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Beta-band activity and connectivity in sensorimotor and parietal cortex are important for accurate motor performance

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ABSTRACT

Accurate motor performance may depend on the scaling of distinct oscillatory activity within the motor cortex and effective neural communication between the motor cortex and other brain areas. Oscillatory activity within the beta-band (13–30 Hz) has been suggested to provide distinct functional roles for attention and sensorimotor control, yet it remains unclear how beta-band and other oscillatory activity within and between cortical regions is coordinated to enhance motor performance. We explore this open issue by simultaneously measuring high-density cortical activity and elbow flexor and extensor neuromuscular activity during ballistic movements, and manipulating error using high and low visual gain across three target distances. Compared with low visual gain, high visual gain decreased movement errors at each distance. Group analyses in 3D source-space revealed increased theta-, alpha-, and beta-band desynchronization of the contralateral motor cortex and medial parietal cortex in high visual gain conditions and this corresponded to reduced movement error. Dynamic causal modeling was used to compute connectivity between motor cortex and parietal cortex. Analyses revealed that gain affected the directionally-specific connectivity across broadband frequencies from parietal to sensorimotor cortex but not from sensorimotor cortex to parietal cortex. These new findings provide support for the interpretation that broad-band oscillations in theta, alpha, and beta frequency bands within sensorimotor and parietal cortex coordinate to facilitate accurate upper limb movement.

Summary statement: Our findings establish a link between sensorimotor oscillations in the context of online motor performance in common source space across subjects. Specifically, the extent and distinct role of medial parietal cortex to sensorimotor beta connectivity and local domain broadband activity combine in a time and frequency manner to assist ballistic movements. These findings can serve as a model to examine whether similar source space EEG dynamics exhibit different time-frequency changes in individuals with neurological disorders that cause movement errors.

1. Introduction

Errors during movement have been studied empirically for the past two centuries (Meyer et al., 1988; Schmidt et al., 1979; Shadmehr et al., 2010; Woodworth, 1899), and it is evident from this literature that minimizing error depends on feedback loops that rely upon both external and internal feedback (Desmurget and Grafton, 2000; Miall, 1996). In the human motor system, a key source of external feedback is visual information, and studies have consistently shown that amplifying the gain of visual feedback improves motor performance by reducing errors during tasks such as drawing, force control, and arm pointing (Contreras-Vidal et al., 2002; Newell and Chew, 1975; Seidler et al., 2001; Sosnoff and Newell, 2005). Despite clear evidence that enhancing visual information about desired task-goals leads to improved motor performance, it is less clear what role cortical dynamics and connectivity observed within the cortex plays in this process.

There is ample evidence across numerous research modalities that the motor and parietal cortex are intricately and cooperatively involved in visually guided motor control (Caminiti et al., 1996; Clower et al., 1996; Dipietro et al., 2014; Jeannerod et al., 1995). Classic work showed that neurons in area 7 of the monkey respond during reaching movements to visual stimuli (Mountcastle et al., 1975). In humans,

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transcranial magnetic stimulation of the posterior parietal cortex has been used to disrupt visually guided reaching movements (Della-Maggiore et al., 2004; Desmurget et al., 1999). Neuroimaging in humans confirmed the role of both the motor cortex and parietal cortex in visually-guided motor control (Ellermann et al., 1998; Hamzei et al., 2002; Vaillancourt et al., 2003), and event-related potentials from the frontoparietal network measured using electroencephalography have been shown to correspond with sub-movements during visually-guided upper limb movements (Dipietro et al., 2014).

With regard to oscillatory activity in the motor cortex and parietal cortex, prior studies have examined oscillations at specific electrodes and reported event-related changes in spectral power in the beta-band that are specific to the stage of movement (Allen and MacKinnon, 2010; Kilavik et al., 2013; Pfurtscheller et al., 1994). Movement-related beta-band oscillations over the bilateral motor cortex exhibit a sharp decrease in spectral power at the beginning of a movement (Cruikshank et al., 2012; Gwin and Ferris, 2012; Kilavik et al., 2013; Pastötter et al., 2012) and beta-band activity increases near the end of the movement and was related to overall movement time (Ofori et al., 2015). In addition, Tan et al. (2014) have shown increased beta-band activity (post-movement event-related synchronization) following movements with small errors and decreased beta-band activity following movements with large errors.

Beta-band activity has also been shown to play a role in attentional processes (Sauseng and Klimesch, 2008; Wróbel et al., 2007). For instance, in the context of online motor control, attending to visual information about a task may also rely on beta-band causal influences from parietal areas. Recent studies have shown that increased sensory processing during behavioral tasks is dependent on the strength of parietal connections with frontal and sensorimotor areas (Akam and Kullmann, 2014; Hillebrand et al., 2012). However, it is difficult to distinguish attention-related processes from sensorimotor control (Engel and Fries, 2010). Recent work suggests that beta-band activity functions to enhance gain of feedback loops at subsequent stages of visual information processing (Gola et al., 2013). Here we test the hypothesis that high visual feedback gain will reduce movement errors, enhance movement related beta-band desynchronization in the motor cortex, and alter directionally-specific connectivity between the parietal cortex and motor cortex.

2. Materials and methods

2.1. Subjects

Sixteen participants (mean age: 29.4 ± 3.8 yrs.; 6 females) were recruited for this study. All participants were young healthy right-handed individuals with normal or corrected vision. Participants were asked to refrain from consuming caffeine and using any hair products on the day of testing. Prior to experimental testing, participants provided informed consent. This experimental study was approved by the local Institutional Review Board.

2.2. Experimental design and task

The experimental setup for the movement task was similar to prior work (Ofori et al., 2015). Participants sat upright in a chair with their right arm supported against a cantilever beam attached to a custom-made manipulandum. Fig. 1A depicts the general experimental procedures for the task sessions. Participants were instructed to perform rapid and accurate arm movements by flexing the elbow to 3 target angles (12°, 36°, and 72°) under two feedback conditions (low and high visual gain) while the experimenters monitored physiological and kinematic data (Fig. 1A). Visual feedback about the participants' angular position was provided to the participant through a 30″ computer monitor (Dell UltraSharp U3011, Dell Co, Round Rock, TX).

As Fig. 1 illustrates, the target location is depicted with a solid green H character, the start position is depicted with a solid gray H character, and a yellow X cursor depicts the current participant position. Visual gain was manipulated by changing the distance between the start and target position on the computer monitor. The high visual gain condition (17 cm/6°) resulted in the distance between the start and target positions on the monitor to appear 25 times farther than the distance in the low visual gain condition (0.68 cm/6°).

The time allotted for each trial was 12 s. For the first 3 s of a trial, the participants' right arm was at the start position. Then for the next 4 s, the participants were asked to use their elbow flexors to move the manipulandum to the required distance as fast and accurately as possible after the participants heard the first 400 Hz auditory cue, and to keep the cursor in the middle of the target before the second auditory cue. Next, the participants heard a second auditory tone that cued them to return to the start position, and this period lasted 5 seconds. Only the first 7 s of the 12 s interval was analyzed. The experimental design resulted in 6 distinct conditions which include: 1) high visual gain feedback in short distance (12° target), 2) low visual gain feedback in short distance (12° target), 3) high visual gain feedback in medium distance (36° target), 4) low visual gain feedback in medium distance (36° target), 5) high visual gain feedback in long distance (72° target), and 6) low visual gain feedback in long distance (72° target). All participants performed 50 trials for each unique condition in a blocked design for a total of 300 trials. Block order was randomized across participants.

2.3. Data acquisition

The MotionMonitor (Innovative Sports Training, Inc., Chicago, IL) system was configured to synchronize data in real time from electromyography (EMG), electroencephalography (EEG), and kinematic systems using an analogue sync pulse. The sync pulse was an analogue signal delivered to each data collection device, and all collected through the MotionMonitor software that was subsequently time-synced using the common analogue signal.

2.3.1. Kinematic data acquisition

The kinematic data were collected with an angular displacement transducer. The transducer was mounted at the axis of rotation of the manipulandum. An excitation voltage of 16 V from a Leader LPS-152 DC Tracking Power Supply (Advanced Test Equipment Rentals, San Diego, CA) that was used to power the angular displacement transducer. The displacement data were transmitted via a 16-bit A/D converter and digitized at 1000 Hz using a USB-1616HS-BNC A/D board (Measurement Computing, Norton, MA).

2.3.2. EMG data acquisition

EMG data were collected with the Delsys Trigno Wireless System (Delsys Inc., Boston, MA). Participants were prepped by rubbing the desired locations on the right arm with alcohol. Four channels were used to measure electrophysiological activity from the muscle. The wireless EMG electrodes were placed at four locations on the participant's right arm. The four locations were the biceps brachii, brachioradialis, triceps lateral head and triceps long head. The EMG data were sampled at 1000 Hz.

2.3.3. EEG data acquisition

EEG data were collected with the ActiveTwo system that was comprised of 128 Ag-AgCl Active Two electrodes. The active electrodes were connected to a cap that was in a preconfigured montage covering the entire scalp. The signals were amplified through the electrodes at the source and had an output impedance of $< 1\ \Omega$.

EEG signals were digitally amplified at DC and sampled at 2048 Hz. Electrical potentials were recorded between each electrode and Common Mode Sense (CMS) active electrode and Driven Right Leg (DRL) passive electrode located at the center of the scalp in relation to