Preliminary Evaluation of a Computerized Auditory Training Program to Enhance Binaural Listening Skills in Children with Specific Learning Disabilities

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ABSTRACT

Objectives

Binaural processing deficits are commonly observed in children with specific learning disabilities (SLD). These deficits can significantly hinder learning, specifically in noisy environments, making rehabilitating binaural processing crucial. This study aimed to implement an auditory training program based on binaural interaction tasks at the brainstem level in children with learning disabilities who exhibit binaural processing issues and to assess its effectiveness.

Materials & Methods

A sample of fourteen children diagnosed with SLD was randomly divided into intervention (n=7) and control groups (n=7). The intervention group participated in a 12-week auditory training program based on binaural interaction. The training exercises were designed with modifications to a test battery classified as assessments of binaural interaction. Pre- and post-intervention assessments included masking level difference and Persian auditory recognition of words-in-noise tests.

Results

The Wilcoxon signed-rank test showed a statistically significant change in the masking level difference and Persian auditory recognition of words-in-noise results from pre- to post-intervention within the intervention group. Additionally, a nonparametric analysis of covariance indicated a significant difference in post-intervention outcomes between the two groups, with both assessments showing a meaningful effect from the rehabilitation ($p < 0.05$).

Conclusion

This study's findings suggest that computerized auditory training focused on binaural interactions may effectively address binaural processing challenges in children with SLD. Further research is recommended to confirm these initial findings and explore the benefits of binaural auditory training for social communication in this population.

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Introduction

A specific learning disability (SLD), classified as a neurodevelopmental disorder, is diagnosed in children who, despite having normal intelligence, struggle to acquire age-appropriate skills in areas such as written expression, reading, and mathematics (1).

Children with SLD often encounter difficulties in processing auditory information (2). Among these challenges, deficits in binaural interaction significantly affect their ability to comprehend speech in noisy environments and accurately localize sounds (3, 4). Binaural interaction begins at the brainstem and continues through the higher levels of the central auditory pathways (5, 6). The benefits of binaural hearing significantly rely on the proper interaction between the acoustic inputs from both ears at the brainstem level (5).

Abnormalities in *assessment* results related to binaural interaction and speech recognition in noise have been observed in children with learning disabilities, suggesting a potential compromise in the auditory brainstem's integrity (7-9). A study on children with learning disabilities has shown that poor results in the binaural masking level difference (BMLD) test are associated with reduced speech perception in the presence of competing signals (7). The binaural fusion (BF) test has also demonstrated abnormal results in this disorder (10).

Intervention for auditory processing disorder (APD) in learning disabilities is crucial and highly recommended because APD can lead to learning difficulties that result in poor educational progress (4, 11).

Multiple studies have assessed the effectiveness of software-based auditory training programs that incorporate various auditory and language tasks for individuals with learning disabilities. For example, the Fast ForWord and Earobics programs target different auditory and language processing skills simultaneously. The findings on their effectiveness vary (12, 13).

Auditory training is frequently advised to follow a process-specific approach, where the training paradigm directly targets the auditory processes impacted by APD (14). In a study, Mahdavi et al. developed a deficit-specific auditory training program called "Dichotic Interaural Time Difference (DITD)" and implemented it on children with learning difficulties who exhibited abnormal results in dichotic listening tests. This study's results demonstrated that the program effectively improved these children's dichotic listening test scores (15).

A review of scientific literature on rehabilitating central processing disorders in children with SLD reveals a lack of targeted approaches to utilize brainstem function to address associated abnormalities.

Studies on animal models and humans have shown that the auditory brainstem exhibits significant neuroplasticity in response to repetitive experiences (16). Since the auditory brainstem does not fully mature until late adolescence, childhood is ideal for implementing targeted auditory training to enhance brainstem-based binaural processing (17). Accordingly, this study aimed to assess the effectiveness of an auditory training program focused on binaural interaction at the brainstem level to enhance impaired binaural listening skills in children with SLD.

Materials & Methods

The present study is a simple randomized clinical trial with a pre-post interventional design including a control group to assess the intervention's efficacy. Participants were selected using convenience sampling from three local learning disabilities centers in Isfahan City, Iran. The Ethics Committee of Iran University of Medical Sciences approved this study under code No. IR.IUMS.REC.1399.300.

The inclusion criteria for the study were:

• Age between 8 and 12 years.
• Standard hearing threshold of 20 dB HL or lower for frequencies ranging from 250 Hz to 8 kHz.
• Symmetrical hearing thresholds with a maximum difference of 10 dB between both ears.
• Normal results in tympanometry and acoustic reflex tests.
• Right-handed.
• Monolingual with Persian as the dominant language.
• Word recognition score of 90% or higher in silence.
• Not participating in other rehabilitation programs.
• No neurological or psychological disorders, vision impairments, or use of relevant medications.
• No significant asymmetry between ears in the Persian Randomized Dichotic Digits Test (PRDDT).
• A score of 7 dB or lower in the differences BMLD test (18).
• Abnormal results in the Persian Auditory Recognition of Words in Noise (PARWIN), based on the norms from Mahdavi et al.'s study (19).
• Normal auditory memory, as indicated by the digit span task.

Exclusion criteria encompass instances where the child is uncooperative during the research or parents fail to maintain ongoing participation. Fourteen students who met the inclusion criteria were enrolled in the study. They were randomly allocated to either the intervention or control group. The study process was explained to the parents, and written informed consent was obtained.

Pre- and Post-Training Assessments

The BMLD and PARWIN tests were used as pre-intervention assessments to evaluate binaural listening skills. Notably, while these tests were part of the inclusion criteria, they also served as initial binaural listening skills evaluations.

BMLD: The BMLD test is widely recognized as one of the most reliable behavioral assessments for evaluating binaural interaction (6). This test was conducted using an application that allowed precise sound intensity adjustments (1 dB steps) (6). Students were instructed to raise their hands or verbally indicate when they detected a tone in the noise, emphasizing focusing solely on the tone (18). During the test, both ears received narrow-band in-phase noise centered at 500 Hz at 60 dB SPL for 4-5 seconds. A 500 Hz tone at 60 dB SPL was presented simultaneously to both ears (S0N0). If the child signaled detection, the signal intensity was initially reduced by 10 dB. If no response was given, the intensity was increased by 5 dB. As the threshold was approached, adjustments were made in 2 dB decreases and 1 dB increases. This process was repeated at least three times near the threshold to ensure accuracy. The procedure was then repeated under SπN0 conditions, where the tonal signals were 180° out of phase while the noise remained in phase. The threshold for detecting a 500 Hz pure tone amidst narrow-band noise was determined for both S0N0 and SπN0 conditions. BMLDs were calculated by subtracting the SπN0 threshold from the S0N0 threshold (4, 6, 7).

PARWIN: This test assessed the necessary signal-to-noise ratio for achieving 50% word recognition. The PARWIN test measures speech recognition using 35 monosyllabic words against a background of multi-talker babble noise. The signal-to-noise ratio (SNR) starts at +24 dB and decreases in 5 dB steps to 0 dB, with five words presented binaurally at each SNR level. The test items were delivered binaurally at a 55 dB sensation level relative to the speech reception threshold. The lower the signal-to-noise ratio (in decibels) at which an individual can accurately repeat 50% of the words, the better the performance outcome achieved (20).

Both tests were conducted using a calibrated laptop, Asus X455LD (connected to headphones), and A4TECH HS-50 in a tranquil room.

Auditory Training Program

In developing the training program for this research, the objective was to modify the acoustic components of the stimuli used in binaural interaction tests at the brainstem level (such as BMLD, binaural lateralization tests, Rapidly Alternating Speech Perception (RASP), and BF). The following outlines the components of this auditory training program.

1. BMLD: When designing exercises based on this test, several parameters were considered to create a gradual progression from easy to complex. The first parameter was the type of noise used. Initial sessions employed amplitude-modulated (AM) noise, providing greater release from masking than narrow-band noise (21). The second parameter was the noise intensity level, which increased up to 70 dB sound pressure level (SPL) to enhance the release of masking. Standard conditions for the BMLD test use a noise intensity level of 60 dB SPL (5, 22). The third consideration was obtaining the threshold at the SπN0 state through several stages before calculating the BMLD (4).

2. Sound lateralization tests using interaural intensity difference (IID) and interaural time difference (ITD) cues: The stimuli used were white noise, filtered through low-pass and high-pass filters with a cutoff frequency of 2000 Hz and an intensity of 50 dB SL, delivered to the subject via headphones. Low-pass filtered noise was used for ITD cue trials, while high-pass filtered noise was used for IID cue trials. The software displayed an image showing several sound sources at different angles corresponding to the time and intensity cues. The subject identified the sound source by pointing to it on the image (clicking or marking the spot) upon hearing each cue (22).To progressively increase the difficulty of the trials, the initial sessions asked the child to determine if the sound was coming from the right or left. Larger ITD and IID values were used initially, gradually decreasing over time. At first, the child selected the correct angle from fewer options, with the number of angles increasing gradually, making the task more challenging (4).

3. BF involves merging two frequency ranges of a band-pass filtered speech unit (word) to understand and reproduce the entire word. Key components for designing exercises in this section included the filter bandwidth, the method of word presentation (diotic or dichotic), and the type of word (monosyllabic or two-syllabic) (5). For instance, if a word in the standard test conditions was filtered through a low-pass filter with a range of 500-700 Hz and a high-pass filter with a range of 1900-2100 Hz, the initial sessions used filters with broader bandwidths for both high and low frequencies, which gradually narrowed. Initially, words were presented diotically to the ears for easier comprehension, progressing to dichotic presentation in more challenging stages. In the beginning sessions, two-syllabic

words with greater redundancy were used, while monosyllabic words were introduced in the final sessions (4).

4. RASP involves merging time segments of sentences presented alternately and sequentially between the ears to ultimately comprehend one message. In the RASP test, sentences of five to seven words are divided into 300 ms segments, alternately presented to both ears (5). In the rehabilitation program exercises, these segments initially exceeded 300 ms, providing more information to each ear. For instance, training began with 500 ms segments and gradually reduced to 300 ms over time. Another consideration in designing these exercises was to start with sentences that were simple to understand or linguistically richer, gradually increasing the complexity of the sentences over time (4).

Eight academic experts in speech therapy and audiology reviewed the designed exercises for content validity. Each expert used a three-point scale to rate each item as suitable, quite suitable, or unsuitable. They evaluated aspects such as the ability to enhance binaural interaction at the brainstem level, the adequacy of the number of exercises per session, the appropriateness of the total number of rehabilitation sessions, the clarity of exercise instructions, the suitability of speech content in BF and RASP exercises, and the stimuli used for BMLD, ITD, and ILD exercises, ensuring a progression from easy to difficult. Based on their feedback, some exercises were modified, and eventually, most experts approved the designed exercises (4).

The rehabilitation program lasted 12 weeks, with sessions scheduled three times weekly and every other day. It featured three difficulty levels: Easy, moderate, and hard. Each level was assigned one month (four weeks). The rehabilitation exercises were provided on DVD, with instructions given to the child's parents on how to perform them at home. After finishing each stage, the parents had to submit the score sheet to the therapist. Progression to the next stage was allowed only after completing the previous one (4).

After completing all treatment sessions, the intervention and control groups were reassessed with the same tests used before the intervention to measure post-intervention outcomes.

Data Analysis

Due to the small sample size in the present study, we were compelled to use nonparametric statistical tests to compare the results. Accordingly, The Mann-Whitney test was used to compare the change in test results between the two groups throughout the study, and the Wilcoxon test was used to assess within-group changes. Additionally, analysis of covariance (ANCOVA) was employed to examine the effect of the intervention, considering the pre-intervention results as a covariate. However, since the assumptions for using ANCOVA as a parametric test were unmet, this study used its nonparametric counterpart, the Quade test. The analyses were conducted using SPSS software version 28, with a significance level set at 0.05

Results

This study involved 14 children with SLD, separated into two groups: Seven individuals in the intervention group (mean age 9.55±0.7 years) and seven individuals in the control group (mean age 9.54±0.8 years). The two groups had an identical gender distribution, with four females and three males participating in each group. Table 1 documents the mean and standard deviation of MLD and PARWIN results before and after

Table 1. Comparison of the MLD and PARWIN test results at pre- and post-training

		Pre			Post			p-Value
Group	Test	Mean	Median	SD	Mean	Median	SD	
Intervention	MLD	6.00	6.00	1.00	8.85	9.00	1.06	0.01*
	PARWIN	3.24	3.30	0.90	2.55	2.50	0.67	0.01*
Control	MLD	5.71	6.00	1.38	6.00	6.00	0.81	0.41
	PARWIN	3.66	3.60	0.60	3.55	3.60	0.44	0.46

BMLD, binaural masking level difference (dB); PARWIN, Persian auditory recognition of words in noise (SNR 50%); SD: standard deviation. *Significant values (p<0.05) - Wilcoxon's test

auditory training in both groups. The results of the Wilcoxon signed-rank test for evaluating intra-group changes indicate a significant difference between the pre- and post-intervention results of the MLD and PARWIN tests in the intervention group. However, comparing pre- and post-intervention results for these two tests in the control group does not show any statistically significant difference.

The observed changes in the results of the MLD and PARWIN tests after the intervention compared to baseline levels in the control group were 0.29 dB and -0.11 dB, respectively, while in the intervention group, these changes were 2.25 dB and 0.69 dB, respectively. The intervention group showed more significant changes compared to the control group. A comparison of the changes for these two tests between the groups using the Mann-Whitney U test demonstrated statistically significant differences. The p-value was 0.003 for MLD and 0.12 for PARWIN. The trends in changes before and after the intervention between the two groups for the MLD and PARWIN tests are shown in Figures 1 and 2.

The comparison of post-intervention results between the two groups to assess the effect of rehabilitation, with pre-intervention results considered a covariate, was performed using a nonparametric analysis of covariance (Table 2). A statistically significant difference between the results of the two groups was observed in both tests following the intervention (p<0.05).

Discussion

Given that the origin of impaired speech perception in noise among children with learning disabilities may reside within the binaural pathways in the brainstem region, this study aimed to implement a binaural interaction-based auditory training program for children with SLD who exhibited abnormal results in the BMLD and word-in-noise tests. Following binaural interaction training, a statistically significant difference was observed between the intervention and control groups in the MLD and PARWIN tests. The results suggest that the hypothesis of this study—enhancement of central auditory processing function concerning binaural interaction tasks through exercises targeting binaural interaction at the brainstem level—has been confirmed.

Limited research is available examining the efficacy of binaural interaction-based auditory

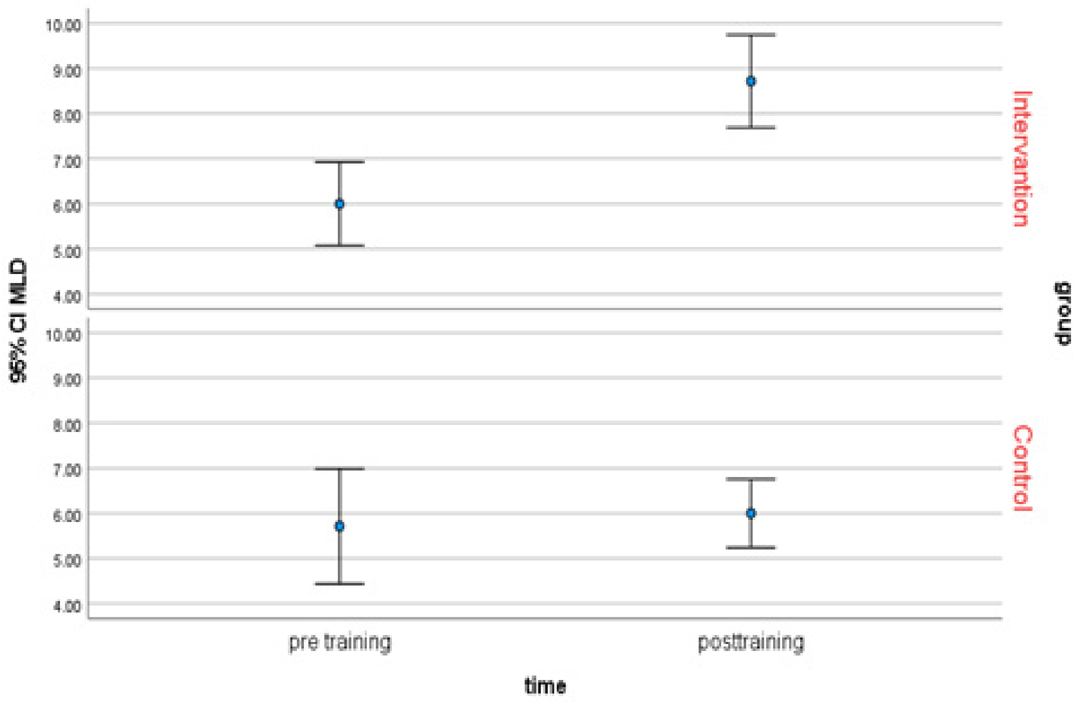

Figure 1. Error bars indicate 95 percent confidence intervals (CI) of MLD scores pre- and post-training for the intervention and control groups

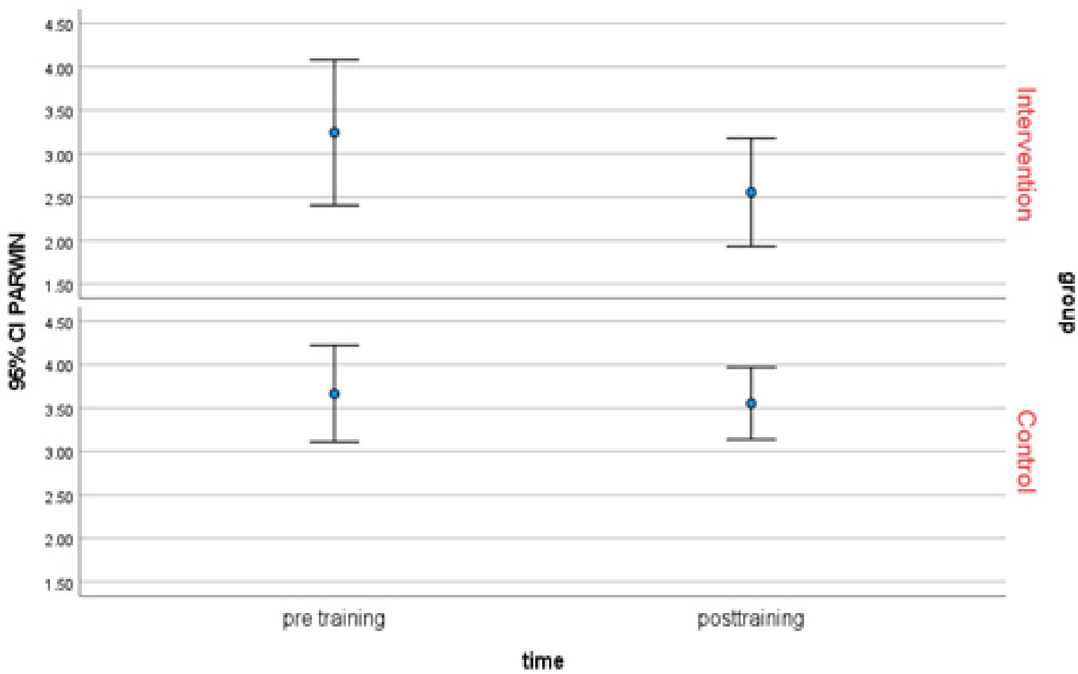

Figure 2. Error bars indicate 95 percent confidence intervals (CI) of PARWIN scores pre- and post-training for the Intervention and Control groups

Table 2. Results of Quade (ANCOVA) test for MLD and PARWIN

Test	F	DFE	p-Value
MLD	38.53	12	≤ 0.001*
PARWIN	29.25	12	≤ 0.001*

DFE equals the number of samples studied minus the number of grouping factors. *Significant values (p<0.05) - Quade test

training in improving associated processing deficits.

Zamiri et al. conducted a study to evaluate whether auditory lateralization training could improve speech perception in noisy settings for children suspected of central auditory processing disorder (CAPD). Sixty children, identified through CAPD assessment subtests, participated in a six-week program featuring 12 training sessions that used ITDs via headphones. After the training, the intervention group demonstrated notable gains in spatial word recognition scores (WRS) and monaural selective auditory attention test (mSAAT) scores. The results indicate that auditory lateralization training may significantly enhance speech comprehension in noise for children with CAPD (23). Although the outcome measurements in this study differ somewhat from those in the present study, and its rehabilitation approach focused solely on enhancing auditory lateralization abilities rather than all binaural interaction skills at the brainstem level, both studies observed improvements in speech perception in noise ability following rehabilitation. The brainstem's encoding of spectral and temporal speech features is a key determinant of our ability to understand speech in noisy conditions (24). Thus, it was not unexpected that by strengthening brainstem-related tasks, speech comprehension in noise would improve.

In another study, Cameron et al. evaluated the efficacy of the LiSN & Learn training program in improving spatial processing abilities in a group of children with spatial processing deficits, as identified by the Listening in Spatialized Noise-Sentences (LiSN-S) test, compared to the Earobics rehabilitation program, targeting a range of linguistic, auditory, and phonological skills. The results demonstrated that the LiSN & Learn program significantly improved binaural processing abilities in children with spatial processing deficits, as measured by the LiSN-S test. Additionally, improvements in everyday listening abilities were reported through relevant questionnaires. In contrast, the Earobics group did not significantly improve in spatial speech perception (25). A study on adults with hearing loss employed an auditory training regimen focusing on auditory processing skills, including intensity and frequency discrimination, dichotic listening, temporal processing, and binaural interaction exercises. The MLD test was utilized to assess the impact of the training. However, results showed no statistically significant improvements in MLD scores from pre- to post-training (26). In a case study by Stroiek et al., a 7-year-old child with language impairments and symptoms indicative of APD showed a decrease in MLD score following auditory training. This training included a variety of tasks targeting memory, attention, discrimination, recognition, and binaural synthesis skills (27). Seemingly, targeted binaural training, customized to address specific interaction deficits, may be more effective in improving those deficits.

In a study similar to that of Cameron et al., Graydon and colleagues implemented the Listen & Learn auditory training program for children with spatial processing disorders. The results demonstrated improvements in LiSN-S test scores following rehabilitation, along with advancements in daily auditory skills, as reported through questionnaires completed by the children, parents, and teachers. Furthermore, the retention of rehabilitation effects was confirmed by follow-up assessments conducted on average ten months after the completion of the auditory training program (28).

The LiSN-S test has significantly correlated with the BMLD (5). Evidently, BMLD is an integral component of spatial hearing, functioning as a binaural auditory mechanism in noisy environments (29). Thus, improving binaural interaction skills through targeted rehabilitation may ultimately enhance spatial processing. In other words, since BMLD is strongly linked to sound localization and speech understanding in noisy environments and functions as a sensitive behavioral indicator of brainstem health, the crucial role of brainstem integrity in generating BMLD (6, 27, 29) —and thereby in supporting effective spatial hearing—becomes increasingly evident.

When the tasks designed within auditory training programs lead to positive changes in the outcomes of behavioral assessments of central auditory processing, it reflects the occurrence of learning-related neuroplasticity (26). The importance of brainstem plasticity is highlighted by evidence showing that modifications in brainstem responses, along with enhancements in brainstem-related binaural skills, may contribute to an improved neural representation of sound at the cortical level (30).

In Conclusion

This preliminary study examines the effectiveness of a speciallydesigned auditory training program based on binaural interaction tasks in children with SLD. The results of this study indicated that the effect of binaural interaction rehabilitation led to improvements in both the Masking Level Difference test and word-in-noise scores. Further studies with larger sample sizes are recommended for more robust conclusions and to evaluate the auditory training program's efficacy by examining children's auditory performance in daily life through questionnaires. The necessity of implementing auditory training tailored to binaural deficits at the brainstem level is underscored by the critical functions of binaural hearing and the fundamental role of the brainstem in transmitting accurate auditory signals to higher neural centers.

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Authors Contribution

Marziyeh Moallemi: Study design, acquisition of data, statistical analysis and writing the manuscript; Nariman Rahbar: Study design and supervision, interpretation of the results and revision of the manuscript; Mohsen Ahadi: Study design, Interpretation of the results and revision of the manuscript; Mohammad Maarefvand: Statistical guidance and revision of the manuscript.

Conflict of Interest

There is no conflict of interest.

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