Prefrontal and Interhemispheric Functional EEG Connectivity Associated with Tactile Stimulation

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Developing quantitative means to measure the effects of tactile stimulation on user experience is gaining increasing attention over the past decade. This paper strives to find quantitative evidence, based on brain wave analysis, of the relationship between tactile stimulation and cognitive processes. In this study, participants performed an active touch task comprising of stroking the strings of a virtual guitar displayed on a touch-screen device while measuring the 64-channel EEG signal. For the analysis, phase locking values from alpha, beta, and gamma frequency bands are extracted and compared during the absence and presence of tactile stimulation. Results demonstrated an increase in the connectivity of beta and gamma bands in the prefrontal cortex in the presence of tactile stimulation. Such increase is potentially associated with the development of Bereitschaftspotential, which reflects the intention, planning, and execution of precise voluntary movements. Another interesting finding was an increased interhemispheric connectivity in the absence of tactile stimulation, which is associated with motor impairments. These findings suggest that tactile stimulation not only trigger sensation, but further activate cognitive processing associated with motor skills.

Introduction

The interest in incorporating haptic modality in human-computer interaction is growing, especially in mobile communication domain. For instance, touch-screen devices, such as mobile phones or tablets, rely merely on visual feedback. This may cause many interaction problems (such as the need for full visual attention to the interface, accessibility for people with visual impairments, etc.). Therefore, tactile feedback provides an additional media to reduce the visual demand [10]. Previous studies have shown that tactile feedback can improve user performance on different tasks using touch-screen devices [22], [13], [16].

The added-value of tactile feedback in human-computer interaction is typically evaluated using self-reporting (subjective questionnaires or think aloud protocols) or on users' performance during the interaction (task completion time, accuracy, error rate, etc.). While both methods have been used successfully for decades, they suffer from several limitations. Self-reporting is inconsistent, unreliable, and difficult to reproduce (e.g., prone to be contaminated by ambiguities [21], sometimes affected by social pressure [25], and difficult to provide real-time insights without disrupting the interaction). On the other hand, metrics inferred from behavior do not provide information about user's mental states (e.g. a high reaction time can be caused either by a low concentration level or by a difficult task [3]). Recently, it has been suggested that brain imaging techniques (such as EEG) have the potential to address these limitations as it provides quantitative measure of user's mental states [6].

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Measuring user experience associated with touch (tactile and/or kinesthetic) is even more challenging due to its complexity [8]. Tactile interaction is classified as passive and active. In passive touch, physical contact is initiated and controlled by an external party (environment or other human), such as someone tapping the shoulder of a friend. On the other hand, active touch involves moving the human body (typically hand) to explore the environment (such as when stroking a surface to learn about its texture). In this study, we will focus on active touch tasks involving tactile feedback with a touch-screen device.

There is a recent trend to study the neural mechanisms associated with touch. A study investigated the brain's response to pleasant touch using EEG imaging [28]. It is shown that right hemispheric beta-band oscillations measured over parietal electrodes allow to differentiate between pleasant and unpleasant tactile sensations in passive touch. In another study, when clothing with a higher mass density was worn, energy percentages of the alpha weave of the EEG at both the left and right occipitalia were higher [30]. Interpersonal touch is shown to enhance cognitive control [26]. Another study investigated the correlation between haptic feedback and EEG signal in a visuomotor tracking task [15]. Results demonstrated significant increases in coherence between different brain networks in response to haptic feedback relative to coherence observed when haptic feedback was not present.

In our previous work [23], we introduced the first study to examine the role of tactile stimulation objectively and quantitatively in an active touch task with a touch-screen device. Our results demonstrated that tactile stimulation is able to affect the cognitive processing and top-down control. Tactile stimulation resulted in statistically significant increase in neural activities compared to the case when no tactile stimulation is applied in active touch task. In particular, a difference in beta oscillation in the middle frontal area at the late period of the active touch task (650 ms to 1000 ms) was measured. Functional connectivity is also a very useful method to understand brain activation as well as analysis of power spectral density [11]. In this paper, we focus on analyzing functional connectivity to investigate the effects of tactile stimulation in both the prefrontal cortex and interhemispheric cortex, being highly associated with precise voluntary movement and motor skills in general.

Materials and Methods

Participants

Twenty-six participants enrolled in this study (14 males and 12 females; age range, 20–39). All participants were right-handed (Edinburgh handedness inventory, 98.46 ± 10.37) and met all inclusion/exclusion criteria. The inclusion criteria was: an age range from 20 to 39, right-handed with no previous knowledge about how to play the guitar, and normal or corrected-to-normal vision and hearing. Exclusion criteria included persons with a history of neurological or psychiatric disorders, persons with an orthopedics problem in the right hand, and person with more than 6 months learning experience in playing guitar. We used a virtual guitar

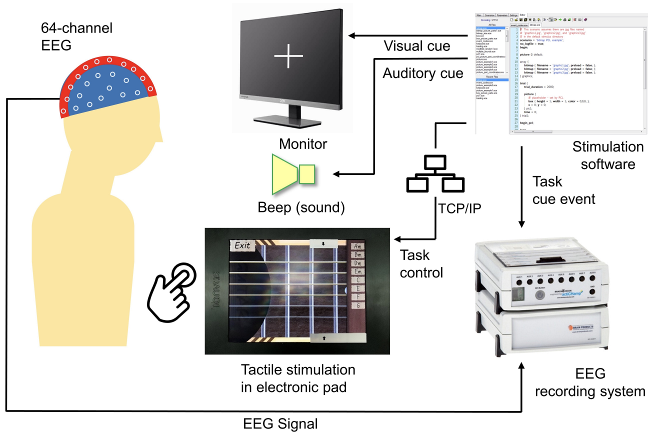

Figure 1: Block diagram of the experimental setup.

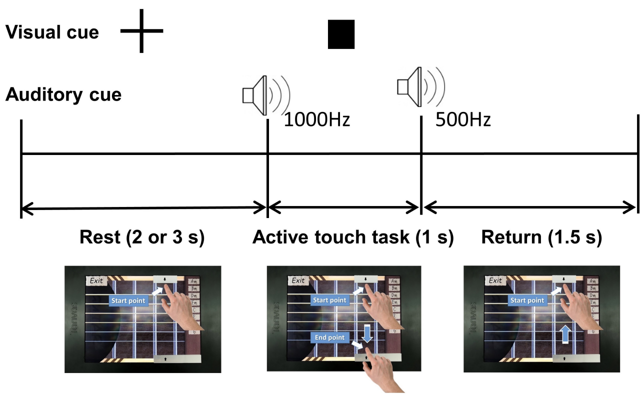

Figure 2: Schematic diagram of the experiment.

application for the active touch task, that is why those who play the guitar were excluded from the experiment. The experimental procedure and participant recruitment was reviewed and approved by New York University Abu Dhabi Institutional Review Board (IRB #073-2017). Written informed consent was obtained from all participants. All research data were collected and analyzed under IRB guidance.

Experimental Design

EEG signals were recorded while participants performed an active touch task that was designed using a tactile touch screen. A block diagram elaborating the experimental setup and design is shown in Figure 1. The Presentation (a software by Neurobehavioral Systems, Albany, CA, USA) software was used for stimulus delivery and experimental control for the active touch task. This software controls visual and auditory cues and provides a synchronized control of these cues with tactile stimulation displayed using the tactile screen tablet, as well as generates event trigger in EEG system. To control tactile stimulation in active touch task, a network socket connection was established between the Presentation software and the virtual guitar application running on the touch-screen device to provide tactile stimulation. An activation message sent over the network socket by the Presentation software then controls the behavior of tactile stimulation on the touch-screen device.

A tactile touch-screen device developed by TanvasTouch[1] was used to provide tactile feedback on the screen. The tactile touch-screen device provides an interface to control the tactile stimulation programmatically. To simulate arbitrary surface texture, electrostatic forces are applied to simulate surface friction between the physical display panel and the user's fingertip [17] [18].

An EEG recording system (BrainAmp by Brain Products, Munich, Germany) was used to store the neurological activities during an active touch task using 64-channel EEG device. Participants were asked to perform an active touch task of stroking virtual guitar strings on a touch-screen device while enabling and disabling the tactile stimulation, in a random order. Figure 2 shows the schematic diagram of the experiment. One trial was divided into three time periods namely rest, active touch task and return time periods. To prevent participants from predicting the task cues the rest period was randomly set to either 2 or 3 seconds. The fixation appears for the rest of the time to draw the participants' attention to the assigned task. Start and end points were marked on the touch screen for the participants reference. Participants were asked to place their index finger on the start point and wait for the cue for the active touch task as shown in the lower left in Figure 2. For the active touch task, a square shaped box and a 1000Hz beep was used to provide visual and auditory cues to the participants.

During the active touch task period, participants were asked to move their index finger from start to end point within one second. During this period tactile stimulation was activated or deactivated randomly to counter balance the task order. However, visual feedback (shaking guitar strings) and auditory feedback (string sounds) always remains present while the user's fingertip swipes through the guitar strings. A 500Hz auditory cue indicated the end of the active touch task. The return period was set to 1.5 seconds, during that time participants moved their index finger back to the starting point while the rectangular visual cues disappeared. All participants had to go through a short training session to reduce the variance of finger movement and to minimize finger movement time variation beyond the allocated time of one second for the active touch task. The whole experiment was divided into four runs with three short breaks between successive runs. Each run consisted of 48 trials, one trial lasted for 4.5–5.5 seconds, therefore it took about 4.5 minutes for one complete run of the experiment. In total, we collected 96 trial data in presence and absence of tactile stimulation per participant. EEG signals were recorded throughout the experiment.

For EEG signal processing, EEGLAB toolbox is utilized [5]. As a preprocessing of EEG signals, they were down sampled from 2500 Hz to 1250 Hz. To remove the effect from the outside locations, EEG signals from locations FT9, FT10, TP9, TP10, PO9, and PO10 were removed from the signal analysis. A zero-phase finite impulse response filter was used for band pass filtering (0.1–55 Hz). A notch filter was applied with a zero-phase digital filter to remove the 50 Hz line noise. The artifact subspace reconstruction method was applied to remove eye movement and muscle artifacts [20]. Then, the filtered EEG signal was divided into epochs corresponding to when tactile stimulation is applied or not. Finally, EEG signals were re-referenced using the common average reference [4]. After preprocessing, power spectral densities of alpha (8–12 Hz), beta (13–30 Hz), and gamma (31–50 Hz) bands at each channel were computed via short-time Fourier transform.

Connectivity Analysis

We defined three regions of interest as the prefrontal area (Fp1, Fp2, AF7, AF3, AF4, and AF8) and the bilateral areas include motor, somatosensory, parietal association and general interpretation areas (C5, C3, C1, CP5, CP3, CP1, P5, P3, P1, PO7, and PO3 in contraletral area and C2, C4, C6, CP2, CP4, CP6, P2, P4, P6, PO4, and PO8 in ipsilateral area). To find the functional connectivity in the brain, we extracted phase locking values (PLVs) [14] between electrode pairs in three regions of interest and the interhemispheric areas. PLVs of 500 ms period before the motor task cue were used as a base line. PLVs in the period of 1 second motor task were subjected by average value of baseline. All pairs of combinations

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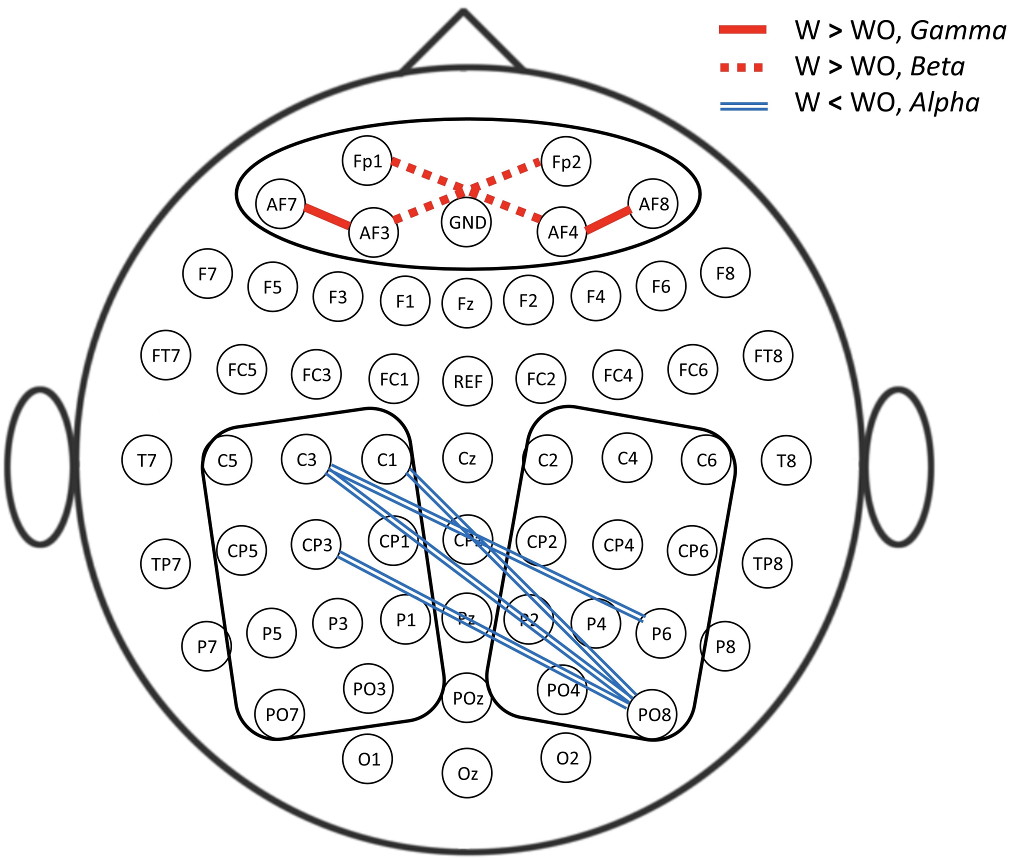

Figure 3: Significant differences of functional connectivity in the prefrontal and interhemispheric areas. Red solid lines, red dashed lines, and blue double lines indicate gamma, beta and alpha connectivity respectively. W > WO indicate that the connectivity in the presence of tactile stimulation is stronger than in the absence of tactile stimulation. W < WO indicate the otherwise.

in each region of interest and each frequency band were compared in the presence and absence of tactile stimulation. All pairs of combination of the interhemispheric connectivity were also compared. To avoid multiple comparison problem, we adjusted the significance level by Bonferroni correction. A statistical analysis technique, t-test, was performed using MATLAB to determine the significance between the two test conditions (presence and absence of tactile stimulation).

Results

Prefrontal Area

Figure 3 shows significant differences in beta and gamma connectivity in the prefrontal area. In particular, two pairs of beta connectivity (namely Fp1-AF4 and Fp2-AF3) were significantly stronger in the presence of tactile stimulation, compared to the case when no tactile stimulation is applied (t-test, $p < 0.0033$). As for the gamma band, two pairs of gamma connectivity (AF7-AF3 and AF4-AF8) were significantly stronger in the presence of tactile stimulation compared to the case when tactile stimulation is not applied (t-test, $p < 0.0033$). Furthermore, no significant differences between the two test cases (with and without tactile stimulation) were found in the functional connectivity within the bilateral sensorimotor and parietal areas.

Previous research by Kim et al. [12] has demonstrated that an increase in the connectivity of beta and gamma bands in the prefrontal cortex is associated with the development of bereitschaftspotential (BP) [27], which reflects the intention, planning and execution of a movement and thus contributing to precise voluntary movement. High intraregional beta and gamma activities in the prefrontal area, resulted from the tactile feedback, may reflect the activation of brain networks related to movement preparation. it also seems that the presence of tactile feedback during an active touch task contributes to developing precise voluntary movement and thus improved motor skills.

Interhemispheric Connectivity

Figure 3 shows significant differences of functional connectivity levels in interhemisperic connectivity. In particular, contralateral motor (C1 and C3) and somatosensory (CP3) areas show stronger alpha connectivity with ipsilateral parietal association (P6) and general interpretation (PO8) areas compared to the case when tactile stimulation was present (t-test, $p < 0.0004$).

A previous study by Amann et al. [2] found that interhemispheric functional connectivity of primary motor cortex is significantly reduced during continuous performance of a unilateral motor task. This phenomenon has also been demonstrated for post-stroke patients [7]. This suggests that increased interhemispheric connectivity during the absence of tactile stimulation may represent a compensatory mechanism for the lack of tactile feedback. It looks likely that the lack of tactile feedback, represented by an increased interhemispheric connectivity, is associated with motor impairment.

Discussion

We found significant differences in beta and gamma connectivity in the prefrontal area. Frontal beta and gamma band oscillation is well known to be related to cognitive processes [9], [29], [24]. The activation of beta and gamma connectivity in the frontal area shows that there is an active communication in the frontal lobe due to more cognitive processing. This suggests that tactile stimulation affects not only sensation but also cognitive function. Furthermore, previous research found relationship between an increase in the beta and gamma bands in the prefrontal cortex and precise voluntary movement. Tactile feedback also seems to contribute to the preparation and execution of precise movements (motor skills).

We also found alpha interhemispheric connectivity. Alpha phase has been reported to be associated with tactile perception as well as the power distribution of EEG [1]. Several interesting observations can be made from the results shown in Figure 3. First of all, regardless of the presence or absence of tactile stimulation, there is a significant difference in the connectivity associated with C3 and C1 that belong to the contralateral motor cortex, even though the participants' behavior was the same. It is also very interesting to note that there are significant differences in connectivity between the contralateral sensorimotor area and the ipsilateral parietal area. The interpretation of sensation occurs first in the association and interpretation areas of the same hemisphere [19]. However, in the absence of tactile stimulation, it could be less obvious in the interpretation area, thus it is presumed that the communication with the analytical areas of the opposite hemisphere to compensate for the lack of sensory information (in this case the lack of tactile feedback). In other words, the participants were able to see and hear the guitar strings, however they could not feel the tactile sensation as expected. Thus, it was assumed that the role of ipsilateral sensation association and interpretation area as well as contralateral sensation association and interpretation were needed for accurate interpretation. More research on tactile perception and functional connectivity is needed to clarify this inference. In this study, the entire period of the motor task was considered for interpreting the brain connectivity. Therefore, more research is needed on how brain activation varies over time.

To make natural, real life touch interaction, we designed active touch motor task. Thus, movement artifacts including muscle signal and additional sensory stimulation could affect EEG signal. However, these artifacts from motor movement are the same for the presence and absence of tactile stimulation conditions. Thus, we assume that these artifacts were cancelled out when we analyzed differences of functional connectivity in the presence and absence of tactile stimulation.

Conclusion

In this study, we investigated brain connectivity associated with tactile stimulation. We found that the beta and gamma connectivity in the prefrontal area ar much higher in the presence of tactile stimulation than the case when tactile stimulation is absent. Furthermore, significantly stronger interhemisheric alpha connectivity between contralateral sensorimotor area and ipsilateral parietal area are observed when tactile stimulation is not applied. This shows that tactile stimulation not only affects sensation but also cognitive processing and shows increased brain network activity to compensate for the lack of tactile sensation.

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