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Research Report

Fluctuation amplitude and local synchronization of brain activity in the ultra-low frequency band: An fMRI investigation of continuous feedback of finger force

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ABSTRACT

Functional magnetic resonance imaging (fMRI) studies of motor feedback have suggested that brain activity in the ultra-low frequency band (0–0.01 Hz) may be physiologically significant for various feedback conditions, i.e., real and sham feedback. However, the functional role of the ultra-low frequency band of brain activity during the feedback procedure remains unclear. Here, we carried out an fMRI study of continuous feedback (8 min) of finger force and assessed two important properties of brain activity: the fluctuation amplitude and local synchronization in the ultra-low frequency band. Two intriguing results were obtained: (1) real feedback recruited a stronger fluctuation amplitude and local synchronization in the basal ganglia compared with sham feedback; however, no significant correlation was found between the two properties across subjects; and (2) the behavioral performance was significantly correlated with the fluctuation amplitude but was not correlated with local synchronization in the basal ganglia. These findings contribute to characterization of the functional role of brain activity in the ultra-low frequency band and further suggest that the fluctuation amplitude and local synchronization in the basal ganglia may contribute differently to motor feedback.

Abbreviations: ALFF, Amplitude of low-frequency fluctuation; $ALFF_{ultra\text{-}low}$, Amplitude of low frequency fluctuation in the ultra-low frequency band; BG, Basal ganglia; FWHM, Full-width-at-half-maximum; fMRI, Functional magnetic resonance imaging; IISD, Intra-individual standard deviation; MPRAGE, Magnetization-prepared rapid gradient echo; MNI, Montreal Neurological Institute; PMA, Premotor area; M1/S1, Primary motor and sensory area; ReHo, Regional homogeneity; $ReHo_{ultra\text{-}low}$, Regional homogeneity in the ultra-low frequency band; SMA, Supplementary motor area

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1. Introduction

Motor feedback is a technique that employs visual or auditory information to help participants control their ongoing movement, modify certain kinetic parameters such as muscle force (Noble et al., 2013), speed (Damian et al., 2012), and gestures (Barrios et al., 2010) and improve certain motor functions such as standing balance (Barclay-Goddard et al., 2004), finger force (Seo et al., 2011), and bimanual coordination (Lodha et al., 2012). Motor feedback also aids in the rehabilitation of motor function in patients with brain injury (Kriz et al., 1995), chronic stroke (Naik et al., 2011) and Parkinson's disease (Vaillancourt et al., 2001). The promising applicable value of motor feedback is potentially linked to its neural basis, which has prompted additional neuroimaging investigations to be conducted.

Evidence from fMRI investigations has revealed the intricate brain activity underlying motor feedback. Brain areas, including 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), basal ganglia (BG) (Spraker et al., 2007; Prodoehl et al., 2009), prefrontal-parietal areas (Ehrsson et al., 2001), and visual cortices (Kuhtz-Buschbeck et al., 2008; Coombes et al., 2010) are functionally prominent in various feedback conditions such as precision versus power force grip (Ehrsson et al., 2000; Kuhtz-Buschbeck et al., 2008), force magnitude (Ehrsson et al., 2001), maintained force duration (Keisker et al., 2010), feedback frequency (Coombes et al., 2011), real and sham feedback (Dong et al., 2012) and hand power grip and force control maturation (Halder et al., 2007). Findings from these investigations have provided evidence to delineate the motor control and visual processing mechanisms during the feedback procedure (Kuhtz-Buschbeck et al., 2008; Ehrsson et al., 2001; Keisker et al., 2010).

fMRI investigations of motor feedback have mostly employed a block paradigm, which is periodically stopped (such as every 30 s); however, motor feedback in everyday life such as car driving usually lasts for several minutes/hours. During such long-lasting feedback, sustained attention also plays an important role in motor control (Oken et al., 2006). Thus, Dong et al. (2012) proposed a continuous performance paradigm for the fMRI investigation of motor feedback. Notably, the continuous performance paradigm allows for frequency analysis of brain activity, and recently, the frequency-dependent property of brain activity has promoted additional fMRI investigations to be conducted (Zuo et al., 2010, Han et al., 2011, Lv et al., 2013). In these investigations, sub-frequency bands of brain activity were usually defined and explored, mainly including Slow-6 (0–0.01 Hz) (Lv et al., 2013), Slow-5 (0.01–0.027 Hz), Slow-4 (0.027–0.073 Hz), Slow-3 (0.073–0.198 Hz) and Slow-2 (0.198–0.25 Hz) (Han et al., 2011). Based on these investigations, our research group has explored frequency-dependent brain activity during motor feedback (Zhang et al., in press). We observed that brain activity in the BG changed between real and sham feedback and that the changes occurred only in the Slow-6 band. This finding supported the physiological significance of brain activity in the ultra-low frequency band (0–0.01 Hz). However, during the feedback procedure, the functional role of brain activity in the ultra-low frequency band remains unclear (Zhang et al., 2015).

Brain activity measured by fMRI exhibits two critical properties: the fluctuation of time courses of a given voxel and the local synchronization of time courses of neighboring voxels. Thus, whether these properties in the ultra-low frequency band could exhibit changes in response to various feedback conditions must be explored. The fluctuation and local synchronization of brain activity have usually been assessed through measures of the amplitude of low-frequency fluctuation (ALFF) (Zang et al., 2007) and regional homogeneity (ReHo) (Zang et al., 2004). In resting-state fMRI studies, elevated ReHo was accompanied by an enhanced ALFF (Yuan et al., 2013). In our previous study, it was revealed that ReHo of BG in the ultra-low frequency band could exhibit the difference between real and sham feedback (Zhang et al., 2015). In the present study, both ALFF and ReHo in the ultra-low frequency band were assessed, and we hypothesized that the variation of feedback conditions could result in the changes of the two measures in similar brain areas, e.g., BG. In this study, we explored fMRI data from an experiment of continuous feedback (8 min) of finger force. The ReHo and ALFF in the ultra-low frequency band were assessed and compared between the two feedback conditions of real and sham feedback. Behavioral performance and the correlation between the two measures were also explored in the present investigation.

2. Results

The $ALFF_{ultra\text{-}low}$ and $ReHo_{ultra\text{-}low}$ were increased in the bilateral BG (Fig. 1a and b) and decreased in the visual cortex (Table 1) for real feedback compared with those for sham feedback. Activities of the visual cortex have been previously shown to exhibit differences between real and sham feedback in multiple frequency bands (Zhang et al., 2015); thus, as brain activity of the visual cortex may not reflect the frequency-dependent properties, it was not addressed in the current study.

The differences in the $ALFF_{ultra\text{-}low}$ and $ReHo_{ultra\text{-}low}$ between real and sham feedback overlapped in the right and left BG (mainly located in the putamen and caudate) (Table 1 and Fig. 2a). However, for the overlapped areas in the right/left BG, a significant correlation between the two measures was not observed across subjects (Fig. 2b and c; $r=0.05$, corrected $p>0.05$ for the left BG; $r=0.27$, corrected $p>0.05$ for the right BG).

Behavioral performance showed significant differences in the intra-individual standard deviation (IISD) and fluctuation between real and sham feedback. The IISD for real feedback was significantly lower than that for sham feedback (mean IISD across all subjects was 0.17 cm H_2O for real feedback and 2.85 cm H_2O for sham feedback, $t=12.46$, $p<0.0001$), and the fluctuation of performance in real feedback was significantly lower than it in sham feedback (mean fluctuation across participants was 0.7% for the real feedback and 25.9% for the sham feedback, $t=2.03$, $p<0.001$). No significant difference was found in the mean force between real and sham