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REVIEW ARTICLE **Open Access**

Monitoring the Efficacy of Auditory Training through Changes in Brainstem and Cortical Auditory Evoked Potentials: A Systematic Review

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Abstract

Introduction Auditory training (AT) exercises as the main part of auditory rehabilitation have emerged as a promising method for enhancing auditory perception and communication skills in individuals with hearing impairments or difficulties in auditory processing. Through AT, the central auditory nervous system (CANS) undergoes changes that optimize neural circuits, resulting in improved auditory perception. Auditory-evoked potentials (AEPs), including the auditory brainstem responses (ABRs) and cortical auditory-evoked potentials (CAEPs), offer objective measurements of neural responses and serve as valuable biomarkers to assess the effectiveness of AT.

Methods For this systematic review, we conducted a comprehensive search in multiple databases, including MEDLINE (via PubMed), Science Direct, Web of Science, and SciELO, up until August 18, 2023. There were no study type restrictions or limitations on publication time. Following a careful assessment of the article quality and their alignment with the inclusion and exclusion criteria, a total of 25 articles were selected for inclusion in this study.

Results Based on the findings of the reviewed studies, it has been reported that AT exercises lead to an increase in the amplitude of waves in both brainstem and cortical AEPs, with the exception of P1 and N2 waves. Furthermore, it has been observed that the latency of these responses decreases following AT.

Conclusion The application of brainstem and cortical AEPs as objective electrophysiological tools holds promise in assessing the effectiveness of AT exercises and confirming the selected approach for AT.

Keywords Cortical auditory-evoked potentials, Auditory training, Auditory-evoked potentials, Auditory brainstem responses

Background

Auditory training (AT) exercises have garnered significant attention within the audiology field as a promising method to enhance auditory perception and improve communication skills in individuals who have hearing impairments or difficulties with auditory processing. AT is an intentional and methodical presentation of sounds that aims to help individuals discern perceptual distinctions among those sounds. It involves the use of strategies to develop or restore auditory perception, which

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plays a crucial role in linguistic and phonemic processing necessary for understanding speech [1, 2].

AT is typically administered either formally or informally. Formal training employs recorded stimuli delivered through a computer or CD player, allowing for more control over the difficulty of the training. Some formal training approaches utilize a computer-based auditory training (CBAT) method. On the other hand, informal training is generally less concerned with controlling the stimuli and may involve face-to-face presentations rather than recorded stimuli. Informal training often takes place in homes or schools and may utilize age-appropriate words, sentences, or nonverbal stimuli [3].

There is a growing body of evidence demonstrating the benefits of AT in the rehabilitation of individuals with hearing impairments, central auditory processing disorder (CAPD) [4], autism spectrum disorder (ASD) [5], language and learning difficulties [6], and cognitive decline in the elderly [7]. AT has shown promising results in improving auditory perception and communication skills in these populations. Furthermore, this intervention has the potential to enhance their overall quality of life by enabling better speech comprehension and communication abilities.

The central auditory nervous system (CANS) undergoes behavioral perceptual improvements and neurophysiological alterations as a result of AT. These changes indicate the transfer of acquired skills and the plasticity of the nervous system, which adapts to meet the demands of the auditory environment. Through AT, the neural circuits are optimized by increasing the involvement of neurons, modifying neural temporal synchronicity, and augmenting synaptic connections. These mechanisms contribute to the refinement and enhancement of the physiological processes underlying auditory perception and processing [8, 9].

Auditory-evoked potentials (AEPs) are objective tests that offer valuable insights into the central auditory pathways and can serve as potential biomarkers for sensory processing. Additionally, AEPs play a crucial role in monitoring the effectiveness of auditory rehabilitation and can be utilized to objectively assess treatment or training outcomes. By providing quantitative data, AEPs enable the evaluation and comparison of participants at different time points, allowing for a comprehensive analysis of their progress. One noteworthy measure of improvement is the decreased latency of AEPs, which is considered a neurophysiological manifestation of neuronal plasticity [9, 10].

AEPs serve as indicators of the neural responses involved in processing complex sounds, representing the activity within various regions of the auditory pathway, including both the brainstem and cerebral structures. AEPs originating from the brainstem encompass the auditory brainstem responses (ABRs) and the auditory brainstem response to complex sounds (cABR), which reflects the encoding of speech characteristics in the rostral brainstem auditory network.

The ABR is a noninvasive method that captures stimulus-locked, synchronous electrical events from the scalp. It consists of seven peaks, with peaks I, III, and V being commonly observed and used for auditory threshold estimation and diagnostic purposes [11].

The cABR provides valuable insights into how the brainstem represents important aspects of the speech signal. The cABR consists of two distinct elements: the onset response (V-A complex), and the frequency-following response (FFR), which includes waves C, D, E, and F. The FFR reflects the brainstem's encoding of the fundamental frequency and harmonic structure of complex stimuli, and the wave O marks the stimulus offset [12].

In addition, cortical auditory-evoked potentials (CAEPs) such as P1, N1, P2, N2, and P3 waves arise from the auditory cortex and other associated cortical areas. The presence of CAEPs indicates that the brain has detected the acoustic signal [1]. Passive cortical AEPs, such as P1, N1, P2, and N2, occur within 300ms of a sound's onset and are believed to represent electrical activity in different cortical areas involved in auditory processing [13]. The P3 component, on the other hand, reflects the process of attention and perception of unique acoustic features during CAEP testing [10].

Combined, brainstem and cortical AEPs offer a valuable tool for comprehending the neural representation of sounds and neuroplasticity following aural rehabilitation, including interventions such as AT, across different levels of the auditory system [14, 15].

Selecting the appropriate method for AT is crucial and can result in optimized outcomes and improvements in auditory processing abilities. This aspect requires particular attention, especially in children with hearing impairments, as effective AT significantly impacts the development of auditory skills and, ultimately, communication abilities. Several studies have reported findings on modified AEPs post-AT interventions, illustrating neuroplastic changes in the CANS following successful AT. Regrettably, professionals in audiology and related fields nowadays lack enthusiasm for conducting electrophysiological assessments as part of their AT procedures. In our systematic review, we seek to summarize past research findings and discuss the alterations in brainstem and cortical AEPs in both normal hearing and hearing-impaired children and adults after AT exercises. We also aim to highlight the significance of incorporating electrophysiological assessment in evaluating the effectiveness of AT interventions and in formulating successful strategies for AT.

Main text

Search strategy

In this review study, we conducted systematic searches in MEDLINE (via PubMed), Science Direct, Web of Science, and SciELO databases and performed a manual search in the Google Scholar database until August 18, 2023. We prioritized a comprehensive approach without limitations on time or study type to ensure a thorough analysis of the available literature. Although we regrettably did not have access to ProQuest, Scopus, and Cochrane Library databases, we made significant efforts to ensure our search encompassed relevant sources.

Two independent reviewers meticulously conducted online database searches, adhering to the rigorous Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [16]. The search strategy applied is presented in Fig. 1, based on the PRISMA flow diagram. To ensure transparency and accountability, the protocol of this review has been registered and assigned the PROSPERO ID: CRD42023463138 in the PROSPERO international prospective register of systematic reviews.

We developed the PECO framework by aligning it with our research question and the inclusion and exclusion criteria outlined for our study. This framework guided us in conducting a systematic search for articles. Our search focused on studies that investigated the alterations in brainstem and cortical AEPs following AT interventions. Specifically, we looked for studies that either compared AEP changes between a group undergoing AT and a control group or examined changes within the same group before and after AT sessions. We chose not to target a specific age group with keywords, as we decided to evaluate the changes in AEPs across both children and adults.

During the article search phase, we used various keywords to cover different aspects of AT interventions, such as "auditory training," "audiologic rehabilitation," "listening training," and "auditory processing training". We also used specific keywords like "cortical auditory-evoked response," "cortical auditory-evoked potential," "P1-N1-P2," "auditory-evoked potential," "auditory-evoked response," "auditory brainstem-evoked response",

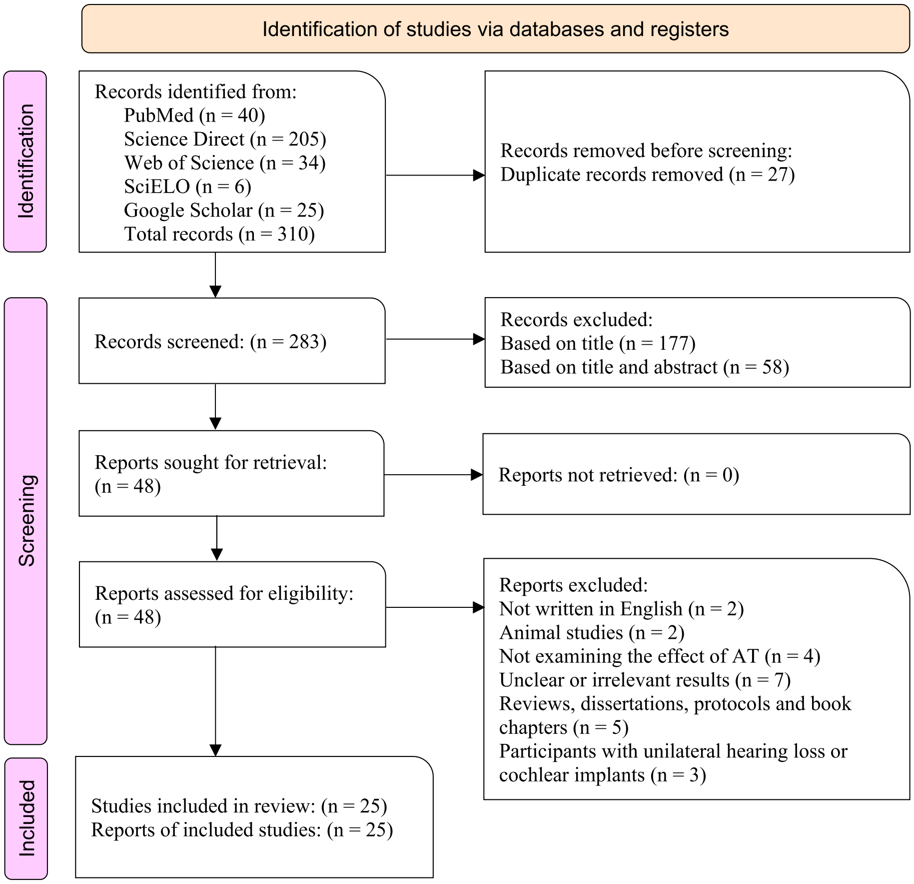

Fig. 1 Flow chart of systematic search and article selection

and "auditory brainstem response" to target articles related to cortical and brainstem AEPs. By utilizing the advanced search features available, we aimed to comprehensively identify articles that covered both fields and provided valuable insights into the effects of AT on AEPs.

Inclusion and exclusion criteria

This review will encompass a range of study types, including randomized controlled trials, cross-sectional studies, case-control studies, and cohort studies, in order to provide a comprehensive analysis. To be eligible for inclusion, articles must meet specific criteria. These criteria include publication in reputable English-language journals, containing relevant indicators related to the research topic and presenting original research on the effects of different types of AT on brainstem or cortical AEPs after inversion. We exclusively included articles that involved the evaluation of human participants in their studies.

Conversely, articles such as letters to editors, book chapters, review guidelines, meeting abstracts, editorials, various review articles and meta-analyses, dissertations and research protocols, animal studies, studies that evaluated AEPs following musical training, and studies with unclear or irrelevant results were excluded from consideration.

We excluded book chapters and review articles as they did not present original research findings relevant to our research question. Additionally, non-English articles were omitted due to language proficiency constraints, which hindered our ability to assess the quality of these articles. However, we did not exclude studies that employed stimuli in languages other than English during their electrophysiology assessment. Furthermore, studies that reported results on AEPs other than our specified target AEPs, such as the auditory middle latency responses and auditory steady-state responses, were also excluded.

Data extraction and quality assessment

We used EndNote software (version X7, Thomson Reuters, 2014) to remove duplicate articles and evaluate the suitability of article titles and abstracts in relation to the study topic. Articles that did not meet the criteria based on title alone, and subsequently based on both title and abstract, were excluded from further analysis.

During the subsequent phase, the full texts of the selected articles were subjected to a quality assessment using the Joanna Briggs Institute (JBI) checklists. The final analysis involved a careful examination of the study's purpose, methodology, results, and conclusions. Only articles and studies that met the inclusion and exclusion criteria were included in the data extraction stage. Both authors independently conducted these steps, and any discrepancies or disagreements were addressed through discussions or, if needed, by seeking the opinion of a third expert. By adhering to rigorous quality assessments and fostering consensus among the reviewers, our aim is to ensure the reliability and validity of the selected articles.

We utilized Excel software for data extraction purposes. The information extracted consisted of various relevant details, including the name of the first author, publication year, study location, participant count and age, study type, details regarding the type and duration of AT sessions, characteristics of stimuli used for recording potentials, and the reported changes observed in AEPs following AT. In the result section, these extracted details will be presented and analyzed.

Results

Literature search

After conducting a thorough search in the databases, we obtained a total of 310 articles, which were imported into the EndNote software for subsequent analysis. Among these articles, 27 duplicates were identified and removed automatically, resulting in 283 articles remaining for further screening. During the screening process, 177 articles were excluded based on their titles as they were deemed unrelated to the research topic. Additionally, after evaluating both the titles and abstracts, another 58 articles were excluded for being unrelated. Subsequently, the full texts of the remaining 48 articles were carefully examined for eligibility evaluation.

Out of the articles that remained, 2 were excluded as they were focused on animal studies, and another 2 were excluded because they were not written in English. Furthermore, 5 articles were excluded as they were review studies, theses, research protocols, or book chapters. We excluded one study that encompassed participants with unilateral hearing loss because of inconsistencies related to hemispheric lateralization and plasticity in the ipsilateral pathway. Two studies were eliminated because they involved participants with cochlear implants, attributing the exclusion to the impact of pre and post-operative factors on the results of AT. Additionally, 4 articles were excluded as they did not examine the changes resulting from AT exercises. Furthermore, 7 articles were excluded as their results were not relevant to the subject of the study or were unclear. Finally, the remaining 25 studies were included for the analysis of results.

Study characteristics

Table 1 presents the extracted information related to the study after assessing the quality of the chosen articles by the authors. We structured the results table according to the age group and hearing status of the participants. The segregation between adults and children was done

Table 1 Characteristics of included studies

Author/year	Study design	Sample size/mean age/hearing status (HS)	AT duration	Stimulus type/intensity/mode of presentation (MOP)	Patient's task/analyzed AEPs	Results
Studies with normal hearing children participants						
Hayes et al. 2003 [6]	Randomized controlled trial (RCT)	Study group: 27 learning problems Control group: 15 learning problems and 7 normal Age: 8–12 years HS: Normal hearing thresholds	1-h training sessions during 8 weeks (35–40h)	/da/ and /ga/ Intensity: 75–80 dB SPL MOP: In quiet and in the presence of background noise	Participants viewed films or animated programs. AEPs: ABRs and CAEPs	After undergoing AT, there was a decrease in the amplitude of the P1-N2 and N2 latency in quiet conditions and an increase in the amplitude of the P2-N2 in background noise.
Russo et al. 2005 [17]	RCT	Study group: 9 learning disabilities Control group: 10 normal Age: 8–12 years HS: Normal hearing thresholds	35–40 1-h sessions of AT over an 8-week period	/da/ Intensity: 80 dB SPL MOP: In quiet and in the presence of background noise	Participants watched a video of their choice. AEPs: cABR and CAEPs	The quiet-to-noise inter-response correlations of the cABR increased significantly for the experimental group after training. Additionally, the trained subjects showed sharper wave C.
Alonso & Schochat 2009 [8]	Clinical trial	Study group: 29 auditory processing disorder Age: 8 to 16 years HS: Normal hearing thresholds	Eight 50-min weekly sessions	1000 Hz (frequent) and 1500 Hz (rare) Intensity: 75 dB NA MOP: AEP examinations were conducted in a quiet environment.	Patient's task: Not mentioned AEPs: ABRs and P3	In the last assessment of the P3, there was a significant decrease in mean latency values.
Filippini et al. 2012 [18]	Controlled clinical trial	Study group: 30 children in four groups Age: 7–13 years (mean= 9.09) HS: Normal hearing thresholds	50-min sessions per week (8 weeks in total)	/da/ Intensity: 80 dB nHL MOP: In the background sound of the movie (40 dB SPL)	participants stayed seated and watched a movie. AEPs: cABR	In the specific language impairment group, peak E had a significantly earlier latency compared to the initial assessment.
Gopal et al. 2020 [9]	Clinical trial	Study group: 15 children and young adults diagnosed with (ASD) Age: 7–21 years HS: Normal hearing thresholds	12 weeks of auditory processing training	ABR: click ALR: 1000 Hz tone pips Intensity: 70 dB nHL MOP: In quiet	Subjects were seated in a chair and watched a silent movie. AEPs: ABR, cABR and CAEPs	After training, there was a significant increase in the amplitude for wave V in ABR and the latencies of P1, N1, and P2 in ALR decreased and their amplitudes showed an increase.

Table 1 (continued)

Author/year	Study design	Sample size/mean age/hearing status (HS)	AT duration	Stimulus type/intensity/mode of presentation (MOP)	Patient's task/analyzed AEPs	Results
Ramezani et al. 2021 [19]	RCT	Study group: 14 individuals with (ASD) Control group: 14 individuals with (ASD) Age: 10–16 years (mean: 14.35±1.86 years) HS: Normal hearing thresholds	30-min sessions, three times a week for 6 weeks	/da/ Intensity: Not mentioned MOP: Not mentioned	Patient's task: Not mentioned AEPs: cABR	After the intervention, the latency of all cABR waves was lower in the intervention group compared to the control group.
Melo et al. 2018 [20]	RCT	Study group: 7 children diagnosed with APD Control group: 7 children diagnosed with APD Age: 7–8 years HS: Normal hearing thresholds	Computerized AT was performed in 12 sessions of 30 min, twice a week.	frequent stimulus /ba/, rare stimulus /di/ Intensity: 75 dB nHL MOP: In quiet	participants sat in armchairs, maintaining a relaxed posture with eyes open and attentively listening. They documented the number of rare stimuli they heard. AEPs: CAEPs	A statistically significant difference was observed in the post-training phase for the decrease of latency in the P2, N2, and P3 components.
McArthur et al. 2010 [13]	RCT	Study group: 74 children with specific reading disorder Control group: 36 children Age: 6–12 years HS: Normal hearing thresholds	30 min a day, 4 days a week, for 6 weeks.	Four blocks of tones, vowels, and CVs Intensity: 80 dB SPL MOP: In the background sound of the movie (50 dB SPL)	Participants stayed seated and watched a movie. AEPs: CAEPs	Following training, there were notable increases in the amplitude of the N1-P2 complex.
Santos et al. 2007 [21]	RCT	Study group: 10 dyslexic boys Mean age: 9.8 years Control group: 10 normal-reading children Mean age: 8.8 years HS: Normal hearing thresholds	20-min sessions, twice a week for six weeks	72 French-spoken sentences Intensity: Not mentioned MOP: In quiet	Children were instructed to listen attentively and to press one of the two response keys when they heard the words. AEPs: CAEPs	Training led to an enhancement in the amplitude of the P3.
Madruga-Rimoli et al. 2023 [22]	Cross-sectional	Study group: 20 children with reading and writing underperformance Control group: 30 normal children Age: 8 to 12 years HS: Normal hearing thresholds	45-min sessions, once a week, for 8 weeks	A: 1000 Hz (frequent) and 2000 Hz (rare) B: /ba/ (frequent) and /da/ (rare) Intensity: 70 dB nHL MOP: In quiet	Participants were seated passively in a chair in a soundproof room. AEPs: ABRs, cABR, and CAEPs	After AT, the latency of wave C (cABR) and P1, N1, P2, N2, and P3 waves diminished, while the amplitude of the N2 wave decreased and the amplitude of P3 increased.

Table 1 (continued)

Author/year	Study design	Sample size/mean age/hearing status (HS)	AT duration	Stimulus type/intensity/mode of presentation (MOP)	Patient's task/analyzed AEPs	Results
Krishnamurti et al. 2013 [11]	Case report	4 children with auditory processing disorder Age: 7–8 years HS: Normal hearing thresholds	50-min sessions, 5 days a week, for 12 weeks	Click /da/ Intensity: 80 dB nHL 80 dB SPL MOP: In quiet	Participants were directed to relax on a table in a dark quiet examination room. AEPs: ABRs	In case 1, there was a post-training increase in the V-A complex amplitude. In case 2, a reduction in latency was observed for waves V, A, and C from pre-training to post-training testing.
Studies with hearing-impaired children participants						
Talebi et al. 2015 [23]	RCT	Study group: 15 hearing-impaired children Control group: 15 hearing-impaired children Age: 4–6 years HS: Bilateral moderate to severe sensorineural hearing loss	Two sessions (duration 2 h) per week for 3–6 months	5 recorded Persian vowels Intensity: 80 dB nHL MOP: Not mentioned	Patient's task: Not mentioned AEPs: CAEPs	N1-P2 amplitude increased after 3–6 months of vowel AT.
Silva & Dias, 2014 [24]	Case report	A male child with speech and language delay Age: 2 years and 6 months HS: Hearing thresholds were 25–40 dB NA across the frequency range of 125–8000 Hz (free field audiometry)	One weekly session with a duration of 40 min for 6 months	Click Intensity: Threshold estimation MOP: Not mentioned	Patient's task: Not mentioned AEPs: ABR	As a result of the AT, all the waves of the ABR showed a decrease in latencies compared to the pre-training phase.
Thabet & Said, 2012 [25]	RCT	Study group: 18 children with hearing loss (age: 4–14 years) Control group: 13 children with hearing loss (age: 5–13 years) HS: Bilateral pre-lingual sensorineural hearing loss	3 sessions of AT weekly	/da/ Intensity: 80 dB SPL MOP: In quiet	Participants were seated in a sound booth viewing an animated program. AEPs: CAEPs	The study group showed a reduction in the latency of the P1 component following AT.
Studies with normal-hearing adult participants						
Anderson et al. 2014 [26]	RCT	Study group: 62 participants control group: 32 participants Age: 55–70 years HS: Normal hearing thresholds	40 h of auditory-based cognitive training for 8 weeks	/da/ Intensity: 80 dB SPL MOP: In quiet and in two-talker babble background noise	Patient's task: Not mentioned AEPs: cABR	A reduction in latency of cABR components was observed in the post-training measurement.

Table 1 (continued)

Author/year	Study design	Sample size/mean age/hearing status (HS)	AT duration	Stimulus type/intensity/mode of presentation (MOP)	Patient's task/analyzed AEPs	Results
Tremblay et al. 2014 [27]	RCT	Study group: 30 normal-hearing participants in 3 groups Age: 18–39 years HS: Normal hearing thresholds	5 consecutive days of AT	/ba/ and /mba/ Intensity: 76 dB SPL MOP: Not mentioned	Participants viewed movies and were directed to remain alert. AEPs: CAEPs	The amplitude of the P2 wave increased after the training sessions.
Tremblay et al. 2001 [28]	Clinical trial	Study group: 10 normal-hearing young adults Age: 21–31 years HS: Normal hearing thresholds	4 days of speech-sound training	Two synthetic speech variants of the syllable /ba/. Intensity: not mentioned MOP: In quiet	Participants were seated in a sound booth watching videos. AEPs: CAEPs	Following training, there was a significant increase in the N1-P2 amplitude and a decrease in the latency of the P3a component.
Picinini et al. 2021 [29]	Clinical trial	Study group: 10 university students with inattention, difficulty in learning languages, etc. Age: 19–33 years HS: Normal hearing thresholds	30-min sessions, twice a week, 12–20 sessions in total	ABR: click Intensity: 80 dB HL ALR: 1000 Hz (frequent) and 2000 Hz (rare) Intensity: 75 dB HL MOP: In quiet	Participants were directed to stay motionless and relaxed during the three assessments. AEPs: ABRs, cABR and CAEPs	A statistically significant increase in the amplitude of the P3 wave, along with decreases in the inter-peak latencies of I–III, III–V, and I–V, as well as the absolute latency of wave I, were observed.
Wisniewski et al. 2020 [30]	Clinical trial	Study group: 16 young adults Age: not mentioned HS: Normal hearing thresholds	AT took place in a single session of 30 min	861 Hz and 1058 Hz tones Intensity: 80 dB SPL MOP: In quiet and in the presence of background noise	Participants were seated in a sound booth. AEPs: CAEPs	The amplitude of the P2 wave was greater for the trained stimulus frequency compared to the untrained frequency, in the individuals who were observed.
Castan et al. 2017 [2]	Case report	A 22-year-old male who had suffered a severe head injury HS: Normal hearing thresholds	Eight sessions of AT, each of them lasting 45 min (twice a week)	1000 Hz (frequent) and 2000 Hz (rare) Intensity: 80 dB HL MOP: Not mentioned	Patient's task: Not mentioned AEPs: ABRs and CAEPs	In the post-training evaluation, there was an improvement in the amplitude of the P3 component.
Tremblay et al. 2009 [31]	Clinical trial	Study group: 13 normal-hearing young adults Age: 21–30 years HS: Normal hearing thresholds	6 days	/mba/, /ba/, and /a/ Intensity: 74 dB SPL MOP: In quiet	Participants were directed to ignore the stimuli while watching a movie. AEPs: CAEPs	The amplitude of the P2 wave showed an increase after training.

Table 1 (continued)

Author/year	Study design	Sample size/mean age/ hearing status (HS)	AT duration	Stimulus type/intensity/ mode of presentation (MOP)	Patient's task/analyzed AEPs	Results
Tremblay & Kraus 2002 [32]	Clinical trial	Study group: 7 normal-hearing adults Age: 21–31 years HS: Normal hearing thresholds	4 days	/ba/ and /pa/ Intensity: Not mentioned MOP: In quiet	Participants sat in a sound booth and were directed to ignore the stimuli while watching a video. AEPs: CAEPs	After AT, there was a decrease in the amplitude of the P1, while increases were observed in the amplitudes of N1 and P2.
Studies with hearing-impaired adult participants						
Gil & Iorio, 2010 [33]	RCT	Study group: 7 hearing aid users Control group: 7 hearing aid users Age: 16–60 years HS: Mild to moderate bilateral sloping sensorineural hearing loss.	Eight 1-h sessions of AT	1000 Hz (frequent) and 2000 Hz (rare) Intensity: 70–85 dB HL MOP: In quiet	Participants remained motionless with their eyes shut, silently counting the rare stimuli. AEPs: CAEPs	There was a significant decrease in latency for the P3 component of CAEPs after comparing pre- and post-training evaluations.
Santos et al. 2014 [34]	Clinical trial	Study group: 7 individuals with hearing loss Age: 46–57 years (mean: 52 years) HS: Symmetrically bilateral moderate hearing loss	Eight 45-min sessions held once or twice a week.	ABR: click ALR: 1000 Hz (frequent) and 2000 Hz (rare) Intensity: 80 dB HL MOP: In quiet	Participants remained still with eyes closed during the ABR testing and with eyes open throughout the CAEPs evaluation. AEPs: ABRs and CAEPs	There were no significant differences found between evaluations in terms of the latency and amplitude of ABR-ALR components.
Alcântara et al. 2022 [10]	RCT	Study group: 4 elderly people with hearing aids Control group: 4 elderly people with hearing aids Age: 65–80 years HS: Symmetrically bilateral sensorineural hearing loss	30-min sessions of musical AT, twice a week for 8 weeks	Frequent stimulus /ba/, rare stimulus /da/ Intensity: 20-25 dB SL MOP: Stimulus were presented in a sound field without background noise.	Participants were attentive and instructed to ignore the stimulus. AEPs: CAEPs	After training, there was a significant reduction in the latencies of the N2, P2, and P3 components.

because alterations in AEPs in young individuals may be influenced by neuroplasticity during their developmental maturation, whereas in adults, changes in these potentials are primarily associated with neuroplasticity resulting from AT.

The selected articles span from 2001 to 2023 and include 3 case reports and 21 clinical trials, out of which 13 were controlled and featured a control group for comparison. All of the reviewed experiments in this study had a combined total of 430 participants who participated in AT sessions. These participants were of various age groups and included children, young adults, and elderly individuals.

The analyzed studies employed different techniques of AT with a broad duration range stretching from 30 min to more than 50 h, conducted through multiple sessions across several months. Various AT methods utilized in the included studies encompass "acoustically controlled auditory training", "auditory training with vocal duets," "voice onset time (VOT) differentiation," "computerized auditory training," "Earobics," "Treinamento musical auditivo," and additional approaches.

Different recording devices were employed, and the stimuli utilized in the recordings included click stimuli, tonal stimuli, and speech stimuli (such as vowels, CVs, and sentences), delivered at intensities between 70 and 85 dB. Additionally, in eight experiments, the oddball paradigm was utilized as a method of transmitting stimuli to elicit responses.

Brainstem auditory-evoked potentials (ABR-cABR)

Out of the total experiments reviewed, 10 have documented the modifications in brainstem-originated AEPs. In the ABR-related articles, one study illustrated a decline in wave I absolute latency and shortening of inter-peak latencies I–III, III–V, and I–V [29], and the other one demonstrated a decrease in the latency of all waves [24]. Furthermore, one experiment recorded an increase in wave V amplitude [9], and the other study suggested no variation in ABR waves before and after AT [34].

Regarding the reports involving cABR, a total of two studies observed reduced latencies for all cABR components [19, 26], while one study noticed an increase in peak C amplitude [17], and one study reported a decrease in peak C latency [22], and another one observed decreased latency for peak E [18]. Additionally, one of the studies documented an increase in V-A complex amplitude and decreased latencies for V, A, and C waves following AT sessions [11].

Cortical auditory-evoked potentials (P1-N1-P2-N2)

Out of the studies examined, a total of 19 reported changes in cortical AEPs after completing AT. Two studies indicated a decrease in P1 amplitude following the exercise [6, 32], two studies signaled reduced P1 latency [22, 25], and seven studies observed an increased N1-P2 amplitude [13, 23, 27, 28, 30–32]. Moreover, two studies reported reduced P2-N2 latency [10, 20], one study recorded an increased amplitude and decreased latency of the P1-N1-P2 complex [9], and two studies mentioned decreased N2 amplitude and latency due to AT [6, 22]. One study indicated a decrease in N1-P2 latency following the exercises [22].

Event-related potentials (P3)

Out of all the experiments, four cases indicated an increase in P3 amplitude after AT [2, 21, 22, 29], while six cases presented reduced P3 latency [8, 10, 20, 22, 28, 33]. Lastly, only one study found no significant difference in CAEPs after completing AT exercises [34].

Discussion

AT can be administered through various methods, including face-to-face sessions and computer-based programs. It aims to enhance a range of auditory skills such as detection, discrimination, identification, and comprehension. Different stimuli, such as syllables, words, phrases, and sentences, are used to train these auditory skills, leading to overall improvement [35]. For children with hearing loss who undergo cochlear implantation or use hearing aids, AT is crucial and should commence as soon as sound transmission becomes possible through interventions.

AT is known to induce neural plasticity, and the organization of the auditory cortex is closely linked to auditory experiences. Evidence of experience-based plasticity in school-age children suggests that electrophysiological measures like AEPs can be utilized to establish the relationship between neural properties and changes in auditory behavior resulting from training [11, 36].

Brainstem AEPs enable the evaluation of synchronized neural activity in response to sounds at the subcortical level, offering valuable insights into the experience-dependent plasticity occurring within this subcortical domain [11]. AT has shown the potential to rewire the biological processing in the auditory brainstem by promoting an increase in synaptic connections within the CANS. This suggests that AT can have a significant impact on the neural circuitry involved in auditory processing at the brainstem level [11].

The majority of the studies found that AT exercises led to improvements in the brain's response to sound. These improvements were seen in the form of reduced latency and increased amplitude of the AEPs originating from the brainstem. The increase in amplitude could be attributed to the enhanced speed, strength, and reliability of the brainstem's response to auditory stimuli, particularly speech. The decrease in latency suggests that there may be improved synchronization in how the brainstem nuclei respond to acoustic stimuli, leading to a better correlation between the stimulus and the brain's response [11].

CAEPs is a method used to evaluate the cortical activities of the brain, specifically its ability to discriminate, integrate, and pay attention to auditory stimuli. This assessment involves the functioning of various cortical auditory pathways, including the primary auditory cortex and associative cortical areas [10].

The majority of the studies reviewed, reported significant alterations in CAEPs. These changes encompassed a reduction in latency for all components of CAEP, including P1, N1, P2, N2, and P3 waves. Additionally, there was an observed increase in the amplitude of the N1-P2 complex (or the amplitude of the P2 wave), which appears to be the most frequently reported change in the literature. Conversely, there was a decrease in the amplitude of the P1 and N2 waves, which aligns with the normal maturation process of these responses. Another noteworthy finding in these studies was an increase in the amplitude of the P3 wave and a decrease in its latency.

The observed reductions in latencies and increases in amplitudes of cortical AEPs provide compelling evidence for improved processing of acoustic signals following AT. These positive changes can be attributed to several factors, including heightened neuronal responsiveness to auditory stimuli, enhanced neural synchrony, and strengthened connections within the neural networks involved in auditory processing [9]. The increase in amplitude, particularly in the P3 wave, following AT, indicates improved neural firing synchrony and enhanced attention, and it has also been associated with neural plasticity [33]. The gradual decrease in latencies is likely attributed to the gradual improvement in neural transmission speed, which can be influenced by changes in myelination and an increase in synaptic synchronization in response to auditory stimulation [25].

Among the six studies involving participants with hearing loss, one was a case report, one was a clinical trial without a control group, and four were randomized controlled trials. The pattern of AEP changes was consistent among studies involving populations with normal hearing and those with hearing impairments. In these studies, where participants received hearing aids, there is a potential for bias, as the increased amplitudes of AEPs could be a consequence of improved audibility facilitated by the hearing aids.

In the mentioned studies, researchers endeavored to reduce bias in the results, ensuring that any contrasts in AEP amplitudes between the two groups were attributed to AT. To establish homogeneity between the groups, various measures were implemented in the studies. For instance, participants were selected with an equivalent duration of hearing deprivation prior to receiving hearing aids, matching ranges of aided auditory thresholds, and consistent average daily hours of hearing aid usage.

Eleven studies involved adults in their research population. In adults, alterations in AEPs result from neuroplasticity induced by AT, whereas in children, changes in AEPs also involve neuroplasticity associated with maturation. However, the pattern of AEP changes following AT was similar in both children and adults.

Brainstem and early cortical AEPs correspond to bottom-up auditory processing, while late cortical AEPs, influenced by memory and attention (N2, P3), are associated with top-down auditory processing [15]. Bottom-up processing involves gathering sensory information from the external environment to construct perceptions according to the current sensory inputs [37]. In contrast, top-down processing involves interpreting incoming information based on past knowledge and experiences [38].

The findings from the included studies indicated changes in both brainstem and cortical AEPs after AT. This suggests that assessing these AEPs could be valuable for examining improvements in both top-down and bottom-up auditory processing.

Finally, considering the observed changes in brainstem and cortical AEPs resulting from AT exercises, such as reduced latency and increased amplitude of the waves aligning with the maturation pattern, it can be concluded that this objective electrophysiological evaluation serves as a practical tool to assess the efficacy and validate the chosen method for AT. This is particularly important during early childhood, as it is a critical period for the development of auditory and language systems, as well as communication skills in children. It is hoped that experts in this field will increasingly recognize the value of this tool and utilize it more frequently as part of their practice.

We refrained from conducting a meta-analysis due to the heterogeneity of studies, which included various age groups and diverse AT methods implemented over different durations. One limitation of our study is that we were unable to search certain databases due to lack of access, which could result in missing some relevant studies for our review. Future research endeavors could involve comparing the impact of various AT methods on the neuroplasticity of the CANS by assessing AEPs. Additionally, there is potential to compare the changes in AEPs following AT across different age groups.

Conclusion

Previous studies have reported changes in brainstem and cortical AEPs as a result of AT exercises. These alterations typically lead to an increase in the amplitudes of both brainstem and cortical responses, with the exception of P1 and N2 waves. Additionally, there is a decrease in the latencies of brainstem and cortical AEPs. The outcomes were consistent across both children and adults, as well as among individuals with normal hearing and those with hearing impairments, indicating neuroplasticity in the CANS following AT, potentially enhancing both bottom-up and top-down auditory processing. As a result, it is evident that electrophysiological assessment of brainstem and cortical AEPs is valuable for evaluating CANS alterations and enhanced auditory processing post-AT and this evaluation can validate the efficacy of the chosen AT method.

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Declarations

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