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Which neurofeedback session is better for motor skill acquisition; before or after training?

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Abstract

This study aimed to compare the effect of two neurofeedback protocols with two different mechanisms on learning a motor task. Forty-two volunteers aged 18–22 years old were placed in three groups of pre-training, post-training, and control. In the pre-training group, Mu (8–12 Hz) amplitude was suppressed at C4 before the motor skill training, while the participants in the post-training group were instructed to increase theta (4–8 Hz) amplitude at Pz and immediately after motor skill training. After the training session, the subjects participated in retention tests at approximately 90 min, 24 h, and 1 week after training. The results showed that the pre-training group performed better in the first retention test ($p = 0.002$). Nevertheless, this superiority was not maintained in subsequent retention tests, where no difference was observed between the groups. Mu amplitude suppression before training led to more beneficial effect on learning of a new motor skill, even though it was not so effective over time. However, it appears that the inhibition of Mu amplitude in the motor cortex and subsequent higher excitability can effect motor skill acquisition.

Keywords

Pre-training and post-training neurofeedback, motor learning, memory consolidation

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1. Introduction

Several studies have been conducted to investigate the effects of neurofeedback on different aspects of human behavior. Neurofeedback (EEG biofeedback) is a process by which a person learns to control certain brain wave features such as frequency, amplitude. The foundation of this procedure is operant conditioning, where the person is enabled to control brain waves through building a connection between brain waves and feedback (Vernon, 2005). The underlying explanation for the use of this method is based on specific correlations between certain brain activity patterns and a number of behavioral and cognitive aspects. Accordingly, people can achieve optimal brain functions and optimum performance in situations where certain cortical activity patterns are active (Gruzelier, 2014). The effectiveness of neurofeedback has been studied within many clinical and non-clinical areas over recent years. For instance, neurofeedback trainings are adopted in improving motor performance, considering the extent of motor skills in different areas such as sports and rehabilitation (Gruzelier, 2014; Hammond, 2007; Landers et al., 1991).

However, most of such researches mainly focus on motor performance, and motor skill acquisition and its relationship with neurofeedback training have been paid less attention to. In addition, in most studies, the timing between motor skill acquisition and neurofeedback sessions were not considered. Nevertheless, the results of certain studies suggest that the dominance of a particular frequency band either before or after

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training sessions may be associated with learning a motor skill. For example, studies show that Mu amplitude suppression in the motor cortex area immediately before the beginning of practices increases the acquisition level of motor skills (Ros, Munneke, Parkinson, & Gruzelier, 2014). The justification for the increase in the acquisition capability lies in the motor cortex excitability because research confirms that motor learning and motor cortex excitability are correlated. Nitsche et al. (2003) examined the impact of increased excitability of the motor cortex through direct current stimulation on serial reaction time task (SRTT). The results indicated that an increase in excitability led to improved motor performance in SRTT. In addition, Boyd and Linsdell (2009) showed that as the excitability of the dorsal premotor cortex increased, the memory consolidation tracking task improved at the retention test. Ros, Munneke, Ruge, Gruzelier, and Rothwell (2010) examined the relationship between changes in brain waves and changes in cortical excitability. Participants in two groups focused on changing brain waves through a single neurofeedback session with two protocols (8–12 Hz suppression and 12–15 Hz enhancement) in motor areas. The results indicated that 8–12 Hz amplitude suppression increases the excitability of the motor cortex. With regard to the relationship between changes in brain waves and cortical excitability and the correlation between cortical excitability and motor learning, Ros et al. (2014) examined the effect of reducing Mu (8–12 Hz) amplitude at right primary motor cortex (C4) in SRTT. The participants were supposed to work on the Mu suppression in the motor cortex area through neurofeedback and immediately before practicing motor skills. The results showed no significant changes in the number of errors and improvement of reaction time during the acquisition phase, while the participants had faster acquisition rates throughout the acquisition blocks under Mu reduction, demonstrating that neurofeedback session immediately before the acquisition of motor skills can be adopted to change the pattern of brain waves and variation in skill acquisition rates (Ros et al., 2014). However, no retention test was used in this study. Thus, researchers emphasized on motor performance rather than motor learning. In addition, the SRTT was found as an indicator of motor performance, involving only reaction time and decision-making features without taking into account the main components of motor control such as movement trajectory, velocity, and acceleration.

The relationship between brain waves and learning a new motor skill does not belong only to a period before acquisition sessions, but also some findings suggest a relationship between brain waves' pattern after training sessions, that is, after learning a new motor skill and memory consolidation (Reiner, Rozengurt, & Barnea, 2014). Accordingly, when the skills are learned and practiced, the process of memory formation and consolidation continues after the initial coding during the acquisition phase which occurs through offline processes without training, known as memory consolidation (Albouy et al., 2013). In this regard, theta rhythm is one of the most common EEG frequencies in the post-training period. Some studies have revealed that theta wave plays an important role in memory formation (Chauvette, 2013; Kropotov, 2010). Reiner et al. (2014) examined the impact of post-training 4–8 Hz rhythm on learning the finger tapping task. The purpose of this task was to improve finger tapping number over time. The performance of individuals in the retention test improved through changing the theta immediately after the motor training session. Although the retention tests were used to examine memory consolidation, the motor skill in this case was self-paced. However, research suggests that theta is created more when the there is need for simultaneous use of sensory information in motion (Kropotov, 2010).

According to that the fact that there are different brain wave patterns before and after training sessions and the relation with motor learning and performance rate as well as certain methodological considerations, it seems essential to assess the effectiveness of neurofeedback protocols before and after training in learning the same motor task. The present study intended to develop an identical research plan so as to compare directly both neurofeedback methods before and after motor skill acquisition. On the other hand, the current study employed the pursuit tracking task, one of the most common tasks in the field of motor learning, to adopt the sensory information during performing the task and apply motor control features such as trajectory accuracy and force control. Finally, the retention tests were used at several time intervals to examine sustainability performance changes over time.

2. Method

Forty-two volunteers aged 18–22 participated in the study. Participants were right-handed, had no medical conditions or medications, and reported more than 6 h of regular sleep per night before and during the experiment. Informed written consent was obtained from all participants. Then, they were randomly placed in three groups of neurofeedback before acquisition, after acquisition, and control.

2.1. Motor 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

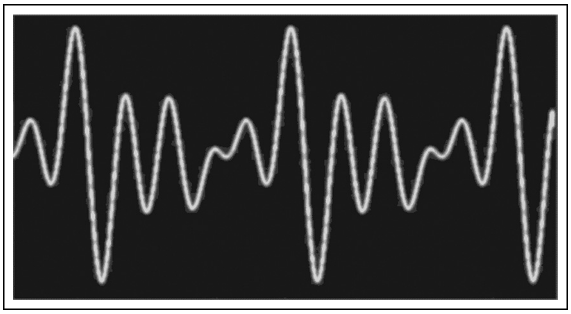

Figure 1. The task trajectory.

and the left (non-dominant) hand with the rationale that people seldom use their non-dominant hand and previous research has shown that learning improvement is greater in the non-dominant hand (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 (Figure 1) (Hill, 2014)

$$f(x) = b0 + a1sin(x) + b1\,cos(x) + a2\,sin(2x) + b2\,cos(2x) + \cdots + a5\,sin(5x) + b5\,cos(5x)$$

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). Each trial lasted 60 s. The participants practiced the task within three blocks of five trials and 1 min intervals between blocks. The motor task training in all groups lasted 20 min, as it has been demonstrated that changes in the excitability of the motor cortex were an outcome of neurofeedback training within an almost identical period.

2.2. Electroencephalography recording

In the neurofeedback sessions, a FlexComp and BioGraph (Version 5.0.3) developed by Thought Technology (TT) of Canada were adopted. 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, & Golpayegani, 2013). For collecting data, the scalp area was carefully scrubbed with NuPrep abrasive gel, followed by application of Ten20 electrode paste. A ground electrode placed on the right ear and left ear was used as the reference electrode. The baseline was recorded during a 2-min eyes open EEG recording at rest just before and after the start of neurofeedback. Prior to the quantitative analysis of brain waves, an experienced electroencephalographer evaluated the data visually. The EEG signals containing greater activity than 50 μV were eliminated, automatically. The offline artifact rejection was done after neurofeedback sessions.

2.3. Neurofeedback session

Participant was given no explicit instructions by the experimenter on how to achieve control over their EEG, but were told to be guided by the visual feedback process. In the pre-training group, the brain rhythm between 8 and 12 Hz was suppressed for 30 min at C4; this frequency was selected because of the relationship between the 8 and 12 Hz amplitude and cortical excitability. Moreover, C4 was chosen because of the use of non-dominant or left hand (Ros et al., 2010). Reward thresholds were set to be 70% of the time below the initial 8–12 Hz mean amplitude. In the post-training group, the theta frequency band (4–8 Hz) was reinforced at Pz immediately after the motor task training for 30 min. The theta rhythm was chosen because of the evidence suggesting a relationship between theta and memory consolidation after training (Reiner et al., 2014). Reward thresholds were set to be 70% of the time above the 4–8 Hz mean amplitude. Moreover, in order to encourage participants to avoid extra movements, in both two protocols, when the participants had an eye-movement or other muscle activity which caused EEG fluctuations, the reward feedback was suspended according to artifact rejection thresholds.

2.4. Procedure

At first, the demographic backgrounds of each participant were collected through a self-report questionnaire. Then, the participants were randomly divided into three groups: control, "pre-training" neurofeedback, and "post-training" neurofeedback (Figure 2). In the pre-training group, the purpose was to change brain waves through neurofeedback before the acquisition session, and then the participants immediately began to practice the motor task. In the post-training group, the participants immediately began to neurofeedback session after the motor task training. In the control group, the motor task training and time spent in the laboratory were similar to other groups, but the participants did not participate in the neurofeedback sessions. Unlike the common plan in the field of neurofeedback, this study did not adopt a sham group. Since it has been shown that using this method leads to a similar state of helplessness and frustration where the participants experience no sense of achievement and learning and cannot establish a relationship between feedback and their status, it gives rise artificially to drop in motivation and performance degradation (Reiner et al., 2014). After the first stage, the subjects participated in retention tests of the task

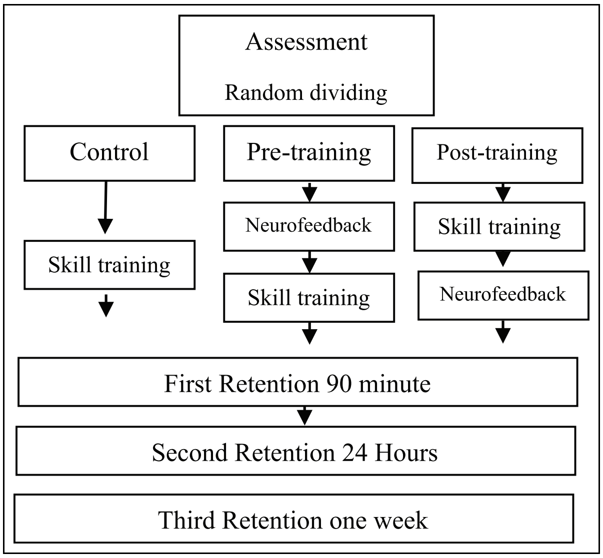

Figure 2. The procedure of experiment.

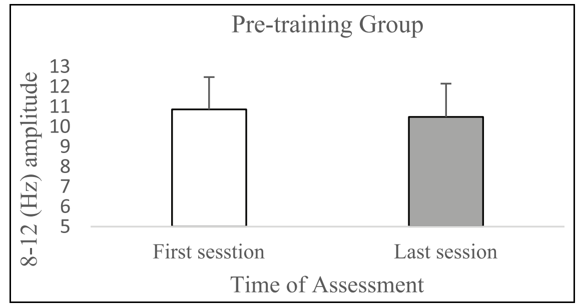

Figure 3. The Mu amplitude change (8–12 Hz) in pre-training group.

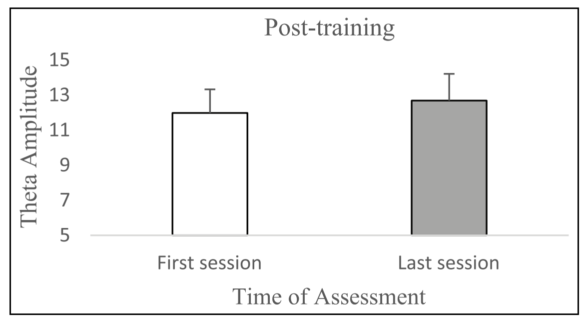

Figure 4. Theta (4–8 Hz) amplitude change in post-training group.

within 90 min, 24 h, and 1 week after the training session at around the same time of day. To evaluate the effectiveness of neurofeedback sessions in altering the brain waves, the variations in EEG were first qualitatively assessed in time intervals so as to determine the ascending or descending patterns of target frequency changes in brain waves. Then, the changes in each frequency in times before and after neurofeedback sessions were compared by t-test. In addition, the effects of performance variations during the acquisition phase were examined through the repeated measures analysis of variance (ANOVA). Moreover, the motor performances between the groups were compared through one-way ANOVA for each test.

3. Results

In order to ensure the data normality, the Shapiro–Wilk test was employed for all variables and groups in both performance and EEG data. Generally, the results indicated no statistically significant difference in the variables ($p > 0.05$). Accordingly, it can be concluded that the data are normal, and the parametric tests can be used.

3.1. Pre-training group

This group aimed to reduce the amplitude of Mu (8–12 Hz). Figure 3 illustrates the 8–12 Hz amplitude range changes before and after neurofeedback training session. The Mu amplitude declined toward the end of neurofeedback sessions. The T-test showed that the Mu amplitude (8–12 Hz) after neurofeedback training declined significantly ($t(13) = 2.53$, $p = 0.025$).

3.2. Post-training group

This group aimed to increase the theta (4–8 Hz) frequency band (Figure 4). As can be seen, the theta range enhanced toward the end of training sessions. The results of *T*-test indicated a significant increase in the theta range after neurofeedback training session ($t(13) = 3.26$, $p = 0.006$).

3.3. Motor performance

In order to ensure that there is no difference between individuals' performances, the first block of training was examined through one-way ANOVA (Figure 5). The results showed that there was no significant difference between the groups ($F_{2,\ 39} = 1.94$, $p = 0.16$, $\eta^2 = 0.09$, $\omega^2 = 0.001$). To examine the progress rate of individuals in every test, the two-way ANOVA was used, showing a significant main effect of training ($F_{3.58,\ 139.81} = 21.8$, $p = 0.0001$, $\eta^2 = 0.359$, $\omega^2 = 0.45$); however, the follow-up test results revealed that the RMSE significantly decreases, that is, a significant difference between the first block and all the training blocks ($p > 0.05$). Nevertheless, the main effect of the groups was not significant ($F_{2,\ 39} = 1.18$, $p = 0.316$, $\eta^2 = 0.06$, $\omega^2 = 0.0009$), that is, there was no statistically significant interaction between the group and test procedures ($F_{7.17,\ 139.81} = 1.92$, $p < 0.05$, $\eta^2 = 0.09$, $\omega^2 = 0.03$).

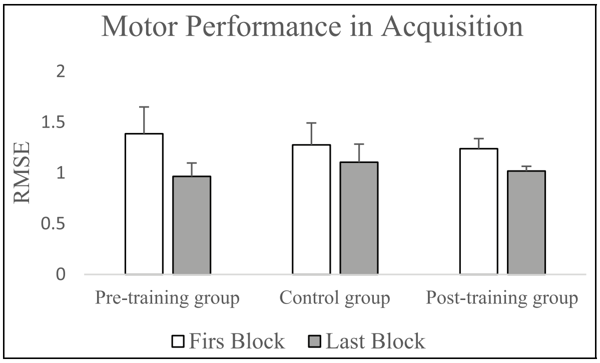

Figure 5. Performance errors changes in acquisition.

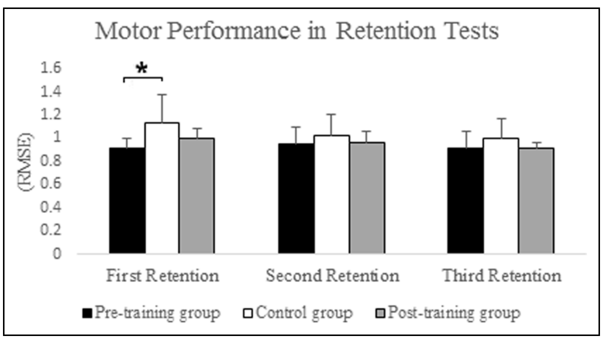

Figure 6. Performance errors changes in retention tests.

To compare the performance of groups in retention tests, one-way ANOVA was used (Figure 6). The only significant difference was observed between groups on the first retention test ($F_{2,\ 39} = 7.58$, $p = 0.002$, $\eta^2 = 0.28$, $\omega^2 = 0.06$). The Bonferroni post hoc test indicated a difference between the pre-training group and control ($p < 0.05$). In tests after 24 h ($F_{2,\ 39} = 1$, $p = 0.37$, $\eta^2 = 0.05$, $\omega^2 = 0.000004$) and 1 week later ($F_{2,\ 39} = 1.95$, $p = 0.155$, $\eta^2 = 0.09$, $\omega^2 = 0.0009$), however, the superior performance of pre-training group was not statistically significant as in the first retention test.

4. Discussion

The effect of two neurofeedback protocols was compared with two different mechanisms on learning a pursuit tracking task. In the pre-training group, Mu amplitude (8–12 Hz) suppressed at C4 before the motor skill training, while the participants in the post-training group intended to increase theta (4–8 Hz) amplitude at Pz and immediately after motor skill training. The application of two different protocols was on the basis of results obtained from previous research, indicating that the two brain rhythms within the mentioned periods were correlated with motor memory consolidation (Reiner et al., 2014; Ros et al., 2014).

4.1. The effectiveness of neurofeedback protocols in changing brain waves

The goal of neurofeedback session in the first group was to reduce the Mu (8–12 Hz) amplitude at C4 region. This was employed because of the use of the left hand during motor learning. Moreover, the 8–12 Hz was employed because of the relationship between this frequency band and the motor cortex excitability on one hand, and the relationship between cortical excitability and motor learning on the other hand. Accordingly, an increase in excitability may lead to greater motor learning rate. Previous data revealed that a decrease in the Mu (8–12 Hz) amplitude in the motor cortex area for 30 min led to higher cortical excitability (Ros et al., 2010, 2014). On the other hand, the goal of neurofeedback protocol in the second group was to increase theta at Pz. This was employed because of the relationship between the theta rhythm at this point and memory consolidation (Chauvette, 2013). In general, the results of theta and Mu frequency bands at times before and after training demonstrated the effectiveness of this training protocol in enhancing the theta and suppressing the Mu amplitude. Accordingly, this result was in line with previous studies (Reiner et al., 2014; Ros et al., 2014).

4.2. Changes in performance during acquisition

Performance in all groups during the acquisition period improved. It can be argued that motor skill training in all participants improved performance. Despite the apparent superiority of the "pre-training" group, there was no significant difference between the groups during the acquisition phase. However, better performance was expected in the pre-training group due to neurofeedback intervention since the results of some studies showed that motor performance can be improved by increasing the excitability of the motor cortex (Nitsche et al., 2003). Lack of significant difference between the groups during the acquisition phase was perhaps because of the optimal level of excitability. Assumedly, the performance would be improved through increasing the excitability of the motor cortex at an optimal level.

4.3. Retention tests

The pre-training group performed better in the first retention test. It was expected that post-training group would perform better after neurofeedback session, but after administering the resting stage and holding the first retention test, the pre-training group performed better than the other two groups. Nevertheless, this superiority was not maintained in the subsequent retention tests, where no difference was observed between the groups.

The results are inconsistent with findings of Reiner et al. (2014), where the theta enhancement neurofeedback group performed better in all the retention tests compared to other groups. The superior performance of theta group in the retention test in previous studies was interpreted via system-level memory consolidation view. Based on this view, there are two major steps in memory formation. In the first step, the neocortex areas rely on hippocampus activity, but in the second step, a memory representation is developed that is independent of the hippocampus (Nieuwenhuis & Takashima, 2011). The initial registration of memories in the hippocampus and the subsequent consolidation process is dependent synchronized theta oscillations (Chauvette, 2013). Furthermore, the non-REM *Rapid eye movement sleep* stage characterized by theta band frequency is associated with memory consolidation (Rauchs, Desgranges, Foret, & Eustache, 2005). According to Reiner et al. (2014), the memory consolidation takes place based on theta enhancement in waking hours through neurofeedback protocol; however, these conditions were not observed, and an increase in theta in the waking hour and immediately after skill training had no superiority over retention tests compared with other groups. In addition, the effect of night sleep on memory consolidation in the following days was similar in all groups. The use of different tasks as well as different research plans and groups and participants with different age ranges are some possible reasons why the results were not replicated. In addition, the memory effect in post-training group at first retention test might be hindered as an additional task (neurofeedback session).

The current findings revealed the superiority of the pre-training group in the first retention test. As noted earlier, the participants in this group suppressed Mu (8–12 Hz) amplitude at C4 before skill training session. Ros et al. (2010) showed that cortical excitability of the motor cortex can increase by reducing the 8–12 Hz frequency. Improvement through reducing this frequency band (8–12 Hz) is consistent with the results of Ros et al. (2014), indicating that as the excitability of the motor cortex increases, the motor learning improves. Accordingly, increased excitability can improve learning in two ways: online or simultaneously occurring at the session and also through changes after training and between training sessions. Therefore, the increased excitability of the motor cortex improves the learning through offline processes (Robertson, Pascual-Leone, & Miall, 2004). Several studies have elaborated that an increase in the excitability can strengthen the synaptic connections (Antal et al., 2004). Increase in performance as a result of increased excitability is via a mechanism similar to long-term potentiation (LTP) (Rosenkranz, Kacar, & Rothwell, 2007). In addition, some animal studies suggest that as the cortical excitability increase in the learning session, there are changes occurring in the synthesis of proteins directly effective on learning (Luft, Buitrago, Ringer, Dichgans, & Schulz, 2004). Moreover, based on pharmacological studies, excitability-enhancing pharmacological agents such as amphetamine improve plasticity (Bütefisch et al., 2002). Superiority of the pre-training group over other groups in the retention test might have been due to the positive effects of excitability on learning through offline processes. In this regard, Ros et al. (2014) showed that although individual performance during the acquisition of motor skills under Mu amplitude suppression condition was not significant, individuals under this condition experienced faster learning rate in the acquisition blocks. However, as noted, the present study focused merely on the acquisition phase and did not use retention tests. However, the findings revealed that the pre-training protocol can affect short-term retention time in the same day. Nevertheless, this advantage was not maintained in the subsequent days. A similar study by Reis et al. (2009) indicated that an increase in excitability of the motor cortex led to higher levels of motor learning within the training sessions but did not change the rate of forgetting across the long-term follow-up period. The type of task and the number of training sessions are among the factors which contribute to the sustainability of results over time. Since the task was continuous, there is possibly a line drawn between the discrete and continuous tasks in warm-up decrement (Catalano, 1978). Since the continuous tasks lasted longer, the decrement at initial section could have been compensated by the better performances of middle and final sections. Thus, memory differences between the groups may become neutralized in this way. Holding a single training session can also be another reason for the lack of consistency. It seems likely that long-term effects would take place in this training method through increasing the number of training sessions in future research studies. In addition, different study designs like using an additional task with same time during the post-training phase or using the different time intervals for retention tests could be considered in further studies. In general, Mu amplitude (8–12 Hz) suppression before training led to more beneficial effect than theta (4–8 Hz) enhancement after motor skill training but these two protocols emphasized on different learning mechanisms and the timing was considered as a part of protocols. The present findings can be considered as changes occurring in the early stages of learning, while consistency of result requires more extensive research. In addition, this method can be tested with respect to other tasks with different motor and cognitive features applied to a wide variety of complex tasks in sport and rehabilitation fields which require longer time.

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