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The Age-Specific Impact of Alpha-Wave Binaural Acoustic Stimulation on Motor-Learning Aptitude

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Abstract

There are some reports on the impact of binaural acoustic beat (BAB) training on motor learning. The current study aimed to explain the possible influences of alpha BAB on motor learning in young and older adult individuals. To this end, 26 male participants were assigned to four parallel groups: two alpha BAB groups (young, older adults) and two control groups (young, older adults). The alpha BAB groups received alpha BAB for 30 min, whereas examinees in the control groups just wore headphones without listening to any music over the experiment period. The digital mirror-tracing task was employed to examine the subjects' motor performance simultaneously with quantitative electroencephalography and after the intervention. In the mirror-tracing task, a significant decrease in the number of errors was found only for the older adults who received alpha BAB. Meanwhile, the reaction time decreased significantly in the young Alpha BAB group. Alpha BAB was associated with a notable increase in alpha current source density dynamics in the young subjects and enhanced beta, high beta oscillations, and gamma power in the older adults. Our findings suggest that alpha BAB might improve motor performance in older adults and young individuals through different patterns.

Keywords: motor learning; alpha binaural acoustic beats; EEG power; mirror-tracing task

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Introduction

Motor learning is essential for processing most activities in daily living. Motor aptitude is also found to be involved in social skills and professional requirements (Haar et al., 2020). Several cortical and subcortical brain areas are known to be implicated in motor learning, including the primary motor cortex (M1), the supplementary motor area (SMA), the premotor cortex (PMC), the cerebellum (C) the cingulate cortex (CC), and basal ganglia (Halsband & Lange, 2006; Hardwick et al., 2013).

There have been few studies investigating neuromodulation or any intervention to preserve or enhance motor learning capacity across the lifespan (Maceira-Elvira et al., 2020; Wang, Xiao, et al., 2021). In previous studies, objective assessments using some behavioral or motor tasks demonstrated learning capacity decline in the older adults (Frolov et al., 2020; Nieborowska et al., 2019), which could be partly attributed to the normal aging process (Iturralde & Torres-Oviedo, 2018; King et al., 2013; Roig et al., 2014).

To either improve or empower cognitive or neurobehavioral aptitude, there are three different approaches to neuromodulation including the noninvasive, minimally invasive, and invasive interventions. Minimally invasive interventional methods, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), involve surface-level interventions, minimizing the risk of complications. On the other hand, noninvasive techniques are mostly diagnostic or investigational. For instance, quantitative electroencephalography (qEEG) and functional magnetic resonance imaging (fMRI) offer a window into brain activity without physical penetration, enhancing safety but sacrificing some precision. Invasive procedures, exemplified by deep brain stimulation (DBS) and intracranial electroencephalography (iEEG), provide a more targeted and continuous modulation of neural circuits but come with increased surgical risks.

In recent years, several forms of minimally invasive brain stimulation techniques such as repetitive transcranial magnetic stimulation (rTMS; Taga et al., 2019), tDCS (Rivera-Urbina et al., 2022), and binaural acoustic beat (BAB; Ross & Lopez, 2020) have been investigated as attractive nonpharmaceutical alternatives to improve or empower motor processes in patients and healthy subjects, respectively.

BAB is a minimally invasive neuromodulation method in which the brainwaves can be altered through acoustic wave training differentially delivered to both ears. In BAB, two sinusoidal waves (tones) are presented to each ear separately with different frequencies which may range from 1 to 60 Hz (Oster, 1973; Perrott & Nelson, 1969). Objective findings have postulated that this process causes a third illusory tone in the brain with a frequency that is equivalent to the difference between the two presented tones, called BAB (Chaieb et al., 2015).

The BAB training is shown to help individuals to boost creativity (Ortiz et al., 2008), relieve stress and anxiety (Norhazman et al., 2014; Young et al., 2014), modify moods (Chaieb et al., 2015; Wahbeh et al., 2007) and even alleviate some symptoms and disorders such as tinnitus (Ibarra-Zarate et al., 2022), depression (Sung et al., 2017), and anxiety (Kraus & Porubanová, 2015) through a subjective sense of perceived calmness, self-awareness, and neurocognitive agility which have partly been investigated through objective findings in several research works (Coffey et al., 2019; Garcia-Argibay et al., 2019a, 2019b; Haar et al., 2020; Huang & Charyton, 2008; Mammarella et al., 2007; Perez et al., 2020; Tarr et al., 2014).

Alpha wave is regarded as the dominant human brainwave in resting state (Halgren et al., 2019) and is found to be related to fundamental cognitive functions (Klimesch, 2012). The alpha activity has also been demonstrated to play a central role motor performance (Ghasemian et al., 2016) and learning (Schubert et al., 2021).

While being innately generated by the brain, alpha waves can simultaneously be induced in the brain by external stimuli such as BAB (Gao et al., 2014).

Some earlier reports have highlighted the effects of alpha BAB in clinical populations and healthy individuals (Beauchene et al., 2017; Goodin et al., 2012). The effect of BAB on enhancing memory function through increased alpha waves has been studied in older individuals with neurocognitive disorders such as Alzheimer's (Calomeni et al., 2017) and Parkinson's disease (Gálvez et al., 2018) and also in healthy subjects (Benwell et al., 2019). However, to our best knowledge, the possible effects of BAB on motor learning and motor task performance and its possible efficacy in remediating age-related decline in motor function have not been systematically examined yet. Therefore, the purpose of the current study was to investigate the possible effects of alpha BAB on motor learning and motor performance in younger and older populations using a motor task and concurrent qEEG recording. Considering the inconclusive evidence on the research question and the empirical nature of the present work, we hypothesized that alpha BAB might improve motor learning and ideomotor performance in our studied young and older adult populations as compared to the control peers who did not receive the BAB intervention.

Materials and Methods

Participants

Twenty-six right-handed participants including 12 older males with an age range of 55–70 years (mean age = 62 ± 5/64) and 14 young males with an age range of 20–30 years (mean age = 24 ± 2/51) were randomly assigned to four parallel groups. There were two experimental groups (young, older adults) and two control groups (young, older adults) in this double-blinded, controlled randomized study. The experimental groups (i.e., alpha BAB treated), received alpha wave BAB as described in an earlier report (Garcia-Argibay et al., 2019b). The control groups received no intervention during the study session while wearing the headphone.

All participants were examined by a medical neuroscientist for mental disorders, learning disabilities, hearing problems, or difficulty performing new motor tasks and they were confirmed to be in proper neurocognitive health status.

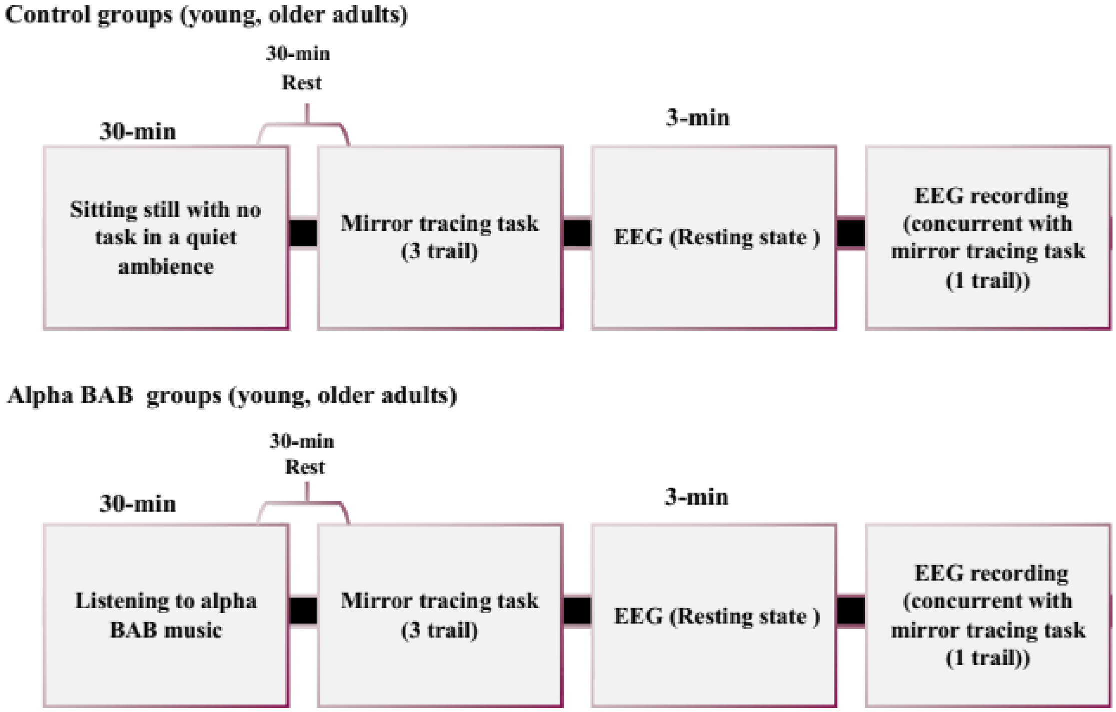
The study was approved by the Ethics Committee of the Shiraz University of Medical Science (Institutional review board approval code: 26819). All participants read and signed the informed consent for the research procedure. The entire procedure was done at the Neuroscience Laboratory (Brain, Cognition and Behavior Unit) at the School of Advanced Medical Sciences and Technologies, SUMS.

Participants were asked not to exercise, smoke, or use alcohol or medications 24 hours before the test.

Study Design

In a quiet room, the participants sat on a comfortable chair located 80–100 cm away from the computer screen. They were required to be relaxed and minimize their movement as much as possible. Before the experiment, the volume gain of alpha BAB was set at 60% by the participants through the headphones (MDR-XB450AP). The alpha BAB groups (young and older adults) were instructed to relax and listen carefully to the alpha BAB through headphones for 30 min. The control groups placed headphones on their heads for the same time without alpha BAB. The participants were asked to keep their eyes closed during the experiment. All participants (alpha BAB, control) rested for 30 min. After that, they performed mirror-tracing tasks three times. A 3-min eyes-open resting-state EEG was recorded. After that, the mirror-tracing task was performed for the fourth time. Figure 1 demonstrates the study protocol.

Figure 1. *The Study Procedures for the Alpha BAB and Control Groups (Young and Older Adults)*.



Note. The alpha BAB groups (young and older adults) received alpha BAB for 30 min. After a 30-min rest, the mirror-tracing task (three trials) was performed. Then, resting-state EEG was recorded for 3 min. Later, the mirror-tracing task (one trial) was performed simultaneously with EEG recording. The control groups (young and older adults) just wore headphones without listening to any sound while their other experiments were identical to the alpha BAB groups.

Motor Learning Assessment (Mirror-Tracing Task)

The digital mirror-tracing task was used to evaluate motor learning through visual-motor interaction (Desmottes et al., 2017). All subjects performed the mirror-tracing task (RT - 912 – T, Sina Psychology, Tehran, Iran). In this task, subjects were asked to move a stylus with their right hand to trace the brass star while they were allowed to look only at the reflection of their right hand in a mirror (Gabrieli et al., 1993). A digital timer and error recorder were attached to the metal stylus for recording both the task time and the number of errors. When the stylus came out of the star and touched the star borders it complemented an electrical circuit and an error was recorded. The star track was 6 mm wide. This task was performed four times, and the number of errors and task time were recorded as an index for assessing motor learning aptitude.

Alpha BAB Stimulation

To induce an alpha binaural beat at a frequency of 10 Hz, a tone of 220 Hz was presented to one ear and a tone of 230 Hz was presented to the other ear in accordance with Kraus and Probanova's protocol (Kraus & Porubanová, 2015).

In this regard, the Alpha frequency was produced by Audacity software (version 2.2) and Adobe Audition CC (version 2017).

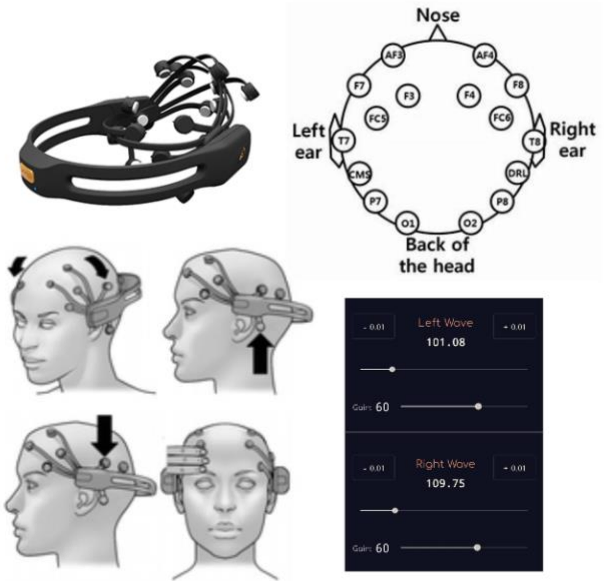
EEG Recording

Several methods can be used to measure motor learning and control, one of which is electroencephalography (EEG), also known as the neural technique (Beik et al., 2020). In fact, EEG is a good tool to analyze neural correlates for both simple and complex movements in humans (Bradford et al., 2016; Pfurtscheller et al., 2003).

The EEG data were recorded using the Epoc+ EEG headset (Emotiv, USA) which included 16 wet saline electrodes and two reference electrodes, providing 14 EEG channels. According to the international 10-20 system, a total of 14 electrodes were placed on the skin surface in the following locations (Yu & Sim, 2016): AF3, F3, F7, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 to record the five well-known frequency bands, namely theta (4–8 Hz) alpha (8–12 Hz), low beta (12–16 Hz), high beta (16–25 Hz) and gamma (25–45 Hz; see Figure 2).

In this study, reference electrodes (CMS/DRL) were placed on P3 and P4. The quality of the EEG signal was checked using the Test Bench software. The collected raw data were processed offline using NeuroGuide software (v. 3.0.2 2001-2018 Applied Neuroscience Inc. USA). Artifacts such as eye movements, motion or muscle artifacts were detected and removed by an EEG expert. Based on the NeuroGuide qEEG normative database, fast Fourier transform (FFT) was used to compute the absolute power.

Figure 2. *Emotive Headset Sensors Placement and Fitting (Left Panel), 16 Channel qEEG Montage and Alpha BAB (8.67 Hz), 60% Gain Setup (Right Panel).*



Left Wave 101.08
Gain: 60
Right Wave 109.75
Gain: 60

Statistical Analysis

All statistical tests were performed with GraphPad Prism (GraphPad Software Inc., San Diego, CA, USA) and the SPSS statistical package (Version 26.0.0, Copyright IBM, 2018). Descriptive statistics were computed for each group. The Kolmogorov-Smirnov test was used to investigate the normal distribution of data. To analyze the differences between control groups (young and older adults) and alpha BAB groups (young and older adults), a series of independent sample *t*-tests were run for the data with normal distribution and homogeneity of variance.

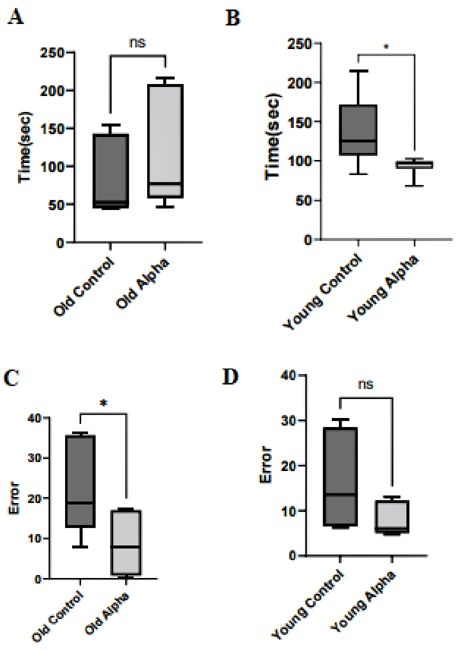
The differences between alpha BAB groups (young and older adults) and control groups (young and older adults) were evaluated by calculating the mean ± the standard error of the mean, for several parameters, including the number of errors and task time in the mirror-tracing task. An independent sample *t*-test was conducted to compare qEEG data in alpha BAB groups (young, older adults) and control groups (young, older adults); $p < .05$ was considered statistically significant.

Results

Motor Learning Assessment (Mirror-Tracing Task)

The results in the control and alpha BAB groups of older adult individuals showed no significant difference in the task time (*p* = .407; Figure 3, A) while there was a statistically significant difference in the task time between the young individuals in the control and alpha BAB (*p* = .015) groups (Figure 3, B). There was a significant difference between both groups in older adult individuals in the number of errors (*p* = .042; Figure 3, C) but there was no significant difference in terms of the number of errors in young individuals between the control and alpha BAB groups (*p* = .06; Figure 3, D).

Figure 3. *Box Plots Illustrate the Average of Each Task Time and the Number of Errors in the Mirror-Tracing Task in the Control Groups (Young, Older Adults) and the Alpha BAB Groups (Young, Older Adults)*.



Note. Panel A shows no significant difference in task time between the control and alpha BAB groups of the older adult participants (*p* > .05). Panel B demonstrates the difference in task time between the control and alpha BAB groups of young individuals (*p* < .05). Panel C indicates the difference in the number of errors between the control and alpha BAB groups in the older adult participants (*p* < .05). Panel D displays no significant difference in the number of errors between the young control and alpha BAB groups (*p* > .05).

* significant difference between the groups *p* < .05
^{ns} nonsignificant difference between the groups *p* > .05

EEG Absolute Power

The results revealed a statistically significant difference in the absolute power between the older adults control group and the older adults alpha BAB group (Figure 4, A). Electrical neural imaging data in the older adult subjects who received and did not receive alpha BAB confirmed the special and spectral distribution of beta and high beta in bilateral frontocentral cortical regions while this has been localized in the left frontocentral cortical zone for the gamma frequency band. However, in the young groups, our result showed a statistically significant difference in the absolute power of theta, alpha and beta frequency bands (*p* < .01) (Figure 4, B).

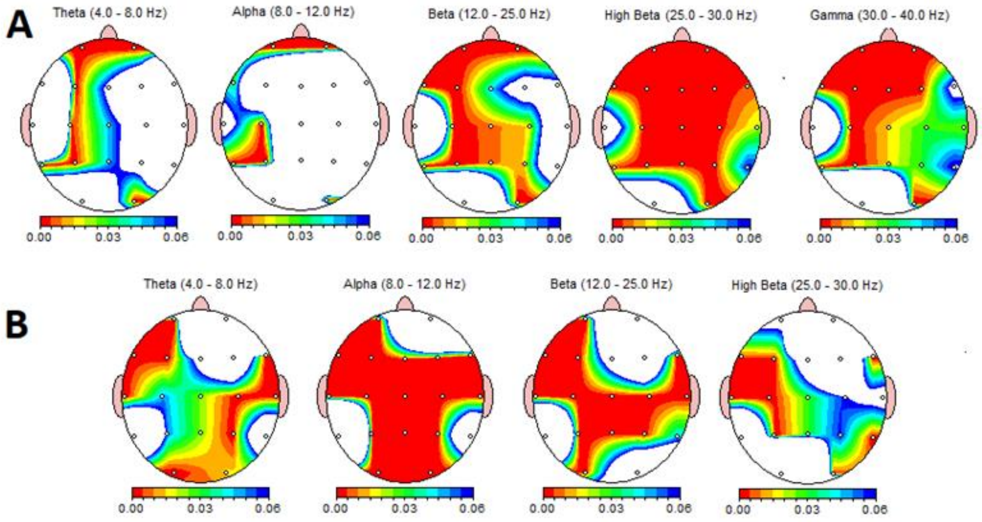
Discussion

The effect of alpha BAB on the distribution and amplitude of the alpha frequency band in the premotor and motor cortex as well as its impact on the process of motor learning has not been systematically evaluated so far. Our study was an attempt to investigate the possible impacts of alpha BAB on the neural dynamics of alpha oscillation within the motor cortices and motor performance in both older and young individuals. Our results demonstrated that the older adult subjects who received alpha BAB had a significantly lower number of errors upon performing mirror-tracing tasks compared to their age-matched control group. Meanwhile, the task performance time by older adult subjects did not differ between the alpha BAB group and the control group.

On the other hand, our study investigated the impact of alpha BAB and motor performance amongst young individuals. Although no significant difference was observed between the young group receiving alpha BAB and their controls in the number of errors in the mirror-tracing task, the intervention resulted in a notable or statistically significant difference concerning task performance time in young individuals. In other words, it took less time for the young individuals who received alpha BAB to perform the mirror-tracing task as compared to the young individuals who did not receive alpha BAB.

Regarding the effect of Alpha BAB on the number of errors in the mirror tracing between the age groups, a reduced number of errors in both older and young individuals receiving Alpha BAB compared to their age-match control suggests a potential positive effect of Alpha BAB training on motor learning; however, the reduction was just statistically significant in the older adult group.

Figure 4. *QEEG Topographical Spectral Brain Maps.*



Note. FFT absolute power independent *t*-test (*p*-value) results across spectra during motor learning tasks in older adult groups (A; control and alpha BAB) and young groups (B; control and alpha BAB). Colors indicate the significance level.

Features including time and precision, are the two main indicators that define motor aptitude (Shekar et al., 2018).

Our motor learning results were in line with the findings that we observed in concurrent EEG recording during mirror-tracing task administration. According to our EEG results, despite its high beta and theta oscillation performance, alpha BAB caused a significant gain in alpha dynamics in young people. The spectral distribution of alpha and low beta bands in frontocentral cortical hubs is consistent with an improved motor sequential planning, which has already been observed in the alpha BAB-treated young subjects. Yet, this has not been the case for theta and high beta frequency bands. A denser EEG array and further statistical analysis on different features and parameters across frequency spectra may shed further light on the possible involvement of cortical, and subcortical neural structures, which justify and improve motor performance speed, which was observed in young individuals who received alpha BAB.

Alpha BAB in the older adult subjects resulted in an enhanced current source density at beta, high beta oscillations, and bilateral frontocentral derivation. Interestingly, the increased gamma power has been localized in the left frontocentral cortical region, which is responsible for right-hand dexterity.

Our brain mapping results demonstrated an increased current source density in frontocentral derivations in young individuals who received alpha BAB. Meanwhile, this has not been the case in the frontopolar and occipital parietal areas. Given the fact that inferior frontal and frontocentral derivations are the cortical areas corresponding to supplementary and association motor cortices, enhanced alpha BAB in those areas (supplementary motor area [SMA] and cingulate motor area [CMA]) are proposed to result in improved motor sequential planning.

One of the main key parameters which correlate with motor sequential planning is the time to perform a motor task (Shekar et al., 2018). Mirror-tracing test is a task that requires both attention and performance speed (Woodard & Fairbrother, 2020).

Alpha BAB was found to improve the performance speed. Given the improved performance speed, it might be expected that motor sequential planning is positively affected and that in turn corresponds to an increased current source density gain (CSD) in supplementary SMA and CMA cortical/subcortical structures. The reason why alpha BAB has resulted in the CSD and a special distribution of not only beta and high beta but even faster frequencies, including gamma in bilateral frontocentral and left frontocentral cortical regions, respectively, has not been up to our expectations. We were expecting to observe enhanced alpha dynamics upon alpha BAB either in both young and older adult subjects. Nonetheless, while we observed an improved distribution of alpha in frontocentral and bilateral inferior frontal cortical areas, this has not been the case for the alpha frequency band in the older adult group. Instead, we have observed a significant increase in the neural dynamics of higher frequency bands, including beta, high beta, and gamma, which corresponds to motor aptitude.

Elder individuals completed the mirror-tracing task with fewer errors following alpha BAB, which suggests better motor aptitude; this is partly related to the function of the primary motor cortex rather than supplementary motor areas. Taking these findings together, it might be speculated that alpha BAB might at least partly impact the dynamics of the neural oscillations and the motor performance outcome amongst the people who were submitted to the mirror-tracing task. Interestingly, the time to perform the mirror-tracing task was mostly affected by alpha BAB in young individuals, whereas no change in the task performance time was observed in older adult subjects after alpha BAB intervention.

The significance of maintenance and improvement of motor learning and related motor aptitude is emphasized in specific populations whose daily life or job-related responsibilities involve motor skills (Haar et al., 2020). Motor skill is normally considered a dynamic change that occurs throughout life by motor learning (Hadders-Algra, 2010) based on neuroplasticity (Dayan & Cohen, 2011) and rewiring within the neural networks (Askim et al., 2009; Wang, Fan, et al., 2013) that control the speed, precision, and aptitude of motor performance (Kitago & Krakauer, 2013).

Earlier studies have indicated that motor learning and planning might get impaired as we age (Frolov et al., 2020; Grose & Mamo, 2012; Nieborowska et al., 2019; Solcà et al., 2016) which might be at least partly due to the possible impairments of neuroplasticity and neurodynamic changes over time (Park & Bischof, 2013; Seidler et al., 2010). The previously published body of scientific evidence suggests that the motor learning impairment or decrease in the learning capacity of motor skills in older adult individuals who have not been trained for motor skills over time might be due to neurodegenerative changes. (Gale et al., 2018; Newson & Kemps, 2005; Wang, Zhang, et al., 2019; Wenk et al., 1989). Previous studies have shown that essential tremors can decline motor learning in older adults (Bermejo-Pareja et al., 2007; Collins et al., 2017; Raethjen et al., 2007). In addition, loss of skeletal muscle and decline in physical activity contribute to impaired motor learning in older adult subjects (Clark, 2019; Hunter et al., 2016). Several studies have reported that the motor performance of older individuals declines more pronouncedly as their task difficulty increases (Bangert et al., 2010; Smith et al., 1999)

Neural entrainment and synchronization of the specific type of neural oscillation within the distinct frequency band in premotor and motor areas has been a central indicator in the process of motor learning (Buzsáki & Draguhn, 2004; Schnitzler & Gross, 2005; Varela et al., 2001). To enhance the capacity of the special and spectral distribution of alpha band in the specific premotor and motor areas, one hypothesis has been the application of neural entrainment through the use of the BAB (Solcà et al., 2016). Some studies have employed BAB as a neural modulatory approach to enhance the special distribution of a distinct frequency and amplitude or power of that frequency within functional cortical hubs (Draganova et al., 2008; Grose & Mamo, 2012; Pratt et al., 2009, 2010), which involves motor performance that might in some way retain implications for a specific indistinct population of individuals who need to employ even more precise, sophisticated, and fine motor skills, including professional athletes (Ross & Lopez, 2020).

The use of alpha BAB has been tested in some studies (Ecsy et al., 2017; Munro & Searchfield, 2019; Shekar et al., 2018). The present report generally suggests that alpha entrainment might partly help remediation of the neural dynamics which correspond to sequential motor planning and motor aptitude in young and older adult populations, respectively. As such, according to our findings, using the alpha BAB could at least be considered as an auxiliary neuromodulation approach to empower motor skills in people who require further motor learning.

The extension of this line of research, together with our findings, might have implications for those who are involved with critical motor responsibilities in their jobs and personal life. Those might include people who need to have maximal precision, reaction time, performance speed, motor learning and the responsibilities they are involved in. Examples might be surgeons, professional athletes, industrial workers who deal with sophisticated machinery, defense personnel, artists, or other creative people.

Conclusion

The present report suggests that alpha entrainment may partly help young and older adult populations improve their neural dynamics which correspond to sequential motor planning and motor aptitude. Considering the effect of the alpha BAB on motor learning, the intervention might enhance motor skills in people who require further motor learning.

Further research needs to be pursued to extend other imaging or neuromodulation modalities further to what we examined here. The idea whether concurrent use of BAB and minimally invasive brain stimulation, including TMS, tDCS, and more specifically, tACS (transcriptional alternating current stimulation) might presumably add value to the level of motor learning in terms of precision, processing speed, reaction time, and performance speed needs further evaluation.

Author Declarations

Authors confirm that they have thoroughly read and approved the manuscript in question. We have ensured that there are no issues or conflicts that could impede the publication process. Furthermore, authors affirm that the outcome of this work has not been influenced by any internal or external factors, including financial considerations.

In addition, authors have diligently reviewed and adhered to all intellectual property guidelines and regulations. The authors followed the ethical principles and guidelines for research and publication with utmost care and diligence.

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