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The effect of transcranial alternating current stimulation over the supplementary motor area on bimanual coordination in elderly people

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Abstract

Background: Transcranial alternating current stimulation (tACS) is a non-invasive method that offers a potential solution to reduce the effects of aging on brain function.

Aim: The aim of this study was to investigate the effect of offline tACS over the supplementary motor area on bimanual coordination in elderly people.

Materials and Methods: Thirty-one women aged of 60-75 years were selected as convenience. They were assigned to 2 conditions: tACS and Sham, in random order, with one-week interval between conditions. After pre-test, each participant completed four trials of 5 min using Purdue pegboard task. Concurrently, participants received beta tACS with a current intensity of 1 mA. Immediate retention test, transfer test, and delayed retention tests after 48 hours and 1 week were conducted. A 2(condition) x 4(test) ANOVA with repeated measures was performed on gain scores.

Results: The main effects of condition and test were significant ($P<0.0001$). The Bonferroni tests revealed the significant improvement of bimanual coordination in the tACS condition compared to the sham condition in all retention and transfer tests ($P<0.05$).

Conclusion: The findings highlights the potential use of offline beta tACS over the SMA as a modulatory factor for enhancing bimanual coordination in the elderly women.

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1. Introduction

The significance of the increase in the elderly population has become thoroughly apparent [1]. The global aging population has emerged as a paramount medical and social concern on a global scale [2]. According to the World Health Organization (WHO) report, the number of individuals aged 60 years and above reached 1 billion in 2019, accounting for 13% of the world's population. Furthermore, projections indicate that this figure will escalate to 2.1 billion by 2050 [3]. The increase in the elderly population can be attributed to declining birth rates, improvements in healthcare and living conditions, as well as increased life expectancy. However, this demographic shift also poses economic challenges for societies, necessitating the need for proactive measures to address their needs [4]. Aging represents a significant biological phenomenon characterized by a progressive decline in tissue function and an increased susceptibility to age-related diseases [5]. This process of aging entails the gradual deterioration of the nervous and muscular systems [6]. Such changes have implications for various brain functions, including memory, cognitive performance, and motor control [7].

One noticeable effect of aging is the decline in motor performance, attributed to alterations in the nervous system and musculoskeletal system. This decline manifests as reduced coordination, diminished movement accuracy, and slowed motor responses [8]. The deterioration of the neuromuscular system caused by aging can significantly effect daily activities that require bimanual coordination, resulting in reduced accuracy [9]. Elderly individuals may experience challenges in performing various coordinated tasks due to this decline [6]. The decline in coordination skills among older adults not only diminishes the accuracy and fluency of their movements, but also increases the likelihood of errors during activities that require bimanual coordination [10]. As a consequence, elderly individuals may face difficulties in engaging in these activities [11]. Considering that the quality of life for older adults is greatly dependent on their ability to perform coordinated activities, particularly bimanual coordination, such as dressing, tying shoelaces, lifting and carrying objects, eating, or even typing emails, recognizing the importance of bimanual movements for their well-being is crucial [12].

Given the alterations that occur during older adulthood, it is crucial to develop safe and cost-effective interventions to counteract these changes. Non-invasive brain stimulation techniques have emerged as a promising avenue for inducing neural activity and promoting neuroplasticity. One such technique that has garnered considerable attention is transcranial alternating current stimulation (tACS), which allows for the modulation of brain oscillations in specific regions of the cerebral cortex [13, 14]. The tACS as a non-invasive brain stimulation method, facilitates changes in neural activity and promote neuroplasticity in healthy people [15], and offers a potential solution for mitigating the effects of aging on brain function. This type of stimulation involves the application of alternating current to two electrodes placed on the participant's head, allowing for the modulation of brain oscillations at specific frequencies [14]. Transcranial alternating current stimulation, a bidirectional flow of current, can exert its effects on cortical excitability across multiple cortical areas. This broad effect facilitates cortical excitability, enabling neural inputs to propagate widely to areas beyond the primary motor cortex [16]. Previous studies have predominantly focused on the effects of transcranial electrical stimulation on the primary motor cortex (M1) rather than other regions within the motor cortex [17].

Most of the research in the field of transcranial electrical stimulation (tES) has predominantly focused on transcranial direct current stimulation (tDCS), while neglecting the other techniques, such as tACS [18]. tDCS and tACS have different mechanisms of action. tDCS applies constant current flow between anodal and cathodal electrodes, but tACS uses the current that switches polarity over time with a sinusoidal wave at a specific frequency [19]. Studies have demonstrated that tDCS applied to the primary motor cortex can induce sustained changes in cortical activity, which in turn can affect subcortical neurons and their connections to cortical areas [20]. However, considering the interconnectedness of the brain, it is possible that stimulating other cortical regions, such as the supplementary motor area (SMA), may yield different outcomes in terms of motor skill learning. This study aims to explore and discuss these potential differences. Functional magnetic resonance imaging (fMRI) studies have demonstrated that the SMA shows increased activity during sequential and continuous bimanual movements compared to single-handed movements, emphasizing its critical role in such tasks [21].

There are three lines of evidence supporting the involvement of the SMA in voluntary bilateral movements. First, the SMA plays a crucial role in the planning and execution of rhythmic bilateral movements involving the upper and lower limbs [22]. Its activation is associated with the coordination and synchronization of movements between both sides of the body. Secondly, the SMA acts as a key inhibitor, preventing the execution of inappropriate motor plans and facilitating the selection of appropriate motor plans based on feedback [23]. It contributes to the adjustment and refinement of motor plans during the execution of bimanual tasks. Thirdly, the SMA is essential for timing and the generation of rhythm in movements [24]. It plays a critical role in the precise temporal coordination and production of rhythmic movements. Taken together, these findings highlight the significant involvement of the SMA in the planning, execution, inhibition, adjustment, and timing of bimanual movements, underscoring its importance in the context of this study. Miyaguchi and colleagues (2020) investigated the tACS of SMA at frequencies of β-tACS (20 Hz) and γ-tACS (80 Hz) in healthy young participants. The researchers reported that as β-tACS was positively and γ-tACS was negatively correlated with motor performance. They concluded that because the neural activities in the SMA are associated with continuous and sequential bimanual movements, tACS modulates bimanual movements [25]. Miyaguchi et al. (2022) found the γ-tACS of the cerebellum relative to SMA was more effective on bimanual movements in healthy young adults [26]. However, there is a lack of research specifically exploring the effect of tACS on bimanual tasks in elderly people. By addressing this research gap, we aim to gain insights into the effect of tACS on bimanual coordination and explore the persistence of its effects over time in the older adults. Therefore, the purpose of this study was to investigate the effects of beta tACS over SMA on immediate and delayed retention and transfer of bimanual coordination in elderly women. By addressing this research gap, we aim to gain insights into the impact of tACS on bimanual coordination in elderly people.

2. Materials and Methods

2. 1. Participation

In this quasi-experimental study, a sample of 34 healthy elderly females, aged between 60 and 75 years (M= 65.26; SD= 4.01) were recruited. The inclusion criteria required participants to have a normal or corrected-to-normal vision and no history of neurological or psychological disorders. The inclusion criteria required participants to have normal or corrected-to-normal vision and no history of neurological or psychological disorders. None of the participants had prior experience with tACS. The dominance of their hand was assessed using the Edinburgh Handedness Inventory scale, and the laterality index (LI) indicated a strong right-hand lateralization, with an average LI of 89.98 (SD= 13.23) out of a maximum LI of 100. Before the experiment, all participants received comprehensive information about the study and provided written informed consent. The study protocol received approval from the local ethics committee at Ferdowsi University of Mashhad. Three participants were excluded from the analysis due to technical errors in data acquisition and fear of stimulation, resulting in a final sample size of 31 participants for the study.

All the participants filled out consent forms, Montreal cognitive assessment (MoCA) [27] along with Edinburgh Handedness Inventory (EHI) [28].

2. 2. Instrument

Brain Electrical Stimulator. In this study, 2-channel brain electrical stimulator (NeuroStim2) made by “Medina Teb” company in Iran was used for actual and sham stimulation of SMA. In the actual stimulation protocol, tACS was administered using two square rubber electrodes measuring 5 cm × 5 cm. These electrodes were covered with a sponge soaked in a saline solution, and a weak intensity of 1 mA at 20 Hz (peak- to- peak current) was applied. The waveform used was sinusoidal, and each trial lasted for a total of 5 min. Prior to placing the electrodes, the skin surface was prepared by applying a high-chloride abrasive electrolyte gel to reduce skin impedance. One of the electrodes, referred to as the active electrode, was positioned on the participants' supplementary motor areas (SMAs), while the other electrode was placed on their left shoulders. The SMA electrode on the participant's scalp was positioned 3.0 cm anterior to the central midline sagittal zone, following the International 10–20 system of Electrode Placement [25, 26, 29]. To eliminate the influence of cortical areas other than the supplementary motor area (SMA) and minimize potential side effects like phosphene [30], the reference electrodes were positioned over the deltoid muscles of the participants' left shoulders. Throughout the stimulation, each participant underwent four trials, with a 2-minute break between each trial.

For the sham stimulation protocol, a specific procedure was followed to effectively blind the participants to the actual stimulation protocol. The current was gradually increased over a 30-second period at a frequency of 20 Hz, then maintained at 1 mA for 10 sec, and finally, gradually decreased over another 30 sec at 20 Hz.

Applying high-intensity tACS has been known to potentially induce neurosensory side effects, including phenomena like phosphenes, pricking sensations, burning sensations, headaches, and dizziness, during the stimulation period [31]. To evaluate these neurosensory side effects, participants were asked to complete a blinded questionnaire before and after the tACS session. The questionnaire assessed their perceived levels of attention, fatigue, and pain, utilizing a self-scored scale ranging from 1 to 7. In this scale, a score of 1 represented minimum attention, maximum fatigue, and maximum pain, while a score of 7 indicated maximum attention, minimum fatigue, and minimum pain [31].

Purdue Pegboard Test (PPT). To evaluate bimanual coordination performance, participants were instructed to complete the Purdue Pegboard Test (PPT). The PPT comprised four subtests that involved a two-handed assembly task. This task required the participants to assemble four components: a pin, a collar, and two washers. Seated comfortably in chairs, participants positioned themselves in front of the Purdue Pegboard, which was placed on a table. The row of cups on the board was positioned at the top, and participants positioned their hands on either side of the pegboard. The task began with the participants using their right hand to insert a pin into a hole, followed by covering the pin with a washer using their left hand. Subsequently, the collar was threaded through the top of the pin using their right hand, and finally, a washer was placed over the collar using their left hand to assemble one unit. Participants were instructed to complete the assembly task as quickly as possible, starting and ending their tasks according to cues provided. They were given a total of 5 min to complete the test, and the total score was determined by the number of correctly assembled units at the end of the trial.

2. 3. Procedure

In the present study, a within-group research design was used. The participants were placed in two conditions of tACS and sham. Each condition was performed in one session with at least one-week interval between sessions. Order effect was controlled by randomization. Thus, half of the participants were trained and assessed under tACS condition in the first session and sham condition in the second session, and the other half were trained and assessed under sham condition in the first session and tACS condition in the second session.

First, the SMA region of each participant was determined and the two electrodes were attached as previously discussed. At the beginning of the first session, participants completed all forms and received a standardized instruction along demonstration of the required bimanual coordination task. To familiarize participants with the equipment and the bimanual coordination task, two practice trials followed. The acquisition phase included four trials of the Purdue Pegboard Test which lasted 20 min, with 2-minute intervals between each. Concurrent with this training, participants received either 20 Hz beta band tACS or sham stimulation. Before tACS and at three time-points after tACS (immediately, 48 hr, 1 week), participants performed retention tests; also to evaluate adaptability, the participants were asked to perform transfer test after immediate retention test. Figure 1 shows the quasi-experimental design used in the study.

2. 4. Statistics

The statistical analyses were conducted using IBM SPSS 26. The normality and homogeneity assumptions were assessed using the Shapiro-Wilk and Levene's tests, respectively. The paired t test was used to compare the means of bimanual coordination scores in pretests of tACs and sham conditions. A 2 (condition) * 4 (test) ANOVA with repeated measures was conducted to analyze the scores of bimanual coordination. Post hoc analyses were conducted using the Bonferroni test to identify significant differences in bimanual coordination performance between conditions and tests, if significant effects were found. The significance level of all analyses was set at $P < 0.05$.

3. Results

Figure 2 displays the mean and standard deviation (SD) of bimanual coordination parameters for both the experimental and sham conditions across various tests: pre-test, immediate retention test, delayed retention tests (after 48 hours and 1 week), and transfer test. The results of the Shapiro-Wilk test confirmed that the normality assumption was met ($P > 0.05$).

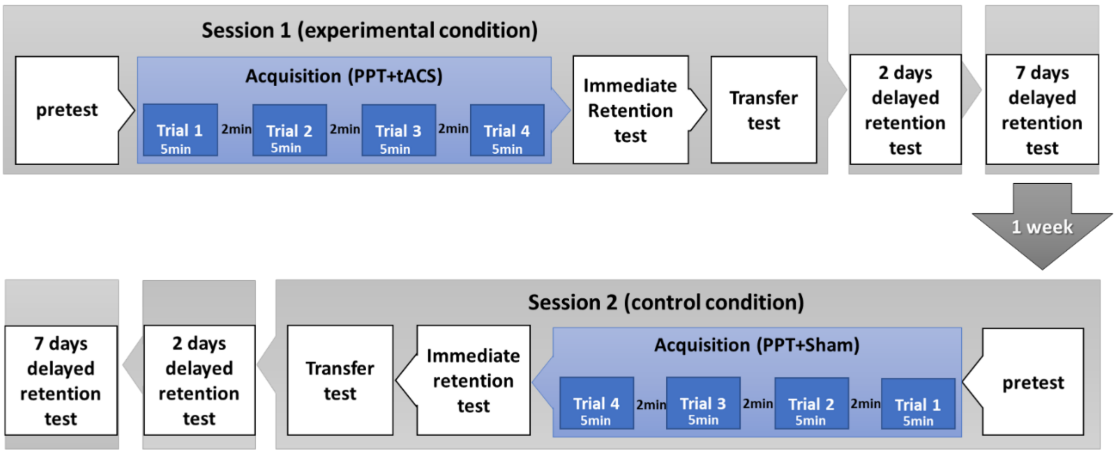

Figure 1. The within-group design

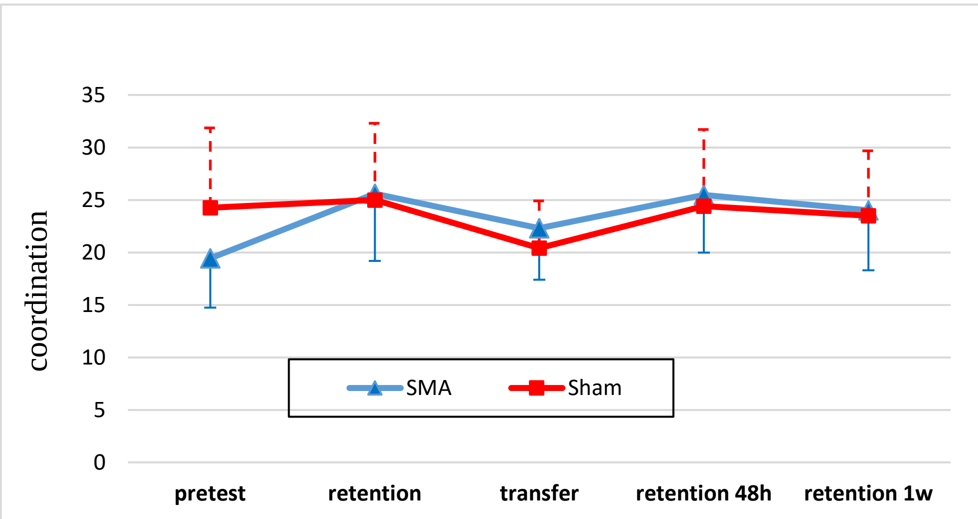

Figure 2. Mean and standard deviation of bimanual coordination of tACS and sham conditions in various tests

The paired t-test results revealed a significant difference between the means of bimanual coordination scores in pretests of tACS and Sham conditions (t(26)= -3.68, *P*= 0.001). Therefore, 2 (condition) * 4 (test) ANOVA with repeated measures was conducted for the difference scores between the pretests and post-tests. Mauchly's test confirmed the assumption of sphericity for the main effect of test ($\chi^2(5)$= 6.615, *P*= 0.251) and the interaction between condition and test ($\chi^2(5)$ = 6.576, *P*= 0.254). The results indicated that the main effects of condition ($F_{(1, 26)}$ = 44.328, *P*< 0.0001, η^2 = 0.63) and test (F(3, 78) = 17.173, *P*< 0.0001, η^2 = 0.398) were significant, but the interaction between condition and test ($F_{(3,78)}$= 0.826, *P* 0.484, η^2 = 0.031) were not statistically significant.

Pairwise comparisons (Table 1) revealed that in tACS condition, the bimanual coordination changes in the transfer test were significantly lower compared to the retention tests. In the sham condition, the bimanual coordination changes in the transfer test were negative and significantly lower than retention tests and bimanual coordination changes in immediate retention test were significantly higher than one-week delayed retention test. When comparing the tACS and sham conditions, a significant superiority in bimanual coordination of tACS condition was observed in the retention tests, as well as in the transfer test (*P*< 0.05).

Table 1. Results of pairwise comparisons of bimanual coordination of tACS and sham conditions in different tests

(I) condition	(J) Condition	Mean difference (I-J)	Std. error	*P*
tACS retention	tACS transfer	3.296*	.786	<0.0001
	tACS retention 48 h	.111	.661	.868
	tACS retention 1 w	1.593	.826	.065
tACS transfer	tACS retention 48 h	-3.185*	.762	<0.0001
	tACS retention 1 w	-1.704	.793	.041
tACS retention 48 h	tACS retention 1 w	1.481	.887	.107
Sham retention	Sham transfer	4.593*	1.042	<0.0001
	Sham retention 48 h	.593	.593	.327
	Sham retention 1 w	1.519*	.695	.038
Sham transfer	Sham retention 48 h	-4.000*	.926	<0.0001
	Sham retention 1 w	-3.074*	.743	<0.0001
Sham retention 48 h	Sham retention 1 w	.926	.517	.085
tACS retention	Sham retention	5.407*	.843	<0.0001
tACS transfer	Sham transfer	6.704*	1.297	<0.0001
tACS retention 48 h	Sham retention 48 h	5.889*	.975	<0.0001
tACS retention 1 w	Sham retention 1 w	5.333*	1.082	<0.0001

* *P*<0.05

4. Discussion

The purpose of this study was to investigate the effects of tACS over the supplementary motor area on bimanual coordination in elderly female participants. A total of 31 elderly females participated in a within-group design. They were assigned to either the transcranial alternating current stimulation over the supplementary motor area or the sham stimulation conditions.

The results of this study demonstrated that stimulating the SMA during motor tasks acquisition had a significant effect on the immediate and delayed motor retention and transfer of elderly females. According to a systematic review and meta-analysis about the effects tACS on motor performance [32], stimulation location, stimulation mode, exercise program, and stimulus frequencies are important influencing factors in healthy individual. Thus, the improvement in bimanual coordination observed in the tACS condition compared to the sham condition may be attributed to alterations in neural networks. Transcranial alternating current stimulation can directly modulate the neural networks of cortical regions situated beneath the stimulating electrodes [13]. Previous studies have indicated that tACS can modulate neural activity not only after the stimulation but also during it, particularly in the neural activity oscillation under the electrodes area [14]. The SMA and pre-SMA are recognized as crucial regions involved in bimanual alternating motor tasks, as highlighted in previous studies [21]. The facilitation of neural oscillations through tACS over the SMA or pre-SMA areas may have contributed to the outcomes of the present study. tACS has the capability to modulate neural oscillations at specific frequencies that are directly connected to the participant's head beneath the electrode placement [13, 14]. A previous investigation reported an increase in β power within the SMA and pre-SMA during motor planning and the maintenance of motor execution [33]. This suggests that the modulation of neural oscillations in these areas could have played a role in the observed effects of the current study.

These findings indicate that the application of β-tACS enhances β power activity in the SMA and pre-SMA. Moreover, this stimulation improves the maintenance of motor plans, leading to enhanced motor performance in the participants who received the stimulation [34]. The SMA and pre-SMA are known to have neural connections with the primary motor cortex and basal ganglia [35]. Therefore, tACS applied to the SMA may modulate the neural networks between the SMA, M1, and basal ganglia [25]. Previous studies utilizing functional magnetic resonance imaging (fMRI) have reported that neural activity in the SMA is more pronounced during bimanual movement tasks compared to unilateral movement tasks. Additionally, the neural networks involving bilateral SMAs and bilateral M1 exhibit increased activity during bimanual movement tasks [36]. Furthermore, a previous study utilizing electroencephalograms (EEG) found that the neural network within the beta frequency range (10-20 Hz), involving the SMA and M1, exhibited increased activity during bimanual movement tasks [37].

Rjosk and colleagues (2016) demonstrated the critical role of beta band activity in coordinating interhemispheric movements [38]. Additionally, a study employing transcranial magnetic stimulation (TMS) reported that individuals with higher excitability of the SMA-to-M1 facilitatory neural circuitry also demonstrated better performance on the Purdue Pegboard Test [34].

Taken together, these findings suggest that the neural network operating within the beta frequency band between the SMA and M1 plays an important role in bimanual tasks, potentially contributing to task accuracy. The present study suggests that tACS over SMA indirectly modulates the strength of neural networks. Specifically, the facilitation of neural oscillations over the SMA through β-tACS may enhance the neural networks operating in the beta frequency band (β-band) between the SMA and M1, leading to improved participant performance. However, further research is necessary to fully understand the relationship between tACS-induced alterations in neural networks and motor performance.

The findings of this study demonstrate that tACS over the SMA influences the maintenance and updating of motor plans. Moreover, the results of transfer test reveal that in a novel task condition where participants started organizing materials using their left hand from the left side of the board, the stimulation condition significantly outperforms the sham condition. Specifically, participants in the stimulation condition make fewer mistakes in performing the new tasks compared to the sham condition. The existing body of research partially supports the effect of brain stimulation on transfer learning in new task conditions. Azarpaikan et al. (2023) conducted a study examining the effects of tDCS on motor learning in healthy college students. They found that tDCS applied to the cerebellar region improved motor performance across the stages of acquisition, retention, and transfer, in a bimanual movement task [39].

Furthermore, Goodwill et al. (2016) reported that stimulation over the M1 resulted in enhanced transfer between different body organs during motor learning [40].

These studies provide evidence suggesting that brain stimulation techniques can have beneficial effects on learning transfer, both within and across motor tasks. Research has demonstrated that tACS over the M1 region enhances performance on the Purdue Pegboard Test, which involves symmetrical movements using both hands. However, no significant effects were observed on complex motor skills that require precise and asymmetrical movements of each hand, such as assembly tasks [41, 42]. Therefore, the present study provides valuable insights into a novel neurorehabilitation approach aimed at improving complex bimanual motor skills in the elderly population.

This study aligns with previous research in which M1 stimulation using tACS has shown significant effects on motor learning [43, 44]. These findings highlight the potential of tACS over M1 as a promising technique for enhancing motor performance and motor learning in certain tasks while also acknowledging its limitations in more complex and asymmetrical movements. Furthermore, the findings of Miyaguchi et al. (2020) align with the present study, as they reported similar results. In their study involving 32 young females, they demonstrated that tACS in the β frequency band (20 Hz) led to improved motor performance within the stimulated group. Conversely, the sham group did not show any significant improvements in bimanual coordination. These outcomes provide further evidence that tACS applied over the SMA influences the maintenance and updating of motor plans [25].

Together, these studies support the notion that tACS over the SMA can effectively enhance motor performance, specifically in the context of bimanual coordination tasks.

Conversely, the findings of the present study are inconsistent with the results reported by Berger et al. (2018). In their study involving 24 females aged 18-32, they found no significant differences in bimanual coordination performance between the stimulation groups (10 Hz and 20 Hz) and the sham group. They concluded that tACS did not have a specific effect on bimanual coordination performance [45]. The discrepancy between the present study and Berger et al. could potentially be attributed to differences in stimulation area and participant age. It is important to consider these factors when interpreting and comparing the results of different studies in the field of tACS and its effects on bimanual coordination.

The present study is subject to several limitations. First, the research focused exclusively on a specific demographic group. While the findings demonstrate the effectiveness of β-tACS in improving bimanual coordination in healthy elderly females, it is recommended to analyze the effects of tACS on similar populations with comparable motor skills that are prone to deterioration.

Secondly, the study only examined the effects of β frequency (20 Hz) stimulation, and it remains unclear whether other stimulation frequencies within the β band or different frequency bands could also yield positive impacts. Further investigation is needed to explore the effects of tACS across a wider range of stimulation frequencies.

Thirdly, the study did not investigate the neural mechanisms underlying the observed stimulation effects. The evaluation of cortical cortex oscillations and neural networks was not conducted, leaving the neural underpinnings of the stimulation effects unexplored. Future studies should address these limitations to provide a more comprehensive understanding of the potential applications and mechanisms of tACS in improving motor skills.

Another limitation of this research is the absence of sophisticated interpretative tools such as functional magnetic resonance imaging (fMRI) or quantitative electroencephalography (QEEG). Given the exploratory nature of our study, the effects observed would benefit from analysis using more complex exploratory tools. Furthermore, variations in electric field strength across different stimulation conditions could potentially effect the stimulation effects. However, we did not compare the electric field strength between conditions. Future researches could incorporate techniques such as magnetoencephalography (MEG) and stimulation location to measure these changes and provide a clearer understanding of the underlying mechanisms. These additional tools and methodologies would help shed light on the intricacies of the observed effects and provide a more comprehensive analysis of the stimulation's impact. While the precise neural mechanisms are not yet fully understood, our findings strongly indicate that β-tACS applied to the SMA is effective in facilitating the recovery of bimanual coordination. This finding introduces a novel technique harnessing the potential benefits of tACS interventions for improving motor coordination in elderly people.

5. Conclusions

In conclusion, our study demonstrated that applying β-tACS over the SMA significantly improved bimanual coordination in elderly people. This intervention led to enhanced stability and efficiency in bimanual motor performance, as well as improved motor learning. The use of tACS over the SMA has the potential to optimize performance and motor learning by tailoring the stimulation frequency to individual motor abilities, rather than employing a fixed frequency for all individuals. Considering its safety, affordability, and availability, tACS can be a highly effective and practical electrical stimulation technique for elderly population. Furthermore, its implementation can potentially reduce unnecessary costs for society as a whole.

Conflict of interest

The authors declared no conflicts of interest.

Authors' contributions

All authors contributed to the original idea, study design.

Ethical considerations

The authors have completely considered ethical issues, including informed consent, plagiarism, data fabrication, misconduct, and/or falsification, double publication and/or redundancy, submission, etc.

Data availability

The dataset generated and analyzed during the current study is available from the corresponding author on reasonable request.

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