Auditory and Vestibular Research

A new method of auditory training through the addition of attentional neuromodulation techniques: A pilot study

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Highlights:

Attention training in children with hearing loss improves speech perception in noise
Combining tDCS with behavioral rehabilitation enhances the effects of training

Abstract

Background and Aim: Effective communication relies on understanding speech in noise, which can be challenging, especially for hearing-impaired children. Auditory attention influences speech perception in noise, and Auditory attention training can help improve this critical auditory skill. Today's neuromodulation methods are used in rehabilitation. Transcranial-direct-current-stimulation(tDCS) is a promising approach among these methods. Our hypothesis is that combining electrical stimulation with behavioral auditory training could accelerate and enhance the effectiveness of auditory training, improving speech comprehension in noise.
Methods: A pilot study was conducted on 8 children with moderate to severe hearing loss. In this study, tDCS was administered to the right and left dorsolateral prefrontal cortex in addition to behavioral auditory attention training. The participants were divided into two groups, one receiving real stimulation and the other receiving sham stimulation. 20 minutes of intervention were conducted through ten sessions. The test-of-everyday-attention-for-children (TEA-CH) and the monaural-selective-auditory-attention-test (mSAAT) tests were used as behavioral assessments, and the auditory P300 were recorded as an electrophysiological test to measure attention. Also, speech-in-noise tests were utilized. All tests were conducted before, immediately, and one month after training.
Results: Children in both groups demonstrated noticeable progress in all tests following the training sessions. There was a significant difference in the level of improvement in mSAAT, TEA-CH, word-in-noise, and P300 latency between the two groups. Improvement was more remarkable in children receiving real stimulation.

Conclusion: When behavioral attention training is combined with attention neuromodulation through tDCS, it may enhance rehabilitation effectiveness and increase the stability of tDCS effects.

Keywords: Auditory training, neuromodulation, electrical stimulation, hearing loss, speech perception in noise, auditory attention

Introduction

People mainly communicate through speech for various purposes, such as socializing and learning. However, noisy environments often make it difficult to understand speech clearly, posing a challenge for everyone. People with hearing loss often struggle with speech perception, especially in noisy group settings, which can significantly impact verbal communication. Understanding speech involves the auditory system's peripheral and central functions. Cognitive skills like attention, memory, and comprehension are necessary, especially in challenging listening environments. Successfully understanding speech relies on a combination of bottom-up (sensory) and top-down (cognitive) processes [1]. The ability to concentrate and sustain attention in the presence of background noise is a crucial cognitive trait that significantly impacts communication effectiveness.

In a recent study, researchers discovered significant differences in cognitive abilities in hearing-impaired children. Children with hearing loss may struggle to maintain focus when listening to multiple speakers [2]. Researchers have identified significant brain changes in children with Congenital Sensorineural Hearing Loss (CSNHL), affecting regions related to auditory processing, and cognitive abilities [3, 4]. This illustrates the broad impact of CSNHL on child development and learning, highlighting the need for targeted interventions. Additionally, preschool children with SNHL show altered functions in the prefrontal cortex, suggesting that early hearing loss can affect cognitive behavior [5]. Recent research has highlighted the crucial involvement of the prefrontal cortex (PFC) in the auditory pathway and its function in top-down regulation [6]. While modern hearing aids can maintain speech qualities with remarkable fidelity, they are limited in their effectiveness in noisy environments. Hearing-impaired children require auditory training to enhance speech perception in noise after they have worn hearing aids. In recent years, training methods such as top-down or bottom-up approaches have been used to address the challenges of speech perception in noise [7]. Training designed to improve auditory attention can significantly enhance a person's ability to understand speech in noise, helping them focus better amid distractions.

Neuroenhancement uses noninvasive techniques to improve cognition, and there is a growing trend in using neuromodulation devices like transcranial direct current stimulation (tDCS) [8]. In recent years, in addition to traditional rehabilitation, neuromodulation has been considered a low-risk approach for addressing cognitive issues. Researchers have observed that tDCS affects healthy individuals' cognitive functions, like attention and memory. According to Rooh Al-Amini et al, the tDCS intervention program improves the selective attention and flexibility of students with learning disabilities [9]. The research conducted by Lema et al. showed the effects of tDCS on improving the attention networks of healthy students [10]. Moslemi et al.'s research demonstrated the effectiveness of tDCS in improving attention and visual-auditory working memory in dyslexic children [11].

The primary method through which tDCS affects the cerebral cortex is by slightly modifying the resting membrane potentials of neurons below the threshold. tDCS stimulates glutamatergic neurons, reduces GABA activity, and modulates N-methyl-d-aspartate (NMDA) and α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptors. The level of post-synaptic AMPA receptors determines whether activation of a presynaptic neuron leads to supra-threshold post-synaptic activation. Therefore, a change in AMPA receptor density is the primary mechanism for both Long-term potentiation (LTP) and Long-term depression (LTD) [12]. The findings demonstrate that tDCS can directly generate LTP-like plasticity in the human cortex [13]. LTP is a critical mechanism underlying brain plasticity, learning, and memory.

Functional magnetic resonance imaging (fMRI) studies have linked selective attention to the dorsolateral prefrontal cortex (DLPFC) functioning, indicating its role in managing attention and task priorities. This suggests that the DLPFC is involved in top-down attentional control. Studies also report that attention processing can be modulated using tDCS [10, 14]. In tDCS studies, carefully positioning both the anodal and cathodal electrodes is crucial. The current flow pathway through the brain depends on these placements. Additionally, it is important to note that tDCS effects extend beyond the immediate cortical areas beneath the electrodes, potentially impacting other cortical regions between the stimulation electrodes [15]. Research findings indicate that the concurrent application of left anodal and right cathodal tDCS to the DLPFC has impacted the attention network [16]. This suggests that specific electrical stimulation to these brain areas can influence attention-related cognitive processes.

Auditory training programs for children also utilize the brain's plasticity to improve function through training. Performing tDCS in the prefrontal cortex is expected to enhance the brain's receptiveness to attention training by increasing plasticity and its impact on LTP. Consequently, behavioral training for auditory attention is anticipated to yield more significant improvement by leveraging the heightened plasticity in these brain regions. The problem with this method is its short-term durability [17], which can be extended by combining it with behavioral rehabilitation.

A pilot study was conducted to assess the plausibility of the hypothesis regarding the combined impact of behavioral training and the neuromodulation method on improving speech perception in noise for children with hearing loss. To test our hypothesis, we used the test of everyday attention for children (TEA-CH) [18] and the monaural selective auditory attention test (mSAAT) [19] tests to evaluate sustained and selective auditory attention. Based on findings from past research on the cognitive engagement with speech material at different levels of nonsense syllables, single words, and sentences [20], this study employs the consonant-vowel-in-noise (CV-In-Noise) [21], word-in-noise(WIN) [22], and Bamford-Kowal-Bench-Speech-In-Noise (BKB-SIN) [23] tests to measure the ability to comprehend speech in noisy settings.

Attention modulates neural responses at the cortical level. Electrophysiological techniques are noninvasively used to study cortical functioning. The late positive event-related potential (ERP) P300 is extensively used to study this cognitive skill and has also been applied to investigate the effects of tDCS [24]. Additionally, understanding and identifying P300 latency has proven to be a reliable indicator of the potential intervention outcomes [25]. In this research, to objectively assess the effects of the intervention alongside behavioral tests, the P300 test was utilized. During the analysis, eight regions of interest were examined. These positions encompassed the z location, and the DLPFC was subjected to stimulation.

Methods

Eight participants aged 8 to 11 had bilaterally 55-75 dB HL sensory-neural hearing loss with type An tympanogram. The children had been using appropriate bilateral hearing aids for at least three years, and the maximum average threshold with hearing aids was 30 dB in both ears .In the forward digit span test, memory capacity should be at least three units, abnormal scores on the WIN , and at least one attention tests were confirmed. The absence of neuropathy

Additional criteria were considered for inclusion: right-handedness with the Edinburgh Handedness Scale, no history of psycho-neurological disorders; normative intelligence score of at least 85 on the Wechsler intelligence scale for children-revised (WISC-R), permission from parents and children to participate in the study; and possessing either standard or modified vision.

Exclusion criteria included the absence of any entry criteria, the loss of criteria during the process, and the inability to record ERP.

Following the establishment of entry criteria, two groups of children were formed using random blocks of six samples One group received active tDCS combined with auditory attention training, while the other group underwent sham tDCS with the same auditory attention training. Each child participated in 10 training sessions based on their assigned group. After completing the training sessions, all the auditory attention and speech perception in noise tests and P300 wave were re-evaluated. All tests were repeated one month later.

The speaker's sound output was calibrated using a sound level meter for tests and training. This calibration was performed for a speaker at a zero- azimuth degree with one-meter distance from participant position, with an intensity level set at 70 dB SPL. According to the degree of hearing loss in participants, the selected intensity level was adjusted to a comfortable listening level (30-40 dB SL) at the time of the test.

All procedures were approved by the Ethics Committee (IR.USWR.REC.1401.128) and the Iranian Registry of Clinical Trials (IRCT20220918055979N1). Before starting the study, the participants received a comprehensive explanation of the experimental procedures, and informed consent was secured from each individual

Selected measures

Auditory attention and speech in noise tests

The mSAAT test was utilized to evaluate selective attention, while the TEA-CH test was used to evaluate sustained auditory attention. The CV-In-Noise, WIN, and BKB-SIN tests were conducted to assess speech perception in noise. During the tests, the child wearing a hearing aid sat in front of the speaker at a zero-degree azimuth, and the tests were administered at the most comfortable level. The order in which the tests were administered was randomized, with no specific pattern or predefined sequence.

Electrophysiology measures P300

We conducted a go/no-go task to record the P300 wave. P300 waves were recorded using the 32-channel electroencephalography (EEG) system and electrode children cap. Electrode positions were based on the international 10-20 system. Acoustic stimuli were presented at the comfortable listening level for the participant in a quiet room. The task comprised two blocks of trials, each containing tone bursts with an 80% probability, along with tone bursts that had a 20% probability of occurrence [26]. Participants were instructed to remain focused on both the frequent and rare stimuli. In response to the rare sound, the child pressed the click button. The P300 peaks were identified by two researchers.

Intervention

Ten intervention sessions were conducted three times a week for each child in both groups.

Auditory attention training

This study used auditory attention training (AAT) with TEA-CH test materials for rehabilitation in a comfortable listening environment based on initial evaluation results. Non-test equivalent lists were used for training session to decrease learning effects. In the following sessions, if the participant achieved a correct response rate of 70% on the tasks, the sustained attention training was adjusted by increasing the duration of each exercise, shortening the interval between stimuli, increasing the number of words to be remembered simultaneously during stimulation, and making the response requirements more challenging. If the correct responses were below 70%, the tasks would have been as challenging as during the previous session.

Transcranial direct current stimulation

The EEG children cap was used to identify specific locations on the scalp where electrodes would be placed for electrical stimulation. These locations were then cleaned. Two electrodes, each measuring 25 cm^2, were placed on the skull, and their pads were moistened with a standard saline solution. The anode was positioned at the dorsolateral prefrontal cortex (DLPFC) (F3) on the left side, while the cathode was located at the DLPFC (F4) on the right side [16]. Studies have shown that when combined methods of electrical stimulation and cognitive training are presented simultaneously (online), the effect is greater than when the training is presented after electrical stimulation (offline). [27]. Also, considering that tDCS requires more than 3 minutes to induce excitability and cortical activity changes[28], similar to the study conducted by Martin et al., the exercises commenced five minutes after the stimulation began for both groups [29]. Behavioral training was carried out for a duration of 15 minutes.

The children in Group sham tDCS and AAT participated in a program that involved behavior training for auditory attention, and they also received sham electrical stimulation. In this group, the electrical stimulator is programmed to operate at 1 mA for a duration of 30 seconds. Children in the active tDCS and AAT group underwent auditory attention training while receiving real tDCS (Figure 1).

Statistical analysis

Statistical analyses were conducted using descriptive statistics, including the mean and standard deviation of auditory attention and speech in noise tests and P300 latencies. Then, the paired t-test compared the before-and-after results. ANCOVA analysis was used to compare the intervention effects of the two groups. All the analyses were conducted using version 17 SPSS. The significance level adopted was 0.05 (5%), with confidence intervals of 95%.

Results

Eight children with moderate to severe hearing loss (3 females and 5 males) aged 8 to 11 years (9.75 ±0.70) participated. Seven children had abnormal results in all tests, while one child was normal in the score and Walk/Don't-Walk tests but abnormal in the others. The analysis of the average mSAAT and TEA-CH tests after the rehabilitation revealed statistically significant differences compared to before in all tests within group sham tDCS and AAT. As for group active tDCS and AAT, statistically significant results were observed in all tests except for the Score and Walk/don't-walk tests. In the comparison between groups in the mSAAT test and the Sky-Search-Dual-Task sub-test of the TEA-CH test, the statistical analysis (ANCOVA test) showed a significant difference between the two groups. In all tests except the Walk/Don't-Walk test, the changes in Group active tDCS and AAT were greater than in Group sham tDCS and AAT (Table 1).

After one month, there were no significant differences in the mSAAT and TEA-CH tests compared to the results immediately after the intervention, as indicated by the paired t-test. Additionally, no significant overall differences were observed in ANCOVA. It was found that recovery remained stable in both groups (Table2).

The intervention significantly impacted three tests: WIN, CV-In-Noise, and BKB-SIN. The paired t-test showed a statistically significant improvement in all three tests. Additionally, the ANCOVA test revealed a significant difference between the two groups in the WIN test. Notably, group active tDCS and AAT showed greater improvement in all the tests.

Following one month, the results from the tests assessing CV-In-Noise, WIN, and the BKB-SIN tests showed no significant differences compared to the immediate post-intervention results, as indicated by the paired t-test. Additionally, no statistical significance was found based on the ANCOVA. These findings suggest that recovery remained stable in both groups over the month (Table3).

The latency in the P300 wave at 8 electrode locations before and after the intervention was assessed using a paired t-test. In both groups, the latency decreased significantly in all locations. ANCOVA analysis indicated a significant difference between groups A and B in the most locations. Group active tDCS and AAT demonstrated a greater reduction in latency in all locations compared to group sham tDCS and AAT. Following the intervention, analyses using paired t-tests and ANCOVA did not reveal any significant changes in p300 latency across all locations one month later (Table4) (Figure 2).

Discussion

In the current study, we examined our hypothesis by investigating the combined impact of auditory attention behavioral training and neuromodulation method on speech perception in noise for children with hearing loss. Based on our findings, there have been no reported complaints regarding the side effects of electrical stimulation. Additionally, no side effects were observed throughout the intervention.

In the analysis of selective attention, it was found that there was a substantial difference in the level of improvement between the two groups. The group that received the combined method demonstrated a notably higher score increase. Moreover, in the evaluations of sustained attention, the group that received the combined method exhibited a more pronounced improvement The results of Boroda et al.'s study support the effectiveness of combining tDCS and cognitive behavioral training for children with fetal alcohol spectrum disorders (FASD)[30]. The study demonstrated that using Anodal tDCS targeted at the left DLPFC with a bipolar montage (placing the anode at F3 and the cathode at Fp2) in conjunction with cognitive behavioral training led to more significant improvements in continuous performance tests for children with FASD compared to cognitive behavioral training alone [30]. Our study's findings are in line with the research conducted by Alvarez-Alvarado et al. they demonstrated that the combination of cognitive behavioral training with active-tDCS, with stimulation delivered over F3 (cathode) and F4 (anode) electrode placements, resulted in sustained increases in excitatory neurotransmitter concentration [31]. Compared to our research results, the findings from Martina et al.' study on cognitive training combined with tDCS for mild cognitive impairment did not show a notable distinction between the groups receiving active stimulation and those receiving sham stimulation. In their study, the anode was positioned over the F3 electrode site and the cathode over F8. Although both groups demonstrated improvement, no significant difference was observed between them [32]. The differences in results could be due to variations in the placement of tDCS electrodes, especially the location of the cathode electrode. To date, no specific research has been found that addresses the effects of using anodal F3/cathodal F4 electrode placement on auditory attention ability in children with hearing loss. This research gap emphasizes the necessity for further exploration into the potential advantages of this particular electrode configuration when combined with behavioral attention training. This research could lead to a better understanding of how to enhance auditory attention in this specific population.

Our pilot study has yielded promising results that inspire us to continue our work in the field of pediatric audiology and neurology. The results show that neuromodulation methods can significantly enhance auditory attention in children with hearing impairments. When combined with behavioral training, these methods not only support but also expedite the progress of these children.

We can influence the resting potential and LTP function by incorporating electrical stimulation alongside attention training. This combined approach has the potential to accelerate the pace at which attention rehabilitation in hearing-impaired children improves, ultimately leading to faster attainment of desired results.

Study involving different speech tests using consonant-vowel sounds, words, and sentences in various background noises demonstrated improvements in both groups. Auditory attention training led to improvement in speech perception in noisy environments. The results of this study aligned with the findings of Soveri et al., indicating that top-down training significantly affects the speech perception of healthy adults[33]. The group receiving real tDCS and behavioral training demonstrated more significant improvements. This could be attributed to the impact of electrical stimulation on enhancing auditory attention, ultimately leading to better speech comprehension in noisy conditions. However, achieving complete recovery may necessitate additional training, such as working memory and bottom-up processing, in conjunction with auditory attention training.

In the assessment of speech comprehension tests conducted in noisy environments, it was observed that following the intervention, there were notable differences in all three tests. Furthermore, during the analysis of the correlation between changes in attention and alterations in speech comprehension in noisy conditions, it was found that the most noteworthy correlation existed between changes in word comprehension in noisy settings and variations in attention. This indicates that changes in attention strongly influenced word comprehension in noisy environments. The perception of vowel and consonant sounds in noisy environments relies more heavily on sensory information directly from the auditory stimulus (bottom-up factors) rather than higher-level cognitive processes. Understanding sentences in noisy environments is a challenging task involving many factors. These factors can differ significantly between individuals with normal hearing and those with hearing impairments, affecting their ability to comprehend sentences [34]. To improve the speech comprehension of hearing-impaired children, it is crucial to identify the specific factors that influence their understanding of sentences in noisy conditions. By pinpointing these factors, targeted exercises and attention training can be developed to address and improve their speech comprehension abilities. This approach is essential for enhancing the ability of individuals with hearing impairments to understand and process speech in challenging, noisy environments.

In our research, we had a limited number of samples and observed significant variations in both intra-individual and extra-individual amplitude levels of P300. Due to these variations, we chose to focus on the latency variable. Considering the amplitude in a study with larger sample size is suggested. In the P300 wave latency, there was a significant decrease in the latency in 8 positions, and this decrease was greater in the combined group than in the group that received behavioral training with sham stimulation. The changes provided concrete evidence of improved behavioral outcomes.

To enhance the robustness of our findings, we strongly advocate for future studies to be conducted with larger sample size. To comprehensively assess the influence of behavioral training on the sustainability of electrical stimulation, it is advisable to include another group in the study that exclusively receives the electrical stimulation method in addition to the two existing groups.

In all assessments of auditory attention, speech perception in noise, and P300, there was no discernible difference in the retention effect between the two groups. The results from our study after one month show differences from the findings of Murugaraja et al., investigated cognitive function in people experiencing mild cognitive impairment [35], and Yadollahpour et al. conducted a study on the management of tinnitus in individuals affected by the condition. [36]. This contrast is noticeable when comparing the average scores obtained in their studies after a month of average reduction. Noninvasive brain stimulation techniques generally lead to transient changes . Incorporating the behavioral method with the tDCS method may offer a solution to the short-term stability issue associated with this approach. Longer follow-up assessments at 3 and 6 months are recommended to evaluate the sustained effects of interventions. According to the study of Watanabe et.al. in rat demonstrated that tDCS of the medial prefrontal cortex induces LTP-like plasticity in the hippocampus-prefrontal pathway in rats [37]. This pathway, critical for cognitive and memory functions, could be positively impacted by this plasticity. Investigating this combined method with neuromodulation through tDCS is suggested by placing the electrode in the medial prefrontal.

Conclusion

Based on the current pilot study's findings, the hypothesis of using neuromodulation techniques, like tDCS, to improve attention along with the use of behavioral auditory attention training methods was investigated. The combined method improves and accelerates the effectiveness of behavioral techniques in increasing attention and improving the main problem of children with hearing loss, i.e., improving speech perception in noise through cognitive and auditory behavioral tests in addition to auditory P300 improvement in objective and electrophysiology evaluations. Properly combining these two behavioral and neuromodulation methods ensures the stability of electrical stimulation's effectiveness in improving auditory attention and speech comprehension in noisy environments. In order to generalize present study's findings, a study with larger sample size and more electrode positions is required. This method is suggested for investigation in other groups with hearing attention and perception speech in noise problems, such as the elderly and those with auditory processing disorders.

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Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Authors' contributions

NM: Study design, acquisition of data, methodology, project administration, interpretation of the results, statistical analysis, and drafting the manuscript; review and editing the manuscript; MS: Supervision, interpretation of the results, review and editing the manuscript; AJ: Acquisition of data, methodology, interpretation of the results, review and editing the manuscript; EB: Statistical analysis, review and editing the manuscript; MJ: Supervision, conceptualization, methodology, project administration, interpretation of the results, review and editing the manuscript

References

1. Woods DL, Yund EW. Perceptual Training of Phoneme Identification for Hearing Loss. Semin Hear 2007;28(2): 110-9. [DOI:10.1055/s-2007-973437]
2. Kral A. Hearing and Cognition in Childhood. Laryngorhinootologie. 2023;102(S 01):S3-11. [DOI:10.1055/a-1973-5087]
3. Simon M, Campbell E, Lepore F. Cross-modal plasticity and central deficiencies: the case of deafness and the use of cochlear implants. Handb Clin Neurol. 2020;174:343-55. [DOI:10.1016/B978-0-444-64148-9.00025-9]
4. Aslan F, Ertugrul G, Sennaroglu G, Sennaroglu L. Unimodal versus bimodal auditory stimulation in inner ear malformations: Cognitive, language, and motor performance. Laryngoscope Investig Otolaryngol. 2023;8(5):1401-9. [DOI:10.1002/lio2.1153]
5. Yin Y, Lyu X, Zhou J, Yu K, Huang M, Shen G, et al. Cerebral cortex functional reorganization in preschool children with congenital sensorineural hearing loss: a resting-state fMRI study. Front Neurol. 2024;15:1423956. [DOI:10.3389/fneur.2024.1423956]
6. Saccone EJ, Tian M, Bedny M. Developing cortex is functionally pluripotent: Evidence from blindness. Dev Cogn Neurosci. 2024;66:101360. [DOI:10.1016/j.dcn.2024.101360]
7. Gohari N, Dastgerdi ZH, Rouhbakhsh N, Afshar S, Mobini R. Training Programs for Improving Speech Perception in Noise: A Review. J Audiol Otol. 2023;27(1):1-9. [DOI:10.7874/jao.2022.00283]
8. Rahimi V, Mohammadkhani G, Alaghband Rad J, Mousavi SZ, Khalili ME. Modulation of auditory temporal processing, speech in noise perception, auditory-verbal memory, and reading efficiency by anodal tDCS in children with dyslexia. Neuropsychologia. 2022;177:108427. [DOI:10.1016/j.neuropsychologia.2022.108427]
9. Rooholamini S, Soleymani M, Vaghef L. [Effectiveness of Transcranial Direct Current Stimulation (TDCS) onExecutive Functions(selective attention and flexibility) in Students with Dyslexia]. Journal of Learning Disabilities. 2018;8(1):23-41. Persian. [DOI:10.22098/JLD.2018.707]
10. Lema A, Carvalho S, Fregni F, Gonçalves ÓF, Leite J. The effects of direct current stimulation and random noise stimulation on attention networks. Sci Rep. 2021;11(1):6201. [DOI:10.1038/s41598-021-85749-7]
11. Moslemi B, Azmodeh M, Tabatabaei SM, Alivandi Vafa M. [The effectiveness of transcranial direct current stimulation (tDCS) on attention and visual-auditory working memory in children with dyslexia]. Journal of Exceptional Children. 2021;20(4):93-104. Persian.
12. Sprengel R. Role of AMPA receptors in synaptic plasticity. Cell Tissue Res. 2006;326(2):447-55. [DOI:10.1007/s00441-006-0275-4]

13. Frase L, Mertens L, Krahl A, Bhatia K, Feige B, Heinrich SP, et al. Transcranial direct current stimulation induces long-term potentiation-like plasticity in the human visual cortex. Transl Psychiatry. 2021;11(1):17. [DOI:10.1038/s41398-020-01134-4]
14. Mattioli F, Bellomi F, Stampatori C, Capra R, Miniussi C. Neuroenhancement through cognitive training and anodal tDCS in multiple sclerosis. Mult Scler. 2016;22(2):222-30. [DOI:10.1177/1352458515587597]
15. Petit L, Simon G, Joliot M, Andersson F, Bertin T, Zago L, et al. Right hemisphere dominance for auditory attention and its modulation by eye position: an event related fMRI study. Restor Neurol Neurosci. 2007;25(3-4):211-25.
16. Miler JA, Meron D, Baldwin DS, Garner M. The Effect of Prefrontal Transcranial Direct Current Stimulation on Attention Network Function in Healthy Volunteers. Neuromodulation. 2018;21(4):355-361. [DOI:10.1111/ner.12629]
17. Kuo MF, Polanía R, Nitsche M. Physiology of Transcranial Direct and Alternating Current Stimulation. In: Brunoni A, Nitsche M, Loo C, editors. Transcranial Direct Current Stimulation in Neuropsychiatric Disorders: Clinical Principles and Management. 1st ed. Cham: Springer International Publishing; 2016. p. 29-46.
18. Fathi N, Hassani Mehraban A, Akbarfahimi M, Mirzaie H. Validity and Reliability of the Test of Everyday Attention for Children (TEACh) in Iranian 8-11 Year Old Normal Students. Iran J Psychiatry Behav Sci. 2017;11(1):e2854. [DOI:10.5812/ijpbs.2854]
19. Aarabi S, Jarollahi F, Jalaie S. Development and determination of the validity of Persian version of monaural selective auditory attention test in learning disabled children. Aud Vestib Res. 2016;25(1):49-54.
20. Chupani J, Javanbakht M, Lotfi Y. Central auditory processing in bilinguals. Aud Vestib Res. 2021;30(3):160-6. [DOI:10.18502/avr.v30i3.6529]
21. Lotfi Y, Kargar S, Javanbakht M, Biglarian A. Development, Validity and Reliability of the Persian Version of the Consonant-Vowel in White Noise Test. JRSR. 2016;3(2):29-34. [DOI:10.30476/jrsr.2016.41090]
22. Lotfi Y, Salim S, Mehrkian S, Ahmadi T, Biglarian A. The Persian version of words-in-noise test for young population: development and validation. Aud Vestib Res. 2016;25(4):194-200.
23. Moossavi A, Mehrkian S, Karami F, Biglarian A, Mahmoodi Bakhtiari B. Developing of Persian version of the BKB sentences and content validity assessment. Aud Vestib Res. 2017;26(1):27-33.
24. Kim M, Lee TH, Hwang WJ, Lee TY, Kwon JS. Auditory P300 as a Neurophysiological Correlate of Symptomatic Improvement by Transcranial Direct Current Stimulation in Patients With Schizophrenia: A Pilot Study. Clin EEG Neurosci. 2020;51(4):252-8. [DOI:10.1177/1550059418815228]
25. Reis AC, Frizzo AC, Isaac Mde L, Garcia CF, Funayama CA, Iório MC. P300 in individuals with sensorineural hearing loss. Braz J Otorhinolaryngol. 2015;81(2):126-32. [DOI:10.1016/j.bjorl.2014.10.001]
26. Bell L, Scharke W, Reindl V, Fels J, Neuschaefer-Rube C, Konrad K. Auditory and Visual Response Inhibition in Children with Bilateral Hearing Aids and Children with ADHD. Brain Sci. 2020;10(5):307. [DOI:10.3390/brainsci10050307]
27. Martin DM, Liu R, Alonzo A, Green M, Loo CK. Use of transcranial direct current stimulation (tDCS) to enhance cognitive training: effect of timing of stimulation. Exp Brain Res. 2014;232(10):3345-51. [DOI:10.1007/s00221-014-4022-x]
28. Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J Physiol. 2000 Sep 15;527 Pt 3(Pt 3):633-9. [DOI:10.1111/j.1469-7793.2000.t01-1-00633.x]
29. Martin DM, Liu R, Alonzo A, Green M, Player MJ, Sachdev P, et al. Can transcranial direct current stimulation enhance outcomes from cognitive training? A randomized controlled trial in healthy participants. Int J Neuropsychopharmacol. 2013;16(9):1927-36. [DOI:10.1017/S1461145713000539]
30. Boroda E, Krueger AM, Bansal P, Schumacher MJ, Roy AV, Boys CJ, et al. A randomized controlled trial of transcranial direct-current stimulation and cognitive training in children with fetal alcohol spectrum disorder. Brain Stimul. 2020;13(4):1059-68.
31. Alvarez-Alvarado S, Boutzoukas EM, Kraft JN, O'Shea A, Indahlastari A, Albizu A, et al. Impact of Transcranial Direct Current Stimulation and Cognitive Training on Frontal Lobe Neurotransmitter Concentrations. Front Aging Neurosci. 2021;13:761348. [DOI:10.3389/fnagi.2021.761348]
32. Martin DM, Mohan A, Alonzo A, Gates N, Gbadeyan O, Meinzer M, et al. A Pilot Double-Blind Randomized Controlled Trial of Cognitive Training Combined with Transcranial Direct Current Stimulation for Amnestic Mild Cognitive Impairment. J Alzheimers Dis. 2019;71(2):503-12. [DOI:10.3233/JAD-190306]
33. Soveri A, Tallus J, Laine M, Nyberg L, Bäckman L, Hugdahl K, et al. Modulation of auditory attention by training: evidence from dichotic listening. Exp Psychol. 2013;60(1):44-52. [DOI:10.1027/1618-3169/a000172]
34. Hwang JS, Kim KH, Lee JH. Factors Affecting Sentence-in-Noise Recognition for Normal Hearing Listeners and Listeners with Hearing Loss. J Audiol Otol. 2017;21(2):81-7. [DOI:10.7874/jao.2017.21.2.81]
35. Murugaraja V, Shivakumar V, Sivakumar PT, Sinha P, Venkatasubramanian G. Clinical utility and tolerability of transcranial direct current stimulation in mild cognitive impairment. Asian J Psychiatr. 2017;30:135-40. [DOI:10.1016/j.ajp.2017.09.001]
36. Yadollahpour A, Rashidi S, Saki N, Kunwar PS, Mayo-Yáñez M. Repeated Bilateral Transcranial Direct Current Stimulation over Auditory Cortex for Tinnitus Treatment: A Double-Blinded Randomized Controlled Clinical Trial. Brain Sci. 2024;14(4):373. [DOI:10.3390/brainsci14040373]
37. Watanabe Y, Dezawa S, Takei H, Nagasaka K, Takashima I. Hippocampal-prefrontal long-term potentiation-like plasticity with transcranial direct current stimulation in rats. Neurobiol Learn Mem. 2023;201:107750. [DOI:10.1016/j.nlm.2023.107750]

Table 1. Distribution of age, gender, and degree of hearing loss among children participating in the study across two groups

Group	n	Age	Percentage (boys)	Hearing loss
Sham tDCS+AAT	4	9.50(±١,٢٩)	75 %	65.4(±1.26)
active tDCS+AAT	4	9.75(±0.95)	50 %	67.1(±1.12)

Table 2. Comparing the auditory attention tests scores at baseline, post-test, and follow-up

			n	Baseline	Post-test	Follow-up	P-value*	P-value**
mSAAT		Sham tDCS+AAT	4	11(±4.89)	15(±4.16)	14(±4.69)	0.006	.092
		active tDCS+AAT	4	13.5(±3.69)	20.25(±4.42)	19.50(±4.65)	<.001	.058
		P-value***: 0.02 Partial Eta Squared***: 0.69 P-value****: 0.77						
TEA-CH	**Score**	Sham tDCS+AAT	4	6.5(±2.08)	9(±0.81)	8.50(±1.29)	0.03	.182
		active tDCS+AAT	4	7.25(±2.75)	9.75(±0.5)	9.50(±.57)	0.12	.39
		P-value***: 0.10 P-value****: 0.92						
	Score Dual Task	Sham tDCS+AAT	4	7(±3.36)	10.50(±3.10)	10.50(±3.10)	0.03	1.00
		active tDCS+AAT	4	9.25(±3.40)	14.50(±3.31)	14.50(±3.69)	<.001	1.00
		P-value***: 0.08 P-value****:0.56						
	Sky search Dual Task	Sham tDCS+AAT	4	30.61(±16.46)	22.78(±12.14)	23.85(±10.38)	0.04	.48
		active tDCS+AAT	4	29.41(±10.84)	13.36(±4.87)	13.47(±4.81)	0.02	.87
		P-value***: 0.02 Partial Eta Squared***: 0.64 P-value****:0.17						
	Code transmission	Sham tDCS+AAT	4	26(±6.68)	31.25(±2.87)	30.25(±2.87)	0.08	.05
		active tDCS+AAT	4	26(±6.05)	33.25(±5.73)	32.50(±6.02)	0.01	.05
		P-value***: 0.30 P-value****:0.51						
	Walk/ don't-walk	Sham tDCS+AAT	4	15.75(±2.5)	18.5(±1.29)	17.75(±1.70)	0.02	.05
		active tDCS+AAT	4	16.75(±2.06)	19(±2)	18.75(±1.89)	0.09	.39
		P-value***: 0.98 P-value****:0.27						

* Paired T-Test (Baseline/Post-Test)
** Paired T-Test (Post-Test/Follow-up)
*** ANCOVA (Baseline/Post-Test)
**** ANCOVA (Post-Test/Follow-up)
AAT: Auditory Attention Training
tDCS: transcranial direct current stimulation
mSAAT: monaural selective auditory attention test
TEA-CH: test of everyday attention for children

Table 3. Comparing the speech in noise tests scores at baseline, post-test, and follow-up

		n	Baseline	Post-test	Follow-up	P-value*	P-value**
Word-In-Noise SNR 50%	Sham tDCS+AAT	4	12.6(±3.29)	8.6(±2.47)	8.20(±1.36)	0.003	.60
	active tDCS+AAT	4	13(±2.1)	6(±3.06)	6.6(±3.01)	0.001	.31
	P-value***: 0.015 P-value****: 0.69						
CV-In-Noise +6 SNR	Sham tDCS+AAT	4	13(±4.08)	19(±2.94)	18.50(±3.41)	0.002	.49
	active tDCS+AAT	4	12(±2.58)	20.25(±2.87)	19.75(±2.75)	0.005	.18
	P-value***: 0.15 P-value****: 0.98						
CV-In-Noise 0 SNR	Sham tDCS+AAT	4	9.75(±2.63)	15.50(±1)	15.25(±.95)	0.005	.63
	active tDCS+AAT	4	9(±1.41)	16.75(±3.5)	16.00(±3.36)	0.01	.05
	P-value***: 0.36 P-value****: 0.53						
CV-In-Noise - 6 SNR	Sham tDCS+AAT	4	3.5(±1.91)	7.75(±0.5)	7.75(±.95)	0.01	1.00
	active tDCS+AAT	4	4.25(±1.89)	13(±2.94)	13.00(±3.36)	0.003	1.00
	P-value***: 0.16 P-value****: 0.90						
BKB-SIN	Sham tDCS+AAT	4	10.75(±4.57)	6.25(±3.3)	6.50(±3.74)	0.01	.63
	active tDCS+AAT	4	8.5(±2.44)	3(±3.31)	3.75(±2.75)	0.002	.21
	P-value***: 0.24 P-value****: 0.70						

* Paired T-Test (Baseline-Post-Test)
** Paired T-Test (Post-Test-Follow-up)
*** ANCOVA (Baseline-Post-Test)
**** ANCOVA (Post-Test-Follow-up)
AAT: Auditory Attention Training
tDCS: transcranial direct current stimulation

Table 4. Comparing the average P300 latency at baseline, post-test, and follow-up

		n	Baseline	Post-test	Follow-up	P-value*	P-value**
Latency P300-F3	Sham tDCS+AAT	4	409(±29.13)	377.5(±29.71)	378.75(±28.02)	0.003	.41
	active tDCS+AAT	4	405.75(±27.76)	353.5(±18.35)	357.00(±19.88)	0.002	.12
	P-value***: 0.01 Partial Eta Squared***: 0.73 P-value****: 0.54						
Latency P300-F4	Sham tDCS+AAT	4	406.25(±36.13)	373.25(±33.61)	375.50(±30.75)	<.001	. .32
	active tDCS+AAT	4	405.25(±28.53)	355.25(±22.01)	360.25(±22.39)	0.004	.08
	P-value***: 0.03 Partial Eta Squared***: 0.64 P-value****: 0.58						
Latency P300-Fpz	Sham tDCS+AAT	4	405.75(±34.04)	374(±24.62)	375.50(±30.74)	0.002	.29
	active tDCS+AAT	4	405(±28.76)	347.5(±18.37)	351.00(±20.92)	0.003	.14
	P-value***: 0.01 Partial Eta Squared***: 0.75 P-value****: 0.56						
Latency P300-Fz	Sham tDCS+AAT	4	413.75(±31.85)	382.75(±30.63)	384.50(±27.87)	0.003	.310
	active tDCS+AAT	4	407.5(±27.67)	352.5(±16.86)	356.00(±19.20)	0.004	.14
	P-value***: 0.01 Partial Eta Squared***: 0.74 P-value****: 0.85						
Latency P300-FCz	Sham tDCS+AAT	4	410.75(±40.70)	382(±41.99)	383.25(±38.87)	0.005	.49
	active tDCS+AAT	4	407.25(±29.22)	353.75(±17.82)	358.25(±19.36)	0.006	.09
	P-value***: 0.02 Partial Eta Squared***: 0.64 P-value****: 0.53						
Latency P300-Cz	Sham tDCS+AAT	4	419(±33.80)	389.75(±33.21)	391.25(±28.96)	0.001	.59
	active tDCS+AAT	4	409.25(±25.78)	356.75(±10.81)	360.75(±12.44)	0.009	.067
	P-value***: 0.02 Partial Eta Squared***: 0.67 P-value****: 0.75						
Latency P300-Pz	Sham tDCS+AAT	4	413(±30.31)	385.5(±31.34)	386(±27.11)	0.003	.86
	active tDCS+AAT	4	408.75(±26.19)	358.75(±13.40)	362.75(±15.32)	0.016	.11
	P-value***: 0.06 P-value****: 0.81						
Latency P300-Oz	Sham tDCS+AAT	4	418.5(±28.67)	392.25(±30.85)	392.75(±26.85)	0.003	.83
	active tDCS+AAT	4	404.75(±43.52)	357.25(±38.22)	360.75(±40.08)	0.016	.11
	P-value***: 0.08 P-value****: 0.55						

* Paired T-Test (Baseline-Post-Test)
** Paired T-Test (Post-Test-Follow-up)
*** ANCOVA (Baseline-Post-Test)
**** ANCOVA (Post-Test-Follow-up)
AAT: Auditory Attention Training
tDCS: transcranial direct current stimulation

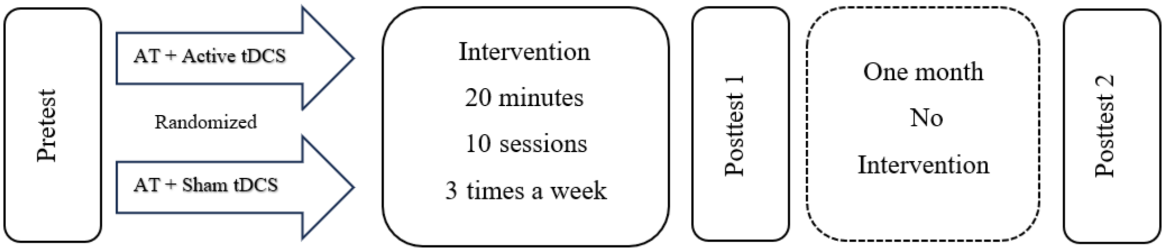

Figure 1. Diagram flow of trial.

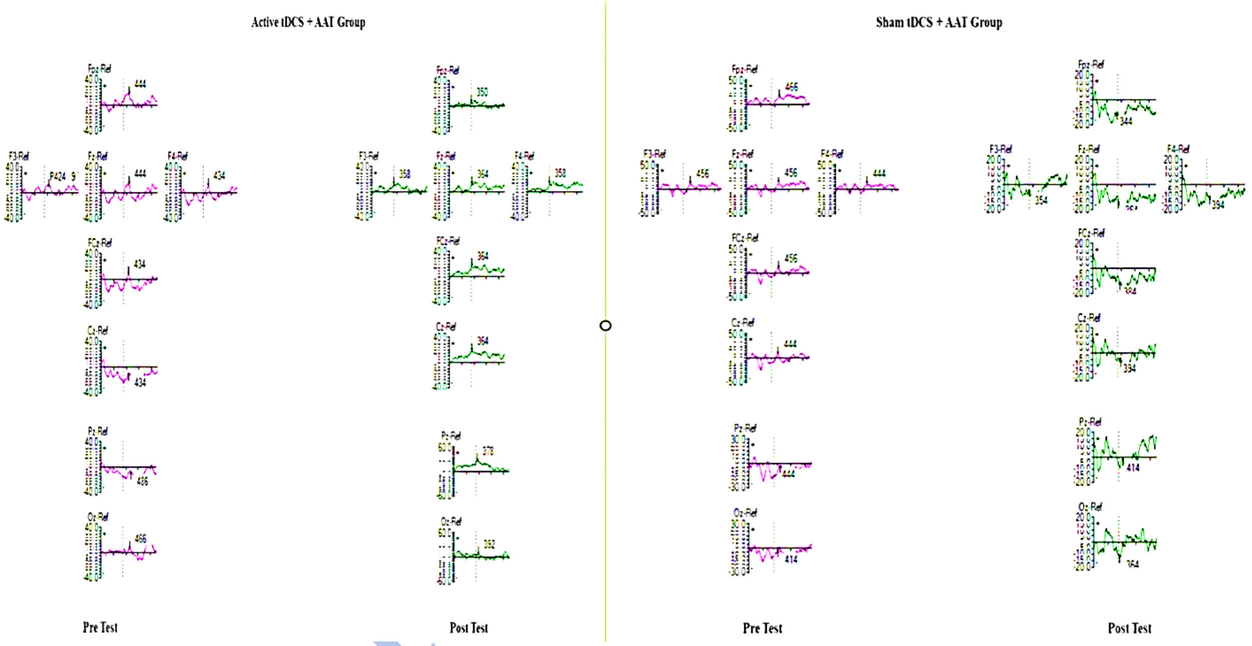

Figure 2. The auditory p300 wave latency in the groups.