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Authors: Roxane EL Hayek[1]
Affiliations: the school of advanced education, research and accreditation (saera)[1]
Orcid ids: 0009-0006-8295-2479[1]
Contact e-mail: roxane.hayek@hourihearing.com

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Auditory Training And Cochlear Implants

Roxane Georges EL Hayek

SAERA. School of Advanced Education Research and Accreditation

Table of Contents

Abstract

Auditory training (AT) is a promising rehabilitation approach for pediatric cochlear implant (CI) recipients, but higher quality evidence is needed. This thesis examined the effectiveness of AT for improving speech, language, cognitive and quality of life outcomes in children using CIs and hearing aids. Nine studies met inclusion criteria. AT led to significant gains on trained tasks across all investigations, with some demonstrating transfer to untrained skills and retention up to 6 months post-training. Both analytic and synthetic training approaches proved effective. However, evidence quality was assessed as low to moderate due to methodological limitations such as lack of randomization, blinding and controls in certain studies. While demonstrating potential, AT merits further investigation employing randomized controlled trials with larger, more diverse samples and broader outcome assessments including quality of life and long-term retention. Future research should prioritize standardized compliance monitoring and detailed reporting of training protocols to facilitate comparison between studies and identification of optimal methods. With more robust methodology and evidence, AT may emerge as a valuable tool for maximizing speech, language and functional outcomes for pediatric CI recipients. Higher quality evidence is needed to strengthen clinical recommendations regarding AT.

Introduction

Auditory access is but one early step in the complex process toward successful communication for hearing aid consumers (Sweetow & Palmer, 2005). As noted by Kiessling et al. (2003), while hearing is fundamental to aural exchange, it alone does not guarantee proficiency. Rather, they proposed hearing simply enables the sequential stages of listening, comprehension, and ultimately interaction. Cochlear implants have proven enormously beneficial for children with profound hearing loss by restoring access to sound (Markman et al., 2011; Pulsifer et al., 2003). However, implant outcomes regarding auditory abilities, speech skills, and language development show substantial diversity (Kane et al., 2004; Niparko & Blankenhorn, 2003; Niparko et al., 2010). Average speech recognition following implantation tends to align across device brands, yet variability within a system implies individual-level influences (Firszt et al., 2004), suggesting nuanced recipient responsiveness (Blamey et al., 2015; Finley et al., 2008).

Numerous considerations shape post-implantation speech and language achievements. For adults, duration of deafness and implant experience best forecast word recognition, with briefer/longer periods portending higher scores (Blamey et al., 1996; Friedland et al., 2003; Rubinstein et al., 1999). In children, earlier implantation, residual hearing beforehand, engaged parenting, higher socioeconomic standing, and pre- vs. postlingual deafness status most impacted outcomes (Kane et al., 2004; Niparko et al., 2010). Those with postlingual deafness implanted sooner from supportive families prospered exceptionally when residual hearing existed and economic security afforded enrichment (Niparko et al., 2010).

Additional factors linked to postoperative speech and language outcomes in CI recipients include mode of electrode integration (Mens & Berenstein, 2005; Pfingst et al., 2001), signal processing approaches (Nogueira et al., 2015; Skinner et al., 2002; Wilson et al., 1988), quality of CI fitting procedures (Holden et al., 2005; Skinner, 2003), as well as age at implantation (Blamey et al., 1996; Connor et al., 2006).

Other recipient-level variables thought to potentially impact recognition abilities but lacking conclusive evidence include spiral ganglion cell survivability (Khan et al., 2005; Nadol et al., 1989; Seyyedi et al., 2014) or morphological alterations to surviving neurons (Briaire &

Frijns, 2006), in addition to disrupted central pathways (Kral et al., 2016; Shepherd & Hardie, 2001; Shepherd et al., 1997).

Some of these influencers such as fitting techniques and sound-processing configurations retain potential for refinement. Meanwhile, other considerations lie beyond practitioner control, like home language immersion and family dedication. Moreover, for some individuals, sound transmission fails to guarantee effective use without supplemental guidance—here, auditory training programs show promise to facilitate optimal benefit realization. Overall, post-implant outcomes appear multi-factorial, necessitating tailored rehabilitation approaches.

Auditory training (AT)

Auditory training (AT) is a sound-focused rehabilitative method aimed at cultivating individuals' speech and hearing abilities through varied listening activities (Sweetow & Sabes, 2006). AT strives to condition the brain to interpret sound contrasts via repetition and variance of stimuli integrated with effective feedback. Through this repetitious habituation to distinguish sound differences, learners progressively gain proficiency (Schow & Nerbonne, 2007).

AT holds promise as an intervention maximizing benefit conferred by hearing technologies. While devices may facilitate sound access for those with hearing loss, they cannot single-handedly enhance listening or comprehension capabilities. Brain remapping occurs to some degree over time naturally, but AT potentially accelerates and expands this process (Sharma et al., 2009). AT outcomes have been gauged via improvement on trained tasks as well as transfer to distinct, untrained activities. A review of AT research in adult CI recipients reported gains on targeted tasks; however, generalization to unaddressed domains and retention of benefits thereafter remain uncertain (Henshaw & Ferguson, 2013). Overall, AT demonstrates ability to cultivate crucial auditory skills but its full impact requires more comprehensive evaluation, particularly regarding durability and spread of learned abilities. Supplemental efforts like AT may play an important role in optimizing outcomes when paired with modern hearing technologies.

Analytic (Bottom-Up) and Synthetic (Top-Down)

Auditory training (AT) techniques are generally classified into two principal categories - bottom-up (analytic) and top-down (synthetic). The analytic method focuses on acoustic-phonetic decoding, conditioning listeners to distinguish speech signals absent context. In contrast, synthetic AT capitalizes on linguistic knowledge like semantics, syntax, lexicon and phonology to supplement gaps in sensory data from hearing devices. An exemplar is connected narrative tracking (De Filippo & Scott, 1978). One seminal AT study (Rubinstein & Boothroyd, 1987) compared synthetic alone versus combined synthetic-analytic training for adults with mild-moderate sensorineural loss. The inclusion of analytic training conferred no additional benefit since synthetic training sufficed for notable improvement. Likewise, a 1970-1996 review evaluated AT effectiveness for adult hearing loss communication (Sweetow & Palmer, 2005). Synthetic training enhanced speech recognition while analytic impacts remained uncertain. Contrary evidence emerged from experiments using analytic techniques with adult CI recipients (Fu & Galvin, 2008; Fu et al., 2004; Galvin et al., 2009; Zhang et al., 2012). Phonemic and word recognition significantly improved post-training. Recent opinions endorse multi-modal AT combining approaches (Amitay et al., 2006). Supporting this, phonemic discrimination through narrative comprehension significantly benefitted from synthetic-analytic AT (Tye-Murray et al., 2012). Overall, a trend favors mixed AT to maximize outcomes. While early work questioned analytics, modern application with hearing device recipients implies broader utility when partnered optimally with synthetics. Further evaluation continues to elucidate how blending modes confers additive value for cultivating auditory skills.

Trained Task Performance and Generalization of Benefits

Literature documents positive outcomes regarding trained task mastery subsequent to AT interventions for both hearing aid and CI users. A systematic review of 1996-2011 adult hearing loss AT studies consistently noted trained task improvements whenever evaluated (Henshaw & Ferguson, 2013). However, one CI recipient study reported trend-level yet non-significant betterment for one trained task alone (Stacey et al., 2010). Reports on learning transfer or generalization of benefits vary. Henshaw and Ferguson (2013) observed modest yet significant generalization to untrained speech intelligibility, cognition and self-reported hearing measures. For example, word training programs led to improved recognition of untrained words and speakers of familiarized words, but familiar words uttered by new voices saw no amplification (Burk et al., 2006). While dedicated skill development reliably occurs, broader application of enhanced abilities remains ambiguous. Overall, AT effectively refines targeted aptitudes but conferral of wider-ranging advantages necessitates deeper scrutiny. Recipient-specific traits and rehabilitation protocol particulars may impact propagation of gains. Teasing apart boundary conditions for generalization holds keys to optimizing AT design to maximize durable, functional results transferable to everyday communication contexts. Continued rigorous investigation of task migration promises valuable insights for remediating remaining handicaps through customized sound rehabilitation therapy.

Retention of Benefits post AT

Assessing retained benefits entails comparing baseline and post-training regimen performance on trained/untrained tasks. Of 13 studies, eight evaluated retention via follow-ups ranging four days to seven months post-training (Henshaw & Ferguson, 2013). For instance, word recognition significantly improved six months following (Burk et al., 2006), while digit recognition sustained for one month (Oba et al., 2011). Other work reported maintained significance on nonsense syllables, easy/hard words through seven weeks (Stecker et al., 2006; Burk & Humes, 2008).

Retention extended beyond trained exercises. Sweetow & Sabes (2007) showed four-week constancy for various speech-in-noise, handicap/communication questionnaires. However, test-retest effects potentially impacted this (authors). Differently, Oba et al. (2011) controlled such confounds comparing immediate versus four-week post-training performance, reporting no difference. This evidenced retained Hearing-in-Noise Test and sentence gains in noise/babble, affirming AT durability (Oba et al., 2011).

Overall, targeted skills reliably strengthen. Yet broader, longitudinal impacts lack full elucidation. Methodological inconsistencies and short follow-up durations potentially obscure durability insights. Precisely characterizing maintaining benefits' boundary conditions could optimize protocol designs to confer sustainable, practically applicable abilities. Rigorously disentangling retention from learning factors with standardized, well-powered investigations offers promise to substantiate AT capable of alleviating residual handicaps through customized, durable rehabilitation.

Brain Plasticity as Evidence of AT

Several investigative studies have contributed to the growing understanding that the malleable properties of the neural framework within the brain allow modifications to occur in resonance with focused auditory stimulations experienced over lengthened timespans (Tremblay et al., 2001; Tremblay et al., 2009). Specifically, inquiries in this domain have proposed that auditory training protocols may assist in cultivating optimal activation patterns within brain areas implicated in processing sounds, with downstream effects including augmented auditory perceptual talents, improved listening skills, and potential reductions in hearing-related difficulties (Kraus & Chandrasekaran, 2010).

Inquiries have also started to uncover which precise locales within the brain appear to exhibit remodeling influenced by training involvement. Techniques including electroencephalography and magnetoencephalography that can track electric and magnetic signals across temporal and spatial dimensions have provided insight into how cortical and subcortical zones modulate their reactions contingent on the specialized learning aims of auditory rehabilitation paradigms (Barrett et al., 2013; Brattico et al., 2003; Shahin, 2011; Tremblay et al., 2010; Tremblay et al., 2009). Notably, studies have perceived amplifications in the magnitudes of particular waveform facets gauged from the cerebral cortex, distinctly the P2 wave, following completion of training (Kühnis et al., 2013; Kuriki et al., 2007; Seppänen et al., 2012; Shahin et al., 2003). While heightened P2 signals seem correlated with advances in perceptual abilities, the exact neural origins generating this output are not yet thoroughly understood (Ross & Tremblay, 2009; Tremblay et al., 2014).

Taken together, these findings furnish preliminary neurological documentation that engaging in auditory training can reshape auditory processing networks within the brain through experience-driven neuroplastic alterations. However, additional exploration is still necessary to dismantle the specific cellular and system-level systems underlying training-induced cortical remapping impacts as well as targeting the precise spots of plastic variations. An exhaustive inspection into brain remodeling triggered by auditory rehabilitation programs promises to assist in refining such techniques to maximize benefit from intrinsic neural malleability for optimized results.

Supplementary analyses have looked into P1 cortical auditory evoked potential latency periods in the lens of experience-driven modifications to cortical acoustic handling over the progression of time (Bauer et al., 2006; Ponton et al., 1996). The auditory thalamus and cerebral hemispheres generate the P1 response, with latency impacted by chronological age, permitting extrapolations involving maturational position of hearing pathways (Bauer et al., 2006; Sharma et al., 2005). Swift post-implantation reductions in P1 latency are hypothesized to echo experience-driven plasticity centrally (Sharma et al., 2002; Sharma et al., 2004).

Anderson and Kraus (2013) established the existence of two particular forms of neural flexibility - transient and long-term. Language engages long-term plasticity while auditory activities induce transient plasticity. A study compared fundamental pitch portrayal dissimilarities between audio system users from Chinese and American lineage at the brainstem stage (Jeng et al., 2011). Amplified encoding of linguistic pitch contours was witnessed in Chinese grownups versus Americans, indicating long-term encounters shape neural tuning (Krishnan et al., 2005).

Bilingualism surfaces as an additional case of neuroplasticity. Inquires found bilingual people displayed elevated brainstem encoding of basic pitch frequency versus monolinguals, a quality underlying pitch notion and auditory item teaming (Krizman et al., 2012). Jointly, these revelations underscore how both temporary and life-long sensory tests mold neural system capabilities assisting acoustic handling.

Examples of transient brain plasticity have been witnessed within musical preparation programs. Accumulating documentation, specifically for listeners with standard hearing acuity, proposes that interconnected networks inside the brain handle melodic traits encountered in music and vocalization. This recommends that musical coaching may possibly generalize to neural encoding of dialog, dialect, and music (Anvari et al., 2002; Besson et al., 2007; Herholz & Zatorre, 2012; Kraus et al., 2009; Patel, 2011). In deaf kids, a recent examination showed signs of enhancements in managerial function following a 5-week music training intercession (Manson, 2017). Additional evidence affirmed that music talents significantly link to phonological consciousness and interpreting (Anvari et al., 2002; Culp, 2017). It was advised that actively listening to music by utilizing greater perceptual demands might further refine the auditory system (Herholz & Zatorre, 2012; Ingvalson & Wong, 2013; Patel, 2011). Not just listening to music but also exploration of sound and singing was attached to improved pitch discrimination, speech perception in noise, and singing ability in children with standard hearing and children with hearing loss (Welch et al., 2015).

Collectively, these findings suggest experiences processing complex auditory features through music can drive temporary neuroplastic changes affecting domains like language through overlapping networks in the brain. Precisely charting experience-dependent alterations to neural encoding mechanisms engendered by various rehabilitative regimens holds promise to optimize training protocols leveraging intrinsic cortical malleability.

Objectives

The overarching objective of this thesis was to explore whether auditory training (AT) proves effective at boosting performance scoring for young cochlear implant (CI) patients regarding metrics of speech and language abilities, cognitive functions, and quality of life standards. Secondary aims looked to assess the impact of diverse AT methods (analytic versus synthetic approaches) as well as to determine if improvements generalize beyond trained exercises or are retained following AT conclusion. Ultimately, outcomes from this thesis aim to potentially assist clinicians in formulating well-informed choices related to AT with pediatric CI clients. Additionally, findings may furnish researchers with the most up-to-date insights regarding AT consequences for young CI users. A variety of assessment tools were considered relevant to addressing these aims.

Methods

The methodology for conducting this thesis was established in advance through registration with PROSPERO. Parameters for inclusion and exclusion of sources were defined using the PICOS framework to delineate the participant, intervention, comparison, outcome, and study design attributes (Richardson et al., 1995 - see Appendix A).

Explicit protocols were drafted prior to commencing the review to promote transparency and reduce bias throughout the process. Seven computerized research collections were mined: Medline, Embase, Cochrane Library, Cinahl, Scopus, PubMed, and Web of Science. Only sources published in English with uncapped timeframes were entertained. Designs granted admittance consisted of randomized controlled trials, non-randomized comparative trials, cohort studies incorporating controls, or repetitive measurement studies. All auditory skills development methods involving human or computer facilitated delivery in clinical, domestic, scholastic, or laboratory circumstances were granted potential inclusion. Descriptors utilized incorporated cochlear implant, cochlear prosthesis, auditory training, auditory learning, and rehabilitation.

To minimize potential for bias, I independently extracted and analyzed the data based on randomization, blinding, controls, sample size calculations, selective reporting, feedback during training, self-assessment, and generalization of improvements if any. All identified articles underwent three primary stages: preliminary screening, more thorough screening, and assessment for meeting criteria. Initially, 96 papers were extracted from the selected databases and references. After removing duplicates, overviews, and papers addressing different outcomes, 19 papers remained. These 19 publications were carefully reviewed, and only nine satisfied the PICOS standards for inclusion in the analysis. The other 10 studies (Barton & Robbins, 2015; Chen et al. 2010; De Bruyn et al., 2011; etc.) were excluded for not meeting inclusion criteria such as irrelevant outcome measure, study design flaws, or lack of controls. The included papers were further evaluated and graded to assess evidence quality and control for biases (see Figure 1).

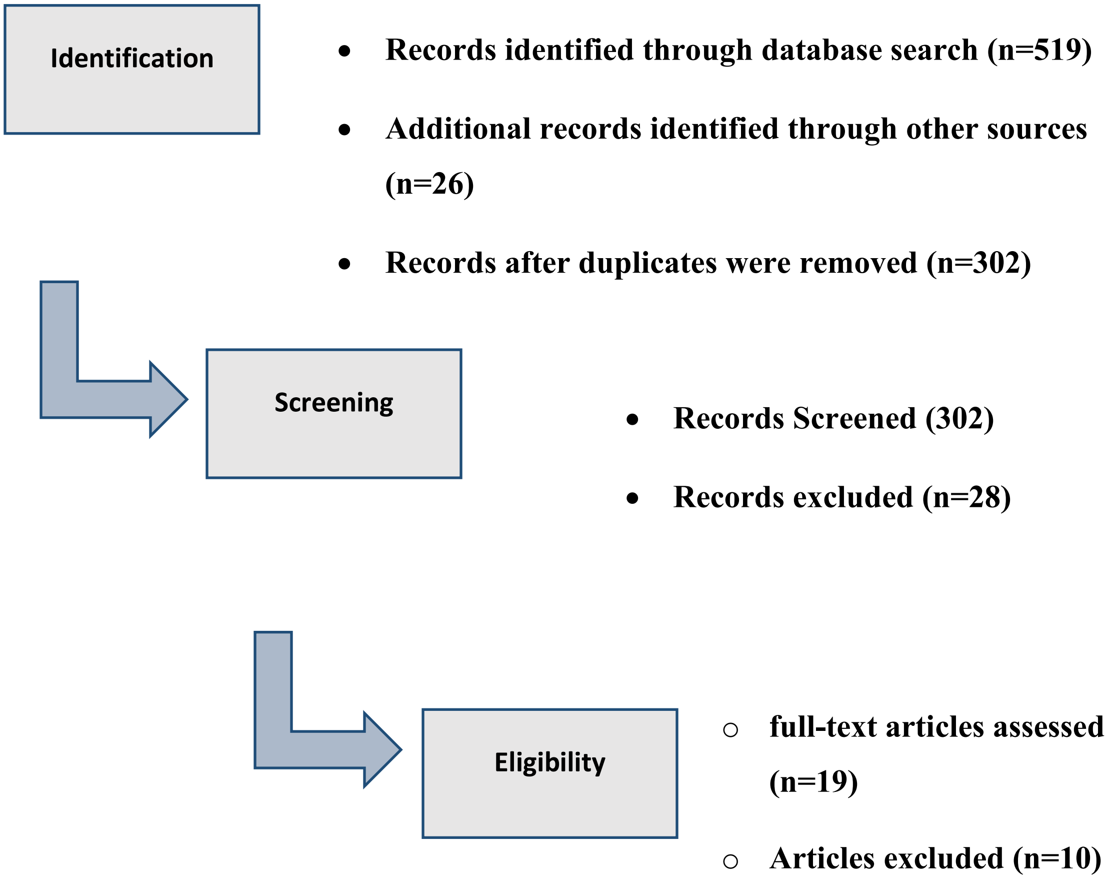

Figure 1. *Process of review articles selection.*

Quality of the articles

All selected research was evaluated and graded to assess strength of evidence based on guidelines from the 2004 GRADE Working Group (see Appendix B; Atkins et al., 2004). Assessment criteria adopted from Henshaw and Ferguson (2013) examined methodology quality. Evidence rating for each study derived from scores across categories within general scientific and auditory training-specific domains. Under scientific measures, scoring evaluated randomization/control techniques, power analysis reporting, blinding approaches, and outcome declaration. Within auditory training, applicability of outcome selection, training feedback, ecological validity (e.g. location like home vs. lab), protocol adherence, and retention of gains obtained scores. Scores were 0 (inadequate/missing data), 1 (weak/vague details), or 2 (appropriate use and thorough reporting). Scores per study summed to a quality index conveying evidence level. Lower scores implied findings hard to replicate while higher scores suggested greater confidence in results (Henshaw & Ferguson, 2013). The aim was to evaluate each study in as much an unbiased manner as feasible given methodology constraints to draw well-supported conclusions for this thesis.

Synthesis of Results

All obtained information such as methodology, participant profiles, training routines, outcome metrics, and key takeaways underwent tabulation. Subsequently, a condensed compilation addressed research inquiries, assessed evidence quality, scrutinized methodology rigor, and evaluated bias potential. Ideally, pooled information lends itself well to quantitative synthesis. However, heterogeneity limited potential for formal meta-analysis in this case due to lack of cross-study homology pertaining to training materials, regimens, and dependent variables evaluated. As a result, narrative evaluation remained the optimal strategy to consolidate disparate yet informative findings while circumventing constraints inherent to aggregation of nonequivalent evidence. The aim was to appraise merit and meaning despite variability in order to derive applicable takeaways within tolerable margins of uncertainty.

Appendix A

Criteria for Inclusion and Exclusion:

Standards for adding or leaving out investigations were characterized as follows:

- Participants: Individuals under 18 years of age who received cochlear implants.
- Interventions: All forms of auditory practice given to those with cochlear implants, whether by people or computers, and in clinical, home, school or research settings.
- Comparators/Controls: Studies contrasting results between a tested group and others getting something different or nothing, as well as those with assessments before and after practice.
- Outcomes: Improvements in speech recognition, cognitive abilities, and quality reported by participants or families, plus keeping benefits later and generalizing them.
- Designs: Experiments randomly assigning treatments, non-random comparisons, repeated measures, or cohort research including control conditions.

Appendix B

Means for Judging Strength of Evidence:

Henshaw and Ferguson (2013) originated a classification system for study quality based on predefined metrics. Studies rated:

- Very low with 0-5 points, since effect estimates seemed doubtful.
- Low for 6-10 points, as extra data could strongly change certainty in effect sizes.
- Moderate with 11-15 points, as new information may alter interpretations.
- High for 16-20 points, as new findings unlikely changed certainties.

Results

Table 1

Study		Participants		Training					Findings		
References	Design	*n*	Age	Stimuli	Skills trained	Frequency and duration	Place of training	Outcome measures	Improved?	Retention	Generalization
Good et al. (2017)	Non-RCT	9 CI EG/ 9 CI CG	6–15 years	Piano training (musical theory and technical exercises and learning a song)	Music theory and technical exercises scales (bilateral finger control and hand positions; learning a song)	24 sessions; private half an hour lesson per week for 24 weeks for 6 months	Lab	– Montréal Battery For Evaluation of Musical Abilities (Peretz et al., 2013) – Perceived Emotional Prosody Based on Diagnostic Analysis of Nonverbal Accuracy Scale (Nowicki & Duke, 1994)	Not assessed (purpose was to investigate generalization not trained task)	Not assessed	Yes
Hagr et al. (2016)	Non-RCT	13 CI EG/ 13 CI CG	3–7 years	Detection of Ling sounds, environmental sounds, and phrases; Discrimination between intensity, duration, pitch, or intonation stress; rhythm and rate; discrimination of	Sound detection and discrimination using Rannan software	1 hour of weekly speech therapy + extra 1 hour of AT using Rannan weekly (in	PC based in clinic	- Listening Progress Profile (Nikolopoulos et al., 2000) – The Infant–Toddler Meaningful Auditory Integration Scale (Zimmerman- Phillips et al., 2001)	Yes	Not assessed	Not assessed

				vowels, consonants, and number of syllables in words		a different day) for 12 months					
Ingvalson et al. (2014)	RCT	10 CI EG/ 9 CI CG	4–7 years	Recalling and sequencing environmental and speech sounds in quiet and noise; matching phonemes to graphemes; identifying and discriminating between phonemes; recalling sequence of drumbeats, speech sounds, syllables, and phonemes; blending words, syllable	Phonological awareness skills and auditory working memory	Interactive exercises, 75 min of training per week for 4 weeks	PC based in school	– Expressive One-Word Picture Vocabulary Test (Martin & Brownell, 2011) – Receptive One-Word Picture Vocabulary Test (Martin & Brownell, 2011) - Oral Written Language Scales (OWLS; Carrow-Woolfolk, 2008)	Yes	Not assessed	Not assessed
Kronenberger et al. (2011)	Repeated measures	9 CI	7–15 years	Cogmed working memory involving auditory, visuospatial, or combined short-term and working memory skills	Working memory	30–40 min per day for 5 days a week for 5 weeks	PC based at home	– Digits forward and backward – Spatial span forward and backward BRIEF: – Sentence repetition	Yes	Yes (all working memory and language for 1 month and language only up to 6 months)	Yes (working memory to language processing)

Mishra et al. (2015)	Non-RCT	13 CI EG/ 14 CI CG	5–12 years	Adaptive speech (numbers) in noise recognition in a white/speech noise (Angel Sound)	Speech in noise	2 sessions 40 min per day for 6 days a week for 5 weeks	PC based at home	– Numbers in white noise – Number in speech-shaped noise (trained) – Digit triplets in speech-shaped noise (untrained)	Yes	Yes for up to 3 weeks	Near transfer but not far transfer
Roman et al. (2016)	RCT	10 CI EG/ 9 CI CG	4–10 years	Environmental sound, music, voices, and abstract	Auditory cognitive processing (identification, discrimination, ASA, and auditory memory)	30 min per 1 session per week for 20 weeks	Sound in hand instrument; in clinic/lab	– Same as training stimuli but different sets used only as outcome measures	Yes in all except ASA	Yes	Yes (phoneme discrimination)
Welch et al. (2015)	Non-RCT	12 9 CI/3 HA	5–7 years	Singing exercises vocal explorations; tongue twisters; explorations in visual imagery for sound, sound imagery, and metaphor	Singing and vocal exploration	Once a week for 20 weeks		– Singing competency profile Sing Up (Welch et al., 2014) – Chord pitch discrimination test – Speech perception in noise	Yes, but not speech in noise	Not assessed	Not assessed
Wu et al. (2007)	Repeated measures	7 CI/3 HA	5–11 years	Discrimination task, trained to identify final vowels. Discriminating between phonemes.	Identification and discrimination of speech sound	30 min per 1 session 5 days a week for 10 weeks	PC based at home	– Vowel and consonants discrimination – Chinese tone recognition	Yes	Yes for 2 months	Not assessed

				For vowels, acoustic speech Features included (F1 and F2) and duration							
Yucel et al. (2009)	Non-RCT	9 CI EG/ 9 CI CG	36-96 monthly hours	Pitch discrimination task; rhythm discrimination and sequence repetition	Child listening to different pairs of notes using electronic keyboard	10 minutes daily for 2 years post CI activation	Keyboard at home	– Music: developed questionnaire – Meaningful Auditory Integration Scale (MAIS; Robbins, Renshaw, & Berry, 1991) and Meaningful Use of Speech Scale (MUSS; Robbins & Osberger, 1994) – Phonetic discrimination – Word identification – Comprehension of simple auditory instructions – Sentence repetition	Yes	Yes	No (no transfer to speech)

Note. RCT = randomized controlled trial; EG = Experimental group; CG = Control group; AT = auditory training; CI = cochlear implant; ASA = auditory scene analysis; HA= hearing aid.

Table 2

Study	Findings				
Authors	**Outcome measures**	**Improved trained skills**	**Retention**	**Generalization**	**Reporting compliance**
Good et al. (2017)	–Montréal Battery for Evaluation of Musical Abilities (Peretz et al., 2013) –Perceived Emotional Prosody Based on Diagnostic Analysis of Nonverbal Accuracy Scale (Nowicki & Duke, 1994)	The purpose of the study was to investigate generalization not trained task	Not assessed	Yes	Not explicitly reported but can be deduced
Hagr et al. (2016)	–Listening Progress Profile (Nikolopoulos et al., 2000); –The Infant–Toddler Meaningful Auditory Integration Scale (Zimmerman-Phillips et al., 2001)	Yes	Not assessed	Not assessed	Not reported
Ingvalson et al. (2014)	–Expressive One-Word Picture Vocabulary Test (Martin & Brownell, 2011) –Receptive One-Word Picture Vocabulary Test (Martin & Brownell, 2011) –Oral Written Language Scales (Carrow-Woolfolk, 2008)	Yes	Not assessed	Not assessed	Not explicitly reported but can be deduced
Kronenberger et al. (2011)	–Digits forward and backward –Spatial span forward and backward BRIEF:–Sentence repetition	Yes	Yes (all working memory and Language for1 month and language only up to 6 months)	Yes (working memory to language processing)	Not explicitly reported but can be deduced
Mishra et al. (2015)	-Numbers in white noise –Number in speech-shaped noise (trained)	Yes	Yes for up to 3 weeks	Near transfer but not far transfer	Explicitly reported

The findings from the analyzed studies were summarized concisely within two tables. Table 1 outlines key details of each investigation, including research design, participant characteristics, training protocol specifics, and primary conclusions reached. Table 2 then recapitulates the principal results seen, such as extent of performance gains attained, duration of benefits, transfer effects observed, and level of compliance.

By organizing the salient information from the diverse works in a tabular format, the most important elements were efficiently displayed and examined. Specifics regarding methodology, sample traits, interventions implemented, assessment tools utilized, and significant practical implications were concisely presented for each study. This permitted readers to readily survey approaches, samples, and outcome variables across investigations. It also facilitated analysis of interactions between factors like training modality, frequency and duration in relation to observed outcomes like skill development and maintenance. The table structure effectively synthesized and presented the critical research data to address the objectives of this review.

Characteristics of the studies

All investigations examined children diagnosed with serious to profound hearing loss. Seven of the nine reports exclusively involved subjects utilizing cochlear implants (CIs) or bimodal appliances combining CIs and listening aids, whereas only two analyses (Welch et al., 2015; Wu et al., 2007) contained children employing CIs/bimodal apparatuses alongside those dependent on listening aids alone. In total, the studies represented outcomes from 89 CI/bimodal clients and six listening aid clients. While originally just aiming to contain CI clients, it became important to incorporate further reports to allow for a more extensive review, necessitating this criterion be relaxed.

Example measurements extended from nine members (Kronenberger et al., 2011) to 29 individuals (Welch et al., 2015; M = 19.67, SD = 7.03). Only three examinations employed a duplicated steps style (Kronenberger et al., 2011; Welch et al., 2015; Wu et al., 2007), with just one investigation (Welch et al., 2015) comprising youths with regular hearing as a comparator. The staying reports utilized non-imitated steps designs evaluating two free gatherings, one test and the other control. Two were randomized controlled trials (Ingvalson et al., 2014; Roman et al., 2016), four nonrandomized controlled trials (Good et al., 2017; Hagr et al., 2016; Mishra et al., 2015; Yucel et al., 2009), and three duplicated steps (Kronenberger et al., 2011; Wu et al., 2007; Welch et al., 2015).

Quality of the studies

The research studies were evaluated based on scientific rigor and relevance to auditory training (AT). Table 2 shows the evidence level for each based on these criteria. Scores considered factors such as randomly assigning participants, using control groups, determining adequate sample sizes, blindly assessing outcomes, and thoroughly reporting results. AT-specific factors included checking if benefits generalized, outcomes measured, real-world benefit evaluated, feedback provided, compliance monitored, and long-term progress reviewed.

This careful examination revealed all but one study (Mishra et al., 2015) had low evidence levels. A key reason was failures meeting scientific standards like randomization, power calculations, or blinding. Four attempted randomization (Good et al., 2017; Ingvalson et al., 2014; Mishra et al., 2015; Roman et al., 2016), two used blinding (Hagr et al., 2016; Mishra et al., 2015), and one did power calculations (Wu et al., 2007). Additionally, lack of follow-up post-training (Hagr et al., 2016; Ingvalson et al., 2014; Roman et al., 2016; Welch et al., 2015; Yucel et al., 2009), compliance reports (Hagr et al., 2016; Wu et al., 2007; Yucel et al., 2009), and feedback given (Good et al., 2017; Kronenberger et al., 2011; Roman et al., 2016; Yucel et al., 2009) lowered overall scores. Lower scores also increase bias risks, potentially undermining clinician confidence in AT recommendations.

Trained skills and outcomes of AT

The research investigated skills developed through training programs like working memory, speech understanding, music perception, pitch/rhythm differentiation, and environmental sound recognition. All nine investigations clearly demonstrated AT benefits participants through boosted performance on practiced tasks. This occurred regardless of duration - from as brief as 4 weeks (Ingvalson et al., 2014) up to 2 years (Yucel et al., 2009) - or training type delivered. Whether training focused narrowly on a single skill or exposed individuals to multiple auditory domains, positive outcomes generalized across diverse learner profiles and abilities. Training efficacy endured even when provided less frequently over more extended periods. While study designs and outcome metrics differed somewhat, collectively results emphasized auditory rehabilitation's potential for empowering clients through customized, experience-driven neuroplasticity. Going forward, delineating dose-response relationships and identifying individual variables predicting optimal training efficiency hold promise to further maximize rehabilitation success. However, present evidence already affirms AT as a clinically meaningful approach for enhancing listening/learning capacities in children.

Working Memory With or Without AT

Two investigations compared the effects of auditory training (AT), which targeted phonological skills (Ingvalson et al., 2014), to cognitive training focusing on enhancing working memory (Ingvalson et al., 2014; Kronenberger et al., 2011). Kronenberger et al. (2011) utilized Cogmed Working Memory Training to assess the program's impact on memory and language abilities in children with cochlear implants. Cogmed is a computer-based program that provides exercises to challenge auditory and visuospatial short-term and working memory. Participation led to improved performance on most tasks, like verbal and nonverbal working memory drills. While gains in working memory diminished after one month, sentence repetition continued enhancing up to 6 months post-training. This enduring benefit suggested to the authors that working memory training could aid memory and language for this population, though distinguishing specific effects of working memory versus visuospatial training remains challenging (Ingvalson et al., 2014; Kronenberger et al., 2011).

Three studies utilized speech stimuli to improve speech skills. Tasks focused on detecting, discriminating and identifying speech sounds/words (Hagr et al., 2016), phonemes, vowels and consonants (Wu et al., 2007), and recognizing digits in noise (Mishra et al., 2015). Wu et al. (2007) examined computerized speech training on recognition in Mandarin children with hearing loss. Stimuli differentiated phonemes and acoustic features of vowels and consonants. Children receiving this intervention showed gains in vowel, consonant and tone identification. The authors suggested moderate auditory training aids speech understanding in children with hearing loss. Mishra et al. (2015) evaluated training recognition of speech in noise using numbers in white/shaped noise. An adaptive, customized speech-in-noise program was used. The intervention group improved on this task over controls. The authors concluded auditory training enhances speech-in-noise abilities in children with cochlear implants.

Music, Pitch and Rhythm Discrimination and Environmental Sounds

Four studies utilized nonspeech stimuli like environmental sounds and music. Roman et al. (2016) examined the "sound-in-hand" apparatus (Rochette & Bigand, 2009) which assesses identification, discrimination, auditory memory, and auditory scene analysis (ASA) skills in children with CIs. Tasks included identifying, discriminating, recalling sound sequences, and detecting changes in auditory scenes. The experimental group significantly improved on identification, discrimination, and memory but not ASA compared to controls. Gains also transferred to speech skills. Good et al. (2017) assessed the impact of individual piano lessons on various auditory processing aspects in CI children. Lessons included music theory, techniques like scales/dynamics, and learning new songs. The experimental group showed enhanced discrimination of melodic contour, rhythm, and melodic memory versus controls. Skills generalized to improved emotional speech prosody perception.

Retention of Improved Performance

Several studies examined retention of improved performance after auditory training. Retention is assessed by comparing baseline and post-training skills on trained and untrained tasks once training ceased. Mishra et al. (2015) found children with CIs maintained gains in recognizing numbers in noise up to 3 weeks post-training. Kronenberger et al. (2011) also assessed retention following working memory training, observing retention of speech skills up to 6 months while working memory lasted 1 month. Wu et al. (2007) trained phoneme and acoustic speech feature discrimination in vowels and consonants. Assessments up to 2 months post-training revealed retention of gains in vowel, consonant and tone recognition. Collectively, these studies demonstrate auditory training can yield benefits that are at least partially sustained in the medium-term, from 1 to 6 months following cessation of formal training activities. This indicates training induces neuroplastic changes supporting longer-term enhancement of auditory functioning.

Generalization and Transfer of Learning

Several of the studies observed positive transfer effects, where improved abilities from auditory training extended to untrained skills. Good et al. (2017) and Roman et al. (2016) found nonspeech training, such as with music and environmental sounds, conveyed benefits to speech-related tasks like prosody perception and phonemic discrimination. Mishra et al. (2015) noted "near transfer" from trained number recognition in noise to a similar untrained digit task in modulated noise. Kronenberger et al. (2011) saw working memory gains transfer to enhanced language functioning. These findings suggest training induces neuroplastic changes supporting broader enhancement of auditory processing. However, two pilot studies by Welch et al. (2015) and Yucel et al. (2009) found mixed or null transfer outcomes, though Yucel et al. detected transfer on one speech measure and Welch et al. noted limitations with training resources and participant heterogeneity. Overall, evidence increasingly points to generalization capabilities of auditory training, but continued research with rigorous methodology could provide stronger confirmation.

AT Approaches

The studies on auditory training approaches can be categorized based on their use of either analytic (bottom-up) or synthetic (top-down) methods. Several investigations incorporated both types of approaches in their training protocols. For instance, Mishra et al. (2015) combined analytic speech discrimination tasks with more synthetically oriented training involving accented speech. Similarly, Roman et al. (2016) targeted lower-level skills like identification and discrimination as well as higher-level auditory memory and scene analysis abilities. A few other studies focused exclusively on one approach versus the other. Some examples utilizing solely analytic training included Wu et al. (2007) and Hagr et al. (2016), which worked on discriminating speech features, while Good et al. (2017) and Welch et al. (2015) exclusively employed synthetic music and singing exercises. Meanwhile, Kronenberger et al. (2011) solely trained working memory using the Cogmed program. Overall, all of the studies reported improvements on the skills targeted regardless of whether an analytic, synthetic, or combined approach was used. No clear advantage of one methodology over the other was evident. However, integrating both lower-level and higher-level training may serve to maximize benefits by strengthening auditory functions at multiple stages of processing.

Discussion

Summary and recommendations

This thesis evaluated the literature on auditory training (AT) benefits for pediatric cochlear implant (CI) users. Two studies also included children using other devices. Trained skills included working memory, phonological awareness, speech perception, music perception, pitch/rhythm discrimination, and environmental sound identification. AT led to improvements on trained tasks across all nine investigations regardless of duration or type of training. Additionally, four of six studies assessing generalization demonstrated transfer effects, such as working memory training enhancing language skills (Kronenberger et al., 2011) and music training improving prosody perception (Good et al., 2017). While encouraging, clinicians must recognize evidence supporting AT use in pediatric CI rehabilitation is still emerging. A recent meta-analysis found working memory training did not improve unrelated abilities like speech perception in the general population (Melby-Lervåg et al., 2016), although limited CI-specific research precludes definitive conclusions. Training type should consider individual needs, as both analytic and synthetic approaches proved effective, with no approach superior. Further work is needed to determine whether technique choice matters or if any AT provides benefit (Melby-Lervåg et al., 2016; Kronenberger et al., 2011; Good et al., 2017).

An interesting trend emerged from examining whether studies assessed generalization of learning to untrained tasks. Studies utilizing solely analytic training tasks, such as Hagr et al. (2016) and Wu et al. (2007), did not evaluate transfer effects, likely because training targeted basic discernible skills not expected to influence other abilities. However, investigations employing synthetic training independently or combined with analytic exercises, including Good et al. (2017), Kronenberger et al. (2011), Mishra et al. (2015), and Roman et al. (2016), reported benefits for skills not directly trained. While no approach was clearly superior, combining synthetic and analytic training seems optimal as it incorporates higher-level processing with more basic perceptual discrimination. This supports the recommendation of Amitay et al. (2006) to employ both approaches to maximize potential gains.

Another important consideration is how long benefits are retained after training ends. Surprisingly, only three studies (Kronenberger et al., 2011; Mishra et al., 2015; Wu et al., 2007) examined this, finding retention lasted 2 weeks to 2 months. Such variability could reflect subject compliance, an understudied yet critical factor influencing training effectiveness. In fact, just one study (Mishra et al., 2015) formally assessed compliance, highlighting the need for future research to investigate how this impacts outcomes. Clarifying retention periods and compliance would help demonstrate auditory training's clinical value by providing insight on whether benefits are sustained and how motivating participants remains. We therefore recommend retention and compliance be priorities for evaluation in upcoming auditory training studies.

Another factor not assessed was quality of life, which directly influences clinicians' and providers' decisions to offer auditory training (AT). Only Yucel et al. (2009) utilized self- or parent-reported questionnaires to gauge participant/family perspectives on changes in everyday speech skills post-training. Such tools are valuable for determining end-users' satisfaction and perception of AT benefits. Study quality was deemed low to moderate in line with Henshaw and Ferguson (2013), who reviewed adult AT literature. This thesis found consistent gains across investigations despite methodological limitations common to pediatric populations, such as difficulties randomizing, powering studies, and blinding participants/assessors. However, current cohorts are larger, allowing greater control over recruitment and training delivery.

Future work should address past issues where possible, carefully monitoring compliance using reliable outcome measures spanning direct, generalized, and real-world listening. Assessing generalization specifically and retention after intervention cessation are essential for demonstrating AT efficacy, regardless of assessments employed. While meta-analysis remains infeasible due to outcome diversity, focusing generalization and retention investigations could eventually facilitate pooled examination. Overall quality of life impacts, generalization, retention, compliance, and controlled methodology should receive heightened priority in upcoming pediatric AT investigations to strengthen evidentiary basis and clinical translation potential for this promising rehabilitation approach.

Limitations

There were three main limitations in this thesis work. First, CI and hearing aid users were included in two studies (Welch et al., 2015; Wu et al., 2007), which could be seen as inconsistent with only examining research involving children with implants alone. However, due to the limited available research at the time investigating solely pediatric CI recipients, it was deemed acceptable. Considering increasing rates of residual hearing preservation, distinguishing CI and aided populations is becoming less clear-cut as well. Secondly, a meta-analysis could not be conducted owing to dissimilar outcome measures across studies. Finally, potential effects of duration and frequency of training intervention on AT results were not addressed. Reports of intervention specifics in the literature were too variable to analyze impacts. Future research would benefit from more consistency and reporting of participant characteristics, metrics, and training protocols to facilitate synthesis and identification of optimal strategies. Overall, this thesis work provides useful insight but could be strengthened through strategies addressing limitations like harmonizing methodology across investigation.

Conclusion

In conclusion, this thesis work systematically examined the literature on auditory training (AT) benefits for pediatric cochlear implant recipients. Studies consistently demonstrated gains on trained tasks, with several also reporting transfer effects to untrained skills. Among investigations assessing retention, benefits persisted after training cessation, albeit over variable periods. No studies evaluated quality of life impacts despite its importance. Agreement with prior reviews was found regarding the need for higher quality evidence on AT outcomes in this population. However, consistently positive findings across investigations to date should not equate to lack of effectiveness simply due to methodological limitations common among pediatric research. Future work achieving higher evidence grades through strategies like randomization, power analyses, blinding and controls would strengthen conclusions. Incorporating additional key indicators such as quality of life, retention periods, and compliance is also recommended to better demonstrate AT success. Overall, AT shows promising potential meriting continued rigorous investigation using optimized methodology prioritizing these broader outcome assessments and quality indicators.

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