Article

Electroencephalography Pattern Variations During Motor Skill Acquisition

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Abstract

The present study examined how motor skill acquisition affects electroencephalography patterns and compared short- and long-term electroencephalography variations. For this purpose, 17 volunteers with no history of disease, aged 18 to 22 years, attended seven training sessions every other day to practice a pursuit tracking motor skill. Electroencephalography brainwaves were recorded and analyzed on the first and last days within pre- and post-training intervals. The results showed a significant decrease in performance error and variability with practice over time. This progress slowed at the end of training, and there was no significant improvement in individual performance at the last session. In accordance with performance variations, some changes occurred in brainwaves. Specifically, θ power at Fz and α power at Cz increased on the last test day, compared with the first, while the coherence of α at Fz-T3 and Fz-Cz decreased. β Coherence between Fz-Cz was significantly reduced from pre- to posttest. Based on these results, power changes seem to be more affected by long-term training, whereas coherence changes are sensitive to both short- and long-term training. Specifically, β coherence at Fz-Cz was more influenced by short-term effects of training, whereas θ power at Fz, α power at Cz, and α coherence at Fz-T3 and Fz-Cz were affected by longer training.

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motor skill learning, learning, electroencephalography, training duration

Introduction

Motor behavior researchers aim to identify, describe, and predict motor performance and its underlying factors to develop methods to enhance human performance. Several factors have either a temporary or long term impact on motor performance; (Magill, 2007) some are hereditary, while others are acquired; some are physical, and others are mental and cognitive. One of the factors contributing to individual performance involves experience, practice, or motor learning. Motor learning results from practice and experience and leads to relatively permanent changes in motor behavior.

During the learning process, several changes occur in physical and mental state (Schmidt & Lee, 2011). The performance improvement occurring as a result of practice is accompanied by changes in the central nervous system underlying behavioral changes (Willingham, 1999). Although major learning changes are expected to be skills at the execution level, sometimes there may not be a tangible change in performance variables after initial progress and training. Changes in metabolic, biomechanical, and cognitive efficiency variables occur when individuals carry out a task. One such change is a variation in brain processing (Magill, 2007).

Several studies, applying different methods, have evaluated brain function during learning and executing motor skills (Blum, Lutz, Pascual-Marqui, Murer, & Jäncke, 2008; Willingham, 1999), and one of the most common of these has involved variations in brainwaves. Electroencephalography (EEG) is a method for recording electrical activity of the brain; EEG reflects a person's psychophysiological state during performance because brainwaves can be sensitive to changes in attention and cognitive demands (Smith, McEvoy, & Gevins, 1999). The study of brainwaves focuses on different components such as frequency, power, and connectivity features. Frequency represents the rate of oscillation of brainwaves per second. Brainwaves are usually divided into frequency bands of δ (<4 Hz), θ (4–8 Hz), α (8–12 Hz), and β (13–30 Hz; Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). Involvement of each frequency band anywhere in the scalp indicates the dominance of a particular psychophysiological state. The index pointing to the amount of energy or activity of a frequency band at one point is called the power (amplitude squared). It can be described alone, along with absolute power, or in comparison with the power of other frequency bands at the same point in time (relative power; Kropotov, 2010). Coherence is another feature in each frequency band, involving the correlation coefficient of a frequency band at two different reference points in the brain, representing the functional communication between these two areas. In various situations, lower coherence between different brain areas can be considered as better processing efficiency or lower ratio of effort invested to achieve a set level of performance (Deeny, Hillman, Janelle, & Hatfield, 2003).

Among studies that have examined brainwave patterns in individuals performing motor tasks, there have been different features of brainwave patterns associated with a skillful performance (Haufler, Spalding, Santa Maria, & Hatfield, 2000; Kerick et al., 2001). For example, some studies have shown that skillful individuals, before performing the tasks, have more α in the left hemisphere. Based on these results, an increase in α power in the left hemisphere is seen as a beneficial learning outcome, indicating lower cognitive effort related to performance (Haufler et al., 2000; Kerick et al., 2001). In addition, when skilled individuals perform skill tasks, there is typically an increase in θ power in the frontal area; increased θ power in midline frontal areas is linked with focused attention (Baumeister, Reinecke, Liesen, & Weiss, 2008; Smith et al., 1999). Brainwave characteristics associated with skillful performance are not limited to the component frequency bands, but include connectivity measures like coherence.

Both cross-sectional and long-term research designs have been used to study EEG characteristics of skillful performance. In the first category, researchers have examined differences between skilled and novice performers, attributing differences to variations caused by learning, without considering the transition through various motor learning stages during acquisition (Deeny et al., 2003; Haufler et al., 2000; Salazar et al., 1990). Past research has found that increased skill level leads to lower functional communication between different regions of the brain. For example, Deeny et al. (2003) compared coherence in skilled and beginner groups before an aiming task. Results showed that the skilled group had lower coherence in β and α waves between frontal midline and left temporal regions (i.e., Fz-T3). In addition, Deeny, Haufler, Saffer, and Hatfield (2009) showed that experts generally exhibited lower coherence compared with novices, and interestingly, they found that coherence was positively related to aiming movement variability. Reduction in cortical activity associated with motor skill expertise was described by Hatfield and Hillman (2001) as a marker of "psychomotor efficiency."

Longitudinal researchers have examined EEG changes originating from motor skill learning with training periods ranging from a few minutes to a few days (Blum, Lutz, & Jäncke, 2007; Blum et al., 2008; Zhu et al., 2010). In longitudinal designs, Landers, Han, Salazar, and Petruzzello (1994) observed that after 14 weeks of practice, α power increased over the left hemisphere, and Kerick, Douglass, and Hatfield (2004) found that after 12 to 14 weeks of training, α power at the left temporal region increased. However, in these two studies, coherence was not considered. In single session designs, some studies reported increased functional connectivity between different brain areas as an indicator of learning and expertise. Blum et al. (2007, 2008) assessed variations in the coupling between motor and sensory networks (parietal and motor areas) after learning a sensory motor task. Zhu et al. (2010) revealed no change in α and β power in different scalp locations after learning, and they interpreted an increase in low β coherence between Fz-T4, as a sign of early stage or cognitive-verbal stage of learning. It seems that as the amount of training increases and passes through learning stages, brainwave characteristics evolve. Thus, some components may be sensitive to early stages and short-term training, whereas others depend on long-term changes induced by practice.

The current study aimed to compare single-session and extended training changes in brainwave features in an identical experiment. We hypothesized that specific brainwave changes (increased α and β coherence and θ power) would result from single session training, while specific others (decreased α and β coherence and increased α power) would result from longer practice. We used the pursuit tracking motor skill task, one of the most common in motor learning research.

Method

Participants

Seventeen male volunteers aged 18 to 22 ($M_{age} = 19.94$, $SD = 0.96$) participated in the study. Participants were right handed, had no medical conditions or medications, and reported more than six hours of regular sleep per night before and during the experiment. Informed written consent was obtained from all participants.

Learning Task

The task used in this study was a modified mode of the pursuit tracking task (Hill, 2014). Participants sat at a 17-in. monitor where a red circle with a diameter of 10 pixels moved in a predetermined direction. Participants were instructed to pursue a moving stimulus with a circular white marker of the same size. The white marker was controlled by individuals via a computer mouse and the left (nondominant) hand with the rationale that people seldom use their nondominant hand, and previous research has shown that learning improvement is greater in the nondominant hand as a result of cortical stimulation (Boggio et al., 2006). The movement path of the stimulus was controlled by a series of sine and cosine motions derived from the following formula adopted by Hill (2014) from Wulf and Schmidt (1997; Figure 1)

$$f(x) = b0 + a1\ \sin(x) + b1\cos(x) + a2\sin(2x) + b2\cos(2x) + \cdots + a5\ \sin(5x) + b5\ \cos(5x)$$

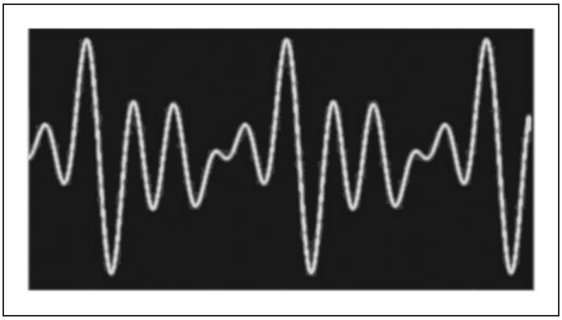

Figure 1. The task trajectory.

The values (a1 . . . a5, b0 . . . b5) ranged randomly from −5 to 5 (Hill, 2014). The task was programmed through MATLAB and presented through C-sharp application (C♯). The performance accuracy was calculated through root mean square error (RMSE). In addition, performance variability was calculated via standard deviation of performance error.

Procedure

On the first day, participants initially performed the task as a pretest. Then, they practiced the task within three blocks of five trials. Each trial lasted 60 seconds; at the end of the day, they participated in a posttest similar to the pretest ($n = 3$ trials). Participants then practiced the motor skill every other day for 5 days. Activities on the last day or Day 7 were similar to those on the first day. Participants were given feedback in training trials, but not during test trials. Post-trial feedback included showing the performance error and a graphic depiction of the path travelled by participants to observe their errors and correct them in future efforts. In general, the process of training and testing was as shown in Figure 2.

EEG Recording and Analysis

EEG was recorded at pre- and posttest on the first and last days. To record brainwaves, the 10-channel device, FlexComp and Biograph, (Version 5.0.3) developed by Thought Technology (TT) of Canada were adopted. Eight channels were used to record brain signals, while one channel was used for the TT AV-Sync sensor aimed at synchronization of the beginning and end of the task and recording brainwaves. Brainwave data were stored in the Biograph database and exported into MATLAB (MathWorks, USA) for brainwaves analysis. EEG data were obtained from Fz, Cz, Pz, C3, C4, T3, and T4 using an elastic cap and electrodes constructed by g.tec in accordance with the standard

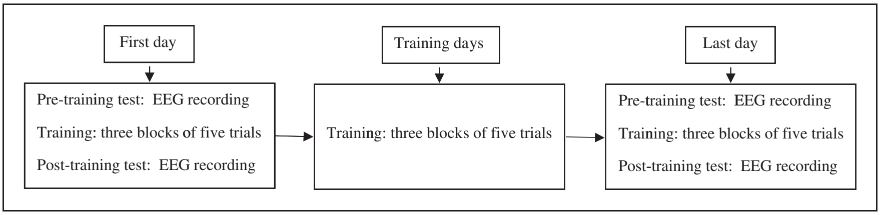

Figure 2. The training and testing process.

international 10-20 system. A ground electrode placed on the right ear and left ear was used as the reference electrode. To ensure the accuracy of data before recording, impedances were kept below 5 kΩ in different electrodes in all trials. The acquired signal was amplified and filtered with an analog elliptic band pass filter ranging from 0.1 to 64 Hz. Furthermore, a 50 Hz notch filter (for line noise) was enabled. Sampling frequency was 256 Hz, and A to D precision was 14 bit (Ghoshuni, Firoozabadi, Khalilzadeh, & Hashemi Golpayegani, 2013). Prior to the quantitative analysis of brainwaves, an experienced electroencephalographer evaluated the data visually, and EEG signals containing greater activity than 50 μV due to obvious artifacts (e.g., movements and eye blinks) were eliminated using MATLAB software. The power spectrum density of EEG signals was approximated by Welch's averaged modified periodogram with 2-second epochs (0.5-Hz frequency resolution), 50% overlap, and a Hanning window (Welch, 1967). EEG coherence was calculated using *mscohere* function in MATLAB software. The coherence was defined as $|Cxy(f)|$, where

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}$$

$P_{xx}(f)$ and $P_{yy}(f)$ represent the power spectral densities for electrode sites X and Y, respectively, and $P_{xy}(f)$ represents the cross power spectral density of x and y applying Welch's averaged modified periodogram method. The power of each frequency band of θ (4–8 Hz), α (8–12 Hz), and low β (13–20 Hz) was initially calculated at Fz, Cz, Pz, T3, and C3, T4, and C4. Coherence of frequency bands for α and β at Fz-Cz, Fz-T3, and Fz-T4 was calculated. SPSS 16 was used for statistical analysis. To evaluate the trend of individual performance changes during training sessions at the acquisition stage and on testing days, repeated measure analysis of variance (ANOVA) was used, separately. In addition, changes in brainwaves were examined during various intervals initially through two-way repeated measures ANOVA (2 × 2) on 2 days (first day–last day) and two test types (pretest–posttest) to compare the short-term or intrasession and intersession effects.

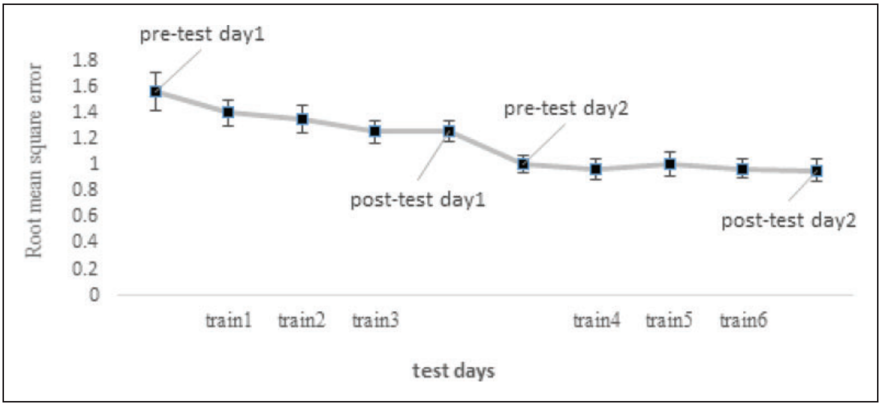

Figure 3. Performance changes trend during the first and last test days.

Results

Trends in Performance Changes on First and Last Test Days

Figure 3 shows the individual performance on different test days, showing much progress made on the first day and slight progress on the second. Moreover, further reduction in the performance error at the end of the first test day compared with the beginning of the last test day was an outcome of separate training sessions that took place between the 2 days.

The repeated measures ANOVA showed significant differences in the performance error across the four stages of testing specified in Figure 3, $F(1.88, 30.14) = 73.12$, $p = .0001$, $\eta^2 = 0.82$. The results of a Bonferroni post hoc test showed significant differences in the performance error on the pretest of the first day compared with all other tests and on the posttest of the first day compared with the second day tests ($p < .01$), whereas there was no significant difference between the pre- and posttest on the last day ($p = .15$). A repeated measures ANOVA showed that the standard deviation of error scores (performance variability) decreased significantly across different blocks of the four stages of testing, $F(2.02, 32.35) = 3.27$, $p = .05$, $\eta^2 = 0.17$. The post hoc test indicated a significant difference between the pretest of the first day and the posttest of the last day ($p < .05$).

Variations Across Training Sessions Between Two Test Days

Changes in performance across the five training sessions were examined with repeated measures ANOVA. Results showed that participants had significant progress across training sessions (Figure 4); the performance error was significantly reduced across training sessions, $F(4, 64) = 21.36$, $p = .0001$, $\eta^2 = 0.57$.

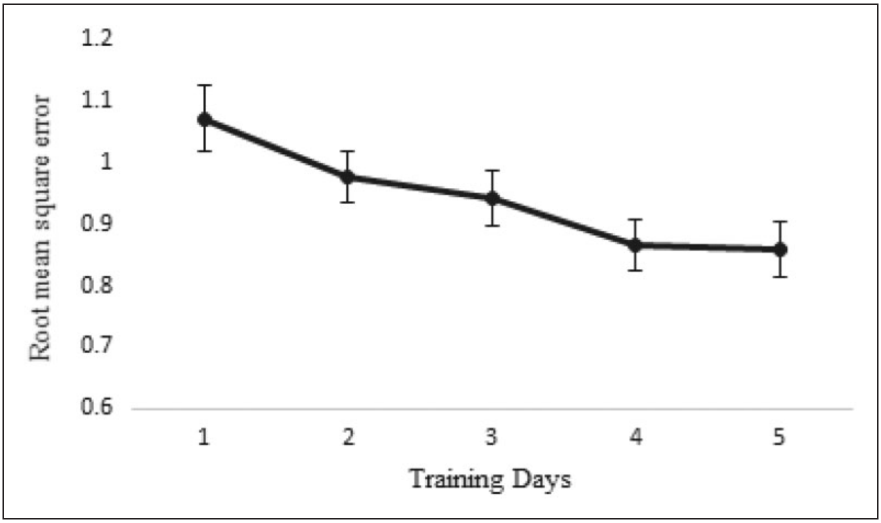

Figure 4. Performance changes trend across training sessions

The reduction was great in initial training sessions and slight in final sessions. The result of a Bonferroni post hoc test showed that, except for the fourth day compared with the fifth day ($p > .05$), there was a significant reduction in performance error across all days ($p < .05$).

EEG Variations between Test Stages

Power changes. Although there were no significant differences between various stages of testing in β frequency band power at Fz, Cz, Pz, T3, T4, C3, and C4, θ at Cz, Pz, T3, T4, C3, and C4 and α power at Fz, Pz, T3, T4, C3, and C4 ($p > .05$), there was a significant increase observed in the θ power at Fz and α frequency power at Cz (Figure 5). Results of two-way repeated measures ANOVA in θ band frequency at Fz showed that the main effect of days was significant, $F(1, 16) = 6.5$, $p = .021$, $\eta^2 = 0.29$, but the main effect of test type, pretest to posttest; $F(1, 16) = 1.04$, $p = .32$, $\eta^2 = 0.06$, and interaction of days x test type were not significant, $F(1, 16) = 1.65$, $p = .22$, $\eta^2 = 0.09$. That is, at the final day, θ increased regardless of the type of test. Evaluation of α frequency band power at Cz revealed that the main effect of days was significant, $F(1, 16) = 8.2$, $p = .011$, $\eta^2 = 0.34$, whereas the main effect of test type, $F(1, 16) = 0.5$, $p = .48$, $\eta^2 = 0.03$, and interaction of day X test type were not significant, $F(1, 16) = 2.05$, $p = .017$, $\eta^2 = 0.11$. That is, at the final day, α increased regardless of the type of test.

Coherence changes. The results of two-way repeated measures ANOVA showed no significant changes in the α frequency band coherence at Fz-T4 and β at

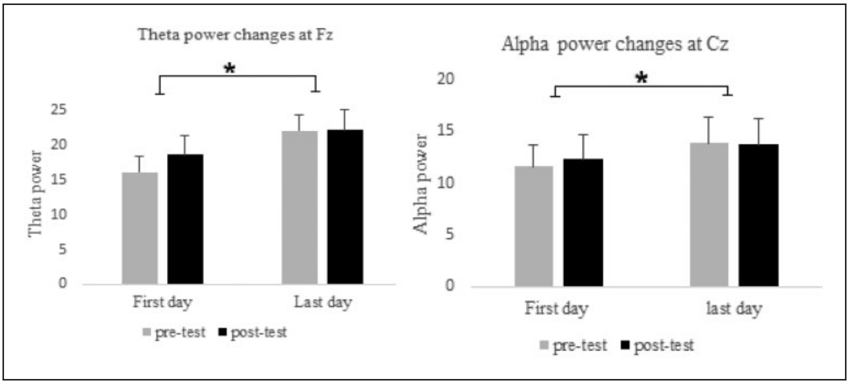

Figure 5. α and θ Changes in first and last test days.

Fz-T3 and Fz-T4 ($p > .05$). β Coherence was significantly reduced between test types (Figure 6). The results of β coherence between Fz-Cz points showed that the main effect of days was not significant, $F(1, 16) = 0.36$, $p = .55$, $\eta^2 = 0.02$, whereas the main effect of test type was significant, $F(1, 16) = 6.9$, $p = .018$, $\eta^2 = 0.3$. There was no significant interaction between days x test type, $F(1, 16) = 0.78$, $p = .39$, $\eta^2 = 0.046$. α Coherence between Fz-Cz was significantly reduced (Figure 6). The results of the statistical test on the main effect of days was significant, $F(1, 16) = 10.42$, $p = .006$, $\eta^2 = 0.4$, while the main effect of test type was not significant, $F(1, 16) = 1.31$, $p = .27$, $\eta^2 = 0.07$, and there was no significant interaction observed between days x test type, $F(1, 16 = 0.69)$, $p = .79$, $\eta^2 = 0.004$.

α Coherence between Fz-T3 was significantly reduced from the first day to the last day (Figure 7). A significant main effect of days was found at Fz-T3, $F(1, 16) = 10.42$, $p = .005$, $\eta^2 = 0.394$, while the main effect of test type was not significant, $F(1, 16) = 0.41$, $p = .53$, $\eta^2 = 0.025$ and there was no significant interaction observed between days and test type, $F(1, 16) = 0.01$, $p = .92$, $\eta^2 = 0.001$.

Discussion

The current study aimed to examine changes in brainwaves when performing a pursuit tracking motor task induced by practice and consequent learning. To examine the intrasession and intersession changes, brainwaves were recorded while performing motor skills at the beginning and end of the first and last test days. The performance error and performance variability were evaluated as motor performance indexes. There was much improvement in initial sessions and less progress in extended training, which is predictable according to the law of practice (Schmidt & Lee, 2011, p. 347). In addition to improvement in performance accuracy, that is, decreased performance error as a result of

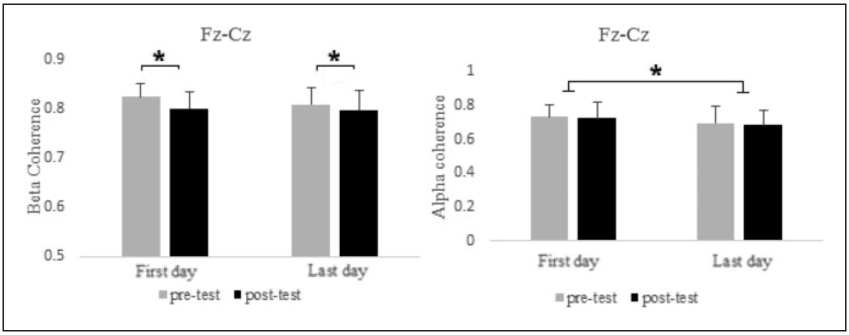

Figure 6. α and β Coherence at Fz-Cz.

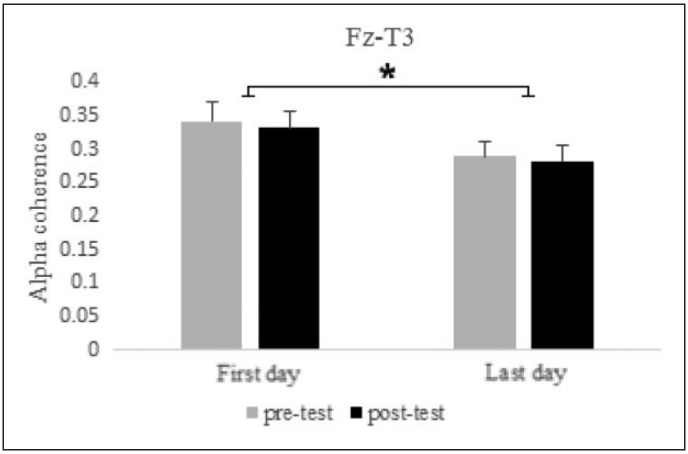

Figure 7. α Coherence at Fz-T3.

practice, performance consistency increased over time "as one of the important factors of motor learning"(Magill, 2007, p. 248). Based on the training stage, it can be concluded that participants learned the required skill. The dramatic reduction in progress in the final session and lower variability in individual performance can be associated with performance plateau. On this basis and given the lack of further variations in performance accuracy as a result of practice, it is essential to apply additional measurements such as brainwaves for more in-depth examination of training effects.

In examination of brainwaves during the practice sessions, some variations occurred at the first test day, whereas some were observed as a result of practice on the last test day. θ Power in midline frontal area (Fz) and α wave power in the central area (Cz) increased as a result of practice at the final test day compared with the first. Although such increase was also present during the first training session, it was not statistically significant. Gevins, Smith, McEvoy, and Yu (1997) suggested that frontal θ stems from anterior cingulate gyrus involved in human attentional system; θ at midline frontal area occurs during problem-solving. This frequency band is also involved in focused attention (Kropotov, 2010). Previous research on computer games by Smith et al. (1999), shooting by Haufler et al. (2000), and golf by Baumeister et al. (2008) proposed that increase in middle frontal θ power was linked with improved attention. The increase in α at Cz at the final test day compared with the first day was among the findings regarding the brain signal variations. Cz overlies the central cortical region and activity in this region is an indicator of activity in the motor cortex linked to motor activities (Deeny et al., 2003). Moreover, increased α power in this area may be associated with the degree of activity and engagement of motor cortex during training. Considering the well-established inverse relation between α power and cortical activation, this finding is consistent with an explanation of decreased effort. Accordingly, as skill level and learning are increased, there will be greater efficiency in execution of motor skills. Although a slight increase in α power was observed in T3, it was not significant, while most research studies in the field of EEG patterns have introduced this component as a crucial feature of skillful performance (Haufler et al., 2000; Kerick et al., 2001; Salazar et al., 1990). Thus, since this area is involved in verbal and cognitive processing, increase in α power is associated with less verbal and cognitive processing during motor performance. Hence, this increase is expected at this stage. However, Zhu et al. (2010) did not observe variations in this component. As most research in which an increase is observed in α power used cross-sectional designs comparing expert and beginner groups and expertise is a time-consuming process, these feature variations require longer training time (Zhu et al., 2010).

In evaluating coherence variations, intrasession and short-term reductions were observed in the lower β frequency at Fz-Cz and long-term or intersession (between first and last test days) changes in the α frequency at Fz-Cz and Fz-T3. According to some relevant literature, Fz is the nearest point to premotor cortex responsible for movements' planning, while Cz point is close to the motor cortex engaged in execution of motor skills (Deeny et al., 2003). Thus, the relationship of the central line between the two points is assumed to be very important in the planning and execution of motor skills. Lower coherence between two points was observed in both low β and α frequency bands although the β variations were intrasession, that is, it curtailed at the end of each session compared with the beginning of the course, but α changes needed more time and a significant reduction was observed at the last test day compared with the first day. The coherence reduction at this point is possibly due to increased efficiency and the reduced coactivation of the two points in planning and execution of skills as a training outcome. Serrien and Brown (2003) reported that coherence of middle line was reduced as a result of practice in β frequency band, indicating the decreasing need for motor integration and coordination. This is consistent with the study by Brown (2000) during the execution of isometric parallel contractions. The intrasession or short-term variations are in line with Zhu et al. (2010) regarding the coherence of lower β frequency band and lack of short-term variations in the α frequency band. Zhu et al. (2010) suggested that middle frequency bands, such as lower β, are sensitive to short-term variations, while lower frequency bands such as α are sensitive to long-term training. Lower coherence in central line (Fz-Cz) was interpreted as reduced need for motor integration and coordination, in line with the observed decline in α coherence between Fz-T3, referred to as lower verbal-cognitive processing in the literature. This variable is interpreted as verbal-cognitive processing efficiency because Fz, as a premotor area, is responsible for motor planning, while T3 in the left hemisphere is involved in the verbal-analytic processing. Hence, the relationship between the two points can indicate the involvement of verbal-cognitive processing in motor planning. Reduction in α coherence between Fz-T3 was observed only in intersession variations, which is insensitive to short-term variations and is associated only with long-term variations. Zhu et al. (2011) demonstrated that individuals who are more dependent on movement control through conscious processing (i.e., individuals who score higher on reinvestment scale) tend to have greater coherence in Fz-T3 when performing a motor skill. Therefore, this component can be considered an indicator of information processing efficiency that gradually occurs as a result of practice.

Lack of increase in coactivation of sensory-motor areas, especially in the first session, contrasted with some research findings (Blum et al., 2007, 2008; Zhu et al., 2010). In these studies, increased communication between different areas, particularly in motor and sensory areas, was regarded as an indicator of motor learning. Hence, as the required integration and coordination for skill performance were enhanced, the connection between different brain regions increased. The binding theory argues that coherence between different parts is enhanced through training (Blum et al., 2007). The observed inconsistencies can be explained from two perspectives. First, it seems that increase in coherence is related to the difference between resting and execution states. Andres et al. (1999) found that on a bimanual coordination task, brainwave coherence increased from the resting mode to the task mode in the α and β frequency bands, while extended training decreased the level of coherence. It seems that increased coherence is more related to the beginning of the practice and varies later as Gerloff and Andres (2002) demonstrated. Given the expected increase of coherence in the first session, such increase was not observed in the current study, possibly due to more experience at the end of the first session. Second, the coherence decline can also be explained by learning stages. In early learning stages, as participants seek the best strategy, there will generally be greater neural activation, such that both relevant and irrelevant cortical connections are activated. Performance at this stage of training is then inconsistent, as it reflects relatively unstable neural processes. With training over time, the ineffective nonfunctional connectivity decreases and performance becomes more efficient and automatic (Deeny et al., 2003). Similarly, in the current findings, reduction in coherence is accompanied by improved accuracy and lower performance variability or greater consistency. Some researchers believe that with learning there is a pruning of brain synapses (Greenough, Black, & Wallace, 1987) such that unrelated connections are pruned, and related connections are enhanced. By extending training, additional input from cognitive areas of the brain to motor planning areas decreases, which may cause interference and reduce motor output quality. Therefore, dependence on cognitive areas and involvement in cognitive processing decrease with increasing skill levels; this neurocognitive efficiency is called economy of effort (Deeny et al., 2003).

Based on current findings, changes in brain functioning may accompany increased practice, performance accuracy, and performance consistency in motor learning. In addition, after initial progress and extended practice, variations in brain processing efficiency continue, even though there may not be visible changes in individual performance. Moreover, some changes in brainwaves occur at the first training sessions, while different brainwave changes require more time. More specifically, EEG power variations are more closely associated with long-term practice, whereas EEG coherence variations are sensitive to both short-term and longer training. β Coherence is more influenced by short-term training effects, while variations in α coherence are affected by long-term training. The present findings can be considered as changes occurring in the middle stages of learning, while variations associated with elite levels of motor achievements require more extensive research. In addition, this trend can be tested with respect to other tasks with different motor and cognitive features applied to a wide variety of complex sports tasks which require longer time for achievement of performance plateau. The persistence of performance improvement and EEG changes after an interval without practice should be considered in future studies. Given that different patterns of brainwaves occur during different motor learning stages, direct EEG training methods such as neurofeedback should be addressed toward specific skill levels to enhance motor performance.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Ferdowsi university of Mashhad research committee.

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