Spectral Modulation of Frontal EEG Activities During Motor Skill Acquisition: Task Familiarity Monitoring Using Single-Channel EEG

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***Abstract*—This study investigates the modulation of frontal EEG dynamics with respect to progress in motor learning. Using a computerized visual-motor task similar to mirror drawing, our work demonstrated that overall EEG activities in all frequency bands decreased with an increase in motor task familiarity. In particular, frontal EEG activities in delta band of the whole trial and gamma band at the beginning of each trial are having a significant negative relationship with the overall familiarity level of the task. The findings suggest that frontal EEG spectra are significantly modulated during motor skill acquisition.**

Keywords— Electroencephalography (EEG); familiarity; visual-motor task; mirror drawing; forehead

I. Introduction

In this study, we aim to study the modulation of frontal EEG dynamics during motor skill acquisition. Familiarity is an abstract but important indicator in quantifying the progress of all sorts of learning. Ranging from playing piano to speaking a new language, the fluency in performing a motor task can be improved through repeated practice. At the cellular level, synaptic connections are strengthened through repeated stimulation and become more ready to be activated. At the systemic level, getting more familiar with a motor task through repeated practice not only improves the fluency in the task completion and reduce the number of errors but also reduces the cognitive resource that is required in completing the task [1]. However, it is a challenging question to quantify the level of familiarity during the learning process. Because of the implicit nature of motor learning, measurements such as self-reported familiarity by learner and visual inspection by educators may not reliably and objectively reflect the actual learning progress.

Current studies in motor learning focus mainly on changes in EEG features with respect to movement onset and coherences between different regions. Serren and Brown showed that task-related coherence of interhemispheric sensorimotor areas and within midline areas decreased in alpha band and beta band respectively as the subjects become more familiar with a motor task [2]. In contrast, functional coupling of the interhemispheric prefrontal areas in the gamma band significantly increased with the number of practice. Lange et al demonstrated that coherence in the alpha band, power and coherence of the beta band were lower prior to the onset of movement in drawing with the non-dominant hand comparing to the dominant hand [3]. After training the non-dominant hand, differences in EEG characteristics between drawing the same figure with left hand and that with right hand were attenuated [4]. Reproducing the figure in mirror orientation with the dominant hand would then correlate with the increase in beta coherence after the movement onset. These individual studies suggested that alpha, beta, and gamma activities were strongly correlated to learning of motor skills.

Yet, traditional coherence and EEG features identified by previous studies are usually impractical in real-world settings because of its specific and structural measurement period, e.g. time locked to movement onset, and its use of multi-channel wet EEG electrodes. With its ergonomic design, mobility and user-friendliness, single-channel dry sensor EEG headset could be a practical solution for everyday applications. EEG signal collected from such devices were shown to be useful in quantifying users' mental states (Neurosky white papers and other research - http://www.neurosky.com/AcademicPapers.aspx).

In light of this, this study set out to investigate the modulation of EEG dynamics with changes in progress of motor skill acquisition using single-channel EEG signal collected from forehead region. Results of this study could help to examine the feasibility of monitoring motor learning progress using single-channel frontal EEG.

II. Methods

A. Experiments

Ten volunteers (age: 26±3 years; male/female: 7/3) were recruited in this study. All the participants have normal or corrected-to-normal vision and have no history of neurological or psychological disorder. Participants received informed consent to the experimental procedure, which was approved by the ethics committee at the City University of Hong Kong.

Each participant was asked to perform 8 trials of computerized visual-motor task similar to mirror drawing. The mirror drawing task was first used by Milner (1962) [5] to assess the impact of memory impairment on acquiring a

This work was supported in part by industrial sponsorship from NeuroSky (Hong Kong) Co. Ltd.

new motor task. To complete the task successfully, participants were required to acquire a new set of sensorimotor associations (i.e., moving their hands to the opposite direction as showed on the screen) and to suppress the well-learned association between vision and motor control [6]. In the present study, participants were asked to complete a computerized visual-motor task similar to mirror drawing, which is programmed with the Psychtoolbox [7,8,9] in Matlab. In each trial, a heptagon (see Figure 1) was presented to the participants who were asked to trace around the heptagon (within the boundary) with a mouse. The program reversed the left and right movement of the mouse. Participants were asked to keep holding on the left key of the mouse through the tracing and the tracing was stopped when the participants released the key. Participants were given no longer than 301s to complete the tracing. The heptagon rotated for 15° clockwise between trials. Participants were reminded to trace within the boundary as accurate as possible and should go back to the boundary at the same location where the tracing left the boundary.

B. Data Collection

EEG data collection was controlled by two separate computers. Clock synchronization was performed before each experiment. The drawing task was presented to the participants with a 24" LCD monitor which was positioned 24" from the forehead of the participants. Behavioral data including the completion time (i.e., the time from the first cursor movement to the last detected movement), completion rate (i.e., the percent of drawing that the subject has completed) and directional accuracy (i.e., the percent of drawing the subject made was within the boundary of the presented image) were collected together with the actual tracing path by the matlab program. Single-channel frontal EEG data were collected from subjects using the NeuroSky MindWave Mobile headset at a sampling rate of 512 Hz. EEG data were transmitted wirelessly, and stored to the data collection computer during the experiment.

Fig. 1. Participants (left) were asked to trace within the boundary of the heptagon (right).

C. Data Processing and Analysis

Raw EEG signal was detrended and then band-passed at 0.5 to 45 Hz. Wavelet-based filtering method [10] was then applied to the data to remove blink and eye movement related artifacts. Continuous EEG was then segmented into epoch based on mouse cursor movement onset and offset time. Short-time Fourier transforms over 50% overlapped 2s Hamming windows were computed for all pre-processed EEG segments. Average power spectra were then computed across segments for each trial performed by individual subjects. Task-related spectral power variations were investigated within eight frequency bands (Delta: 1-4Hz; Theta: 4-8Hz; Lower Alpha: 8-11Hz; Upper Alpha: 11-14Hz; Lower Beta: 14-25Hz; Upper Beta: 25-36Hz; Lower Gamma: 36-40Hz; Upper Gamma: 40-44Hz).

The familiarity level of subject in the drawing task was quantified by the following equation, using the task-specific behavioral data measured as

$$Familiarity\ Index = \frac{Directional\ Accuracy \times Completion\ Rate}{Completion\ Time} \quad (1)$$

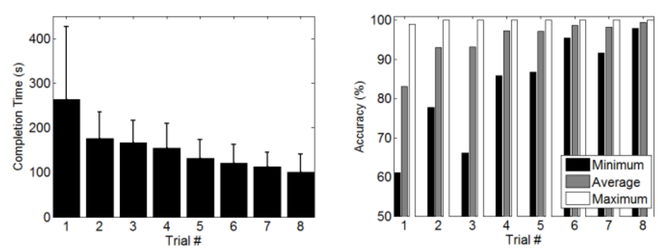
To reduce the between-subject effect, familiarity index x_{ij} was transformed to normalized index y_{ij} using

$$y_{ij} = \frac{x_{ij} - \mu_j}{\mu_j} \quad (2)$$

where x_{ij} is the task familiarity level of subject j in trial i; μ_j is the average familiarity level of subject j. We would then explore the relationship between EEG frequency band activities with the normalized familiarity indexes. To further explore the timely relationship between task familiarity and EEG activity, the EEG data were segmented into 60-s segments for additional correlation analysis.

III. RESULTS

Fig. 2 illustrated the completion time of each trial and the tracing accuracy. In general, the subjects became more familiar with the motor tasks with more practices as expected as shown in Fig 3. Correlation coefficient between accuracy and the time taken to finish whole trial is -0.5388 ($p < 0.001$).



(a) (b)

Fig. 2. (a) Time taken to finish whole trial and (b) performance accuracy.

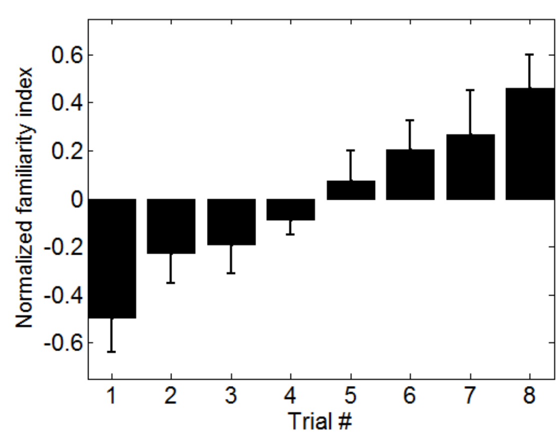


Fig. 3. Normalized familiarity index.

As shown in Table 1, overall EEG activities in all frequency bands decreased when the subjects became more familiar with the task. Table 1 also indicated that the average EEG power in delta band, but not the power in other bands, of whole trial had a significant negative correlation with drawing accuracy and the normalized familiarity index.

TABLE I. RELATIONSHIPS BETWEEN AVERAGE BAND POWERS AND INDIVIDUAL PERFORMANCE IN EACH TRIAL

Band	Correlation with average band power	
	Performance Accuracy	***Familiarity Index***
Delta	**-0.2507***	**-0.2245***
Theta	-0.0470	-0.1084
Lower Alpha (Alpha1)	-0.0838	-0.1069
Upper Alpha (Alpha2)	-0.1443	-0.1690
Lower Beta (Beta1)	0.0460	-0.1172
Upper Beta (Beta2)	0.1196	-0.0212
Lower Gamma (Gamma1)	0.0062	-0.1215
Upper Gamma (Gamma2)	0.0053	-0.1532

*Statistical significance at $p < 0.05$.

However, we also found that all band powers, except upper beta activities, are significantly correlated with experimental time from the start of each trial as shown in Fig 4. Inasmuch as the EEG power spectra were time-varying, relationships between data collected from different time segments with tracing accuracy and subject familiarity with the task were evaluated in Table 2 and Table 3 respectively. Upper alpha power and consistent delta power at the end of the task were negatively correlated with drawing accuracy. More importantly, gamma activities demonstrated negative relationships with task familiarity but their significance decreased with time, especially lower gamma power. Gamma activities in the first minute of each trial are indicative of subject's familiarity level of the visual-motor task.

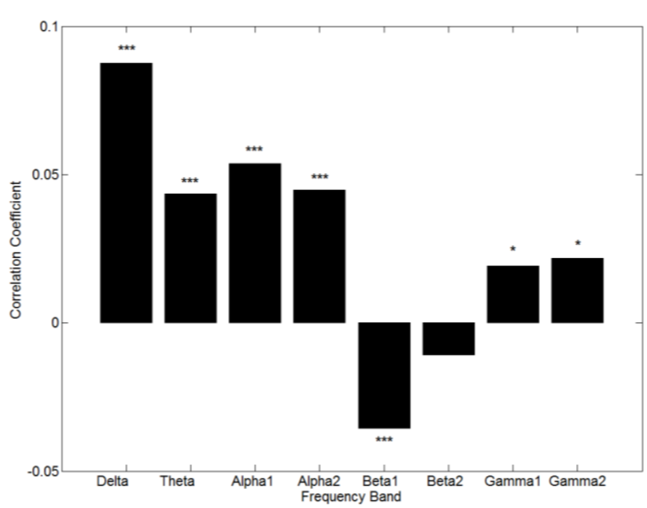


Fig. 4. Correlation coefficients between experimental time from the start of each trial and individual band powers (*** $p < 0.001$; * $p < 0.05$).

TABLE II. RELATIONSHIP BETWEEN ACCURACY AND INDIVIDUAL EEG FEATURES IN DIFFERENT TIME SEGMENTS

EEG Features	Correlation with accuracy		
	First 60s	***Mid-60s***	***Last 60s***
Delta Power (1-4Hz)	-0.1508	**-0.2645***	**-0.2578***
Theta Power (4-8Hz)	-0.0361	-0.0915	-0.0484
Lower Alpha Power (8-11Hz)	-0.0258	-0.0995	-0.1620
Upper Alpha Power (11-14Hz)	0.0144	-0.1625	**-0.2583***
Lower Beta Power (14-25Hz)	0.0650	-0.0001	0.0155
Upper Beta Power (25-36Hz)	0.0766	0.0835	0.1405
Lower Gamma Power (36-40Hz)	-0.0496	-0.0318	0.0550
Upper Gamma Power (40-44Hz)	-0.0335	-0.0048	0.0297

*Statistical significance at $p < 0.05$.

TABLE III. RELATIONSHIP BETWEEN TASK FAMILIARITY AND INDIVIDUAL EEG FEATURES IN DIFFERENT TIME SEGMENTS

EEG Features	Correlation with familiarity index		
	First 60s	***Mid-60s***	***Last 60s***
Delta Power (1-4Hz)	-0.1862	-0.2104	-0.2157
Theta Power (4-8Hz)	-0.0970	-0.1231	-0.0946
Lower Alpha Power (8-11Hz)	-0.0725	-0.0889	-0.1765
Upper Alpha Power (11-14Hz)	-0.1334	-0.1768	-0.2171
Lower Beta Power (14-25Hz)	-0.1252	-0.1496	-0.1583
Upper Beta Power (25-36Hz)	-0.0987	-0.0207	-0.0368
Lower Gamma Power (36-40Hz)	**-0.2240***	-0.1273	-0.1140
Upper Gamma Power (40-44Hz)	**-0.2318***	-0.1351	-0.1650

*Statistical significance at $p < 0.05$.

These results could also be visualized by the average power spectral density in the first minute as shown in Fig 5. Gamma activities significantly decreased from the first practice trial with lowest familiarity to the last practice trial, with highest familiarity.

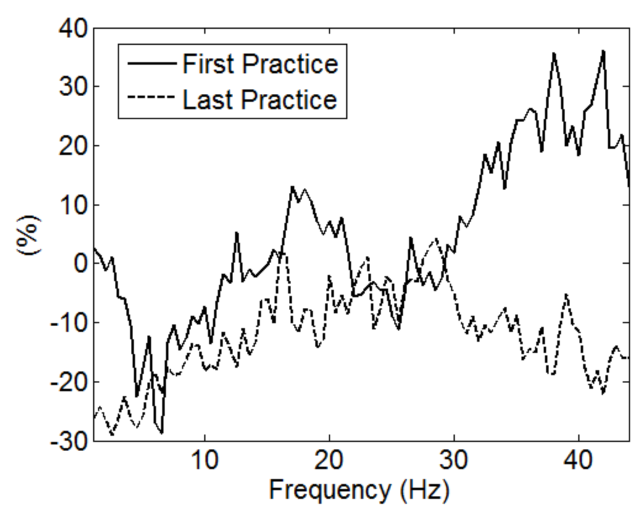


Fig. 5. Percentage changes in average power spectral density with respect to the overall mean activities in the first 60s of the first and last practice.

IV. DISCUSSION

From the experimental results, consistent decrease of EEG activities in all frequency bands was associated with an increase in task familiarity. Specifically, significant decrease of EEG activities in delta (1-4Hz) and gamma (36-44Hz) frequency bands were induced by increases in accuracy and familiarity respectively in a visual-motor task. The connection between frontal gamma activities and visual-motor task familiarity happens in the first minute with its significance decrease over time. Other temporal factors might influence the EEG activities afterwards. Thus, multilevel models shall be derived to study such temporal effects after further data collection.

From our results, overall frontal delta power demonstrated negative relationships with motor task familiarity. Relationships between EEG delta activity with task loading and motor learning had been reported previously [12,13]. Specifically, Harmony *et al.* reported an increased delta power may be related to attention to internal processing during the performance of the task [13]. Also, EEG delta activity has also been reported to be sensitive to changes in effortful attention [12].

Another important EEG feature to task familiarity is the power of gamma oscillations. The finding of a decrease in gamma power with an increase in task familiarity agrees with previous research showing the amplitude of gamma oscillations in the subjective experience of familiarity is lower than that of conscious recollection [11]. Yet, in this experiment, such negative relationship between gamma power and task familiarity is only statistically significant at the beginning of each trial, that is, the first minute.

This study demonstrated the possibility of monitoring motor skill acquisition progress using single-channel EEG measurements collected from the forehead area. The application of this finding could have tremendous impact to different areas including education, sports, gaming, etc. Such technology allows users to monitor their own task performance and familiarity level easily, leading to a more effective and efficient training and a more pleasant learning experience.

Thus far, we have focused on the exploration of EEG activities related to task familiarity in relatively simple visual- motor task using some of the most commonly used EEG features. Next, we will repeat the experiment with mental task and possibly with additional EEG features. It is possible that a different set of EEG features would be found due to the different nature and neural activation pattern between motor and mental tasks.

ACKNOWLEDGEMENT

This work has been supported by industrial sponsorship from NeuroSky (Hong Kong) Co. Ltd., HKIEd (internal grant no. RG65/11-12), the Innovation and Technology Fund (ITS/074/12FX) provided by the Innovation and Technology Commission, HKSAR. Any opinions, findings, conclusions or recommendations expressed in this material/event (or by members of the project team) do not reflect the views of the Government of the Hong Kong Special Administrative Region, the Innovation and Technology Commission or the Panel of Assessors for the Innovation and Technology Support Programme of the Innovation and Technology Fund.

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