral motor cortex decreased during transition period (van den Hurk et al., 2007).

Although findings from these studies were encouraging, and fMRI recordings provided extensive detail of the spatial distribution and relationship of activations, the relatively short time length of transition period made the temporal resolution very critical for reliable FC analysis during the transition period. fNIRS measures hemodynamic response similar to fMRI but can provide much higher sampling rate and therefore a good candidate for further follow-up studies for the investigation of the temporal dynamics of the brain network modulation during the transition period (Ayaz et al., 2011; Ferrari & Quaresima, 2012; Obrig & Villringer, 2003). In addition, compared with fMRI, fNIRS is cost effective (close to zero run-time cost) and without any operation ambient sound which would help focusing on the task at hand, especially for the transition period (Ayaz et al., 2013; Derosière, Mandrick, Dray, Ward, & Perrey, 2013). fNIRS has been applied to neuroergonomics, such as for examining workload and training-related brain dynamics with human performance assessment (Ayaz et al., 2012; McKendrick, Ayaz, Olmstead, & Parasuraman, 2014). For FC analysis, fNIRS has emerged as a new tool that complements the fMRI-based FC analysis and also enable new applications because of its portable and wearable nature. For example, patients with brain-injured or intensive care patients in remote country or outdoors environments (Mckendrick et al., 2016), or participant groups that cannot be easily transported to an fMRI facility, can be monitored with portable fNIRS.

The reliability of fNIRS in FC analysis has already been demonstrated by several studies. One of the early pilot studies by White and colleagues demonstrated robust correlation maps of fNIRS-based FC in motor and visual cortices (White et al., 2009). Another study investigated resting-state FC in bilateral sensorimotor and auditory cortices through fNIRS (Lu et al., 2010). Mesquita and colleagues further used fNIRS to investigate the FC over the whole head during resting state and found strong correlations between two hemispheres for both sensorimotor and visual cortices (Mesquita, Franceschini, & Boas, 2010). Other than the seed-based FC analysis method (Xiong, Parsons, Gao, & Fox, 1999) used in the above three studies, Independent Component Analysis of FC was also used in fNIRS, and its feasibility was validated (H. Zhang et al., 2010). Furthermore, analysis of frequency-specific FC (Sasai, Homae, Watanabe, & Taga, 2011) and Granger causality (Medvedev, 2014) have been reported on fNIRS. Several studies have also investigated the topological configuration of brain networks through fNIRS (Fekete, Beacher, Cha, Rubin, & Mujica-Parodi, 2014; Niu, Wang, Zhao, Shu, & He, 2012).

In addition to the resting-state FC and network based analysis, fNIRS can be used to assess task related activation. High temporal resolution capacity enables fNIRS to capture more information regarding the task modulation riding on the intrinsic brain networks through the task-state FC. In fact, a recent study has used fNIRS to investigate the FC during resting state and finger movement and proved the effectiveness of fNIRS in task-state FC analysis (Bajaj, Drake, Butler, & Dhamala, 2014).

In the current study, fNIRS was used to examine FC as well as the activation during the transition period between rest and hand movement. Given the high temporal resolution of fNIRS, the fNIRS-based FC during transition period was expected to provide more information regarding adaptation of brain networks for the upcoming task. Understanding the detailed relationship with movement intention could be utilized to improve precision and latency of future intention-based brain-computer interface and neuroergonomics research in general.

2. Materials and Methods

2.1 Participants

Nineteen healthy, right-handed volunteers (12 males; 24.68±3.06 years) participated in this study. Subjects did not have any reported history of mental health, seizures, head injury, or neurological dysfunction (e.g. stroke or seizure). All subjects provided written informed consent and procedures were reviewed and approved by the Institutional Review Board of Drexel University.

2.2 Data Acquisition

Neuroimaging data were collected using the 24-channel Hitachi ETG-4000 NIRS system (Hitachi Medical Co., Tokyo, Japan) at the Cognitive Neuroengineering and Quantitative

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Experimental Research Collaborative, Drexel University (Philadelphia, PA, USA). Absorptions of near-infrared light at two wavelengths (695nm and 830mm) were measured with a sampling rate of 10 Hz, and changes of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) concentrations were calculated by the modified Beer-Lambert law (Delpy et al., 1988) at each time point for each channel. Eighteen fiber probes (10 emitter probes and 8 detector probes) were placed on subjects' head using a custom-made cap (Fig. 1(A)) and the probes were arranged with Cz (according to the international 10/20 system) located directly in the center of the probes. The probes were connected to the recording device by flexible optical fiber bundles. As a result, 24 optical channels (12 for each hemisphere) were recorded (Fig. 1(C)). The positioning of the probe array was determined according to the international 10-20 system and referred to prominent anatomical landmarks such as the bilateral tragus, nasion and inion (Ayaz et al., 2011). Based on the measured real coordinates of the probes, we also used NIRS-SPM (Ye, Tak, Jang, Jung, & Jang, 2009) to perform spatial registration and obtained the standard coordinates of probes and channels in MNI (Montreal Neurological Institute) space (Fig. 1(B) and (C)). According to the MNI coordinates of channels, four regions of interest (ROIs) (i.e. Primary Motor Cortex, Premotor and Supplementary Motor Cortex, Primary Somatosensory Cortex and Dorsolateral Prefrontal Cortex; Abbrev. M1, PMSMC, S1 and DLPFC, respectively) were covered by the channels in each brain hemisphere (Fig. 1(C)).

2.3 Experiment Protocol

The experiment was completed in a single sitting and had three main parts/sessions. The first session consisted of three blocks, involving rest, left fist opening and closing (FOC), and right FOC. Each block lasted for 4 minutes. During the rest block, subjects were instructed to relax

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and refrain from any movement. After the rest block, subjects were cued to perform left FOC and right FOC with randomized order. During the FOC, “0” and “1” were displayed to pace subjects’ movements. Subjects were instructed to open their fist when they saw “0” and close when they saw “1”. The frequency was set as opening and closing once per second (Fig. 2(A)). There were six trials in session 2 and each trial consisted of three blocks which were rest, transition period and left/right FOC. Rest and FOC blocks were identical to the session 1 only with different length (30s in session 2). During the transition periods between rest and FOC, subjects had already known which hand they were going to use in the coming FOC block through the cue displayed just after rest block, but they were instructed to get ready for the upcoming movement without any movement and waiting for another cue to start the FOC. When the starting cue was displayed, they started FOC as soon as possible. Therefore, the transition periods in session 2 were defined as preparation periods preceding the externally-triggered movement (Cunnington, Windischberger, Deecke, & Moser, 2002). We applied three different lengths of transition periods (5s, 15s and 30s) for both left FOC and right FOC (Fig. 2(B)). For session 3, only the transition period was different from session 2. In session 3 (Fig. 2(C)), there was no cue for FOC start, and subjects decided when to start FOC by themselves, making these transition periods equivalent to preparation period preceding self-initialed movement (Cunnington et al., 2002). In order to make the analysis feasible, we told subjects to neither make the length of transition period too long (more than 30s) nor too short (less than 5s). There were also six trials in session 3 (three for left and three for right). During the experiment, subjects’ immobility was visually checked and no excessive motion was found for any subjects.

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2.4 Data Preprocessing

Raw fNIRS data were band-pass filtered with 0.01 Hz to 0.1 Hz to remove physiological noise such as respiration and cardiac activities, following previous studies (Fekete et al., 2014; Medvedev, 2014; White et al., 2009; H. Zhang et al., 2010). Data from one of the participants were rejected due to low signal quality and artifacts. In addition, motion artifacts were marked by visual inspection (i.e., spikes and deformed burst with large changes of magnitude in less than 1s would be marked as motion artifacts) and confirmed with a variation of coefficient based algorithm using the suggested parameters in these studies (Ayaz, Izzetoglu, Shewokis, & Onaral, 2010; Sweeney et al., 2012). The Sliding-window Motion Artifact Rejection (SMAR) algorithm uses statistical filtering to automatically mark temporally localized artifacts on fNIRS signals and has been shown to be effective for various types of noises such as Burst and Gaussian (Ayaz et al 2010). We used oxy-Hb signal changes in the current analysis since previous findings showed that oxy-Hb was the most sensitive to locomotion-related activities (Miyai et al., 2001; Suzuki et al., 2004).

2.5 Functional Connectivity Analysis

For FC analysis, five segments of data were used to generate FC which included three blocks (rest, left FOC and right FOC) in session 1 and two 30s-long transition periods preceding the left and right FOC (left trans and right trans) in session 2. For each segment of each subject, oxy-Hb time courses of channels located in the same ROI were averaged to generate a representative oxy-Hb time course for this ROI. Thus, eight representative oxy-Hb time courses (four for each brain hemisphere) were obtained. Based on that, the pair-wise FC was estimated by Pearson's correlation analysis and the correlation coefficient (r) was transformed to z-score by Fisher's transformation (Fisher, 1915). As a result, an 8×8 association matrix was obtained for each segment of each subject. Element a_{ij} in an association matrix represent the FC strength between the ith ROI and the jth ROI (Fig. 3). In order to find how transition periods and FOC would modulate the FC compared with resting state, group-level paired t-tests were performed to identify significantly changed FC during transition periods and FOC compared with resting-state. False Discovery Rate (FDR) approach was used to do the multiple comparison correction (Benjamini & Hochberg, 1995).

2.6 Activation Analysis

For each channel, baseline-adjusted mean level of oxy-Hb was calculated for each block in session 2 and 3. The first 10 time points (1s) of each block were regarded as the baseline and the data of each block were adjusted by subtracting the mean of corresponding baseline. After that, baseline-adjusted mean level of oxy-Hb was obtained by averaging the baseline-adjusted time courses of each block across time. With respect to the transition-related activation, activation during left trans and right trans were estimated for session 2 and 3 respectively. For each session, the six transition blocks were divided into two conditions (left trans and right trans) according to which hand was cued. An averaged baseline-adjusted mean level of oxy-Hb was obtained for left trans and right trans for each subject, and group-level paired *t*-tests were used to compare left trans and right trans with resting state for each channel and FDR approach was used to do the multiple comparison correction (Benjamini & Hochberg, 1995). For FOC-related activation, the FOC blocks in session 2 and 3 were compiled to do the same analysis as transition-related activation. Statistical significance was concluded when $p < 0.05$.

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3. Results

3.1 Modulated FC during transition period

For FC analysis, significantly increased FC were found during left FOC, left trans and right trans compared with resting state (Fig. 4), while no significant change in FC was found during right FOC. Table 1 summarizes the increased FC during left FOC, left trans and right trans. There were more modulated FC during transition periods than FOC periods and the average strength of FC during transition periods was greater than that during rest and FOC periods according to the average association matrices (Fig. 4(D-G)). With respect to increased FC during transition period compared with resting state (Fig. 4(B) and (C)), most FC were inter-hemispheric FC for both left trans and right trans. Especially, FC connecting the right DLPFC with contralateral (right side in left trans and left side in right trans) S1 and M1, and FC connecting contralateral S1 with ipsilateral (left side in left trans and right side in right trans) S1 and M1 were significantly increased for both right trans and left trans, implying the relationship between modulated FC during the transition period and the side of FOC subjects were about to perform.

3.2 Task-Related Activation

In addition to FC analysis, activation analysis is another method which can directly demonstrate how transition periods modulate brain activities. Activated channels during FOC and transition periods were identified by paired t-tests and multiple comparison was corrected by FDR. Activated channels were identified (FDR corrected $p < 0.05$) during FOC periods (Fig. 5(A) and 5(B)) as well as transition periods in session 3 (Fig. 5(E) and 5(F)), which corresponded to the preparation before self-initialized movement. Table 2 listed these activated channels and their statistical results. Nine channels were activated during left FOC, which located in bilateral

DLPFC, right PMSMC, and right M1, and three channels located in left PMSMC and left M1 were activated during right FOC (Table 2). For transition periods in session 3, fifteen channels were activated during left trans, which located in bilateral DLPFC, bilateral M1, bilateral S1 and right PMSMC, and eight channels located in bilateral M1, right S1, right PMSMC and right DLPFC were activated during right trans (Table 2). However, no channels were activated during transition periods in session 2, which corresponded to the preparation before externally-triggered FOC, after multiple comparison correction by FDR, even though several activated channels were identified before multiple comparison correction (Fig. 5(C) and 5(D)).

4. Discussion

We examined how the transition period between rest and FOC modulated the motor-related brain activities from the perspectives of FC and activation. Our results demonstrated that the actual movement in FOC modulate the brain activities, and the transition period without actual movement also modulates the brain activities from the perspectives of both FC and activation.

For FC analysis, our results showed that FC connecting the right DLPFC with contralateral S1 and M1, and FC connecting the contralateral S1 with ipsilateral S1 and M1 were significantly increased for both right trans and left trans (Fig. 4). These findings might give us an idea about how brain would achieve the preparation state before actual motor task execution. DLPFC is an intensively researched brain region and many functions have been attributed to it such as executive control of motor system (Vogt et al., 2007) and response inhibition (Zheng, Oka, Bokura, & Yamaguchi, 2008). Specifically, right DLPFC might be involved in the attention to motor timing and decision on when to move based on other studies (Lewis & Miall, 2003; Lewis

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& Miall, 2006). In addition, M1 and S1 is known to be the primary brain regions in charge of sensorimotor function. Thus, it is reasonable to believe that these increased FC indicated that right DLPFC was controlling M1 and S1 to maintain the preparation state. Based on the functions of DLPFC found by previous studies, the controlling aspect might consist of two parts. First part was to make the sensorimotor system be ready for the upcoming motor task. Furthermore, since which hand subjects would use in the upcoming task had already been cued, DLPFC might also exert control over contralateral M1 and S1 to withhold the execution of motor task during the preparation, which was supported by previous finding that DLPFC might be important for making the decision on when to move and withholding movement until the right moment (Bortoletto & Cunnington, 2010). Increased FC connecting contralateral S1 with ipsilateral S1 and M1 further indicated an interaction of bilateral sensorimotor system to process the sensory information and further collaborate with DLPFC to balance the activities in both hemispheres and maintain the preparation state. In summary, these findings proved that brain regions with high-level cognitive functions such as DLPFC collaborated with sensorimotor networks in bilateral hemispheres to maintain the preparation state, under which motor system was ready for the upcoming motor task but also was withheld to execute motor task until the right moment.

With respect to comparison between FOC and rest, only two FC were found significantly increased (unc. $p < 0.05$) in left FOC which were FC between right PMSMC and right S1 as well as left S1 (Fig. 4(A)). Premotor and supplementary cortex was known to play an important role in control of movement, especially for the sequential movement according to previous studies (Halsband, Ito, Tanji, & Freund, 1993; Sadato, Yonekura, Waki, Yamada, & Ishii, 1997). During

FOC, subjects were instructed to open and close their fist according to the numbers displayed on the screen. Therefore, there might be an interaction between the sensory component and control component to pace the movement based on external information during this process. The two increased FC between right PMSMC and bilateral S1 might be the “bridge” of information transmission and PMSMC contralateral to moving hand was receiving sensory information from bilateral S1 through them and therefore exerted control over FOC.

For activation analysis, more activation were identified during transition periods in session 3, which corresponded to preparation before self-initialed FOC (Fig. 5(E) and 5(F)), as no channels survived the multiple comparison correction during transition periods in session 2. Previous studies had similar findings by examining the readiness potentials before movements and they found that the readiness potential preceding self-initialed movements was significantly greater compared with externally-triggered movements (Jahanshahi et al., 1995; Papa, Artieda, & Obeso, 1991). Nevertheless, right DLPFC was activated during left trans and right trans in both session 2 and session 3, which further supported our speculation of the important role that right DLPFC played in the preparation state through the FC analysis. In addition, bilateral S1, M1 and PMSMC which were key brain regions for motor execution and motor control, were also activated even though there was no actual movement, which was in line with previous study (Cunnington et al., 2002). In general, combing these activated channels together, the activation findings also supported our speculation, through FC analysis, that brain regions with high-level cognitive functions such as DLPFC collaborated with sensorimotor networks in bilateral hemisphere to maintain the preparation state.

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Activation during FOC was not our major target in this study, but was instead used for validation by comparisons with other studies. We found that motor-related brain regions contralateral to the moving hand were activated during FOC (Fig. 5(A) and 5(B)), which is similar with other studies based on either fNIRS or fMRI (Kuboyama, Nabetani, Shibuya, Machida, & Ogaki, 2004; Mostofsky et al., 2006). Therefore, the results and findings in our study are considered reliable.

In addition, our findings regarding transition periods, especially the modulated FC, could be applied in anticipation-based BCI. Previous studies of anticipation-based BCI mainly targeted the anticipation-related potentials obtained through EEG and developed classification methods to detect the anticipation-related potentials to guide the BCI (Gangadhar, Chavarriaga, & del R Millán, 2009; Gangadhar, Chavarriaga, & Millan, 2009; Ibáñez et al., 2011). However, our findings might provide another option for anticipation-based BCI. The increased FC during transition period before actual movement could be used to guide the BCI. Especially, the relationship between modulated FC during transition period and the side of FOC subjects were about to perform, that is, FC connecting the right DLPFC with contralateral (right side in left trans and left side in right trans) S1 and M1, and FC connecting contralateral S1 with ipsilateral (left side in left trans and right side in right trans) S1 and M1 were increased during transition periods, would further help the BCI to understand the anticipation of subjects more specifically.

There were several limitations due to the neuroimaging technique used in this study. Although there was considerably higher temporal resolution of fNIRS compared with fMRI, the lower spatial resolution and limited coverage of the measurement area of fNIRS limit its ability to capture the modulation of brain activity during the transition. An fNIRS system with higher number of channels could be used in the future to capture additional cortical areas. Although

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motor cortex and prefrontal cortex has been the main focus area for this task, other type of tasks might require monitoring additional brain areas. In addition, the FC analysis in this study was not directional and unable to provide the information regarding the directionality of FC during transition period.

In summary, we used fNIRS to evaluate how the transition period preceding a task modulates brain activities compared with the rest period from perspectives of FC and task-related activation. We found several increased FCs during the transition period, especially the FC connecting right DLPFC with contralateral S1 and M1 as well as the FC connecting contralateral S1 with ipsilateral S1 and M1. Channels located in sensorimotor networks and right DLPFC were also found activated during the transition period by activation analysis. These results demonstrate that the sensorimotor network was interacting with high-level cognitive brain network during the transition period to maintain the preparation state. Furthermore, and consistent with the neuroergonomic approach, fNIRS is a suitable tool for region specific task-related and resting-state FC analysis, and can be used for investigating brain dynamics reorganization and adaptation to the preparation state and task state. Our findings could be employed in complex command and control or human machine systems, where operators' movement intention can be perceived by the system to adapt itself to the user and provide more natural and intuitive user interfaces. Application areas can range from aerospace (air traffic controller, piloting) to surgery (operations, robotics) and training of operators for such systems.

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Table 1. Results of paired *t*-tests of FC during left FOC, left trans and right trans compared with the resting state.

Left FOC > Rest			Left trans > Rest			Right trans > Rest		
FC	*t* value	Unc. *p*	FC	*t* value	Unc. *p*	FC	*t* value	Unc. *p*
R. PMSMC – R. S1	2.134	0.024	R. S1 – R. DLPFC	1.936	0.035	R. S1 – R. M1	2.979	0.009
R. PMSMC – L. S1	2.122	0.024	R. S1 – L. S1	2.374	0.015	R. S1 – R. PMSMC	2.166	0.031
			R. S1 – L. M1	1.757	0.049	R. S1 – L. S1	3.066	0.008
			R. S1 – L. PMSMC	1.742	0.050	R. S1 – L. PMSMC	1.923	0.045
			R. M1 – R. DLFPC	2.399	0.015	R. S1 – L. DLFPC	1.984	0.041
			R. M1 – L. M1	2.207	0.021	R. M1 – R. DLPFC	1.975	0.045
			R. DLPFC – L. S1	1.995	0.032	R. M1 – L. S1	2.522	0.018
			L. S1 – L. M1	1.806	0.044	R. PMSMC – R. DLPFC	2.347	0.026
						R. DLPFC – L. S1	1.932	0.047
						R. DLPFC – L. M1	2.388	0.024
						R. DLPFC – L. PMSMC	2.031	0.041

Unc. *p* = uncorrected *p* value; R. = Right; L. = Left.

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Table 2. Activated channels and the paired t-test results (after FDR correction) during left and right trans in session 3, as well as left and right FOC.

Activated channels during trans in session 3			Activated channels during FOC		
Channel (ROI)	*t* value	FDR. *p*	Channel (ROI)	*t* value	FDR. *p*
Left trans in session 3			Left FOC		
1 (R.M1)	2.390	0.029	2 (R.PMSMC)	3.052	0.025
2 (R.PMSMC)	2.512	0.025	4 (R.PMSMC)	2.475	0.044
3 (R.S1)	3.288	0.013	5 (R.PMSMC)	2.980	0.025
4 (R.PMSMC)	2.722	0.023	6 (R.M1)	2.293	0.047
5 (R.PMSMC)	3.053	0.017	7 (R.PMSMC)	2.998	0.035
6 (R.M1)	3.358	0.013	9 (R.M1)	2.474	0.044
7 (R.PMSMC)	3.050	0.018	10 (R.DLPFC)	3.360	0.025
8 (R.S1)	2.298	0.033	12 (R.PMSMC)	3.046	0.025
10 (R.DLPFC)	3.426	0.013	17 (L.DLPFC)	2.744	0.030
11 (R.S1)	2.165	0.037			
12 (R.PMSMC)	3.410	0.013			
15 (L.S1)	2.567	0.025			
16 (L.M1)	2.893	0.018			
17 (L.DLPFC)	2.229	0.036			
18 (L.M1)	3.016	0.018			
Right trans in session 3			Right FOC		
3 (R.S1)	2.368	0.045	14 (L.DLPFC)	3.111	0.031
5 (R.PMSMC)	2.509	0.045	16 (L.M1)	3.200	0.031
6 (R.M1)	2.908	0.045	19 (L.DLPFC)	3.246	0.031
8 (R.S1)	2.377	0.045			
10 (R.DLPFC)	3.885	0.018			

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11 (R.S1)	2.589	0.045			
16 (L.M1)	2.687	0.045			
23 (L.M1)	2.494	0.045			

FDR. *p* = FDR corrected *p* value; R. = right; L. = left.

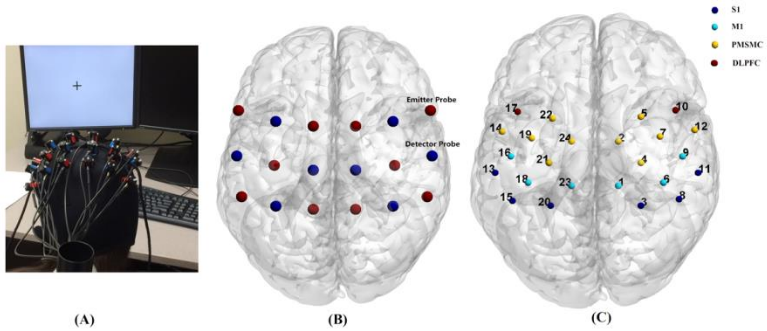

Figure 1. (A) Probes configuration and cap placement during the experiment. (B) Positions of the eighteen probes on standard brain template (MNI). (C) Positions of the twenty-four channels on standard brain template and the colors represent the ROI they locate in.

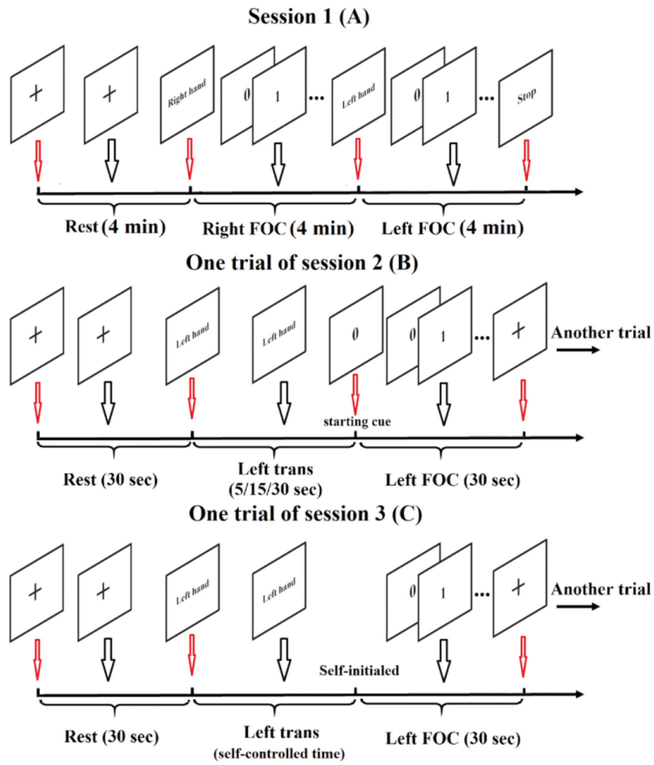

Figure 2. Illustration of the experiment protocol. (A) Protocol of session 1 consisted of three blocks which were rest, right FOC and left FOC and each block lasted for 4 minutes; (B) One of the six trials in session 2 consisted of three blocks which were rest, transition period and left/right FOC and the FOC was initialed by a cue; (C) One of the six trials in session 3 consisted of three blocks which were rest, transition period and left/right FOC and the FOC was initialed by subjects themselves. Note that the order of cues of “Left hand” and “Right hand” were randomized for all three sessions.

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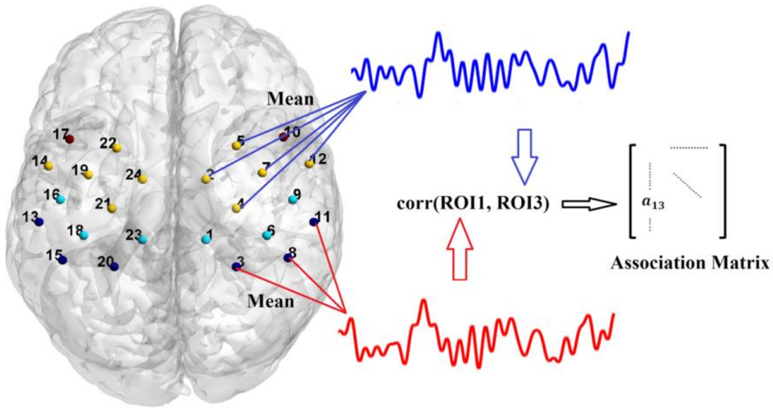

Figure 3. Summary of the ROI-based FC analysis. A representative time course of oxy-Hb for each ROI, that is the mean time course of channels in the ROI, was obtained and the pair-wise FC was estimated by Pearson's correlation of time courses for two ROIs.

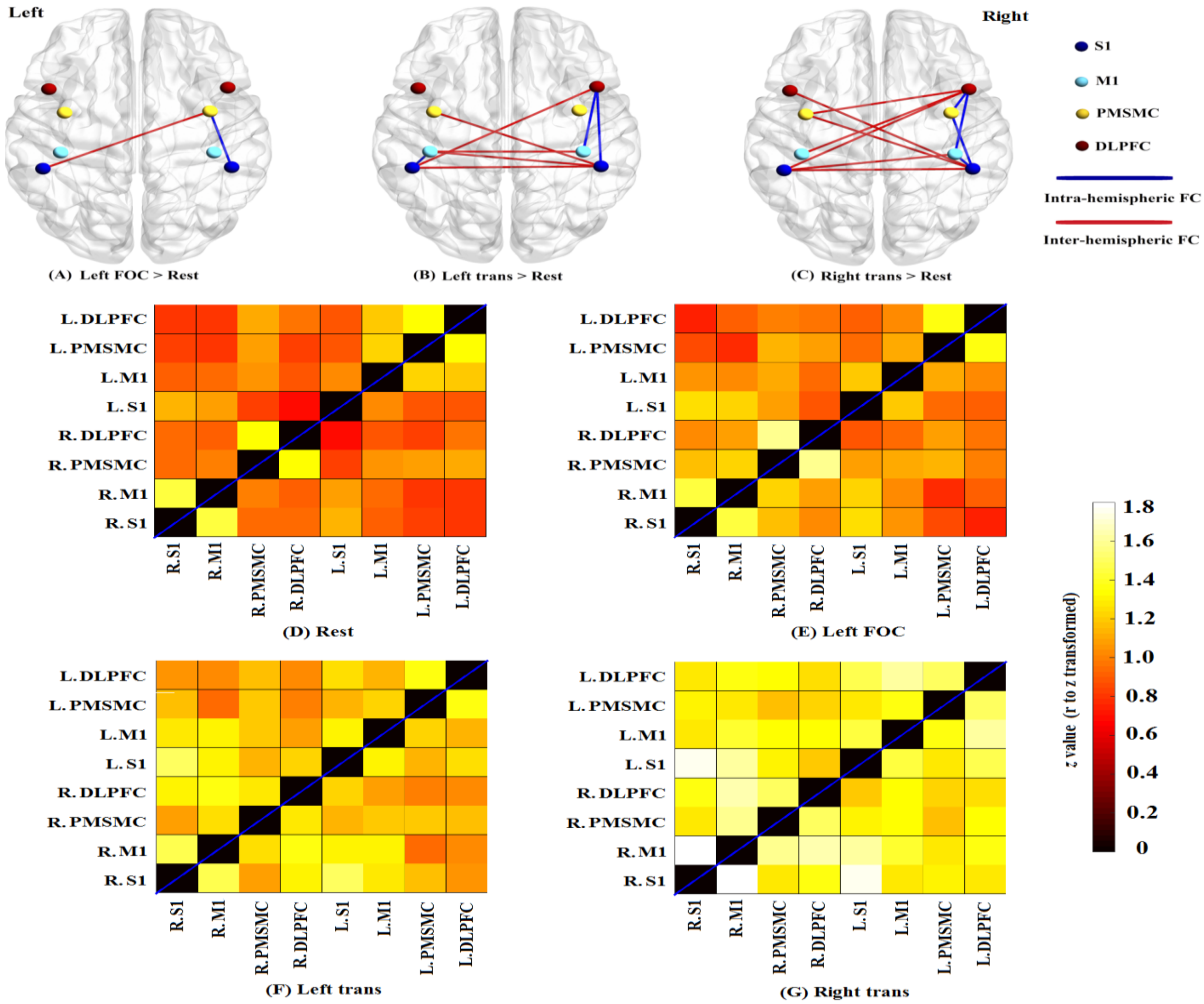

Figure 4. Significantly ($p < 0.05$) increased FC during left FOC (A), left trans (B) and right trans (C) compared with resting-state by paired t-test. In addition, the average association matrices across subjects are illustrated for rest (D), left FOC (E), left trans (F), and right trans (G). R. = Right, L. = Left.

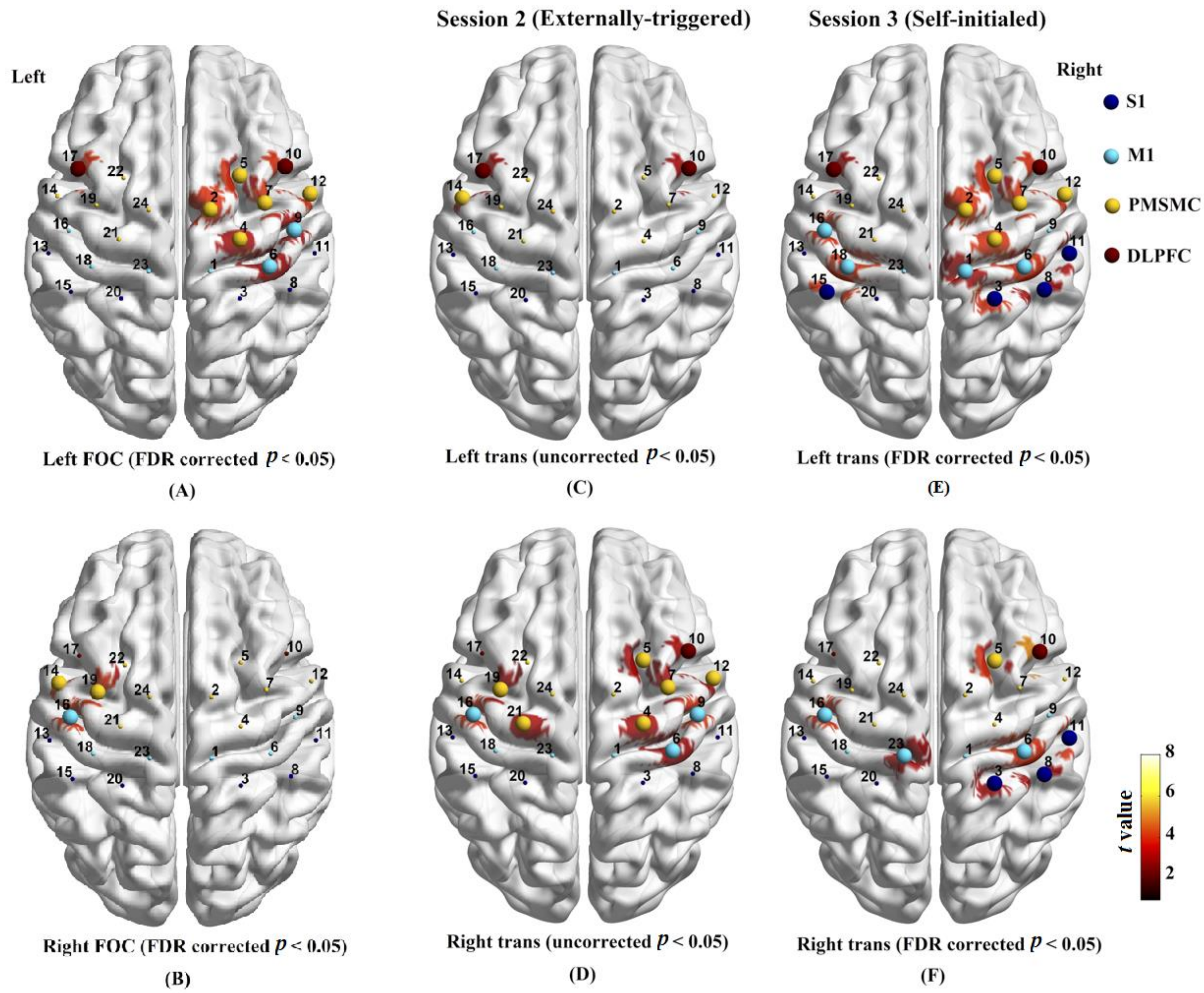

Figure 5. Activation of channels during left FOC (A), right (B), left trans and right trans in session 2 (C, D), and session 3 (E, and F). Note that activation of channels during left and right trans in session 2 did not survive the multiple comparison correction by FDR. Spheres represent the channels and color of the spheres indicate which ROI they locate in according to the legend in the figure. Larger spheres indicate that these channels were activated and smaller ones mean no activation in these channels.