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# FUNCTIONAL CONNECTIVITY AMONG BRAIN NETWORKS IN CONTINUOUS FEEDBACK OF FINGER FORCE

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**Abstract—Motor feedback usually engages distinct sensory and cognitive processes based on different feedback conditions, e.g., the real and sham feedbacks. It was thought that these processes may rely on the functional connectivity among the brain networks. However, it remains unclear whether there is a difference in the network connectivity between the two feedback conditions. To address this issue, we carried out a functional magnetic resonance imaging (fMRI) study by employing a new paradigm, i.e., continuous feedback (8 min) of finger force. Using independent component analysis and functional connectivity analysis, we found that as compared with the sham feedback, the real feedback recruited stronger negative connectivity between the executive network (EN) and the posterior default mode network (pDMN). More intriguingly, the left frontal parietal network (lFPN) exhibits positive connectivity with the pDMN in the real feedback while in the sham feedback, the lFPN shows connectivity with the EN. These results suggest that the connectivity among EN, pDMN, lFPN could differ depending on the real and sham feedbacks, and the lFPN may balance the competition between the pDMN and EN, thus supporting the sensory and cognitive processes of the motor feedback.**

**Key words: motor feedback, continuous feedback paradigm, functional connectivity, brain functional networks.**

## INTRODUCTION

Motor feedback is a technique that employs visual or auditory signals to help participants control and modify their ongoing movement. It exhibits benefits in improving some kinetic parameters such as muscle force (Noble et al., 2013), speed (Damian et al., 2012) and gestures (Barrios et al., 2010). Behavioral evidences also support the clinical significance of motor feedback in the motor function rehabilitation for patients with brain disorders, such as brain injury (Kriz et al., 1995), chronic stroke (Naik et al., 2011) and Parkinson disease (Vaillancourt et al., 2001). This promising applicable value has been linked with the neural basis underlying motor feedback, which prompts more and more neuroimaging investigations recently.

Evidences from functional magnetic resonance imaging (fMRI) studies suggest that the brain activity in motor cortices (primary motor and sensory area, M1/S1, premotor area, PMA and supplementary motor area, SMA) (Kuhtz-Buschbeck et al., 2001; Keisker et al., 2010), prefrontal–parietal areas (Ehrsson et al., 2001; Poon et al., 2013) and visual cortices (Kuhtz-Buschbeck et al., 2008; Coombes et al., 2010) exhibit functional prominence for varied feedback conditions, such as precision versus power force grip (Ehrsson et al., 2000; Kuhtz-Buschbeck et al., 2008), force magnitude (Ehrsson et al., 2001), duration of maintained force (Keisker et al., 2010), feedback frequency (Coombes et al., 2011) and maturation of hand power grip and force control (Halder et al., 2007). The activity of these brain areas mainly responds to the motor control and visual processing during the feedback procedure (Ehrsson et al., 2001; Kuhtz-Buschbeck et al., 2008; Keisker et al., 2010). Notably, these findings mainly came from the investigations on the block paradigm in which the feedback procedure is intermitted periodically (such as 30 s), however, motor feedback in practice, usually lasts for several minutes/hours, e.g., when driving a car, and during such long-lasting feedback procedure, sustained attention also plays important roles for motor control (Helton, 2009). Thus, our recent study introduced a continuous performing paradigm to the fMRI investigation and revealed that the brain activity in motor cortices, prefrontal–parietal areas, visual cortex and posterior cingulate cortex/precuneus significantly differed between the real and sham feedback conditions (Dong et al., 2012). These findings consistently support the recruitments of distributed brain areas in motor feedback.

Spatially distributed brain areas could work together as different brain functional networks (De Luca et al.,

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*Abbreviations:* DMN, default mode network; EN, executive network; fMRI, functional magnetic resonance imaging; FOV, field of view; ICA, independent component analysis; ICs, independent components; IISD, intra-individual standard deviation; lFPN, left frontal parietal network; PCA, principle component analysis; PCC, posterior cingulated cortex; pDMN, posterior default mode network; PMA, premotor area; rFPN, right frontal–parietal network; SMA, supplementary motor area; TE, echo time; TR, repetition time; VN, visual network.

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2006; Stevens et al., 2009; Fornito et al., 2012). Several brain networks such as the default mode network (DMN), the executive network (EN), the visual network (VN) and the left and right frontal–parietal networks (lFPN and rFPN) have been intensively investigated in many fMRI studies (Calhoun et al., 2001; Kelly et al., 2008; Spreng et al., 2010), and it was observed that these networks contain the brain areas that are usually recruited in the motor feedback (Ehrsson et al., 2001; Kuhtz-Buschbeck et al., 2008; Dong et al., 2012). The DMN, involving the areas, e.g., posterior cingulate cortex is usually deactivated in many cognitive and sensory tasks, and it is also referred as the "task-negative" network (Fox et al., 2005). The EN known as the "task-positive" network commonly recruits parts of parietal and sensory motor areas which are mostly activated for cognitive control (Dove et al., 2008). The VN mainly involves primary visual cortex, usually contributing to the visual processing (Ganis et al., 2004; Mantini et al., 2007). The parietal, temporal and prefrontal areas are mostly lateralized to the rFPN and the lFPN (Damoiseaux et al., 2006). The rFPN may play the role of monitoring attention (Fassbender et al., 2006), and the lFPN is thought to be associated with executive inhibition control (Zhang and Li, 2012). Brain networks usually exhibit functional connectivity in the form of the temporal correlation and anti-correlation among their activity (Sporns et al., 2004; Rogers et al., 2007). This network connectivity was suggested to support many cognitive and sensory processes (Bressler and Menon, 2010; Spreng et al., 2013), and these processes may differ depending on feedback conditions, e.g., the real/sham feedback usually engages externally/internally driven force production respectively (Vaillancourt et al., 2003). However, it remains unclear whether there is a difference in the network connectivity between the two feedback conditions.

The present study focuses on the connectivity among brain networks of the DMN, EN, VN, lFPN and rFPN, and we aim to investigate the difference in the network connectivity between the real and sham feedbacks. The negative connectivity between the DMN and EN is usually observed in the resting state and goal-directed tasks (Uddin et al., 2009; Spreng et al., 2010; Kelly et al., 2008). In goal-directed tasks, this negative connectivity appears to be related to the stimulus-driven processes which suppress the activity of the DMN (Greicius and Menon, 2004; Singh and Fawcett, 2008) and induce the activation of the EN (Fan et al., 2005). These processes are primarily involved in motor feedback, especially the real feedback. Thus, we hypothesize that the real feedback could recruit stronger negative connectivity between the DMN and EN as compared with the sham feedback. It is notable that periodical intermission in conventional block paradigm was not accordant to the procedure of motor feedback in practice, and such intermission potentially induces simultaneous responses of brain areas/networks, leading to artifacts in measuring the functional connectivity (Arfanakis et al., 2000; Sun et al., 2004). Therefore, we employed a new experimental paradigm, i.e., continuous feedback (8 min) of finger force in our exploration.

## EXPERIMENTAL PROCEDURES

### Participants

Forty-three right-handed college students participated in the study (22.7 ± 1.6 years, range 19–25; 23 females). No participant had histories of brain injury, neurological illness or psychiatric disorders. Five subjects were excluded for the malfunction of experimental equipments (three subjects, leakage from the air tube resulted in the negative value of finger force) or excessive head motion (two subjects, head motion was $>2$ mm translation or $>2°$ rotation in any direction), and at last, data from 38 subjects (mean age, 22.3 ± 1.6 years; 19 females) were involved in further analysis. All experiments conducted in this study were approved by the Institutional Review Board of National Key Laboratory of Cognitive Neuroscience, Beijing Normal University. All the subjects gave written informed consent before the experiment.

### Experimental design

The current data were from our previous study, in which the amplitude of low-frequency fluctuation (ALFF) was analyzed at single-voxel level and no functional connectivity was analyzed (Dong et al., 2012). Each participant first underwent a scanning of resting state for adapting to the fMRI environment, and thus, data from this scanning was not included in the analysis of the current study. Then, two sessions of continuous feedback with different conditions, i.e., real and sham, were performed with the order counterbalanced across all participants. Each session lasts for 8 min. In the session of real feedback, the participants pinched a pressure sensor between the right index finger and thumb. This sensor is one module of an MRI-compatible physiological multi-channel analyzer (model MP150, BIOPAC Systems, Inc., Goleta, CA, USA). The sampling frequency was 250 Hz and the pressure sensitivity was 0.01 cm $H_2O$. The pressure was recorded by a sensor via an airtight tube, and the force of pressure was synchronously fed back to the participant on a projector. At the same time, each participant was requested to continuously regulate the finger force and try to maintain it at 20 cm $H_2O$ according to the feedback. This target force was set in order to reduce the possibility of muscular fatigue for all subjects (van Duinen et al., 2007). In the session of sham feedback, participants also maintained the finger force at 20 cm $H_2O$, and the feedback they received was the performance of another participant in the session of real feedback. Because the sham feedback of finger force could be easily detected, we have informed participants of this fact in advance. The participants were requested to watch the feedback and keep their own performance unaffected. Before each session, the participants had a short training period to get familiar with the related procedure.

### Data acquisition

Brain scans were performed at the MRI Center of the Beijing Normal University using a 3.0-T Siemens