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The Effects of Dynamic Spatial Hearing Rehabilitation Combined With Transcranial Electrical Stimulation on Speech Perception in Noise in Elderly Men: A Randomized Clinical Trial

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Abstract

Objectives: Speech perception problem in noise is the most common complaint among elderly people. Based on previous evidence, auditory training improves central auditory system plasticity in the elderly. The aim of the present study was to evaluate the effectiveness of the designed hearing rehabilitation program in overcoming this problem.

Materials and Methods: This randomized, controlled clinical trial was performed on 80 elderly people aged 60-75 years old who were randomly assigned to four equal groups. One group received only dynamic spatial hearing rehabilitation (DSHR) while the other group received the DSHR combined with transcranial direct current stimulation (DSHRWTDCS). Groups 3 and 4 were the control and sham groups, respectively. All participants were evaluated by behavioral and electrophysiological tests and a questionnaire was administered before, after, and one month after the end of the intervention.

Results: Based on the results of behavioral, electrophysiological tests and the intended questionnaire, there was a significant difference between the means of the second and third stages with the first stage in ODSHR and DSHRWTDCS groups. Further, there was a significant difference between the means of the second and third stages in both ODSHR and DSHRWTDCS groups and those of the other two groups.

Conclusions: The positive effects of the spatial hearing rehabilitation program with tDCS are confirmed by various aspects of self-assessment, electrophysiological and behavioral tests, and thus can be the basis for developing comprehensive rehabilitation programs.

Keywords: Elderly, Spatial hearing, Auditory rehabilitation, Transcranial electrical stimulation, Speech perception

Introduction

Spatial hearing is the ability to use the spatial evidence to detect the sound source, pay attention to the sound source, and receive the desired signal (especially speech) in noise. Spatial hearing tools comprise localization, distance estimation, signal distinguishing from noise, and attention to the sound source. These abilities are accomplished by the comparison of the interaural intensity difference and interaural time difference of the arrived signal at the ears. The use of this skill helps the listener to take advantage of the spatial separation of speech and noise sources to recognize the speech. The older people benefit less than young people from this advantage (1-6).

Although hearing loss resulting from aging is an inevitable phenomenon, the reduction in localization accuracy and the weakness of the use of spatial hearing are not purely related to hearing loss due to aging, and the difficulty of speech perception in the presence of noise in the elderly has been reported despite the normal hearing thresholds (2,7-11).

Considering the importance of the spatial hearing role, especially the correct localization in speech perception, some exercises can be used to increase the localization skill in addition to speech perception exercises in different signal-to-noise ratios in order to improve speech perception in noise, that is presenting a sentence among the speakers while noise source location is constant, the components of sentences are heard from different angles, and the person must repeat the sentence heard in this condition. Thus, it can be an appropriate practice in people with spatial auditory processing impairments to improve their speech perception in noise (12).

Fundamental studies have shown that a weak electrical direct current can effectively induce bilateral changes depending on the polarity in the cerebral cortex (13, 14). Recent findings indicate that transcranial direct current

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Key Messages

- Declined speech perception in noise, a common complaint in the elderly, in addition to deprivation of active life causes depression and isolation, which needs to be addressed.
- Dynamic spatial hearing rehabilitation as a specific audiological intervention alone or in combination with tDCS improves their spatial hearing processing and the ability to perception speech in noise.

stimulation (tDCS) can change perceptual auditory processing and thus can be used as a clinical tool to improve neuronal excitability and to treat hearing-related illnesses and speech processing, leading to improvements in speech perception in noise (15-18).

In old ages, the lack of speech communication in addition to the deprivation of active life causes depression and isolation. It seems that any action to reduce this problem (e.g., appropriate and timely rehabilitation) will have scientific and social justifications (19,20). Currently, there are no routine evaluations and rehabilitation of spatial hearing in audiology clinics. Considering that tDCS modulates spatial auditory processing and auditory scene analysis that improves the correct localization in noise, the aim of this study was to investigate the effects of a dynamic spatial hearing rehabilitation (DSHR) program in combination with tDCS on speech perception in noise in the elderly.

Materials and Methods

The current randomized clinical trial study was performed on 80 elderly men aged 60-75 years old with a mean age of 66.03 (SD = 4.66) after approval by the Ethics Committee of Tehran University of Medical Sciences.

The inclusion criteria included the mean of the thresholds of 500, 1000, 2000 Hz, less than or equal to 25 dB HL in both ears, and the threshold of each of the higher frequencies (3000-8000 Hz) alone, equal to, or less than 40 dB HL, and the auditory symmetry in both ears (with the maximum mean difference of the threshold for each similar frequency in both ears as 5 dB HL). Other criteria were having normal external auditory canals with intact tympanic membranes, and normal middle ear function (Type A tympanogram and present ipsilateral acoustic reflexes) according to (21), being right-handed (22), and being monolingual (Persian as the mother language). Moreover, other parameters were having mini-mental state evaluation (MMSE) scores greater than 21 so that having no apparent cognitive problems (23), having no history of ear diseases, head trauma, or accident, no head and neck surgery, and nervous system medications, and finally, not having neurological diseases and high blood pressure or uncontrolled diabetes and a statement of speech perception problem in the presence of noise. After completing the informed consent form, participants were randomly divided into four equal groups (n=20 in each group). One group received only dynamic spatial auditory rehabilitation (the ODSHR group). For this group, the designed exercises were administered in three months (12 weeks, 2 sessions weekly, and 1 hour each) in the center and on a daily basis at home. The other group was given DSHR combined with tDCS (the DSHRWTDCS group). In addition to the designed exercises for other groups, this group received tDCS during the three months (four sessions weekly in the first two weeks, and then one session per week, each session lasting for 20 minutes). The third group received no spatial hearing rehabilitation and tDCS (the sham group). The electrodes were placed on their heads although no electrical stimulation was applied during the three months according to the protocol timeline for the DSHRWTDCS group. The last group received no intervention in this period (the control group). For all participants, behavioral and electrophysiological auditory assessments were performed before the intervention, immediately, and one month after the end of the intervention.

Behavioral Assessments

Quick Speech in Noise Test

The Persian version of the QSIN (Quick Speech in Noise) test was used in the present study. This test consists of five lists which are equal to each other with the signal-to-noise ratio (SNR50) average of 0.35 dB (24). Each list contains 6 sentences with 5 keywords in each sentence in the presence of the babble noise (four-speaker). The material of this test, according to the amount of head-related transfer function, was spatially designed using MATLAB software (2016a version) and was binaurally presented using a player connected to the audiometer (from headphone-Virtual) with 70 dB intensity. The sentences were presented in the signal-to-noise ratio of 25, 20, 15, 10, 5, and 0 dB and reduced by 5 dB steps. The experimenter was asked to consider and repeat the sentences. A score was assigned to each keyword that was replicated correctly. The SNR loss index was calculated using the formula of 25.5 minus the total correct words repeated in a list. The norm of SNR loss is between -2.5 and +2.5 dB in this version.

Binaural Masking Level Difference

The binaural masking level difference (BMLD) test was applied to investigate the ability to use the release from masking. Masking level difference refers to the improvement in detecting a tone or speech in noise when the phase of the tone or the noise is reversed by 180 degrees. It aims to assess central auditory function and is specifically sensitive to brainstem lesions. The BMLD test includes two steps. In the first stage, the signal and noise are simultaneously provided to both ears with the same phase (S0N0) and the hearing threshold of the signal is obtained accordingly. In the second stage, the phase of the signal is reversed by 180 degrees (SπN0), and the threshold of the signal in the presence of noise is obtained accordingly. Then, the obtained thresholds in the first and second sections are deducted from each other and the threshold difference is recorded as the MLD (21). In this test, a pure tone of 500 Hz as signal and narrowband noise (NBN 500 Hz) with 60 dB intensity was used, and stimuli were provided using a two-channel clinical audiometer (Interacoustics AC40, Denmark).

Speech, Spatial, and Qualities of Hearing Scale (SSQ)

The Persian version of the SSQ questionnaire includes 47 items on three aspects of speech perception, spatial hearing, and hearing quality. Each item evaluates participants' abilities using a 10-point scale ranging from 0 to 10 representing the minimum and maximum abilities (25).

Electrophysiological Assessments

The long-latency response (LLR) test was performed using Bio-Logic Navigator (version 7.2.1). The test was carried out in a calm condition and a reclining position on a comfortable chair in a soundproof room with low light and low magnetic and electrical noise. The evoked potential was obtained by disc electrodes in which the active electrode in the Cz region and the reference electrode were placed on the two-way right and left mastoids (connected by a jumper) and a ground electrode was placed on the Fpz region. During the recording phase, impedance was kept below 5 kΩ and inter-electrode impedance was maintained below 2 kΩ. In this study, a speech stimulus (da) with 40 ms duration, 1/1 Hz rate, and the alternative polarity was presented binaurally with the intensity of 75 dB HL. (Calibrated with a 2 cm^3 DB0138 coupler audiometer, Bruel and Kjaer Type 2203, and a microphone with a 1 inch diameter). The amplification 50 k, the time window of 600 ms with a pre-stimulus time of 100 ms, a bandpass filter 0.1-100 Hz, and the sweep number 1000 was considered based on the aim of the study (21).

Dynamic Spatial Hearing Rehabilitation

The exercises were performed in three months (twelve weeks, every week twice one-hour sessions) in the center, and on a daily basis at home through the CD and CD player, in appropriate conditions and under headphones according to the instruction given to the person. In the designed exercises for the center, the target signals were used, including meaningless sentences and the competition noise (babble noise-four speakers). Each sentence contained 5 keywords that were dynamically presented (starting at +90° and ending at -90°), just like that sound source moves at a distance of one meter on a semicircular while the source of noise in both sides (±90°). These exercises were made using MATLAB software (version 2016a) and were bilaterally presented under headphones (virtual). The sentences and the noise were initiated at levels of 60 and 55 dBSPL, respectively, and then the level of intensity of sentences is changed in relation to the listener response. The intensity level of sentences increased by 4 dB following a wrong answer (Maximally repeats the two words correctly), and the 2 dB was reduced following a correct answer (Minimally repeat the three words correctly). By decreasing the signal-to-noise ratio, the training gradually became harder and continued until the individual in the signal-to-noise ratio of -10 dB correctly recognized at least three words from the entire sentence. Home-based exercises, including listening to a short story with restaurant or traffic noise, was designed spatial dynamically (3D) by MATLAB software for presentation under headphones (virtual). To ensure that the exercises were carried out at home, some questions were asked about the story each session. These exercises are designed to stimulate hearing skills such as auditory closure, Dichotic listening, work memory, auditory attention, and binaural integration.

Transcranial Direct Current Stimulation

For the electrical stimulation of the brain, the direct current was used, which was gradually increased from 0.5 to 2 mA (voltage = 9 V) using a pair of carbon-rubber electrodes (diameter = 21 mm, area = 3.5 cm^2) that were embedded in the salt solution-impregnated sponge and montaged with the anode/left - cathode/right array on the superior temporal gyrus (STG) area containing planum temporal and auditory cortex (T7, T8) with an impedance of less than 20 kΩ (17) during three months (in the first two weeks, four sessions in a week and then one session in a week) and each session lasted for 20 minutes.

Statistical Analysis

All data are reported as the mean and standard deviation (SD). Shapiro-Wilk test was used to evaluate the normal distribution of data. The results of QSIN and BMLD tests, the latency of the N1 wave, and the amplitude of the N1P2 complex in the LLR test represented no normal distribution for all three times and in all four groups. Therefore, non-parametric tests were applied for mean comparison. In addition, Kruskal-Wallis and Friedman tests were employed for the multiple comparisons of the means (between the groups) and the multiple comparisons of the means of all three steps simultaneously (within the groups), respectively. The results of the first (Speech perception) and second (Spatial hearing) sections of the SSQ questionnaire, and the latency of P1 and P2 waves from the LLR test had normal distributions at all three times and in each of the four groups. Thus, the repeated-measures ANOVA test was used to compare the means in each of the three stages within and between the groups. Finally, the statistical analysis of data was performed using SPSS, version 22, (SPSS Inc., Chicago, IL, the USA), and P values <0.05 were considered statistically significant for all tests.

Results

The Effects of DSHR and tDCS on Behavioral Assessments

Figure 1A shows the means (SD) of the SNR loss assessed by the QSIN test for the four study groups (in three stages of the assessment). The comparison of SNR loss means between the groups showed a significant difference between ODSHR and DSHRWTDCS groups with two other groups in the second and third stages (Table 1). Despite the greater impact of DSHR combined with tDCS compared to ODSHR on SNR loss mean reductions, no significant difference was observed between the ODSHR and DSHRWTDCS groups in the second and third stages (Table 1). The comparison of SNR loss means within groups during the time demonstrated that ODSHR and DSHRWTDCS groups had significant differences in the second and third stages with the first stage (Table 2). There was no significant difference between the SNR loss means after the intervention and one month after the end of the intervention in the ODSHR and DSHRWTDCS groups, indicating the durability of the effect of the interventions (Table 2).

The means (SD) of the MLD assessed by the BMLD test for the four study groups (in the three stages of the assessment) are depicted in Figure 1B. The comparison of MLD means between the groups represented a difference between the ODSHR and DSHRWTDCS groups with two other groups in the second and third stages (Table 1). Despite the greater effect of DSHR combined with tDCS compared to ODSHR on MLD means increases, no significant difference was found between the ODSHR and DSHRWTDCS groups in the second and third stages (Table 1). Based on the comparison of MLD means within groups during the time, the ODSHR and DSHRWTDCS groups revealed significant differences in the second and third stages with the first stage (Table 2). There was no significant difference between the MLD means after the intervention and one month after the end of the intervention in the ODSHR and DSHRWTDCS groups, demonstrating the durability of the effect of the interventions (Table 2).

Figure 1C-D illustrates the mean (SD) of the SSQ questionnaire section scores. In the speech perception section (Figure 1C), the comparison of mean scores between the groups showed a significant difference between the ODSHR and DSHRWTDCS groups and the two other groups in the second and third stages (Table 1). The difference between ODSHR and DSHRWTDCS groups was significant in the second and third stages, confirming the more impact of DSHR combined with tDCS in comparison with ODSHR on the increasing mean scores (Table 1). The comparison of mean scores within the groups during the time demonstrated that the mean scores had significant differences in the second and third stages compared with the first stage in ODSHR and DSHRWTDCS groups (Table 2). No significant difference was detected between the mean scores after the intervention and one month after the end of the intervention in the ODSHR and DSHRWTDCS groups, indicating the durability of the effects of the interventions (Table 2).

In the spatial hearing section (Figure 1D), the comparison of the mean scores between the groups showed the difference between ODSHR and DSHRWTDCS groups with the two other groups was significant in each of the second and third stages (Table 1). The difference between ODSHR and DSHRWTDCS groups was

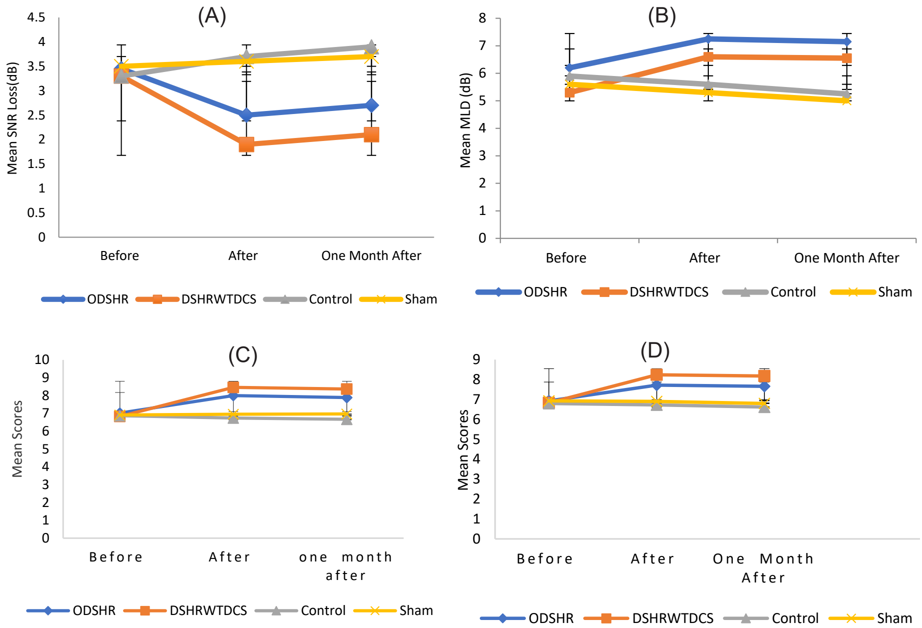

Figure 1. Mean (SD) of SNR Loss (A), MLD (B), Speech Perception Score (C), Spatial Hearing Score (D) in 4 Groups. Note. SD: standard deviation; SNR: Signal noise ratio; MLD: Masking level difference.

Table 1. The Statistical Analysis of Behavioral and Electrophysiological Test Results and SSQ Subscale Scores in Four Groups Immediately and One Month After the Intervention

Variable	Group	After		One Month After		df
		Z/F	*P*-value	Z/F	*P* Value	
SNR Loss	ODSHR-DSHRWTDCS	-1.701	0.089	-1.176	0.240	
	ODSHR-Control	-4.536	<0.001	-3.972	<0.001	
	DSHRWTDCS-Control	-4.967	<0.001	-4.557	<0.001	
	ODSHR-Sham	-3.637	<0.001	-3.204	<0.001	
	DSHRWTDCS-Sham	-4.313	<0.001	-3.809	<0.001	
	Control-Sham	-0.920	0.354	-0.928	0.471	3
MLD	ODSHR-DSHRWTDCS	-0.357	0.721	-0.302	0.762	
	ODSHR-Control	-3.435	0.001	-3.410	0.001	
	DSHRWTDCS-Control	-2.759	0.006	-2.801	0.005	
	ODSHR-Sham	-3.005	0.003	-2.910	0.004	
	DSHRWTDCS-Sham	-2.612	0.009	-2.612	0.009	
	Control-Sham	-0.343	0.732	-0.439	0.661	
Speech perception	ODSHR-DSHRWTDCS	79.637	<0 .001	78.768	<0 .001	
	ODSHR-Control	79.637	<0 .001	78.768	<0 .001	
	DSHRWTDCS-Control	79.637	<0.001	78.768	<0.001	
	ODSHR-Sham	79.637	<0 .001	78.768	<0 .001	
	DSHRWTDCS-Sham	79.637	<0 .001	78.768	<0 .001	
	Control-Sham	79.637	0 .652	78.768	0 .493	
Spatial hearing	ODSHR-DSHRWTDCS	52.232	0.004	50.640	<0 .001	
	ODSHR-Control	52.232	<0 .001	50.640	<0 .001	
	DSHRWTDCS-Control	52.232	<0.001	50.640	<0.001	3
	ODSHR-Sham	52.232	<0 .001	50.640	<0 .001	
	DSHRWTDCS-Sham	52.232	<0 .001	50.640	<0 .001	
	Control-Sham	52.232	0 .465	50.640	0.081	
LP1	ODSHR-DSHRWTDCS	66.154	0 .002	65.570	0.030	
	ODSHR-Control	66.154	<0.001	65.570	<0.001	
	DSHRWTDCS-Control	66.154	<0 .001	65.570	<0 .001	
	ODSHR-Sham	66.154	<0 .001	65.570	<0 .001	
	DSHRWTDCS-Sham	66.154	<0.001	65.570	<0.001	
	Control-Sham	66.154	0.994	65.570	0 .997	
LN1	ODSHR-DSHRWTDCS	2.813	0.030	2.810	0.020	
	ODSHR-Control	-3.705	0.001	-3.702	0.001	
	DSHRWTDCS-Control	-6.518	<0.001	-6.512	<0.001	3
	ODSHR-Sham	-3.698	0.001	-3.695	0.001	
	DSHRWTDCS-Sham	-6.502	<0.001	-6.505	0.001	
	Control- Sham	0.995	1.000	0.995	1.000	
LP2	ODSHR-DSHRWTDCS	24.415	0 .530	24.131	0.549	
	ODSHR- Control	24.415	<0.001	24.131	<0.001	
	DSHRWTDCS- Control	24.415	<0.001	24.131	<0.001	3
	ODSHR-Sham	24.415	<0.001	24.131	<0.001	
	DSHRWTDCS-Sham	24.415	<0.001	24.131	<0.001	
	Control-Sham	24.415	1.000	24.131	1.000	
N1-P2 Complex amplitude	ODSHR-DSHRWTDCS	-2.685	0.043	-2.698	0.042	
	ODSHR-Control	2.763	0.034	2.739	0.037	
	DSHRWTDCS-Control	5.449	<0.001	5.438	<0.001	3
	ODSHR-Sham	2.971	0.018	2.940	<0.001	
	DSHRWTDCS-Sham	5.656	<0.001	5.576	0.020	
	Control-Sham	0.208	1.000	0.201	1.000	

Note. ODSHR: Only dynamic spatial hearing rehabilitation; DSHRWTDCS: Dynamic spatial hearing rehabilitation combined with transcranial direct current stimulation; SSQ: Speech, Spatial, and Qualities of Hearing Scale; SNR: Signal noise ratio; MLD: Masking level difference; L: Latency.

Table 2. The Statistical Analysis of Behavioral Test Results and SSQ Subscale Scores Within Groups Before, Immediately, and One Month After the Intervention

Variable	Group	Stage	Z/F	*P*-value	df
SNR loss	ODSHR	Before - After	-3.945	<0.001	
		Before - One month after	-3.690	<0.001	
		After - One month after	-1.011	0.493	
	DSHRWTDCS	Before - After	-3.839	<0.001	
		Before - One month after	-3.619	<0.001	
		After - One month after	-1.431	0.656	
	Control	Before - After	-1.124	0.561	
		Before - One month after	-1.412	0.484	
		After - One month after	0.011	0.895	
	Sham	Before - After	-1.113	0.740	
		Before - One month after	-1.123	0.462	
		After - One month after	0.015	0.923	
MLD	ODSHR	Before - After	-4.185	<0.001	2
		Before - One month after	-3.945	<0.001	
		After - One month after	-1.414	0.157	
	DSHRWTDCS	Before - After	-4.099	<0.001	
		Before - One month after	-4.134	<0.001	
		After - One month after	-1.000	0.317	
	Control	Before - After	-1.326	0.198	
		Before - One month after	-1.425	0.781	
		After - One month after	-1.000	0.317	
	Sham	Before - After	-1.245	0.541	
		Before - One month after	-1.143	0.765	
		After - One month after	-2.000	0.083	
Speech perception	ODSHR	Before - After	67.222	0.003	
		Before - One month after	67.222	0.004	
		After - One month after	67.222	0.352	
	DSHRWTDCS	Before - After	518.956	0.005	
		Before - One month after	518.956	0.007	
		After - One month after	518.956	0.259	
	Control	Before - After	9.648	0 .075	
		Before - One month after	9.648	0.151	
		After - One month after	9.648	0.097	
	Sham	Before - After	4.643	0.182	
		Before - One month after	4.643	0.089	
		After - One month after	4.643	0.644	
Spatial hearing	ODSHR	Before - After	162.86	<0.001	2
		Before - One month after	162.86	<0.001	
		After - One month after	162.86	0.182	
	DSHRWTDCS	Before - After	942.48	<0.001	
		Before - One month after	942.48	<0.001	
		After - One month after	942.48	0.365	
	Control	Before - After	76.701	0.225	
		Before - One month after	76.701	0.103	
		After - One month after	76.701	0.115	
	Sham	Before - After	11.047	0.352	
		Before - One month after	11.047	0.524	
		After - One month after	11.047	0.252	

Note. ODSHR: Only dynamic spatial hearing rehabilitation; DSHRWTDCS: Dynamic spatial hearing rehabilitation combined with transcranial direct current stimulation; SSQ: Speech, Spatial, and Qualities of Hearing Scale; SNR: Signal noise ratio; MLD: Masking level difference.

significant in the second and third stages, representing the more impact of DSHR combined with tDCS compared with ODSHR on increasing the mean scores (Table 1). There was a significant difference between ODSHR and DSHRWTDCS groups in the second and third stages (Table 1). Based on the comparison of the within-groups mean scores during the time, mean scores had significant differences in the second and third stages compared with the first stage in the DSHRWTDCS group (Table 2). There was no significant difference between the mean scores after the intervention and one month after the end of the intervention in the ODSHR and DSHRWTDCS groups (Table 2). Moreover, no significant difference was found between the mean scores after the intervention and one month after the end of the intervention in the ODSHR and DSHRWTDCS groups, indicating the durability of the effects of the interventions (Table 2).

The Effects of Dynamic Spatial Hearing Rehabilitation and tDCS on Electrophysiological Assessments

Figure 2A depicts the mean (SD) of the latency of the P1 wave assessed by the LLR test for the four study groups (in three stages of assessment). The comparison of the P1 latency mean between the groups revealed that the difference between ODSHR and DSHRWTDCS groups and the two other groups was significant in each of the second and third stages (Table 1). Additionally, the difference between ODSHR and DSHRWTDCS groups was significant in the second and third stages, showing further impacts of DSHR combined with tDCS compared to ODSHR on the reduction of the P1 latency mean, and the difference between ODSHR and DSHRWTDCS groups was significant in each of the second and third stages (Table 1). The comparison of P1 latency mean within groups during the time showed P1 latency mean in each of the second and third stages with the first stage had significant differences in ODSHR and DSHRWTDCS groups (Table 3). There was no significant difference between the P1 latency mean after the intervention within one month after the end of the intervention in each of the ODSHR and DSHRWTDCS groups, implying the durability of the effects of the intervention (Table 3).

The data related to the mean (SD) of the latency of N1 wave evaluated by the LLR test for the four study groups (in three stages of assessment) are shown in Figure 2B. The comparison of the N1 latency mean between groups demonstrated the difference between ODSHR and DSHRWTDCS groups and the two other groups was significant in each of the second and third stages (Table 1). Further, the difference between ODSHR and DSHRWTDCS groups was significant in each of the second and third stages, showing the more effect of DSHR combined with tDCS compared with ODSHR on N1 latency mean reductions (Table 1). The comparison of the N1 latency mean within groups during the time represented that the N1 latency mean in each of the second and third stages with the first stage had significant differences in the ODSHR and DSHRWTDCS groups (Table 3). There was no significant difference between the N1 latency mean after the intervention with one month after the end of the intervention in each of the ODSHR and DSHRWTDCS groups, indicating the durability of the effect of interventions (Table 3).

Figure 2C illustrates the mean (SD) of the latency

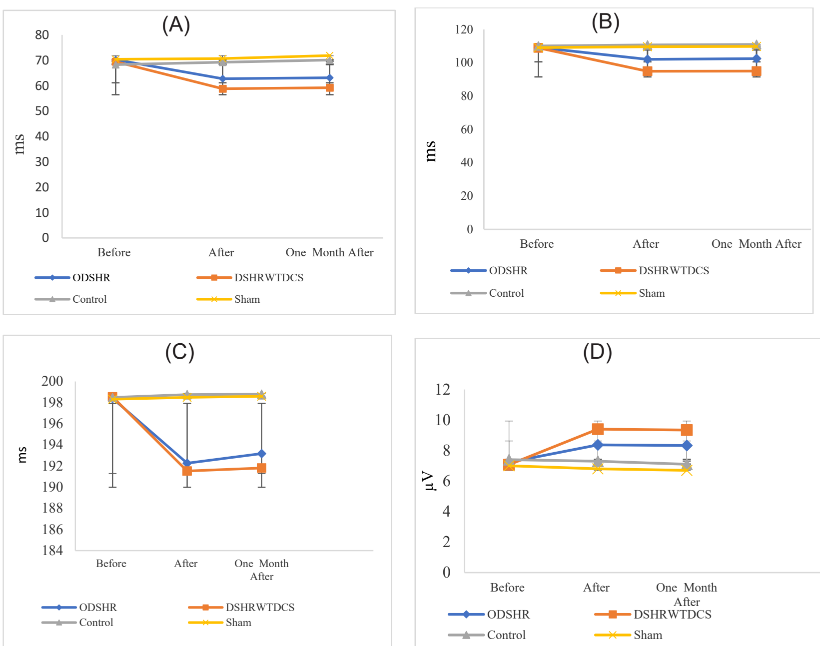

Figure 2. Mean (SD) Latencies of P1 (A), N1 (B), and P2 (C), and N1-P2 Amplitude (D) in Four Groups. Note. SD: standard deviation; µV: Micro volte; Ms: Millisecond.

Table 3. The Statistical Analysis of Electrophysiological Test Results Within Groups Before, Immediately, and One Month After the Intervention

Variable	Group	Stage	*P*-value	Z/F	df
LP1	ODSHR	Before - After	<0 .001	2.166	2
		Before - One month after	<0 .001		
		After - One month after	0.452		
	DSHRWTDCS	Before - After	<0 .001	2.635	
		Before - One month after	<0 .001		
		After - One month after	0.253		
	Control	Before - After	0.153	507.594	
		Before - One month after	0.098		
		After - One month after	0.376		
	Sham	Before - After	0.258	579.840	
		Before - One month after	0.058		
		After - One month after	0.841		
LN1	ODSHR	Before - After	<0.001	-5.850	2
		Before - One month after	<0.001	-4.185	
		After - One month after	0.081	-2.214	
	DSHRWTDCS	Before - After	<0.001	-5.376	
		Before - One month after	<0.001	-4.099	
		After - One month after	0.618	-1.265	
	Control	Before - After	0.157	-1.414	
		Before - One month after	0.180	-1.342	
		After - One month after	0.317	-1.000	
	Sham	Before - After	0.245	-1.342	
		Before - One month after	0.569	-1.342	
		After - One month after	1.000	0.000	
LP2	ODSHR	Before - After	<0.001	212.332	2
		Before - One month after	<0.001		
		After - One month after	0 .058		
	DSHRWTDCS	Before - After	<0.001	251.259	
		Before - One month after	<0.001		
		After - One month after	0 .152		
	Control	Before - After	0.268	4.257	
		Before - One month after	0.079		
		After - One month after	0.441		
	Sham	Before - After	0.463	3.265	
		Before - One month after	0.146		
		After - One month after	0.497		
N1-P2 Complex amplitude	ODSHR	Before - After	<0.001	-5.613	2
		Before - One month after	<0.001	-3.874	
		After - One month after	0.246	1.739	
	DSHRWTDCS	Before - After	<0.001	-5.850	
		Before - One month after	0.001	-3.637	
		After - One month after	0.081	2.214	
	Control	Before - After	1.000	0.000	
		Before - One month after	0.185	-1.340	
		After - One month after	0.180	-1.342	
	Sham	Before - After	0.317	-1.000	
		Before - One month after	0.320	-1.000	
		After - One month after	1.000	0.000	

Note. ODSHR: Only dynamic spatial hearing rehabilitation; DSHRWTDCS: Dynamic spatial hearing rehabilitation combined with transcranial direct current stimulation; L: Latency.

of P2 wave examined by the LLR test for the four study groups (in three stages of assessment). The comparison of P2 latency mean between groups showed the difference between ODSHR and DSHRWTDCS groups and the two other groups was significant in each of the second and third stages (Table 1). Despite the greater impact of DSHR combined with tDCS compared to ODSHR on reducing the P2 latency mean, the difference between ODSHR and DSHRWTDCS groups was not significant in each of the second and third stages (Table 1). The results related to the comparison of P2 latency mean within groups during the time indicated that the P2 latency mean in each of the second and third stages with the first stage had significant differences in ODSHR and the DSHRWTDCS groups. No significant difference was found between the P2 latency mean after the intervention with one month after the end of the intervention in each of the ODSHR and DSHRWTDCS groups, confirming the durability of the effects of the intervention (Table 3).

The mean (SD) of N1-P2 amplitude waves assessed by the LLR test for the four study groups (in three stages of assessment) is depicted in Figure 2D. The comparison of N1-P2 amplitude means between the groups revealed a significant difference between the ODSHR and DSHRWTDCS groups and the two other groups in each of the second and third stages (Table 1). The difference between ODSHR and DSHRWTDCS groups was significant in each of the second and third stages, showing the more impact of DSHR combined with tDCS in comparison with ODSHR on the N1-P2 amplitude mean increase (Table 1). Based on the comparison of the N1-P2 amplitude mean within groups during the time, the N1-P2 amplitude mean in each of the second and third stages with the first stage had significant differences in ODSHR and DSHRWTDCS groups (Table 3). There was no significant difference between the N1-P2 amplitude mean after the intervention and one month after the end of the intervention in each of ODSHR and DSHRWTDCS groups, indicating the durability of the effect of interventions (Table 3). Furthermore, the differences between control and sham groups were not significant in each of the second and third stages (between groups), and the means in the second and third stages of the evaluation were worse than those of the first stage and there was no significant difference between the means in the second and third stages compared with the first stage. Eventually, no significant difference was detected between the means in the second and third stages (within groups) in all behavioral and electrophysiological tests and SSQ subscale scores (Tables 1, 2, and 3).

Discussion

Many previous studies have emphasized the reduction of auditory processing skills and the problem of speech perception in noise in the elderly. Processing skills related to the binaural auditory can also be investigated with two approaches. The bottom-up approach focuses on skills such as orientation and localization and the up-down approach that deals with phenomena such as attention and dichotic listening (8-11,26).

This study sought to investigate the effect of above-mentioned skills on how to make changes and on the developmental possibility of rehabilitation methods based on these phenomena. Although many studies have already been conducted on the issue of speech perception in noise in the elderly, many of them were unable to differentiate between the effects of peripheral hearing loss and cognitive impairments on speech perception ability, on the one hand, and pure processing impairments on the other hand (9).

In the present study, it was attempted to select the elderly people whose peripheral hearing was normal, and based on the MMSE test, they had no cognitive problem despite the existence of speech perception problem in a noisy environment, according to their personal statement to examine the net aging effect on central auditory processing and the development possibility of the skills associated with this process through rehabilitation.

To survey the development possibility of processing skills related to spatial hearing, the DSHR program was designed and combined with transcranial electrical stimulation. This program focused on binaural hearing skills and speech perception.

The intervention effect was evaluated by self-assessment, behavioral, and electrophysiological tests. It was determined that the designed rehabilitation program combined with tDCS improved the results of behavioral tests (QSIN and BMLD), the SSQ questionnaire score, and the auditory electrophysiological test (LLR).

The improvement of behavioral test results indicated the efficacy of the rehabilitation program on these skills. Additionally, in the self-assessment, the participated elderly had a better function in items related to communication skills based on speech perception in a noisy environment, attention, and the separation of the auditory stream. The results of the electrophysiological test showed amplitude increments while reductions in the latency waves of the LLR test (an increase in nerve conduction velocity).

The above results in the group receiving tDCS in addition to the DSHR program were better compared to other groups, confirming the tDCS facilitating effect on the designed rehabilitation program.

In the context of the effectiveness of hearing rehabilitation programs on speech perception in noise in the elderly, multiple studies showed the positive effect of these programs on speech perception in noise in the elderly using verbal and nonverbal stimuli and emphasizing perceptual skills such as the discrimination of monosyllabic from disyllabic and the discrimination and determination of the order of presented pure tones, the localization of the signal source and cognitive skills such as working memory, along with the motor and visual exercises (27-35).

Regarding the effect of the reduction of the localization ability and spatial auditory processing, thereby reducing speech perception ability in noise in the elderly, when the stimulus is presented from different angles in a free field (36,37), it can improve speech perception in noise. This is different from experiments where the signal is presented from different directions (29,38) or it moves from one side to the other while using the constant noise source.

The findings of the present study are consistent with those of all the above-mentioned studies, demonstrating the effectiveness of DSHR on speech perception in noise in the old men after three months of practice and their survival after one month from the end of the intervention.

Different studies used electrophysiological tests as objective tests to investigate the effect of auditory rehabilitation and plasticity (39). For instance, Alain et al confirmed the effect of a one-hour exercise on the amplitude increasing of speech LLR waves (40). The amplitude increasing and reductions in the latency of recorded waves were reported in some studies after the completion of rehabilitation sessions (39, 40).

In the present study, an increase in the amplitude and a reduction in the latency of recorded LLR waves with the speech stimulus were observed after the end of intervention sessions, which was significantly different with the control group, indicating an increase in nerve conduction velocity.

The tDCS can increase the cognitive function depending on the region being stimulated, which improves auditory processing and increases the range of attention and memory (16). The tDCS does not initiate the action potential although it is more likely to affect the firing rate of neuronal cells during the super-threshold stimulation (14). The tDCS causes cell migration, electro taxis phenomena, cellular orientation, changes in the general functions of the cell to differentiation and metabolic changes (14). Although the mechanism of action has not been clearly identified, changes in the orientation, migration rate, and the growth of the neural cell after the electrical stimulation of the brain can be justified by altering the concentration location of the intracellular calcium ion (14, 16).

In addition, the change of the non-symmetric location of receptors in the cell membrane, including acetylcholine receptors and tropomyosin-receptor-kinase (TrK) families and accumulations at one end of the electric field causes the electrotaxis phenomenon. The tDCS can also change the synapse of N-methyl-d-aspartate (NMDA) receptors and change GABAergic synaptic activity (14).

These changes increase when the post-synaptic membrane is depolarized on the cellular body or dendrite. The electrical stimulation of the brain facilitates the opening of voltage-dependent ion channels and the function of NMDA receptors by removing magnesium blocker ions. Another factor that plays a role in neuromodulatory action is a change in the expression of the brain-derived neurotrophic factor (41).

Although the anodal stimulation of approximately 0.75 mA increases the amplitude of the peak of the excitatory postsynaptic potential, this is impossible in the absence of brain-derived neurotrophic factor or when TrkB receptors are blocking (14,16,42). In total, the continuous electric field affects several different tissues (i.e., vessels and connective tissues) and pathophysiologic mechanisms (inflammation and cell migration). Further, the effects of electrical stimulation have been observed in several cell structures such as membrane, mitochondria, and cytoskeleton. As stated above, this stimulation can affect the non-neuronal components of the central nervous system (CNS). This theory is confirmed by the expansion of cerebral vessels under the anode electrode (42).

The mechanism of the tDCS effect is not completely clear. This mechanism may have various synaptic and non-synaptic effects on neuronal and non-neuronal cells and CNS tissues (14,42). New research shows that the use of amplifier sessions in many subsequent weeks (weekly or biweekly) is highly helpful in maintaining the achieved therapeutic effects (41).

There is little information about the effect of tDCS on the excitability of the auditory system (16,17). The effect of tDCS on the activity of the auditory nerve is a multifactor phenomenon in which the arousal level is strongly influenced by perceptual processes and the amount of the provided stimulation. If the stimulation is more than the optimal level, the result will be reversed, thus it will worsen the function of the CNS (15,18).

Auditory processing disorder due to the function reduction of the auditory cortex can be compensated by increasing the nervous excitability of the auditory cortical. Therefore, the electrical stimulation of the auditory cortex can be a background for the treatment of pathologies associated with speech processing (16).

In a review article by Heimrath et al about the effect of brain electrical stimulation on the central auditory system function, it was revealed that the electrical stimulation of the brain, according to the target area and the intended training type, increased auditory attention (increases in the amplitude of the mismatch negativity wave), verbal auditory working memory, temporal resolution, and the amplitude of P50 and N1 waves, as well as affecting the discrimination of pitch and phonemes (16).

Limited research is available in the context of the tDCS effect on the spatial aspects of auditory scene analysis, which requires similar conditions to a cocktail party. A special spatial auditory location is required to separate the signal source from other intervening sources in addition to the location-encoding process (17).

Zündorf et al conducted a study in the context of the effective areas of the cortex in localization in a similar condition to the cocktail party, and the results of the functional magnetic resonance imaging indicated that effective areas in localization include planum temporal and inferior frontal gyrus (43).

Recent findings demonstrated that anodal electrical stimulation in the STG region affects speech perception (44). In a study by Wang et al on patients with aphasia, it was revealed that the anodal stimulation of left STG improves speech perception (45). You et al also showed that tDCS with anode left/cathode right montage in the STG area improves speech perception in patients with a stroke (46). Lewald et al reported that brain electrical stimulation with anode left/cathode right montage in the STG region (T7, T8) improves the localization accuracy of the pseudo-word stimulus from other disturbing sources provided by 4 speakers (the cocktail party condition) while decreasing errors in the response to normal people (17).

In the recent study, owing to the effect of electrical stimulation with anode left/cathode right montage in the STG area of the localization. The results of the present study represented that DSHR combined with transcranial electrical stimulation, according to the mentioned protocol, had a significant superiority in the scores of the SSQ questionnaire and the results of the electrophysiological test in comparison to DSHR alone. However, this superiority can also be observed in QSIN, BMLD, and latency of P2 in the LLR test although this difference was not significant. Probably an increase in the presentation duration or stimulation sessions can have better results.

Therefore, tDCS can be used as a facilitator in auditory hearing rehabilitation, especially spatial hearing, in order to improve speech perception in the presence of noise.

Regarding the effect of age, hand superiority, and gender (47) on the results, those within similar age ranges, right-handed, and only male elderly people were included in this study.

It is believed that with an increase in age, the nervous system structure changes and the pattern of the learned behavior at the end of the rehabilitation sessions will return the person to the normal state. The living environment and the individual's needs reinforce the acquired pattern and affect survival (2,27,28). Hearing aids only compensate for the decrease in sensitivity, but cannot resolve the problems of speech perception in the presence of noise (27). Moreover, our findings showed that spatial hearing plasticity is possible in the elderly era. The results of this study emphasize the need for the development of rehabilitation programs for different groups of elderly people who also have different needs. Even the elderly who use hearing aids and continue to suffer from speech perception problems in the presence of noise could benefit from such a rehabilitation program.

Conclusions

Age increasing has adverse effects on auditory processing such as decreased speech perception, especially in the presence of another competitive signal. The positive effects of the program of hearing rehabilitation designed with the electrical stimulation of the brain as a facilitator to overcome this problem in the elderly were confirmed by various aspects of self-assessment, electrophysiological and behavioral tests, and might be the basis for developing comprehensive rehabilitation programs for improving the elderly's central auditory processing skills.

Limitations

This study did not examine the relevance of speech perception and auditory processing ability to the active memory capacity, which is one of the limitations of our study. In addition, considering the low number of elderly people with normal hearing, the variable of education was not considered, which could have affected our results.

Authors' Contribution

MA, MAG, and GM: Study concept and design. MA: Acquisition of data and drafting the manuscript. MAG and GM: Study supervision and critical revision of the manuscript for important intellectual content. SJ: Statistical analysis. HS: Technical and material support. All authors read and approved the study.

Conflict of Interests

The authors declare that they have no competing interests.

Ethical Issues

This article is based on a PhD dissertation by Majid Ashrafi. The study was approved by the Ethical Committee of Tehran University of Medical Sciences, Tehran, Iran (IR TUMS FNM.REC.1397.025) and supported by Grant No. 97-02-32-38674 from Tehran University of Medical Sciences. The study was confirmed by the Iranian Registry of Clinical Trials (with the registration reference IRCT20160131026279N2).

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References

1. Andreeva IG. Spatial selectivity of hearing in speech recognition in speech-shaped noise environment. Human Physiol. 2018;44(2):226-236. doi:10.1134/S0362119718020020
2. Adel Ghahraman M, Ashrafi M, Mohammadkhani G, Jalaie S. Effects of aging on spatial hearing. Aging Clin Exp Res. 2020;32(4):733-739. doi:10.1007/s40520-019-01233-3
3. Kumpik DP, King AJ. A review of the effects of unilateral hearing loss on spatial hearing. Hear Res. 2019;372:17-28. doi:10.1016/j.heares.2018.08.003
4. Rennies J, Kidd G. Is there spatial release from listening effort in noise and reverberation? J Acoust Soc Am. 2018;143(3):1938. doi:10.1121/1.5036340
5. Wenzel EM, Begault DR, Godfroy-Cooper M. Perception of spatial sound. In: Immersive Sound. Routledge; 2017:5-39.
6. Van Esch TE, Lutman ME, Vormann M, et al. Relations between psychophysical measures of spatial hearing and self-reported spatial-hearing abilities. Int J Audiol. 2015;54(3):182-189. doi

:10.3109/14992027.2014.953216
7. Eddins AC, Ozmeral EJ, Eddins DA. How aging impacts the encoding of binaural cues and the perception of auditory space. Hear Res. 2018;369:79-89. doi:10.1016/j.heares.2018.05.001
8. Freigang C, Richter N, Rübsamen R, Ludwig AA. Age-related changes in sound localisation ability. Cell Tissue Res. 2015;361(1):371-386. doi:10.1007/s00441-015-2230-8
9. Glyde H, Hickson L, Cameron S, Dillon H. Problems hearing in noise in older adults: a review of spatial processing disorder. Trends Amplif. 2011;15(3):116-126. doi:10.1177/1084713811424885
10. Morita K, Osawa T, Toyoda K, Sakashita J, Toi T. Characteristics of horizontal sound localization of elderly individuals. Proc Meet Acoust. 2018;35(1):050006. doi:10.1121/2.0000994
11. Peng J, Zhao L, Jiang Y. Investigation of word recognition for the elderly in speech and noise spatial separation. Appl Acoust. 2019;153:48-52. doi:10.1016/j.apacoust.2019.04.013
12. Lotfi Y, Samadi-Qaleh-Juqy Z, Moosavi A, Sadjedi H, Bakhshi E. The effects of spatial auditory training on speech perception in noise in the elderly. Crescent J Med Biol Sci. 2020;7(1):40-46.
13. Nitsche MA, Cohen LG, Wassermann EM, et al. Transcranial direct current stimulation: state of the art 2008. Brain Stimul. 2008;1(3):206-223. doi:10.1016/j.brs.2008.06.004
14. Pelletier SJ, Cicchetti F. Cellular and molecular mechanisms of action of transcranial direct current stimulation: evidence from in vitro and in vivo models. Int J Neuropsychopharmacol. 2014;18(2):pyu047. doi:10.1093/ijnp/pyu047
15. Hanenberg C, Getzmann S, Lewald J. Transcranial direct current stimulation of posterior temporal cortex modulates electrophysiological correlates of auditory selective spatial attention in posterior parietal cortex. Neuropsychologia. 2019;131:160-170. doi:10.1016/j.neuropsychologia.2019.05.023
16. Heimrath K, Fiene M, Rufener KS, Zaehle T. Modulating human auditory processing by transcranial electrical stimulation. Front Cell Neurosci. 2016;10:53. doi:10.3389/fncel.2016.00053
17. Lewald J. Modulation of human auditory spatial scene analysis by transcranial direct current stimulation. Neuropsychologia. 2016;84:282-293. doi:10.1016/j.neuropsychologia.2016.01.030
18. Zaehle T, Beretta M, Jäncke L, Herrmann CS, Sandmann P. Excitability changes induced in the human auditory cortex by transcranial direct current stimulation: direct electrophysiological evidence. Exp Brain Res. 2011;215(2):135-140. doi:10.1007/s00221-011-2879-5
19. Daugherty JA. The Relationship between Hearing Status and Cognitive Performance and the Influence of Depressive Symptoms in the Older Adult [dissertation]. University of South Florida; 2015.
20. Sadoughi F, Shahi M, Ahmadi M, Davaridolatabadi N. The comparison of the minimum data set for elderly health in selected countries. Acta Inform Med. 2015;23(6):393-397. doi:10.5455/aim.2015.23.393-397
21. Katz J, Chasin M, English KM, Hood LJ, Tillery KL. Handbook of Clinical Audiology. 7th ed. Philadelphia: Wolters Kluwer Health; 2015.
22. Williams SM. Handedness inventories: Edinburgh versus Annett. Neuropsychology. 1991;5(1):43-48. doi:10.1037/0894-4105.5.1.43
23. Mitchell AJ. The Mini-Mental State Examination (MMSE): update on its diagnostic accuracy and clinical utility for cognitive disorders. In: Larner AJ, ed. Cognitive Screening Instruments: A Practical Approach. Cham: Springer; 2017:37-48. doi:10.1007/978-3-319-44775-9_3
24. Shayanmehr S, Tahaei AA, Fatahi J, Jalaie S, Modarresi Y. Development, validity and reliability of Persian quick speech in noise test with steady noise. Audit Vestib Res. 2015;24(4):234-244.
25. Lotfi Y, Nazeri AR, Asgari A, Moosavi A, Bakhshi E. Iranian version of speech, spatial, and qualities of hearing scale: a psychometric study. Acta Med Iran. 2016;54(12):756-764.
26. Henkin Y, Yaar-Soffer Y, Givon L, Hildesheimer M. Hearing with two ears: evidence for cortical binaural interaction during auditory processing. J Am Acad Audiol. 2015;26(4):384-392. doi:10.3766/jaaa.26.4.6
27. Anderson S, Kraus N. Auditory training: evidence for neural plasticity in older adults. Perspect Hear Hear Disord Res Res Diagn. 2013;17:37-57. doi:10.1044/hhd17.1.37
28. Anderson S, White-Schwoch T, Choi HJ, Kraus N. Training changes processing of speech cues in older adults with hearing loss. Front Syst Neurosci. 2013;7:97. doi:10.3389/fnsys.2013.00097
29. Delphi M, Lotfi Y, Moossavi A, Bakhshi E, Banimostafa M. Envelope-based inter-aural time difference localization training to improve speech-in-noise perception in the elderly. Med J Islam Repub Iran. 2017;31:36. doi:10.14196/mjiri.31.36
30. Kim J, Lee K. Effects on word and sentence recognition by auditory training using environmental sound for elderly hearing impaired. Audiol Speech Res. 2017;13(2):115-122. doi:10.21848/asr.2017.13.2.115
31. Moradi S, Wahlin A, Hällgren M, Rönnberg J, Lidestam B. The efficacy of short-term gated audiovisual speech training for improving auditory sentence identification in noise in elderly hearing aid users. Front Psychol. 2017;8:368. doi:10.3389/fpsyg.2017.00368
32. Morais AA, Rocha-Muniz CN, Schochat E. Efficacy of auditory training in elderly subjects. Front Aging Neurosci. 2015;7:78. doi:10.3389/fnagi.2015.00078
33. Recanzone G. The effects of aging on auditory cortical function. Hear Res. 2018;366:99-105. doi:10.1016/j.heares.2018.05.013
34. Shojaei E, Ashayeri H, Jafari Z, Zarrin Dast MR, Kamali K. Effect of signal to noise ratio on the speech perception ability of older adults. Med J Islam Repub Iran. 2016;30:342.
35. Vitti SV, Blasca WQ, Sigulem D, Torres Pisa I. Web-based auditory self-training system for adult and elderly users of hearing aids. Stud Health Technol Inform. 2015;216:168-172.
36. Morita K, Osawa T, Toyoda K, Sakashita J, Toi T. Characteristics of horizontal sound localization of elderly people and analysis of its potential influential factors. J Acoust Soc Am. 2018;144(3):1861. doi:10.1121/1.5068185
37. Ouda L, Profant O, Syka J. Age-related changes in the central auditory system. Cell Tissue Res. 2015;361(1):337-358. doi:10.1007/s00441-014-2107-2
38. Firszt JB, Reeder RM, Dwyer NY, Burton H, Holden LK. Localization training results in individuals with unilateral severe to profound hearing loss. Hear Res. 2015;319:48-55. doi:10.1016/j.heares.2014.11.005
39. Anderson S, Jenkins K. Electrophysiologic assessment of auditory training benefits in older adults. Semin Hear. 2015;36(4):250-262. doi:10.1055/s-0035-1564455
40. Alain C, Campeanu S, Tremblay K. Changes in sensory evoked responses coincide with rapid improvement in speech identification performance. J Cogn Neurosci. 2010;22(2):392-403. doi:10.1162/jocn.2009.21279
41. Sellaro R, Nitsche MA, Colzato LS. Transcranial direct current stimulation. In: Colzato LS, ed. Theory-Driven Approaches to Cognitive Enhancement. Cham: Springer; 2017:99-112.

doi:10.1007/978-3-319-57505-6_8
42. Giordano J, Bikson M, Kappenman ES, et al. Mechanisms and effects of transcranial direct current stimulation. Dose Response. 2017;15(1):1559325816685467. doi:10.1177/1559325816685467
43. Zündorf IC, Lewald J, Karnath HO. Neural correlates of sound localization in complex acoustic environments. PLoS One. 2013;8(5):e64259. doi:10.1371/journal.pone.0064259
44. Zoefel B, Davis MH. Transcranial electric stimulation for the investigation of speech perception and comprehension. Lang Cogn Neurosci. 2017;32(7):910-923. doi:10.1080/23273798.2016.1247970
45. Wang J, Wu D, Chen Y, Yuan Y, Zhang M. Effects of transcranial direct current stimulation on language improvement and cortical activation in nonfluent variant primary progressive aphasia. Neurosci Lett. 2013;549:29-33. doi:10.1016/j.neulet.2013.06.019
46. You DS, Kim DY, Chun MH, Jung SE, Park SJ. Cathodal transcranial direct current stimulation of the right Wernicke's area improves comprehension in subacute stroke patients. Brain Lang. 2011;119(1):1-5. doi:10.1016/j.bandl.2011.05.002
47. Zündorf IC, Karnath HO, Lewald J. Male advantage in sound localization at cocktail parties. Cortex. 2011;47(6):741-749. doi:10.1016/j.cortex.2010.08.002