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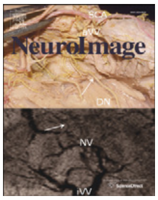

EEG correlates of haptic feedback in a visuomotor tracking task

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ABSTRACT

This study investigates the temporal brain dynamics associated with haptic feedback in a visuomotor tracking task. Haptic feedback with deviation-related forces was used throughout tracking experiments in which subjects' behavioral responses and electroencephalogram (EEG) data were simultaneously measured. Independent component analysis was employed to decompose the acquired EEG signals into temporally independent time courses arising from distinct brain sources. Clustering analysis was used to extract independent components that were comparable across participants. The resultant independent brain processes were further analyzed via time–frequency analysis (event-related spectral perturbation) and event-related coherence (ERCOH) to contrast brain activity during tracking experiments with or without haptic feedback. Across subjects, in epochs with haptic feedback, components with equivalent dipoles in or near the right motor region exhibited greater alpha band power suppression. Components with equivalent dipoles in or near the left frontal, central, left motor, right motor, and parietal regions exhibited greater beta-band power suppression, while components with equivalent dipoles in or near the left frontal, left motor, and right motor regions showed greater gamma-band power suppression relative to non-haptic conditions. In contrast, the right occipital component cluster exhibited less beta-band power suppression in epochs with haptic feedback compared to non-haptic conditions. The results of ERCOH analysis of the six component clusters showed that there were significant increases in coherence between different brain networks in response to haptic feedback relative to the coherence observed when haptic feedback was not present. The results of this study provide novel insight into the effects of haptic feedback on the brain and may aid the development of new tools to facilitate the learning of motor skills.

Introduction

Learning a new movement or motor skill utilized in our daily lives is often guided by external stimuli and feedback (Blum et al., 2007; Grindlay, 2007). Previous studies have shown that the association of external stimuli with motor commands is useful for motor learning; thus, systematic practice can improve an individual's performance (Maxwell et al., 2001; Schmidt and Wulf, 1997). An external stimulus usually originates from an outside source. The external stimulus is an alternative to an intrinsic stimulus related to an individual's sensory-perceptual information (Wolpert et al., 2001; Yamagishi et al., 2001). Intrinsic stimuli often involve three primary communication channels: visual, auditory, and tactile (Hawk and Shah, 2007; Williams, 1983). In contrast, external stimuli can assume many forms in motor learning applications, including verbal communication and visual, auditory, tactile, and haptic signals (Deutsch et al., 2004; Lee et al., 1990; Lieberman and Breazeal, 2007; Merians et al., 2002; 2006; Millar and Al-Attar, 2004). In addition, Brosvic et al. (2010) suggested that novices could rapidly improve their performance when provided with immediate feedback and more specific information regarding error correction.

In recent years, electroencephalograms (EEGs) have increasingly been utilized as a means to study the neuronal mechanisms underlying behavioral changes associated with the acquisition of motor skills (Hatfield et al., 2004; Hillman et al., 2000). EEG frequencies of interest vary in relation to the actual physiological and psychological brain state (Jancke, 2005). Pre-stimulus theta (4–8 Hz) and alpha (8–12 Hz) activities reflect pre-stimulus top-down preparation for the performance of subsequent tasks (Min and Park, 2010). Recent studies have revealed that movement, speed and direction could be decoded by low-frequency modulation (in the range of delta and low theta bands; <7 Hz) during the execution of movement

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(Acharya et al., 2010; Waldert et al., 2008). Perfetti et al. (2011a) also found that initial visuomotor learning was associated with the enhancement of gamma (>30 Hz) power during movement execution as well as gamma/theta phase coherence during movement planning. Late-stage learning was accompanied by an increase of theta power during movement planning, which was correlated with the degree of learning and retention. Furthermore, Perfetti et al. (2011a) suggested that delta, alpha and gamma phase coherences were related to motor and sensory demand during motor learning. Smith et al. (1999) reported a task-specific enhancement of alpha activity over somatomotor areas when preceded by several days of practice with a visuomotor tracking task; however, the augmented alpha activity was diminished after the subjects mastered the task. These investigators concluded that regional alpha-power changes might reflect the development of task-specific neurocognitive strategies. Other studies found that there were movement-related power and coherence changes in the beta (13–30 Hz) band during the initial learning of a motor task (Mima et al., 2000; Serrien and Brown, 2002; 2003). Furthermore, some studies have suggested that the cortical beta amplitude co-varies with motor performance (Boonstra et al., 2007; Toma et al., 2002). Boonstra et al. (2007) reported an enhancement of event-related alpha desynchronization during implicit motor skill learning, increased cortico-spinal beta synchronization following visuomotor skill learning and increased inter-hemispheric synchronization during early stages of bilateral learning. Other studies suggested that visuomotor skill learning is related to long-range oscillatory neuronal synchronization in the beta and gamma frequency ranges (13–80 Hz) (Babiloni et al., 2006; Huo et al., 2011; Lee, 2003). Ng et al. (2011) further extended the connection between beta- and gamma-band rhythms and motor behaviors. Task-dependent gamma activity is related to various types of cognitive processes, including attention, motor planning, visual processing, working memory (WM) and long-term memory (LTM) (Meeuwissen et al., 2011). However, most prior studies have employed visual and/or auditory feedback to provide continuous guidance for motor commands (Blum, 2008; Blum et al., 2007, 2008). Haptic feedback is now receiving increasing attention related to motor-skill learning due to its novelty and potential for real-world applications (Perrin et al., 2008). Importantly, no EEG study reported to date has explored the temporal brain dynamics and interactions between different brain regions during motor skill learning in conjunction with haptic feedback.

To coordinate an individual's sensory perception with imminent external stimuli, extensive transformation and integration processes are required. In this regard, different brain regions are assumed to constitute a cooperative network that facilitates the synchronization of task-specific brain activities (Blum, 2008; Blum et al., 2008). Such cooperation between brain regions has been studied using coherence and phase-locking analysis of EEG signals (Blum, 2008; Blum et al., 2007, 2008; Classen et al., 1998; Lehmann et al., 2006). However, previous studies have analyzed coherence and phase-locking measures on the basis of confounded mixed EEG signals recorded from the scalp. Such measurements could not specifically represent the relationship between different brain areas because the recording from each electrode incorporated contributions from several brain sources. Zervakis et al. (2011) also suggested that the separation, identification and analysis of independent activities of different brain regions are critical for characterization of the neurophysiological origins of the brain processes in question. Therefore, separating the recorded signals into independent brain source activities is an important first step toward relating a specific task (sensory, motor or cognitive) with the topography and/or time–frequency content of the brain sources (Gwin et al., 2010; Jung et al., 2001; Lee et al., 2003; Zervakis et al., 2011). In these studies, independent component analysis (ICA) (Bell and Sejnowski, 1995; Makeig et al., 1997) was utilized to decompose recorded EEG signals into temporally independent components. Time–frequency analysis and the topographic origins of components were then used to characterize event-related brain dynamics.

The present study is also focused on event-related changes in the coupling of field activity in different regions of the cortex (Sarnthein et al., 1998). Recent results from several datasets have indicated that maximally independent EEG signals can be rapidly synchronized and desynchronized following significant task events (Delorme and Makeig, 2004; Makeig et al., 2002). The structure of EEG synchronization events, as revealed by ICA, is largely or wholly invisible to analyses based on average measures of evoked responses or scalp channel coherences. In the present study, the independent brain sources separated by ICA were then analyzed by time–frequency analysis and event-related coherence (ERCOH) to observe brain activities during tracking tasks in the presence and absence of haptic feedback.

Previous studies have suggested that practice and learning would increase coherence between the participating brain regions (Andres et al., 1999; Serrien and Brown, 2003; Singer, 1993; Singer and Gray, 1995). Because non-haptic feedback trials rely solely on internal movement representation, this study addresses the hypothesis that the ERCOH of these trials would be smaller than those of haptic trials.

Methods and materials

Subjects

A total of 19 right-handed volunteers (9 females and 10 males; mean age 23 ± 4 years) with normal or corrected-to-normal vision participated in the experiment. In the experiment, the subjects used their dominant (right) hands to control a joystick. All subjects were healthy and had no history of neurological disease. To obtain an accurate evaluation of their performance, the subjects were required not to have imbibed alcoholic or caffeinated drinks or to have participated in strenuous exercise 1 day prior to the experiments. The Institutional Review Board of Taipei Veterans General Hospital approved the experimental protocol used in this study. The participants were subjected to the experiments either in the morning (9–12 AM) or afternoon (2–5 PM). Each subject was well instructed regarding the experimental procedures, and none of the participants were aware of the hypotheses being tested. All subjects delivered their informed consent prior to any experimentation.

Experimental equipment

The basic principle of the tracking task used in this study was aimed at increasing the subjects' tracking precision. In the tracking paradigm, all subjects sat in front of a 19" monitor (resolution of 1024×768 pixels) and learned to control a joystick (Immersion Impulse Stick, USA, Fig. 1C) to minimize the deviation between a green cross and a moving target stimulus (a purple trajectory), as shown in Fig. 1A). The purple trajectory was a straight line (6×35 pixels) and appeared when the task started, first at the upper-right corner of the box frame. To control the speed of the subject's movement, the purple trajectory moved at a constant velocity. The subjects maneuvered a green cross to closely follow the purple trajectory in an 80-pixel-thick black frame in the shape of a large box frame (660×660 pixels, Fig. 1B). The movement that took place in this experiment was therefore simple and one-dimensional. A shelter was used to prevent subjects from watching their hands and avoiding the screen as they controlled the joystick (Fig. 1B). Furthermore, an armrest was designed to make the subjects comfortable with control of the joystick (Fig. 1C).

The joystick employed in the experiments provided two force feedback axes and movement of up to three degrees of freedom. The joystick used electric motors that could be programmed to