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Phoneme Training for Adult Cochlear Implant Users: A Review of the Literature and Study Protocol

Nikki Philpott,[a,b] Birgit Philips,[b] Kayla Tromp,[c] Sophia Kramer,[d] Emmanuel Mylanus,[a] and Wendy Huinck[a]

[a] Department of Otorhinolaryngology, Donders Institute for Brain, Cognition and Behaviour, Radboud university medical center, Nijmegen, the Netherlands [b] Cochlear Ltd., Mechelen, Belgium [c] Independent Researcher, Manitoba, Canada [d] Department of Otolaryngology-Head and Neck Surgery, Vrije Universiteit Amsterdam, Amsterdam UMC, the Netherlands

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ABSTRACT

Purpose: This study describes a protocol for a novel individualized phoneme training program for adult cochlear implant (CI) users, based on individual phoneme confusion errors. The protocol is underpinned by a literature review on phoneme training and a focus group with adult CI users.
Method: After a literature search, five studies were included for review and evaluation of quality and level of evidence. A focus group with experienced adult CI users (*n* = 7) was then conducted to gain insights into their experiences of auditory training post-implantation and recommendations for future training programs. The knowledge gained from the literature review and focus group was used as the foundation for a novel, individualized phoneme training program for adult CI users, for which the protocol is described in this study.
Results: A review of the literature shows that phoneme training in adult CI users has variable outcomes for on-task and off-task measures. Overall, the concept of individualized training relates to adaptive difficulty within training tasks and not to tailoring training content to participants' individual needs, as indicated by clinical outcomes. The focus group revealed that participants want to be able to track their training progress, have training content tailored to their individual needs, and expressed a preference for shorter training sessions.
Conclusions: Using learnings from a literature review and focus group, this study describes a protocol for a novel, individualized phoneme training program for adult CI users. Study findings from this phoneme training program will be disseminated when available.
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The importance of audiological rehabilitation in the area of cochlear implantation is well documented for children (Rayes et al., 2019). While this is also true for adult cochlear implant (CI) users (Tye-Murray, 2020), there is a lack of high-quality, evidence-based data supporting individualized rehabilitation in adult CI users (Henshaw & Ferguson, 2013; Sweetow & Palmer, 2005). As part of their post-implantation trajectory, CI users typically require auditory training that empowers and teaches them to make use of their CI to ensure maximum benefit for both themselves and their communication partners (Moberly et al., 2016). Auditory training programs typically focus on improving performance in auditory tasks; promoting self-management of hearing difficulties; refining auditory perceptual skills; and, in turn, improving speech perception (Henshaw & Ferguson, 2013).

Various factors are known to affect the outcomes of adult CI users, who often struggle with a more severe level of hearing loss before implantation when compared to most individuals who utilize hearing aids. Some of these factors include duration of deafness; age at implantation; residual hearing; intracochlear electrode position; and, although less studied, family involvement and patient motivation (Green et al., 2007; Lazard et al., 2012; Leung et al., 2005). Even with this knowledge, outcomes among adult CI users cover

Correspondence to Nikki Philpott: nikki.tromp@radboudumc.nl. ***Disclosure:*** *Nikki Philpott is affiliated with Cochlear, Ltd. as a researcher, through an EU grant as part of the MOSAICS project. This affiliation has in no way affected the initiation, formulation and content of the manuscript. Birgit Philips is an employee of Cochlear, Ltd. The authors have declared that no competing financial or nonfinancial interests existed at the time of publication.*

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a wide range and are variable, and even "good candidates" can present as "low performers" (Firszt et al., 2004; Gifford et al., 2008; Holden et al., 2013; Moberly et al., 2016). Research in this field typically brings authors to the same conclusion: Individualized auditory training should be considered to address CI users' listening priorities and difficulties on an individual level (Clark et al., 2012; Moberly et al., 2016, 2018; Tye-Murray, 2020; Wilson & Dorman, 2008). It is this individualized approach to rehabilitation that is hypothesized to improve outcomes in CI users and reduce variability in outcomes.

Auditory training typically focuses on a bottom-up (synthetic) approach, top-down (analytic) approach (Erber, 1982), or a combination of the two. While the latter focuses on comprehension of contextual information using cognitive skills and communication strategies (Sweetow & Sabes, 2006), a bottom-up approach may be required for individuals who need to focus on isolated sounds, words, or phrases before comprehension on a contextual level (Stecker et al., 2006). This bottom-up approach may be especially relevant for lower-performing CI users with lower clinical outcomes, such as a word or phoneme score. Recently, Cambridge et al. (2022) published a systematic review looking at the efficacy of auditory training on outcomes in postlingually deafened adult CI users. The review included 10 papers, focusing on whether auditory outcomes are improved with auditory training compared to no training. The authors conclude that while some auditory training is suggestive of improving outcomes, higher-quality studies are needed to demonstrate which type of auditory training is most effective for improving specific auditory outcomes.

Objectives and Rationale

To date, a comprehensive review of a bottom-up approach to auditory training in adult CI users, and specifically how the training is prescribed and individualized to meet individuals' needs based on clinical diagnostics, has yet to be conducted. Four articles reviewed in the Cambridge et al. (2022) study are also included for review in this study, with the addition of a new publication. However, this study looks at the included literature through a different lens, namely, individualized phoneme training. Here, we approach the topic of individualized phoneme training in three parts. In Part I, we first review the current literature on phoneme training for postlingually deafened adult CI users. The primary objectives of the literature review were to evaluate timing (commencement, frequency, and total duration), indications (which participants are allocated to a specific phoneme training program), content, and outcomes of phoneme training programs in adult CI users, with or without contralateral amplification. In Part II, we describe insights from a focus group that we conducted with experienced adult CI users, aimed at understanding their prior experience with auditory training and what an ideal auditory training program would look like. Together with the learnings from the literature review and focus group, Part III describes a study protocol for a novel, individualized phoneme training program for adult CI users.

Part I: A Literature Review of Phoneme Training Programs for Adult CI Users

Inclusion Criteria

All study designs were eligible for review. Studies examining adults (age 18+ years) with postlingual bilateral moderate-to-profound sensorineural hearing loss, making use of a CI with or without contralateral amplification, were included. The degree of hearing loss had to be defined/definable in included studies. Interventions of interest included any auditory training specifically relating to phoneme detection, discrimination, identification, or comprehension provided to the included population, with follow-up metrics (to allow for within-subject outcome comparison over time, where possible). Where studies reported information relating to the timing (commencement, frequency, and/or total duration) of phoneme training, this information was included for review. Indications for allocation to phoneme training (which participants underwent training, if not all) were also recorded. True control groups were defined as participants who did not undergo any phoneme training. Within-subject controls were not considered true controls. Studies without a control group or with an active control group were also included. Qualitative and/or quantitative data outcome measures for evaluating pre– and post–phoneme training outcomes were included. Specific outcomes of interest included, but were not limited to, pre- and posttraining outcome measures for the trained auditory task, phoneme, word and/or sentence recognition score, quality of life/health-related quality of life, cognition, listening effort, communication ability, environmental awareness, and self-reported hearing disability (with or without the use of questionnaires). Where other pre- and posttraining outcome measures were reported that are not mentioned in the above list, these were considered on a case-by-case basis.

Literature Sources

Literature search strategies were developed using medical subject headings and, where relevant, included

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specific words for title/abstract searches. Databases searched included PubMed, EMBASE, Cochrane Library, CINAHL, PsycINFO, and Web of Science. No limits were set for publication dates. Only articles available in English were included. Reference lists of included studies, as well as those of other relevant systematic reviews registered in Cochrane Library, were also scanned for additional studies. Unpublished research and gray literature, including white papers, dissertations, conference papers, and abstracts were also assessed for inclusion.

The specific search strategies were developed in consultation with the research team, as well as a Health Science Librarian with expertise in literature searches for systematic reviews. Search terms included: (cochlear implant*) AND (phone* training OR phone* identification OR phon* recognition OR phone* learning OR phone* OR auditory training OR perceptual training OR auditory rehabilitation) AND (Adult OR adult* OR elderly OR middle age* OR young adult* OR star perform* OR poor perform* OR poorly perform* NOT (Child NOT Adult)). An example search strategy can be found in the Appendix.

Study Records

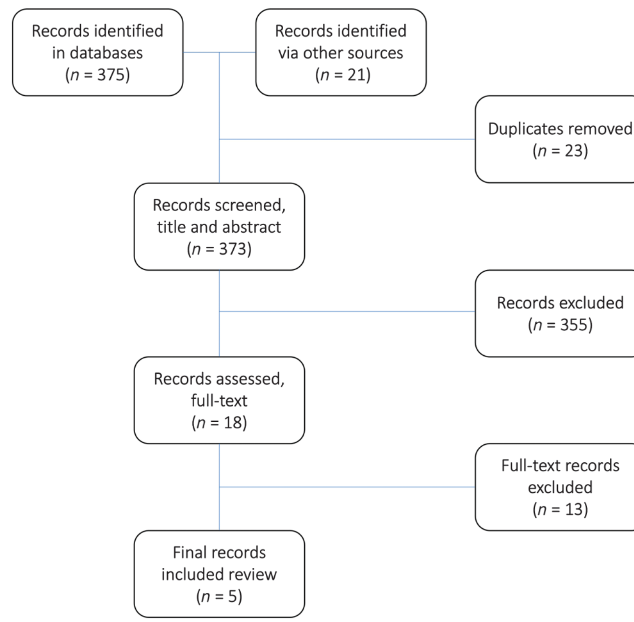
Data Management

Initial record screening for duplicate removal, inclusion, and exclusion was done using Rayyan (Ouzzani et al., 2016), an Internet-based program that allows for collaboration and blinding among reviewers during study selection.

Selection process. Two independent reviewers (N.P. and K.T.) were responsible for screening and inclusion decisions of the study. In cases where disagreement arose during the screening process, full texts were also reviewed before making an inclusion decision.

Screening. A summary of the screening process is represented in Figure 1. The initial database search yielded 375 records. An additional 21 records were identified through Google Scholar and reference-list screening. Of the 373 records screened after duplicate removal (*n* = 23), 18 were included for full-text review. Excluded articles failed to cover interventions of interest, namely, training involving phoneme detection, discrimination, identification, or comprehension, or follow-up metrics that did not allow for pre- to posttraining outcome comparison over time. Thirteen records were excluded for duplicate study populations, for having mostly prelingually deaf participants, or where it was not possible to disentangle phoneme training outcomes from the broader auditory training program utilized for a given study. Five records were eligible for inclusion in the final review.

Figure 1. Flow diagram of literature identification, screening, and inclusion process.



Data Items

Data were extracted and recorded in a standardized form in Microsoft Excel. Extracted data were composed of study design, sample size, participant characteristics (age, sex, duration of hearing loss, type of amplification, experience with CI, post-implantation performance), intervention (type, content, frequency, duration; see Table 1), outcome measures, intervention outcomes (see Table 2), and quality of evidence (see Table 3). Quality of evidence was assessed using the adapted version of the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) criteria (Guyatt et al., 2008), from the systematic review of Henshaw and Ferguson (2013).

For study quality scores: 0 = *flawed or no information*; 1 = *weak information, incorrect use or lack of detail*; and 2 = *appropriate use and reporting*. For level of evidence, Very low = The effect estimation is uncertain; Low = Further evidence is very likely to impact on confidence in the estimated effect and is likely to change the estimate; Moderate = There is moderate confidence in the estimated effect: The true effect is likely to be close to the estimated effect, but there is a possibility that it is substantially different; and High = There is high confidence that the true effect lies close to estimated effect.

Outcomes of the Literature Review

Participants

The reviewed studies comprised three repeated measures studies and two randomized controlled trials. Sample

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Table 1. Individual responses as recorded on sticky notes by focus group participants.

Study	Design	Group	*N* participants	Age mean, *SD* (range), in years	Duration of HL mean, *SD* (range), in years	Device use	CI experience mean, *SD* (range), in years
Zhang et al. (2012)	Repeated measures	Intervention	7 (5 female)	63, 8.8 (51–78)	36.3, 23.9 (2–10)	7 bimodal CI + HA	3.4, 4.3 (2–10)
Ingvalson et al. (2013)	Repeated measures	Intervention	5 (3 female)	71.4, 11.9 (51–80)	29.8, 15.9 (20–50)	1 bilateral CI 2 bimodal CI + HA 2 unilateral CI	5.8, 5 (2–14)
Schumann et al. (2015)	RCT	Intervention	15 (11 female)	60, 10.1 (42–75)	16.9, 13.5 (2–44)*	7 bilateral CI 5 bimodal CI + HA 3 unilateral CI	4.2, 1.7 (2–7)
		Control	12 (7 female)	61.1, 17.9 (30–82)	13.5, 9.6 (3–30) *duration of deafness, not only HL	3 bilateral CI 9 bimodal CI + HA	4.6, 2.1 (2–9)
Miller et al. (2016)	Repeated measures	Intervention	9 (7 female)	58.2, 9.7 (45–75)	15.3, 11.8 (< 1–27)	5 bilateral CI 4 unspecified (either unilateral CI or bimodal CI + HA)	7.9, 7.6 (< 1–23)
		Control	5 (3 female)	65.5, 10.3 (53–75)	12.4, 10.9 (< 1–25)	4 bilateral CI 1 unspecified (either unilateral CI or bimodal CI + HA)	6.9, 4.1 (1–13)
Magits et al. (2023)	RCT	Intervention	20 (11 female)	63.1, 8.4 (–)	23, 15 (–)	1 bilateral 7 unilateral 12 bimodal	2.1, 3.1 (0.1–15.9)
		Active control	20 (11 female)	65.2, 9.2 (–)	21, 13 (–)	2 bilateral 3 unilateral 15 bimodal	1.6, 5.0 (0.1–12)

Note. Responses per row are not linked to one participant and are presented in random order. (-) indicates that data for range is not available for this paper. HL = hearing loss; CI = cochlear implant; HA = hearing aid; RCT = randomized controlled trial; n/a = not applicable; LUISTER = Leuven Interactive Scheme for hearing Training Evaluation and audiological Rehabilitation; yrs = years.

*duration of deafness, not only HL.

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Table 1. *(Continued)*

Study	Pretraining clinical performance	Type of intervention	Mode of intervention	Training condition	Testing condition
Zhang et al. (2012)	Not specified. Varying degrees of residual hearing in the non-implanted ear.	Adaptive phoneme identification training	Laptop (Sound Express) at home	Free-field in the best aided condition	Free-field in 3 conditions: CI-only, HA-only, and CI + HA. All subjects tested in noise, except for 1 participant
Ingvalson et al. (2013	Warble tone free-field aided thresholds < 30 dB HL at 250–6000 Hz All reported difficulty in noisy environments	Adaptive phoneme identification training	Desktop computer at the clinic using custom training software (Seeing and Hearing Speech program)	Free-field. Aided condition during training not specified	Free-field. Aided condition during testing not specified
Schumann et al., 2015)	Mean monosyllabic word recognition 79% ± 12%	Adaptive phoneme discrimination training	Desktop computer at the clinic using training program from Serman (2012)	Free-field. Bimodal users trained with CI-only, bilateral users could choose to train with one or both CIs	Free-field in quiet and noise. All users tested in bimodal or bilateral condition
	Mean monosyllabic word recognition 77% ± 11%	None	n/a	n/a	Free-field in quiet and noise. All users tested in bimodal or bilateral condition
Miller et al. (2016)	Mean phoneme identification score < 70%	Adaptive multiple talker phonetic identification training	Desktop computer at the clinic using custom training software	Free-field. Aided condition during training not specified	Free-field. Aided condition during testing not specified
	2 high-performing (> 70% phoneme identification score) and 3 low-performing (< 70% phoneme identification score)	None	n/a	n/a	Free-field in quiet. Aided condition during testing not specified
Magits et al. (2023)	Not specified	Adaptive analytic and synthetic training for phoneme identification	Mobile app (LUISTER) at home	Direct streaming in quiet for phoneme identification and in noise for digits. Bilateral CI users chose which side to stream	Direct streaming with noise for CI-only, where bilateral CI users chose which side to stream. Free-field with noise in the best aided condition.
	Not specified	Non-adaptive generic auditory training	Mobile app at home	Direct streaming. Bilateral CI users chose which side to stream	Direct streaming with noise for CI-only, where bilateral CI users chose which side to stream. Free-field with noise in the best aided condition

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Table 2. Summary of phoneme training content and findings.

Study	Group	Training content	Training duration	Pre- and posttraining tests	Within-training tests	On-task findings
Zhang et al. (2012)	Intervention	Phoneme identification in noise using monosyllabic words (one subject trained in quiet)	60 min/day 5 days/week 4 weeks	Phoneme identification Voice gender identification Emotion identification Monosyllabic word identification (CNC) Sentence identification (AzBio)	None	n/a
Ingvalson et al. (2013)	Intervention	Phoneme identification in noise using words, phrases, and sentences	60 min/day for 4 days	Speech in noise (QuickSIN and HINT) SSQ (pretraining and after retention)	None	n/a
Schumann et al. (2015)	Intervention	Phoneme discrimination in quiet using nonsense-syllable combinations in CVC and VCV format	45–60 min/day, 2 days/ week 3 weeks (duration/day depended on progress speed)	Sentences in moderate noise (+5 dB SNR; Goettingen sentence test) Sentences in difficult noise (0 dB SNR; Goettingen sentence test)	None. Pre–post training phoneme identification was compared by post hoc analysis of accuracy during training activities	Varying degrees of improvement for phoneme depending on the syllable Mean improvement of 16.4% points for VCV /a/, 10% points for VCV /e/, and 9.5% points for VCV /i/ Mean improvement of 5.4% points for CVC vowel training materials
	Control	None	n/a	Sentences in moderate noise (+ 5 dB SNR; Goettingen sentence test) Sentences in difficult noise (0 dB SNR; Goettingen sentence test)	None	n/a
Miller et al. (2016)	Intervention	Phonetic identification of /ba/, /da/, /wa/, /ja/ contrasts with multiple talkers in quiet	4 × 2–hr sessions over 2 weeks	Phoneme identification of /ba/, /da/, /wa/, /ja/ contrasts (unfamiliar and/or talkers) in quiet	Phoneme identification of /ba/, /da/, /wa/, /ja/ contrasts (newly familiar talkers) in quiet	Not reported
	Control	None	n/a	Phoneme identification of /ba/, /da/, /wa/, /ja/ contrasts (familiar and/or unfamiliar talkers) in quiet	n/a	n/a
Magits et al. (2023)	Intervention	Phoneme identification Themes Voice gender identification Sound emphasis in words Clock reading Completing sentences*	15–20 min/day 5 days/week 16 weeks	Speech in noise (LIST) Executive functioning (Stroop Color–Word test, Trail Making Test, Letter Memory test) Quality of Life (NCIQ)	Phoneme identification in quiet Digits in noise	Improvement by ≥ 2 dB SNR in starting stimulus training intensity Significant improvement for DiN and phoneme identification No improvements in executive functioning
	Active control	Amplitude modulation detection Frequency modulation detection Music scale discrimination Gap detection Speech in quiet (themes)	15–20 min/day 5 days/week 16 weeks	Speech in noise (LIST) Executive functioning (Stroop Color–Word test, Trail Making Test, Letter Memory test) Quality of Life (NCIQ)	Phoneme identification in quiet	Could not assess on-task improvement related to stimulus training intensity Significant improvement for DiN and phoneme identification No improvements in executive functioning

Note. CI = cochlear implant; n/a = not applicable; QuickSIN = Quick Speech-in-Noise Test; HINT = Hearing-in-Noise Test; SNR = signal-to-noise ratio; CVC = consonant–vowel–consonant; VCV = vowel–consonant–vowel; NCIQ = Nijmegen Cochlear Implant Questionnaire; DiN = Digits in Noise; LIST = Leuven Intelligibility Sentences Tests; CNC = Consonant Nucleus Consonant.

*All tasks available in quiet, speech-weighted noise and babble.

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Table 2. *(Continued)*

Study	Off-task findings	Retention period	Retention findings	Personalization	Notes
Zhang et al. (2012)	Significant improvement for phoneme identification and CNC words for 6/7 subjects Nonsignificant improvement for AzBio sentences for 6/7 participants No improvement for voice gender identification and emotion identification for all participants Improvements were the same for all tasks for CI-only and best aided conditions	4 weeks	Improvements were largely retained after the 4-week follow-up period	Adaptive difficulty based on on-task performance during training	Participants did not receive any active auditory training post-implantation Subject 5 had no improvement on any tasks, but had the most experience in the group (10 years)
Ingvalson et al. (2013)	Significant improvements for QuickSIN and HINT In all cases, significant improvements were only noted for favorable SNRs	4 days	Improvements were retained after the 4-day follow-up period No significant changes from pre- to post-intervention SSQ score	Adaptive difficulty (manually managed by clinician) based on on-task performance during training	
Schumann et al. (2015)	Significant mean improvement for sentences in moderate noise (+5 dB SNR) Nonsignificant mean improvement for sentences in difficult noise (0 dB SNR)	6 months	Improvements were retained after the 6-month follow-up period but were still only significant for moderate noise.	Adaptive difficulty based on on-task performance during training	Aided status during training and testing conditions differed.
	No significant differences between pre- and posttest sentence recognition in moderate and difficult noise	n/a	n/a	n/a	
Miller et al. (2016)	Significant increase in average phoneme identification scores, specifically for /ba/ and /wa/, even for unfamiliar talkers	None	n/a	Adaptive difficulty based on on-task performance during training	-
	No significant increase in average phoneme identification scores	n/a	n/a	n/a	-
Magits et al. (2023)	Speech in noise: around half of participants reached a clinically significant improvement of ≥ 2 dB No improvement in executive functioning Significant improvement in quality of life	8 months	Speech-in-noise findings maintained Improvement from baseline to retention session for updating skills, but no other executive functions Quality of life improvements maintained	Adaptive difficulty based on on-task performance during training	5 participants had < 6 months CI experience and were also undergoing standard auditory training in the clinic in parallel with this study
	Speech in noise: around half of participants reached a clinically significant improvement of ≥ 2 dB No improvement in executive functioning Significant improvement in quality of life	8 months	Speech-in-noise findings maintained Improvement from baseline to retention session for updating skills, but no other executive functions Quality of life improvements maintained	None	5 participants had < 6 months CI experience and were also undergoing standard auditory training in the clinic in parallel with this study

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Table 3. Levels of evidence and quality of the five included studies, as per Grading of Recommendations, Assessment, Development and Evaluation criteria adapted by Henshaw and Ferguson (2013).

Reference	Randomization	Control group	Power calculation	Blinding	Outcome measure reporting	Outcome measure selection	Training feedback	Ecological validity	Compliance reporting	Follow-up	Study quality score	Level of evidence
Zhang et al. (2012)	0	0	0	0	2	2	2	0	2	2	10	Low
Ingvalson et al. (2013)	0	0	0	0	2	1	0	0	0	1	4	Very low
Schumann et al. (2015)	1	2	0	0	2	1	2	1	2	2	13	Moderate
Miller et al. (2016)	0	0*	0	0	2	1	0	0	1	0	4	Very low
Magits et al. (2023)	2	0*	2	2	2	2	2	1	2	2	17	High

*Control group present, but not a true control.

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sizes ranged from five to 20 participants, with only Magits et al. (2023) making use of power calculations. This was also the only study to use blinding for intervention and control group allocation, with an age-matched placebo control group that underwent non-adaptive generic auditory training for the same duration as the intervention group. Control groups in studies by Schumann et al. (2015) and Miller et al. (2016) were noncontact controls, with no alternative interventions provided, and were only tested at the same intervals as the intervention groups. While the control group from Schumann et al. (2015) was comparable to the intervention group, the control group from Miller et al. (2016) mostly constituted poor performers and individuals who did not want to undergo training and are referred to as a "pseudo control" group. Zhang et al. (2012) and Ingvalson et al. (2013) did not include control groups in their studies.

Regarding baseline performance, Magits et al. (2023) and Zhang et al. (2012) did not specify the pre-training performance of their participants. The same was true for Ingvalson et al. (2013), although all participants reported difficulties listening in noisy conditions. The intervention group of Miller et al. (2016) were lower performers (< 70% phoneme identification score), whereas CI users in Schumann et al.'s (2015) study were relatively higher performers, with monosyllabic word recognition scores of 79% ± 12% in the intervention group and 77% ± 11% in the control group.

Duration of CI use was another factor with big differences both within studies and between studies. In the study by Magits et al. (2023), 25% of participants in both the intervention and active control group were newly implanted CI users with < 6 months of experience, whereas for Zhang et al. (2012), Ingvalson et al. (2013), and Schumann et al. (2015), all participants had at least 2 years of experience with their CI. Some studies included participants with CI use of 15.9 years (Magits et al., 2023) and 23 years (Miller et al., 2016), with newly implanted participants in the same intervention group. Zhang et al. (2012) reported improvements in all but one participant, who had the most CI experience (10 years).

Testing and Training Conditions

Aided modalities during testing and auditory training also differed between studies. Ingvalson et al. (2013) and Miller et al. (2016) did not specify aided conditions during testing and training, although all stimuli were presented in the free field. Schumann et al. (2015) allowed participants to train with either CI-only (if using a contralateral hearing aid) or, if implanted bilaterally, with one or both CIs. For testing, however, participants were always tested in a binaural listening condition (CI + hearing aid or CI + CI). Participants in the study by Magits et al. (2023) trained and were tested via direct streaming to a single CI side, with the addition of testing in the free field in the best-aided condition.

Training Format and Materials

In line with the focus of this review, all studies provided some form of phoneme training. Only Zhang et al. (2012) and Magits et al. (2023) opted for home-based training on a laptop and mobile app, respectively. Training in the remaining studies took place on a desktop computer at the respective clinics. Zhang et al. (2012) and Ingvalson et al. (2013) targeted phoneme identification training in noise, whereas Magits et al. (2023) offered training in both quiet and noise. Schumann et al. (2015) focused on phoneme discrimination training in quiet, whereas Miller et al. (2016) targeted phonetic identification contrasts using multiple talkers. The duration of training sessions also varied across the reviewed studies. Magits et al. (2023) opted for 15–20 min of training per day over a period of 16 weeks (80 training sessions in total). Zhang et al. (2012), Ingvalson et al. (2013), and Schumann et al. (2015) all opted for approximately 60 min of training per day, with the training program running over 4 weeks, 4 days, and 3 weeks, respectively. Miller et al. (2016) had the longest training duration per single session, 2 hr, but these sessions only took place 4 times over a period of 2 weeks.

Personalization of Training

All reviewed studies reported their phoneme training programs to involve personalization. Throughout, personalization was obtained with adaptive difficulty based on performance during, and not before, auditory training. This personalization varied in the form of background noise level, response options (e.g., closed vs. open set, or multiple response token options), or training activity (analytic vs. synthetic).

Training Outcomes

On-Task Outcomes

On-task outcomes were only reported in two studies, although continuous monitoring was informally carried out across all studies to personalize difficulty (see Personalization of Training section above). In Schumann et al. (2015), clinicians who conducted the training sessions noted varying degrees of improvement for consonant and vowel identification over the course of training sessions, but this was not formally assessed. Training materials by Miller et al. (2016) comprised phonetic contrasts in quiet with multiple talkers, which yielded a significant increase in phoneme identification of the trained phonetic contrasts, even for unfamiliar talkers.

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Off-Task Outcomes

Off-task outcomes ranged from phoneme and word identification to sentence recognition in varying degrees of noise. Phoneme identification was measured as a pre- to post-intervention outcome by Zhang et al. (2012) and Miller et al. (2016), although the latter authors only assessed the identification of trained phonemes (but with unfamiliar talkers compared to the training materials). Speech perception in noise was measured by Zhang et al. (2012); Ingvalson et al. (2013); Schumann et al. (2015), who had two levels of noise: moderate and difficult; and Magits et al. (2023). Based on their phoneme training using words in noise, Zhang et al. (2012) only noted significant improvements in phoneme and word identification in noise, but these findings did not hold for sentences in noise. Ingvalson et al. (2013) used words, phrases, and sentences in noise as training materials and found significant improvements in sentence perception in noise. However, this was only true for favorable listening conditions (greater signal-to-noise ratio [SNR]). When using training stimuli consisting of nonsense syllable combinations in quiet, Schumann et al. (2015) reported significant mean improvements for sentences in moderate noise. These findings were not replicated for sentences in difficult noise, and aided conditions during training were not the same as during testing (see Testing and Training Conditions section above). Magits et al. (2023) offered auditory training in both quiet and noise. The authors found that approximately 50% of participants in the intervention group achieved a clinically significant (≥ 2 dB) improvement in sentence recognition in noise. Where post-intervention follow-up testing was conducted in the relevant studies, improvements were largely retained.

Ingvalson et al. (2013) and Magits et al. (2023) also measured nonaudiological outcomes relating to hearing-related quality of life, using the Speech, Spatial and Qualities of Hearing Scale (SSQ) and the Nijmegen Cochlear Implant Questionnaire (NCIQ), respectively. No changes were noted in the SSQ score post-intervention, whereas significant improvements in quality of life (NCIQ) were observed, and maintained, post-intervention.

With the exception of Magits et al. (2023), improvements in clinical, off-task outcomes in the reviewed studies are only reported in terms of statistically significant improvements. Bernstein et al. (2021) suggest that, unlike statistical significance, clinical significance reflects a more meaningful change by reflecting the magnitude of the performance difference, where a 10% change is deemed clinically significant. In other words, while studies may report statistically significant improvements post-training, whether these improvements represent true clinical or perceived benefit is not known. This is important when considering the real-world implications of auditory training.

Quality of Evidence

Based on the GRADE Working Group guidelines by Guyatt et al. (2008), adapted by Henshaw and Ferguson (2013), the majority of reviewed studies contained very low or low levels of evidence. This suggests that the estimation effect is uncertain or is likely to be changed with the addition of further evidence. This is largely due to the lack of a true control group, power calculation, and blinding. All studies performed well in the outcome measure selection domain but lacked ecological validity in selecting outcome measures to reflect daily real-world listening.

Learnings From the Literature Review

Overall, these studies suggest that personalized phoneme training does appear to hold benefits for some CI users for certain clinical outcomes, even when compared to groups who received alternative or no training. For the reviewed literature, personalization takes on the form of adaptive difficulty based on within-task performance while training, as opposed to individualization, where tasks are targeted based on the pretraining clinical performance of individual participants. While the reviewed interventions often only translate to improved measures on a phoneme or word level, or favorable listening conditions (less noise) for sentence perception, it is important to note that these significant improvements were observed from training that involved largely bottom-up (analytic) training. This suggests that even nonindividualized phoneme training (not based on pretraining clinical performance) has some benefit for certain groups of CI users.

By having adult CI users first undergo a specific test battery to diagnose their user-specific phoneme perception error patterns, individualized intervention to target these error patterns can be put in place. We hypothesize that, by first targeting individual, bottom-up perception errors (i.e., phonemes, the analytic building blocks of speech perception), a strong foundation can be created on which to build upon improved top-down speech perception. This targeted, individualized approach to phoneme training aims to improve speech perception outcomes of adult CI users. In doing so, long-term objectives of phoneme training can look at transferring improvements to speech understanding in quiet and noise in daily life. These real-world improvements may lead to an overall improved quality of life, although contributors to quality of life are multifactorial (Punch et al., 2019). Whether the impact of such an individualized phoneme-based training program will generalize to real-world performance remains to be explored. The outcome metrics utilized in our intervention study are described in Part III of this article.

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As e-Health and telerehabilitation gain increasing popularity in the field of audiology, such as the mobile training app used by Magits et al. (2023), so does the investigation into user engagement in mobile training apps. User engagement and motivation are key in ensuring users remain compliant with their training program. The COM-B model (capability, opportunity, motivation - behavior) of behavior change examines what elements need to be considered to get someone to change (Maidment et al., 2019; Michie et al., 2011), which implies starting a new behavior or stopping or changing a current behavior (Manchaiah, 2012). It considers the role of motivation, opportunity, and capability in changing health behaviors and has been successfully applied to develop interventions for adult aural rehabilitation (Maidment et al., 2019). By utilizing this model, Maidment et al. (2019) found that allowing individuals with hearing loss to make hearing device adjustments on their smartphone app gave them greater autonomy and empowerment, leading to greater motivation. Using e-Health to personalize rehabilitation also allows for greater self-management, which, coupled with sustained motivation and active participation, leads to better health behaviors and better outcomes (Ferguson et al., 2019).

Part II: A Focus Group on Auditory Training Experiences and Desires of Experienced Adult CI Users

Using the learnings from our literature review and concepts of self-determination theory (Deci & Ryan, 2013) and the COM-B model of behavior change (Maidment et al., 2019) that would influence the uptake of an auditory training program, we conducted two focus group sessions. Each focus group lasted 90 min, with a total of seven adult CI users (four women and three men) participating. Participants ranged in age from 51 to 81 years, ranging from 4 to 10 years of experience with their CI. All participants were Cochlear™ users and had some degree of formal clinic-based and home-based auditory training post-implantation. The overall goal of these focus groups was to gain insights into the experiences of adult CI users who underwent auditory training and what takeaways they had from these experiences that they would like to see implemented (or not) in future auditory training programs.

Participants were posed with five questions:

1. What did your rehabilitation experience look like?
2. Was a family member/partner/friend involved in your rehabilitation trajectory?
3. What would you like to see changed/added to rehabilitation in the future?
4. What did you like most about your rehabilitation?
5. Did your rehabilitation have an impact?

Participants were invited to answer five questions by first reflecting on their own experiences in written responses on sticky notes, which were placed on poster boards around the room. All individual responses written on sticky notes were translated from Dutch to English and verbatim transcribed. Responses are presented in Supplemental Material S1. Authors B.P. and N.P. then collectively shared all participants' responses with the group, allowing them to elaborate on their responses and for other participants to reflect on how their experience was similar or different to someone else's.

In these discussions, we focused on Questions 1, 3, and 4 (above), as they were most relevant to the development of a mobile training app. Participants' main conversation points were captured and summarized by author N.P. during the discussions and are reported below.

Participants' Previous Rehabilitation Experiences

All participants underwent a similar auditory training program, where they were sent home with a standardized pack of auditory training exercises to complete with a communication partner. Training activities lasted for several weeks to 3 months, with no formal feedback on training progress supplied. Training activities were reportedly not individualized to participants' individual needs (based on clinical outcomes).

What Participants Would Like to See Done Differently in Rehabilitation in the Future

The majority of participants saw value in continuous progress tracking throughout the training period, not just at infrequent clinical visits. They also highlighted a preference for "short and sweet" training periods, with shorter intervals multiple times a day, as opposed to a single longer training session per day. This was especially true for a user with younger children, who felt that a longer training session kept her "offline from the world" for a significant amount of time, which was undesirable.

What Participants Liked Most About Their Rehabilitation

All participants enjoyed the prospect of progress monitoring throughout their rehabilitation programs and felt that evidence of improvement in speech perception skills was motivating. Participants also enjoyed seeing

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their progress in the clinic as a result of training (i.e., improvements in speech perception scores).

Part III: Design of a Novel Phoneme Training Program

Using our learnings from the literature review and focus group, we propose a novel phoneme training program that targets specific phoneme perception errors of adult CI users. The individualized phoneme training program will be presented in an e-Health mobile app. Phoneme training will be provided to experienced CI users on a loaner research mobile device, via the Cochlear Mobile Research App (MRA), a research application developed by Cochlear.

Aims and Objectives

This study will aim to improve phoneme confusion errors of adult CI users through individualized phoneme training on a mobile app. It is hypothesized that this novel approach to targeting specific individual phoneme confusion errors based on diagnostic testing will result in improved phoneme perception, with the aim to carry over these effects to word perception.

Study Design

A repeated-measures study design was chosen to assess the effects of the intervention over multiple time points (pre- and post-intervention), within subjects.

Participants

Given the exploratory nature of the study, effect size and power calculation to determine sample size was not conducted. Twenty-six experienced (> 12 months post-implantation) adult users of a CI have been recruited for participation. This number was deemed sufficient when compared to other phoneme training studies mentioned in the review (see Table 1). All participants will undergo 4 weeks of phoneme training. This study is part of a larger repeated measures (pre- to post-intervention) clinical trial, to assess the effects of the intervention over multiple time points. See ClinicalTrials.gov; Auditory Diagnostics and Error-based Treatment, NCT05307952; https://clinicaltrials.gov/ct2/show/NCT05307952 for information about recruitment and eligibility criteria.

Interventions

Diagnostic Testing for Phoneme Confusion Errors

To provide individualized phoneme training, each participant will undergo diagnostic testing to evaluate their phoneme recognition performance in quiet. Using nonsense monosyllabic words, the phoneme recognition in quiet (PRQ) test will measure participants' ability to identify consonants in a vowel–consonant–vowel context and vowels in a consonant–vowel–consonant (CVC) context, in a closed-set response format. Response choices consisted of all possible response options, based on the most common phonemes in Dutch (17 consonants and 13 vowels). Eight repetitions for each consonant stimulus and six repetitions for each vowel stimulus will be presented, with a total of 214 presentations. Stimuli will be presented in quiet via direct streaming to the speech processor, at an input of 65 dB SPL.

The results of the PRQ test will be computed and represented based on error dispersion, in the form of a phoneme confusion matrix—one for consonant and one for vowel confusions (van Son, 1994). The five phoneme confusion errors with the highest percentage of confusions for vowels and consonants (e.g., where "aMa" is continuously confused for "aPa," or "hAd" is continuously confused for "hUd") will be recorded for each participant. These results will be combined, and the five highest systematic phoneme confusion pairs (vowel and consonant confusions combined) will be selected as the phoneme confusion pairs to be trained for a given participant.

Training Materials for Phoneme Confusion Errors

Recently, a new corpus of monosyllabic Dutch words ("Thomas More lists") was validated by Vanpoucke et al. (2022) for use in diagnostic speech audiometry testing. These word lists, although validated, are currently not utilized by our research site (Radboud university medical center) for speech audiometry testing and are therefore appropriate to use as auditory training materials. Using the results from the PRQ for each participant, a MATLAB (MATLAB R2017a, MathWorks) script will be run to compare phonemes across the lexicon, to select five phoneme confusion pairs and their corresponding word lists. These word lists will be used as training materials for the duration of the study. All stimuli have been recorded by a female native Dutch speaker, in order to remain consistent with the use of a female speaker that is also used in the pre-existing speech materials within the diagnostic test battery.

Training Paradigm

During training tasks, participants will be presented with various Dutch monosyllabic minimal pairs from the Thomas More Lists in specific phonetic categories (such as place and manner of articulation, and voicing). Following Erber's (1982) hierarchy of listening skills, three training modules will be utilized: discrimination, identification, and comprehension. Each module will comprise five

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difficulty levels, varying in the difficulty of phonetic differences between presented and target words, how many closed-set response options are available, and whether background noise is present.

The decision to include the option to train in noise within all training modules was supported by the literature review in Part I, where training in the presence of background noise translated to improved off-task speech perception, even if this improvement was not statistically significant (Zhang et al., 2012) or only for favorable noise conditions (Ingvalson et al., 2013). A visual representation of this training scheme is summarized in Figure 2.

Training Frequency

Using MRA on a loaner mobile phone, participants will be required to train for 4 × 5–min sessions per day, 5 days per week, for 4 weeks. This decision was based on input from CI users during the focus group, who preferred the option of accessing multiple shorter training sessions throughout the day, at their convenience. For each new training session, participants can choose the phoneme pairs and difficulty levels to train at based on their diagnosed phoneme confusions. Upon initial selection of a phoneme confusion pair, participants will first be required to undergo a preview activity, where all words within that given phoneme confusion pair will be audio-visually presented before the training commences. This process will be repeated each time a new phoneme confusion pair is selected and will not form part of the 5-min training session. Participants will have access to the preview list of words throughout their training program, should they want to refamiliarize themselves with the words in each training list.

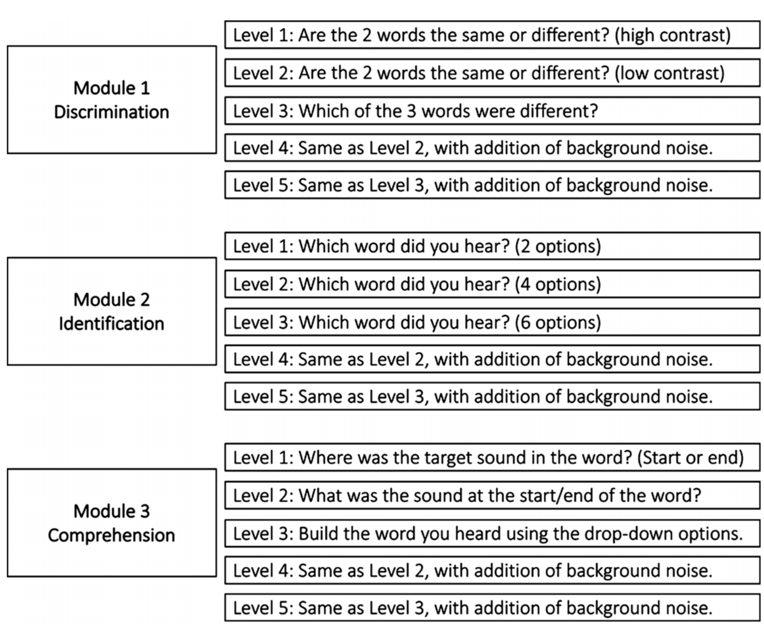
Training Feedback

A common theme within the focus group was the ability to monitor progress and have access to feedback while training. For focus group participants, these elements were previously not available for their standard post-implantation home-based phoneme training. Therefore, at the end of each 5-min training block, participants will be presented with a screen detailing how many correct responses were recorded while training, including the percentage of correct responses, followed by an opportunity to rate how effortful they found it to train, on a scale of 1 (*not effortful*) to 10 (*very effortful*). A free-text field will also be provided for any additional feedback on the training block.

Outcomes

All participants will be tested at three time points: pre-intervention, after the 4-week training period, and again after 4 weeks of no intervention to establish outcome retention. All outcome measures are off-task measures, as no formal assessment takes place during the training phase. A significance level (α) of .05 will be used for all statistical tests. For both primary and secondary outcomes, repeated-measures analysis of variance (ANOVA) will be used to assess for statistically significant changes pre- and post-intervention. As part of post hoc

Figure 2. Summary of the five difficulty levels for each of the three training modules.



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analysis and to see which outcomes are significantly different from each other at each time point (pre-intervention, 4 weeks post-intervention, 4 weeks after no intervention), pairwise *t* tests will be performed between all the possible combinations of time points. Should the data not satisfy the assumption of normality for ANOVA, the nonparametric Friedman test will be used. Due to multiple post hoc comparisons, the Bonferroni-Holm correction will be used to mitigate the occurrence of false positives of statistical significance.

Primary Outcomes

PRQ. The same PRQ described above to diagnose phoneme perception errors will also be used as an off-task outcome measure. Each correctly or incorrectly identified phoneme within the word will be individually scored, yielding a total percentage correct score.

Secondary Outcomes

Word recognition in quiet. Standard Dutch Nederlandse Vereniging voor Audiologie speech audiometry (Bosman & Smoorenburg, 1992) will be performed to assess the recognition of meaningful CVC monosyllabic words in quiet. Fifteen lists, each containing 12 words, will be presented via direct streaming at 65 dB SPL. A correct response is only considered if the whole word is correctly repeated, yielding a total percentage correct score.

Digits in noise. Participants will be presented with 24 digit triplets at 65 dB SPL via direct streaming. Noise will be speech weighted at various SNRs, in increments of +2 dB for a correct response and −2 dB for an incorrect response. Participants will type their responses into a numeric keypad. The outcome metric is the SNR at which the participant can correctly identify 50% of the digit triplets (SNR-50).

Study Initiation and Planning

This study was approved by the Radboud university medical center Research Ethics Committee (File number: 2022–13495). Written informed consent to participate will be obtained from all participants. Research findings will be published in a peer-reviewed journal. As of July 2023, 26 adult CI users were enrolled in the study. Data collection related to the phoneme training program commenced in April 2023 and is expected to be complete by November 2023.

Conclusions

Based on the review of current literature on individualized phoneme training, it is evident that individualization is only implemented once training is already underway and typically takes the form of adaptive difficulty. We hypothesize that the individualization of the training content itself, based on granular diagnostic information about PRQ, can be used to overcome individual phoneme errors. The focus group we conducted further emphasized the need for targeted training, as well as trackable feedback and progress monitoring throughout training. Contrary to the literature reviewed on this topic, where the duration of training sessions ranged from 15 to 60 min per day across studies, our focus group revealed that participants would prefer shorter spurts of training throughout the day. This was especially relevant where, when training in a home environment, users preferred not to be disconnected from their surroundings for extended periods while streaming training materials to their speech processor. Using the insights gained from our review of the literature and the focus group, this article goes on to outline a protocol for a novel individualized auditory training program on a mobile app to address phoneme confusion errors in adult CI users. It is hoped that addressing these fundamental bottom-up perception errors will translate to greater speech understanding at word level and improve the overall speech perception of study participants.

Data Availability Statement

The authors confirm that the data supporting this study are available within the article and its supplemental materials.

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Appendix

Example PubMed Search Strategy, With Limits (From May 4, 2020, With 1,273 Results)

(((((“Persons With Hearing Impairments”[Mesh] OR “Hearing Disorders”[Mesh:NoExp] OR “Hearing Loss”[Mesh:NoExp] OR “Deafness”[Mesh:NoExp] OR “Hearing Loss, Bilateral”[Mesh] OR “Hearing Loss, High-Frequency”[Mesh] OR “Hearing Loss, Sensorineural”[Mesh:NoExp] OR “Hearing Aids”[Mesh:NoExp] OR “Cochlear Implants”[Mesh] OR “Cochlear Implantation”[Mesh] OR cochlear implant*[tiab] OR Deaf[tiab] OR Deafness[tiab] OR hearing aid*[tiab] OR Hearing Disorder*[tiab] OR Hearing Impair*[tiab] OR hearing loss[tiab] OR HL[tiab] OR SNHL[tiab]) AND (“Correction of Hearing Impairment”[Mesh:NoExp] OR “Communication Methods, Total”[Mesh] OR “Telerehabilitation”[Mesh] OR “Patient-Centered Care”[Mesh:NoExp] OR “Rehabilitation”[Mesh:NoExp] OR “Patient-Centered Care”[Mesh:NoExp] OR “Therapies, Investigational”[Mesh:NoExp] OR Aural habilitation*[tiab] OR hearing impaired habilitation*[tiab] OR hearing loss correction[tiab] OR hearing impaired rehabilitation*[tiab] OR audiologic rehabilitation*[tiab] OR audiological rehabilitation*[tiab] OR audiologic habilitation*[tiab] OR audiological habilitation*[tiab] OR aural rehabilitation*[tiab] OR telerehabilitation*[tiab] OR tele-rehabilitation*[tiab] OR patient-focused care[tiab] OR Innovative therap*[tiab] OR Investigational therap*[tiab] OR Experimental therap*[tiab] OR pre-treatment[tiab] OR pre-treatment program*[tiab] OR personalized rehabilitation[tiab] OR personalized rehabilitation[tiab] OR rehabilitative program*[tiab] OR auditory rehabilitation[tiab] OR cochlear implant rehabilitation[tiab] OR auditory training[tiab] OR auditory therapy[tiab] OR aural rehabilitation[tiab] OR telephone training[tiab] OR music appreciation[tiab] OR music therap*[tiab] OR musical therap*[tiab] OR music training[tiab] OR musical training[tiab] OR speech reading[tiab] OR communication strategies[tiab] OR communication strategy[tiab] OR repair strategies[tiab] OR repair strategy[tiab] OR environmental manipulation[tiab]) AND (“Speech perception”[Mesh] OR “Speech intelligibility”[Mesh] OR “Quality of life”[Mesh] OR “Recovery of function”[Mesh] OR “Auditory perception”[Mesh] OR “Treatment outcome”[Mesh:NoExp] OR “Surveys and Questionnaires”[Mesh:NoExp] OR “Cognition”[Mesh] OR “Activities of Daily Living”[Mesh] OR “Personal autonomy”[Mesh:NoExp] OR “Reaction time”[Mesh:NoExp] OR “Social change”[Mesh:NoExp] OR “Treatment outcome”[Mesh:NoExp] OR “Auditory fatigue”[Mesh] OR “Social participation”[Mesh] OR “Community participation”[Mesh] OR “Work engagement”[Mesh] OR Life quality[tiab] OR Health-related quality of life[tiab] OR Health related quality of life[tiab] OR HRQOL[tiab] OR Response time*[tiab] OR Reaction time*[tiab] OR Clinical effectiveness[tiab] OR Rehabilitation outcome*[tiab] OR Treatment Efficacy[tiab] OR Clinical Efficacy[tiab] OR Patient Relevant Outcome*[tiab] OR Patient-Relevant Outcome*[tiab] OR Auditory perception*[tiab] OR Social impact[tiab] OR quality of life[tiab] OR speech outcomes[tiab] OR outcome*[tiab] OR societal impact[tiab] OR performance[tiab] OR music[tiab] OR music appreciation[tiab] OR speech-in-noise[tiab] OR speech in noise[tiab] OR self-efficacy[tiab] OR self efficacy[tiab]))) AND (“Adult”[Mesh] OR adult*[tiab] OR elderly[tiab] OR middle age*[tiab] OR young adult*[tiab] NOT (Child[MeSH] NOT Adult[MeSH]))))

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