

Effective Duration of Auditory Training for Speech Perception in Hearing-Impaired Listeners: A Systematic Review and Meta-Analysis

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Purpose: The purpose of this study was to conduct a meta-analysis to determine the effective duration of auditory training for hearing aid users and cochlear implant users and to identify factors that influence the effectiveness of auditory training.

Methods: We searched literature published from January 1996 to August 2021 in Pubmed, Web of Science, Embase and Cochrane Library. A total of 24 studies that met the selection criteria were systematically reviewed and analyzed through meta-analysis. Standardized mean differences and 95% confidence intervals were calculated.

Results: The overall meta-analysis results for auditory training showed an effect size of -0.833, and the effect size was larger in "more than 600 minutes of auditory training" compared to "less than 600 minutes". There was no statistically significant difference in effect size during follow-up observation after the completion of auditory training, with an effect size of 0.057 (95% CI: -0.113-0.112, $p=0.988$). Subgroup analysis showed that the effect size was larger in the "children" group than in the "adult" group. The effect size of auditory training was larger when the auditory training and measurement conditions were the same.

Conclusions: Auditory training can improve speech perception in individuals wearing HA and/or CI, and the training effect was shown to be maintained even after the completion of auditory training. In addition, it was found that the longer the duration of auditory training (more than 10 hours), the greater the training effect.

Keywords: Rehabilitation, Intervention, Hearing aid, Cochlear implant, Speech perception



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INTRODUCTION

Approximately 500 million people globally have hearing loss, and this number is expected to increase with the aging population [64]. The World Health Organization [65] reported that more than 430 million people worldwide need rehabilitation to address their hearing loss. It is predicted that more than 700 million people will have hearing loss in 2050 [65]. Hearing loss can negatively affect daily functions and quality of life, causing cognitive and functional deterioration, social isolation, increased risk of fall, and reduced social and emotional function [12,31,35].

The use of hearing aid (HA) and cochlear implant (CI) is the most common method for restoring the hearing of the hearing-impaired. However, it is difficult to expect an im-

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provement in communication ability solely through the use of HA and CI. Despite using such amplifiers, hearing-impaired individuals face communication difficulties every day, especially in environments that are not ideal for communication, such as noisy environments [21,29]. HA and CI mount various technologies to enhance communication in noisy environments. For example, noise reduction and directional microphones are technologies that reduce noise and emphasize sound, but communication in noisy environments remains a challenging task for hearing-impaired individuals [53,66]. Many researchers [1,36,43] have reported that hearing-impaired individuals continue to face communication difficulties even with the use of amplifiers due to the decline in their cognitive abilities, such as working memory, executive function, and attention.

One way to improve the cognitive abilities of the hearing-impaired is through auditory training. Auditory training involves actively listening to sounds and has been shown to be effective in many studies. Auditory training can be divided into two approaches: the bottom-up approach, which involves training to discriminate speech sounds, and the top-down approach, which involves training to comprehend the content of sentences. Many researchers report that both approaches result in neural plasticity and increased communication ability [18,36,42]. Neural plasticity can occur when an individual acquires new knowledge/skills through training, resulting in the growth of neural pathways, the creation of new circuits, and the formation of synapses between neurons. Additionally, auditory training can lead to positive effects such as increased satisfaction with hearing aid use and improved quality of life [10,27,68].

To demonstrate the effectiveness of auditory training, two factors must be confirmed. The first is the ‘transfer of learning,’ which means that the performance should improve not only in the trained tasks but also in untrained tasks. That is, auditory training can be considered effective if it improves communication skills in the real world. The second factor is the retention of the training effect. If the effect of the training disappears shortly after the training, it cannot be considered effective. Many studies have been conducted on the transfer of learning and retention of training effect in auditory training, but the optimal duration of training for achieving effective results is still unclear.

To our knowledge, no systematic review or meta-analysis has been published to provide data that focuses on improving speech perception for individuals with HA or CI by quantita-

tively integrating the results using statistical methods. Although Lawrence et al., [34] conducted a meta-analysis on the efficacy of auditory training for hearing impairment, their focus was on cognitive function. In this meta-analysis, we aimed to calculate the overall effect size of efficacy on speech perception for HA or CI users and identify the effective training duration, including methodology of the auditory training.

The primary aim of this systematic review and meta-analysis is to examine the effectiveness of the most effective auditory training period for hearing aid users or cochlear implant users. The secondary goals are to (i) examine the retention of training-related improvement and (ii) investigate factors affecting training outcomes.

METHODS

All the processes, including inclusion criteria, exclusion criteria, article search strategy, and article selection, followed a Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols (PRISMA-P) statement [41].

Search strategy

The search was performed to find published articles on improving speech perception after auditory training of hearing-impaired listeners with HA or CI.

The search was conducted using the same keywords suggested by [19], including “hearing loss” OR “cochlear implant” OR “hearing aid” OR “hearing impair*” AND “auditory training” OR “auditory learning” OR “perceptual training” OR “perceptual learning” AND “speech perception,” The search was conducted on four databases, namely PubMed, Web of Science, Embase, and Cochrane Library. The search was included articles published from January 1996 to August 2021. Only original articles were included, while proceedings, book reviews, conference abstracts, and review studies were excluded. Sweetow & Sabes [60] did review seven papers on the auditory training, and they studied the papers published before 1996. Thus, the articles that have been included in this study have been published from January 1996 to August 2021.

Article selection

For the homogeneity and reliability of the eligible studies, a strategy of Participants, Intervention, Control, Outcomes, and Study design (PICOS) was applied. The PICOS criteria used in this study are displayed in Table 1.

A total of 6,105 records were searched using four electronic

journal databases. After removing duplicate articles, a total of 5,756 articles remained. Then, the following criteria were used to screen for eligibility. After first screening the titles and abstracts, 5,330 articles were excluded from the full-text assessment. The full texts of the remaining 426 articles were then examined for inclusion based on the PICOS criteria and relevance. In the evaluation process, two researchers assessed the eligibility of identified studies independently. The articles were again reviewed and discussed if the two researchers did not agree.

Three hundred fifty-eight papers were excluded based on PICOS criteria, and 68 remained. In the process of data extraction, a total of 44 studies that had no standard deviation data

Table 1. Inclusion criteria for the current study based on Participants, Intervention, Control, Outcomes, and Study designs (PICOS)

PICOS	Specific information
Participants	Hearing-impaired with hearing aid or cochlear implant
Intervention	Auditory training
Control	Comparison with a control group or repeated measures (pre- and post-training comparison)
Outcomes	Outcome measure(s) related to speech perception (Either behavioral measures or self-reported outcomes)
Study design	Randomized controlled trials, non-randomized controlled trials, repeated measures (pre- and post-training comparisons)

(n = 31), no specific data presented (n = 10), and mixed data of participants (n = 3) were excluded. Finally, 24 articles met the PICOS criteria for this study. The flow of articles and screening procedure is shown in Figure 1.

Study quality and potential sources of study bias

The Physiotherapy Evidence Database (PEDro) scale [5] evaluated the study quality and any potential sources of study bias. The PEDro scale is composed of 11-items aimed for rating the methodological quality of Randomized Controlled Trials (RCTs). A total of 11 questions were used to evaluate the quality of RCTs on two aspects, including internal validity (criteria 2-9) and sufficient statistical information to make it interpretable (criteria 10 and 11), and shown in Table 2. The risk of bias for each item was rated as “yes” or “no.” “Yes” indicated a low risk of bias, and “no” showed a high risk of bias. Each item was assigned 1 for “yes” or 0 for “no.”

A grade of studies with PEDro scores ranging from 9 to 11 was of “excellent” quality, 6 to 8 was supposed to be of “good” quality, while studies scoring 4 or 5 were of “fair” quality, and below four were of “poor” quality. Two investigators independently assessed the 24 studies using the PEDro scale.

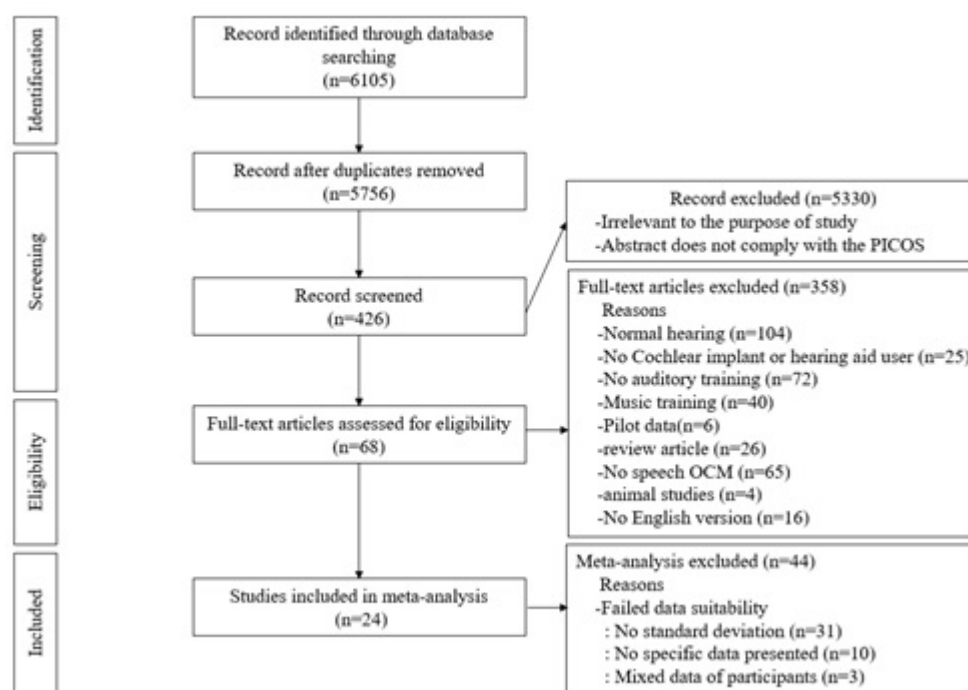


Figure 1. PRISMA flow diagram. PICOS, Participants, Intervention, Control, Outcomes, Study Designs; OCM, outcome measure; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Meta-analysis

We obtained the following information for the meta-analysis: author, year of publication, participant characteristics (number, age, and hearing device), intervention details (auditory training duration and condition), control group details (number, age, and hearing aid/CI use), study design, and outcome measures (measurement condition, unit, and follow-up duration). The Comprehensive Meta-Analysis software (Ver. 3, Biostat Inc., Englewood, NJ, USA) were used for all analyses. For the analysis, the 24 articles included speech perception results of pre-and post-auditory training, appropriate outcome measures, and auditory training. The effect size was calculated using sample size, mean, and standard deviation of pre-and post-training outcomes. The effect size was also calculated as the standard mean difference (SMD) because the characteristics of the qualitatively synthesized data from the included articles were continuous, and the types of outcome measures were different. Negative effect size indicates greater effectiveness of auditory training. The effect size of the standard mean difference was considered as -0.2 for small, -0.5 for moderate, and -0.8 for high [9].

To estimate the pooled effect of auditory training on each outcome measure, we used the random-effect model. We analyzed the data according to the total training duration to investigate the effective duration of auditory training, which we divided into two groups: short (< 600 minutes) and long ($\geq$ 600 minutes) durations.

When we extracted multiple outcome results from one study, we considered individual data and performed separate analyses. For example, we treated each result as separate data when evaluating auditory training effectiveness with different outcome measurements. We also considered measurements taken during and after training in the same subject as independent data.

To conduct subgroup analysis, we divided subjects into adults (18 years of age and older) and children (below 18 years of age) based on their age, and hearing devices into HA and CI (including bimodal users) based on the type of device used. We also investigated effective training conditions by dividing them into "in noise" or "in quiet".

To evaluate publication bias, we used a funnel plot and Egger's regression test, as well as Rosenthal's classic fail-safe N. Specifically, we considered publication bias not to be an issue if the fail-safe N value was greater than the "5 $\times$ number of studies (k)+10" that contributed to each analysis.

Heterogeneity and subgroup analysis

The quantitative exploration of variance heterogeneity across the included studies involved the use of Cochrane's Q and Higgins I²-statistic values. A Q-test *p*-value of less than 0.10 was considered present. The I²-values were used to measure the proportion of observed variance between trials in individual studies due to real differentials in effect size. These values were presented as a percentage ranging from 0 to 100. Heterogeneity was regarded as low if the I²-value was below 25%, moderate if it was between 25-75%, and high if it was between 75-100% [20].

The statistical significance at a 95% CI indicated the presence of heterogeneity across the dataset of articles.

To further analyze the heterogeneity, a subgroup analysis was performed, with planned variables including (1) the age of the participants and (2) the auditory training condition. The significance of the findings, heterogeneity between subgroups, and study's effect size were also compared.

Sensitivity analysis

A sensitivity analysis was conducted to determine the impact of excluding each study on the overall results.

RESULTS

Quality assessment of study

PEDro scores were received by the articles reviewed in this study (Table 2).

Twenty-four of the two studies were ranked as "excellent," with total values of 9 to 11 [13,56]. The 15 studies were evaluated as "good," with scores between 6 and 8 [2,3,7,22,23,37,39,45,49,50,54,58,61,62,67]. The remaining seven studies [4,17,24,40,43,44,55] were assessed as "fair," with scores between 4 and 5. The overall methodological quality was acceptable (total mean score = 6.4, SD = 1.3, range 5-10).

Characteristics of the study

The characteristics of included studies are shown in Table 3. Data extracted from the 24 studies are presented in the PICOS criteria.

Participants

All participants included in the studies had hearing impairment and were using either hearing aids or cochlear implants. Among the twelve studies, only hearing aid users were included [2,3,7,13,22,45,49,56,58,61,62,67], while in seven studies, only cochlear implant users were included [4,23,37,39,

Table 2. List of quality assessment of study by PEDro scale

Study	1	2	3	4	5	6	7	8	9	10	11	Total	Study quality
Yu et al. (2017,2015)	1	1	0	1	0	0	0	1	1	1	1	7/11	Good
Green et al. (2019)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Abrams et al. (2015)	1	1	0	1	0	0	0	1	1	1	1	7/11	Good
Chisolm et al. (2013)	1	0	0	1	0	0	0	1	1	1	1	6/11	Good
Moberly et al. (2018)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Olson et al. (2013)	1	1	0	1	0	0	0	1	1	1	1	7/11	Good
Barcroft et al. (2011)	1	1	0	1	0	0	0	1	1	1	1	7/11	Good
Ihler et al. (2017)	1	1	0	0	0	0	0	1	1	1	1	6/11	Good
Moberly et al. (2020)	1	0	0	1	0	0	0	1	1	1	1	6/11	Good
Barlow et al. (2016)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Miranda et al. (2008)	1	1	1	1	1	0	0	1	1	1	1	9/11	Excellent
Rishiq et al. (2016)	1	1	0	1	0	0	0	1	1	1	1	6/11	Good
Oba et al. (2011)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Ingvalson et al. (2013)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Shafiro et al. (2015)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Schumann et al. (2015)	1	1	0	1	0	0	0	1	1	1	1	7/11	Good
Roman et al. (2016)	1	1	0	1	0	0	0	1	1	1	1	7/11	Good
Smith et al. (2016)	1	1	1	1	1	1	0	1	1	1	1	10/11	Excellent
Talebi et al. (2015)	1	0	0	1	0	0	0	1	1	1	1	6/11	Good
Humes et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	8/11	Good
Tye-Murray et al. (2017)	1	0	0	1	0	0	0	1	1	1	1	6/11	Good
Miller et al. (2016)	1	0	0	0	1	0	0	1	1	1	1	6/11	Good
Oba et al. (2013)	1	0	0	0	0	0	0	1	1	1	1	5/11	Fair
Sullivan et al. (2013)	1	1	0	0	1	0	0	1	1	1	1	7/11	Good

*1 and 0 stand for "Yes" and "No," respectively.

*The Physiotherapy Evidence Database (PEDro) scale consisted of 11 items as follows: (1) eligibility criteria were specified (2) subjects were randomly allocated to groups (3) allocation was concealed (4) the groups were similar at baseline regarding the most important prognostic indicators (5) there was a blinding of all subjects (6) there was a blinding of all therapists who administered the therapy (7) there was a blinding of all assessors who measured at least one key outcome (8) measures for at least one key outcome were obtained from more than 85% of the subjects who were initially allocated to groups (9) all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, the data for at least one key outcome was analyzed using the intention to treat (10) the results of between-group statistical comparisons reported for at least one key outcome (11) the study providing both point measures and measures of variability for at least one key outcome.

40,50,55]. Five studies included both cochlear implant and bimodal users [17,24,43,44,54]. The majority of the studies were conducted with adults, while only three studies included children as participants [50,58,61].

Intervention

The intervention analyzed in the study was auditory training, which varied in duration and condition across the included studies. Training duration was classified as short (<600 minutes) or long (≥ 600 minutes). Ten studies had a training duration of less than 600 minutes [2,4,13,24,37,39,40,54,55,58],

while 11 studies had a complete training duration of more than 600 minutes [3,8,17,22,23,44,49,50,61,62,67]. Three studies had a total training time of both less than 600 minutes and more than 600 minutes [43,45,56]. The training condition was not standardized across studies.

The conditions for auditory training were categorized as "in quiet" and "in noise". Eleven studies conducted auditory training under "in noise" conditions [2,3,13,17,22,24,43,44,49,58,62], while eight studies conducted auditory training under "in quiet" conditions [23,37,39,40,50,54,61,67]. Five studies completed auditory training under both "in noise" and "in quiet"

Table 3. Characteristics for all enrolled studies for the participants, the intervention, control group, and the outcome measures

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Yu et al.	2015	- Number of participants=10 - Age Mean=75.4 - Hearing device Hearing aid user	- Training duration : At least 40 min per day, 6 days per week, for 4 weeks : Total 960 min - Training material Consisted of 10 Korean nonsense syllables - Training condition In quiet	- Number of participants=10 - Age Mean=75.8 - Hearing device Hearing aid user	Comparison to the control group and the repeated measures	- Measurement material Consonants, vowels, and sentences perception test - Measurement condition In quiet - Measurement unit Total error percent (%)	- After 2 weeks
Green et al.	2019	- Number of participants=9 - Age Range=48-70 - Hearing device : CI user : 3 participants used a hearing aid on an unimplanted ear	- Training duration : 30 min per day, 6 days a week, for four weeks Total 720 min - Training material Phrases of 2 to 10 words - Training condition In 20-talker babble	None	Repeated measures	- Measurement material : BKB and IEEE sentences of SRT, vowel and consonant identification from one male and one female talker - Measurement condition In 20-talker babble, In speech-shaped noise - Measurement unit dB SNR, correct percent (%)	- After 4 weeks
Abrams et al.	2015	- Number of participants=15 - Age Mean=65.6 - Hearing device Hearing aid user	- Training duration : 30 min each day, five days a week, for 3 weeks total 450 min - Training material RMQ (Read My Quips) is an adaptive audio training - Training condition In noise	- Number of participants=14 - Age Mean=61.8 - Hearing device Hearing aid user	Comparison to the control group and the repeated measures	- Measurement material Hearing in noise test, Words-in-noise test - Measurement condition In noise, in seven speech-to-babble - Measurement unit dB SNR	None
Chisolm et al.	2013	- Number of participants=42 - Age Range=58-85 - Hearing device Hearing aid user	- Training duration : 30 min per day, 5 days per week, until all 20 sessions Total : 600 mins - Training Material compute LACE (Listening and communication enhancement: Speech in babble, time compression, competing speaker, auditory memory, missing word) - Training condition In noise, in quiet	None	Repeated measures	- Measurement material Words-in-noise test, 45%, 65% compressed speech, and competing message - Measurement condition In noise, in quiet - Measurement unit dB SNR, correct percent (%)	None

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Table 3. Continued

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Moberly et al.	2018	- Number of participants=9 - Age Adult - Hearing device CI user - Post-lingually deaf	- Training duration : 8 weekly one-hour sessions : Total 480 min - Training material A combination of analytic and synthetic training tasks - Training condition In quiet	None	Repeated measures	- Measurement material AzBio sentences in quiet and in multi-talker babble, Consonant-Nucleus- Consonant words - Measurement condition In quiet, In multi-talker babble - Measurement unit Correct percent (%)	None
Olson et al.	2013	- Number of participants=22 - Age Range=52-79 - Hearing device Hearing aid users - Two groups 1) New HA plus training 2) Experienced HA plus training	- Training duration : 30 min, for 2 weeks, total 300 min : 30 min, for 4 weeks, total 600 min - Training material DVD version of LACE (Listening and communication enhancement: speech in babble, time compression, competing speaker, auditory memory, missing word) - Training condition In noise, in quiet	- Number of participants=7 - Age Range=54-81 - Hearing device Hearing aid users	Comparison to the control group and the repeated measures	- Measurement material Quick SIN, compressed speech, and SSI - Measurement condition In four talker babbles, in quiet - Measurement unit dB SNR, correct percent (%)	None
Barcroft et al.	2011	- Number of participants=69 - Age Range=18-89 Mean=66 - Hearing device Hearing aid users - Two groups 1) Multi-talker training 2) Single-talker training	- Training duration : 2 times per week, for 6 weeks : Total 720 min - Training material Meaning-based training (sound identification, picture-based four-choice discrimination, completing the sentence, sentence identification, and listening comprehension) - Training condition In four-talker babble	None	Repeated measures	- Measurement material Multi-talker and single talker versions of the Four-choice Discrimination test - Measurement condition In four-talker babble - Measurement unit Correct percent (%)	None

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Table 3. Continued

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Ihler et al.	2017	- Number of participants = 20 - Age Mean = 57.1 - Hearing device CI user - Post-lingually deaf - Two groups 1) Unfiltered training 2) Filtered training	- Training duration : During 10-14 weeks 1) Unfiltered training: total 16.8 ± 10.4 hours 2) Filtered training: 19.9 ± 21.9 hours - Training material : Heidelberg training CD (word, poem, and story) : Filtered version- filtered between 300 Hz and 3.4 kHz and downsampled the emulate telephone quality - Training condition In quiet	None	Repeated measures	- Measurement material A modified version of the Oldenburg Sentence Test and Freiburg Monosyllabic test - Measurement condition In quiet - Measurement unit Correct percent (%)	None
Moberly et al.	2020	- Number of participants = 6 - Age Range = 55-77 - Hearing device CI user - Post-lingually deaf	- Training duration : 1 hour weekly for eight weeks : Total 480 min - Training material : Combination of analytic and synthetic training tasks - Training condition In quiet	- Number of participants - Two groups 1) Passive control 2) Active control - Age Range = 49-91 - Hearing device CI user - Post-lingually deaf	Comparison to the control group and the repeated measures	- Measurement material Control Word and sentence recognition - Measurement condition In quiet, In babble - Measurement unit Correct percent (%)	- After 16 weeks
Barlow et al.	2016	- Number of participants = 10 - Age Range = 39-78 - Hearing device CI user	- Training duration : 1 hour per day, 7 days : Total 420 min - Training material Temporal & spectral training (GAP in noise, three alternative forced choice, Iterated ripple noise, spectral ripple noise, and temporal modulation transfer function) - Training condition In noise, in quiet	None	Repeated measures	- Measurement material Lexical Neighborhood speech score - Measurement condition In quiet, In noise - Measurement unit Correct percent (%)	None

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Table 3. Continued

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Miranda et al.	2008	- Number of participants=6 - Age Range=60-74 - Hearing device Hearing aid users	- Training duration : 50 min, 7 session, once a week : Total 350 min - Training material Phrases in noise, digit in noise - Training condition In noise	- Number of participants=7 - Age Range=60-74 - Hearing device Hearing aid users	Comparison to the control group and the repeated measures	- Measurement material Speech Recognition Perceptive Index, Speech with white noise, and phrase recognition threshold in noise - Measurement condition In noise, in quiet - Measurement unit dB SNR, correct percent (%)	- After 4 weeks
Rishiqr et al.	2016	- Number of participants=12 - Age Range=51-84 - Hearing device Hearing aid users	- Training duration : 30 min each day, 5 days a week, for 4 weeks : Total 600 min - Training material RMQ (Read My Quips) is adaptive training - Training condition In noise	- Number of participants=12 - Age Range= 51-84 - Hearing device Hearing aid users	Comparison to the control group and the repeated measures	- Measurement material Multimodal Lexical Sentence Test for Adults sentence test - Measurement condition In noise, in quiet - Measurement unit Correct percent (%)	None
Oba et al.	2011	- Number of participants=10 - Age Range=46-78 - Hearing device : CI user : 4 participants used a hearing aid on an unimplanted ear	- Training duration : 30 min each day, 5 days a week, for 2 weeks, total 300 min : 30 min each day, 5 days a week, for 4 weeks, total 600 min - Training material Digits identification in speech babble - Training condition In noise	None	Repeated measures	- Measurement material Recognition of digits, HINT sentences, and IEEE sentences in steady noise and speech babble - Measurement condition Steady speech-noise and six-talker speech babble - Measurement unit dB SNR, correct percent (%)	- After 4 weeks
Ingvalson et al.	2013	- Number of participants=5 - Age Range=50-85 - Hearing device CI user Post-lingually deaf : 2 participants used a hearing aid on an unimplanted ear	- Training duration : 1 hour each day, for 4 days : Total 240 min - Training material Speech in noise (i.e., word, phrase, sentence) - Training condition In noise	None	Repeated measures	- Measurement material HINT, Quick SIN - Measurement condition In noise - Measurement unit dB SNR, correct percent (%)	- After 4 days

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Table 3. Continued

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Shapiro et al.	2015	- Number of participants = 14 - Age Range = 51-87 - Hearing device CI user	- Training duration : 4 session, 4 days a week (40-60 min) : 160-240 min - Training material Environmental sound - Training condition In noise, in quiet	None	Repeated measures	- Measurement material Consonant-Nucleus-Consonant (CNC), monosyllabic word recognition test, and Speech-in-Noise (SPIN-R) sentence test - Measurement condition In noise - Measurement unit Identification accuracy (%)	- After 1 week
Schumann et al.	2015	- Number of participants = 15 - Age Range = 42-75 - Hearing device CI user : 5 participants used a hearing aid on an unimplanted ear	- Training duration : Twice per week for 45 to 60 min, for 3 weeks : Total 270-360 min - Training material Nonsense-syllable combinations for consonants (VCV) and vowels - Training condition In quiet	- Number of participants = 12 - Age Range = 30-82 - Hearing device CI user : 9 participants used a hearing aid on an unimplanted ear	Comparison to the control group and the repeated measures	- Measurement material Goettingen sentence test in noise - Measurement condition In noise, In quiet - Measurement unit Sentence recognition correct percent (%), Identification accuracy (%)	- After 24 weeks
Roman et al.	2016	- Number of participants = 10 - Age Range = 4.8-10 - Hearing device Unilateral CI users - Pre-lingually deaf	- Training duration : 30 min weekly, for 20 weeks : Total 600 min - Training material Auditory cognitive processing (identification, discrimination, ASA, and auditory memory) - Training condition In quiet	- Number of participants 9 - Age Range = 4-11.6 - Hearing device Unilateral CI users - Pre-lingually deaf	Comparison to the control group and the repeated measures	- Measurement material Identification, discrimination - Measurement condition In quiet - Measurement unit Correct percent (%)	None
Smith et al.	2016	- Number of participants : Two groups 1) LACE-C training = 61 2) LACE-D training = 63 - Age 1) LACE-C mean = 68.7 2) LACE-D mean = 68 - Hearing device Hearing aid users	- Training duration 1) LACE-C training 30 min for 20 days, total 600 min 2) LACE-D training 30 min for 10 days, total 300 min - Training material LACE-D, LACE-C - Training condition In noise, in quiet	- Number of participants : Two groups 1) Placebo = 69 2) Control = 70 - Age 1) placebo mean = 67.5 2) control mean = 70.2 - Hearing device Hearing aid users	Comparison to the control group and the repeated measures	- Measurement material Word in Noise test - Measurement condition In noise - Measurement unit dB SNR	None

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Table 3. Continued

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Talebi et al.	2015	- Number of participants = 15 - Age Range = 4-6 - Hearing device - Binaural HA users	- Training duration 1) 2 sessions (duration of each ~2 hours) per week, for 3 months, Total 2,880 min 2) 2 sessions (duration of each ~2 hours) per week, for 6 months, Total 5,760 min - Training material Vowel auditory training, nonsense syllables - Training condition In quiet	- Number of participants = 15 - Age Range = 4-6 - Hearing device - Binaural HA users	Comparison to the control group and the repeated measures	- Measurement material Vowel identification 5 vowels-/æ/, /e/, /ae/, /i:/, and /u:/ - Measurement condition In quiet - Measurement unit Identification scores (%)	None
Humes et al.	2019	- Number of participants : Two groups 1) Intervention = 13 2) Additional intervention = 10 - Age 1) Intervention mean = 71.9 2) Additional intervention mean = 69.4 - Hearing device Bilateral Hearing aid users	- Training duration : 3 session a week for 5 weeks : Total 1,350-1,800 min - Training material Frequent-word (word, phrase, and sentence in noise) - Training Condition In noise	- Number of participants : Two groups 1) Placebo = 15 2) Control = 15 - Age 1) Placebo mean = 71.3 2) Control mean = 72.0 - Hearing device Bilateral Hearing aid users	Comparison to the control group and the repeated measures	- Measurement material Frequent words, Frequent words sentence, CID (central institute for the deaf sentence material) sentences recognition in noise, CST (connected speech test) sentences recognition in noise - Measurement condition In noise - Measurement unit RAU; Rationalized arcsine units	- After 5 weeks, 10 weeks, and 34 weeks
Tye-Murray et al.	2017	- Number of participants : Two groups 1) Spaced training = 24 2) Massed training = 23 - Age 1) Spaced training mean = 64.6 2) Massed training mean = 69.6 - Hearing device Hearing aid users	- Training duration : Total 1,200 min 1) Spaced training = two days a week for 10 weeks 2) Massed training = five times each week for 2 weeks - Training material Four-choice word identification, four-choice discrimination, fill-in-the-blank, three-choice sentence context - Training condition In noise	None	Repeated measures	- Measurement material Four-choice word identification, four-choice discrimination, fill-in-the-blank, three-choice sentence context - Measurement condition In noise - Measurement unit Correct percent (%)	- After 12 weeks

(Continued to the next page)

Table 3. Continued

Study	Years	Participants	Intervention	Control group	Study design	Outcome measures	
						Post-training	Follow-up
Miller et al.	2016	- Number of participants=9 - Age Range=45-75.3 - Hearing device CI users - Post-lingually deaf	- Training duration : 2 hours, 4 session for 2 weeks : Total 480 min - Training material Multi-talker identification training on perception /ba/-/da/ and /wa/-/ja/ - Training condition In quiet	- Number of participants=5 - Age Range=53.3-75 - Hearing device CI users - Post-lingually deaf	Comparison to the control group and the repeated measures	- Measurement material Identification for /ba/-/da/ and /wa/-/ja/ - Measurement condition In quiet - Measurement unit Correct percent (%)	
Oba et al.	2013	- Number of participants=10 - Age Range=20-91 - Hearing device CI users : 2 participants used a hearing aid on an unimplanted ear - Post-lingually deaf	- Training duration : 30 min a day, 5 days a week, for 2 weeks, Total 300 min : 30 min a day, 5 days a week, for 4 weeks, Total 600 min - Training material Visual digit span training - Training condition In noise	None	Repeated measures	- Measurement material Speech recognition in noise, Phoneme recognition - Measurement condition In noise - Measurement unit dB SNR, correct percent (%)	- After 4 weeks
Sullivan et al.	2013	- Number of participants : Two groups 1) ATI (auditory training interrupt noise)=8 2) ATC (auditory training continuous noise)=8 - Age 1) ATI mean=12 2) ATC mean=11 - Hearing device Bilateral HA users	- Training duration : 1 hour, 7 sessions, Total 420 min - Training material 3,000 Sentence in noise - Training condition In noise	- Number of participants=8 - Age Mean=11 - Hearing device Bilateral HA users	Comparison to the control group and the repeated measures	- Measurement material HINT- in continuous noise, HINT-in interrupt noise - Measurement condition In noise - Measurement unit dB SNR	

CI, Cochlear Implant; BKB, Bamford-Kowal-Bench; IEEE, Electrical and Electrical Engineers; SRT, Speech Reception Threshold; SNR, Signal-to-Noise Ratio; HA, Hearing Aid; SIN, Sentence-in-noise; SSI, synthetic sentence identification; HINT, Hearing In Noise Test; ASA, Auditory Scene Analysis; LACE, Listening and communication enhancement; LACE-D, Listening and communication enhancement-DVD based; LACE-C, Listening and communication enhancement-computerized; ATI, auditory training interrupt; ATC, auditory training continuous.

conditions [4,7,24,43,44,45,55,56,62].

Controls

Of the 24 articles, 13 studies included a control group consisting of individuals with hearing loss who used hearing aids or cochlear implants [2,13,22,45,67,37,39,49,50,54,56,58,61]. The remaining 11 studies employed repeated measures for pre- and post-training comparison [3,4,7,17,23,40].

Outcome

All studies evaluated speech perception outcomes, including syllables, words, and sentences. In ten studies, speech perception was measured in noisy conditions such as multi-talker babble and steady speech-noise [3,17,22,24,43,44,55,56,58,62]. In five studies, speech perception was measured in quiet conditions [23,37,50,61,67]. Nine studies measured speech perception outcomes in both quiet and noisy conditions [2,4,7,39,40,45,49,54].

Follow up

To confirm the maintenance of training effects, eleven studies were followed up [13,17,24,39,43,44,54,55,62,67].

Study design

All 24 studies included repeated measures, while 13 of them used control groups for comparison [2,13,22,37,39,45,49,50,53,56,58,61,67].

Overall results of auditory training effects

The effect sizes for the studies using the random-effects model are presented in Figure 2. SMD were used to analyze data with mean and SD to consider the dataset's characteristics. The results showed a significant improvement in speech perception after auditory training (SMDs -0.833, 95% CI: -0.960~-0.707, $p=0.000$), as depicted in Figure 3 which displays the funnel plot. We conducted Egger's regression analysis, which revealed evidence of publication bias (Intercept: -2.92, 95% CI: -3.74~-2.07, $p=0.000$). However, the fail-safe N analysis using Rosenthal's [51] method suggested that 8,790 studies with zero-effect would be needed to render the mean effect size of auditory training non-significant. Therefore, publication bias was unlikely to interfere with the main results of this meta-analysis. The Higgins I^2 -statistics and Cochran's Q-test indicated a moderate level of heterogeneity (I^2 : 70.12%, Q: 478.65, $p=0.000$).

Efficacy duration of the auditory training

To analyze the effect of auditory training duration, we divided the duration into two groups: 'Short' (<600 minutes) and 'Long' (≥ 600 minutes), as shown in Figure 4. The effect size for the 'Short' group was -0.747 (95% CI: -0.932~-0.562), while the effect size for the 'Long' group was -0.890 (95% CI: -1.061~-0.719). As demonstrated, the effect size of the 'Long' group was larger than that of the 'Short' group.

Training retention

Retention of auditory training was defined as a non-significant decrease in post-training performance at a delayed post-training follow-up assessment. Such follow-up assessments were reported in 11 studies, ranging from 4 days to 34 months after post-training. Figure 5 displays the effect size at follow-up, which was 0.057 (95% CI: -0.113~-0.112, $p=0.988$).

Subgroup analysis

The meta-analysis conducted a subgroup analysis based on age and training conditions.

Age

The effect sizes for the 'Adult' and 'Children' groups were -0.674 (95% CI: -0.789~-0.559) and -1.915 (95% CI: -2.410~-1.420), respectively, as shown in Figure 6. The effect size for the 'Children' group was significantly larger than that for the 'Adult' group.

Training condition

Due to the small number of studies for the 'children' group, the subgroup analysis of training conditions was only conducted for the 'adult' group. The 'Training in quiet' group had effect sizes of -0.784 (95% CI: -1.050~-0.518) and -0.560 (95% CI: -1.054~-0.066) in the 'in quiet' and 'in noise' tests, respectively. The 'Training in noise' group had effect sizes of -0.233 (95% CI: -0.412~-0.053) and -0.757 (95% CI: -0.908~-0.606) in the 'in quiet' and 'in noise' tests, respectively. Notably, the effect size of the outcome measurement performed in the 'in noise' condition was significantly larger than that in the 'in quiet' condition for the 'Training in noise' group. Conversely, for the 'Training in quiet' group, the effect size was significantly larger in the 'in quiet' condition than in the 'in noise' condition.

Sensitivity analysis

The sensitivity analysis revealed that the exclusion of any individual study did not have a significant impact on the overall

Meta Analysis

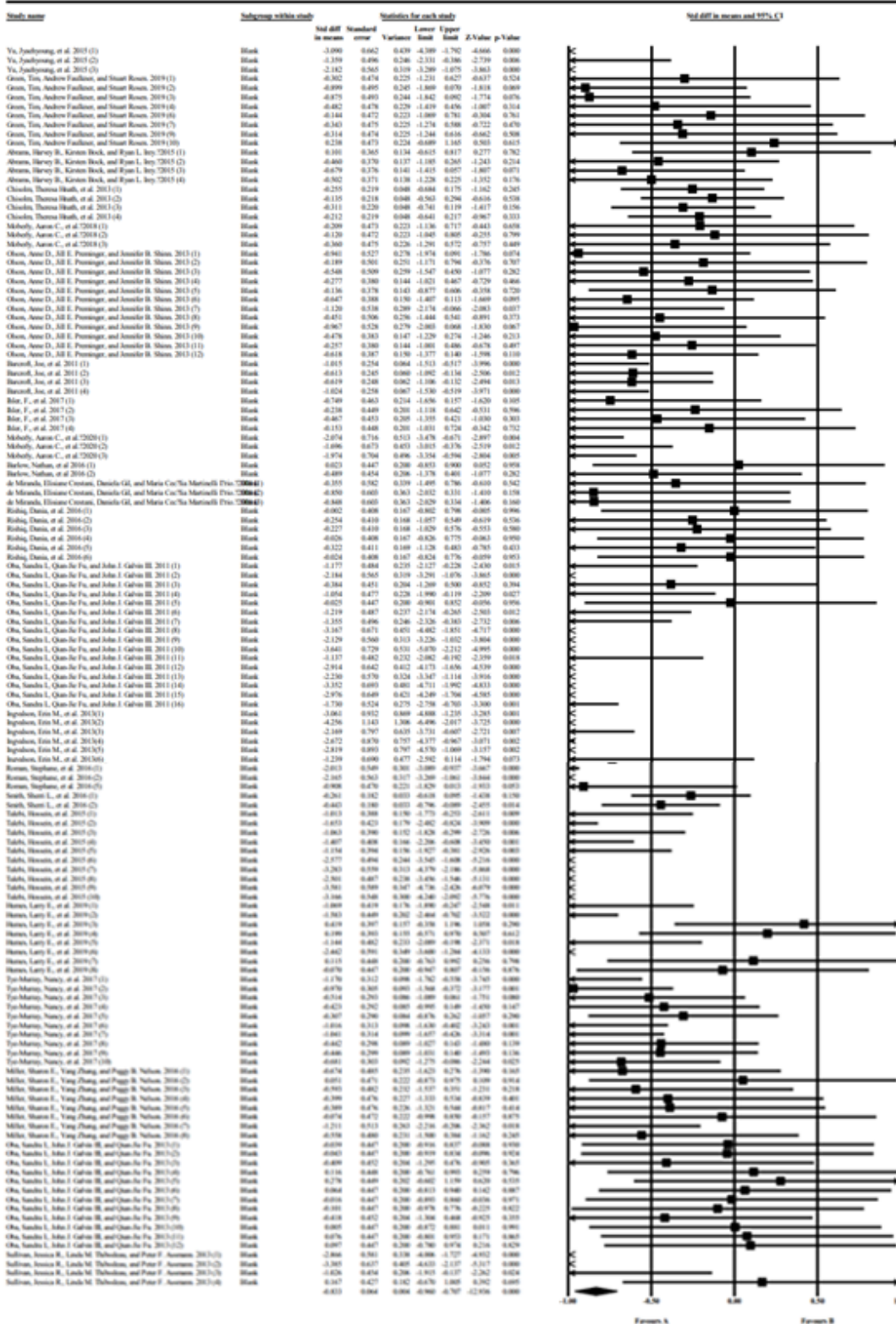


Figure 2. Forest plot of auditory training effects. Including 24 studies.

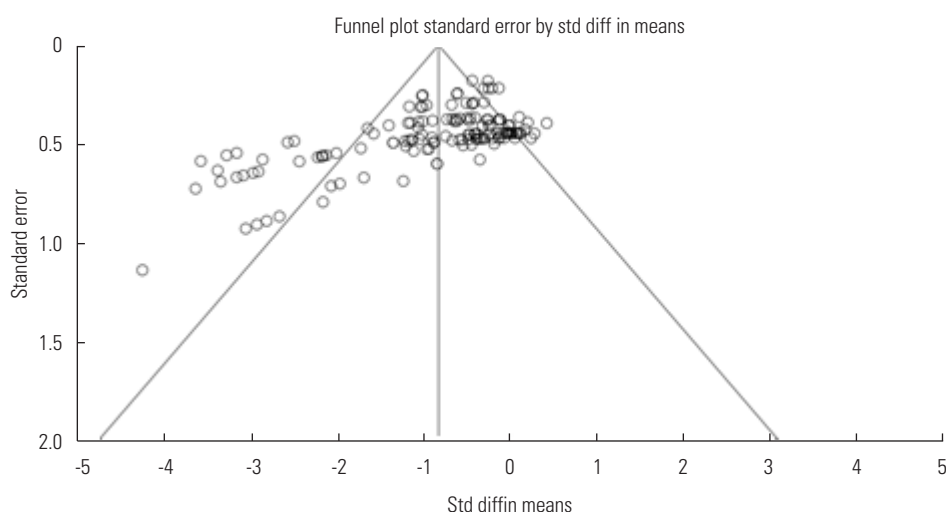


Figure 3. Funnel plot for publication bias of auditory training effects. including 24 studies.

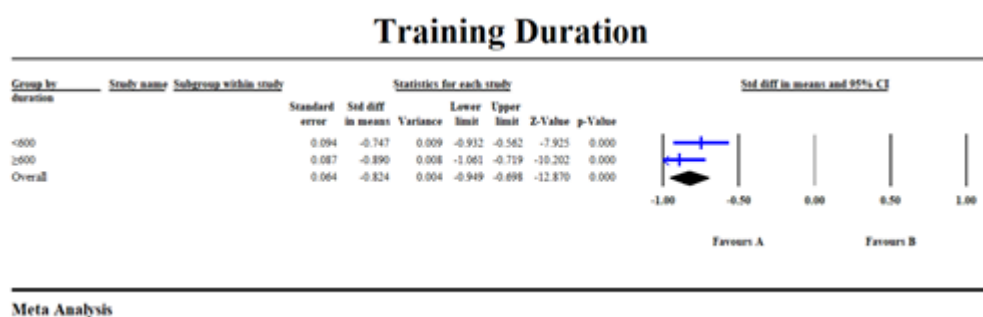


Figure 4. Meta-analysis according to the training duration.

pooled effect size.

DISCUSSION

This study examined the efficacy of auditory training on speech perception in individuals with hearing loss who use hearing aids, cochlear implants, or both. The results showed that auditory training was effective in improving speech perception in this population. A total of 24 studies [2,3,4,7,13,17,22-24,37,39,40,43-45,49,50,54-56,58,61,62,67] were included in this meta-analysis, and significant improvements in speech perception were observed in the individuals who underwent auditory training.

These meta-analysis results confirm previous findings that auditory training is more effective than no intervention for improving speech perception in individuals with hearing loss, which is consistent with the findings of several studies [7,15,19,28,45,47,63]. The following sections discuss the research questions addressed by our study.

What is the most effective training duration for auditory training?

This study examined the impact of auditory training duration on speech perception improvement. The results revealed that both short-term and long-term auditory training interventions had a positive effect on speech perception improvement, and the training duration depended on the specific goals or purposes of the training [55,61]. The duration of auditory training used in the studies ranged from 160 to 5,760 minutes. The largest effect size was found for training periods longer than 600 minutes, compared to periods shorter than 600 minutes [3,7,17,22,23,44,49,50,61,62,67].

Therefore, we suggest that a longer training period (e.g., more than 600 minutes) can optimize the effectiveness of a rehabilitation program for individuals with hearing impairment. However, it is important to note that a short training duration in this study also provided a certain amount of improvement in speech perception [24,25,57].

Determining the retention of learning after auditory training

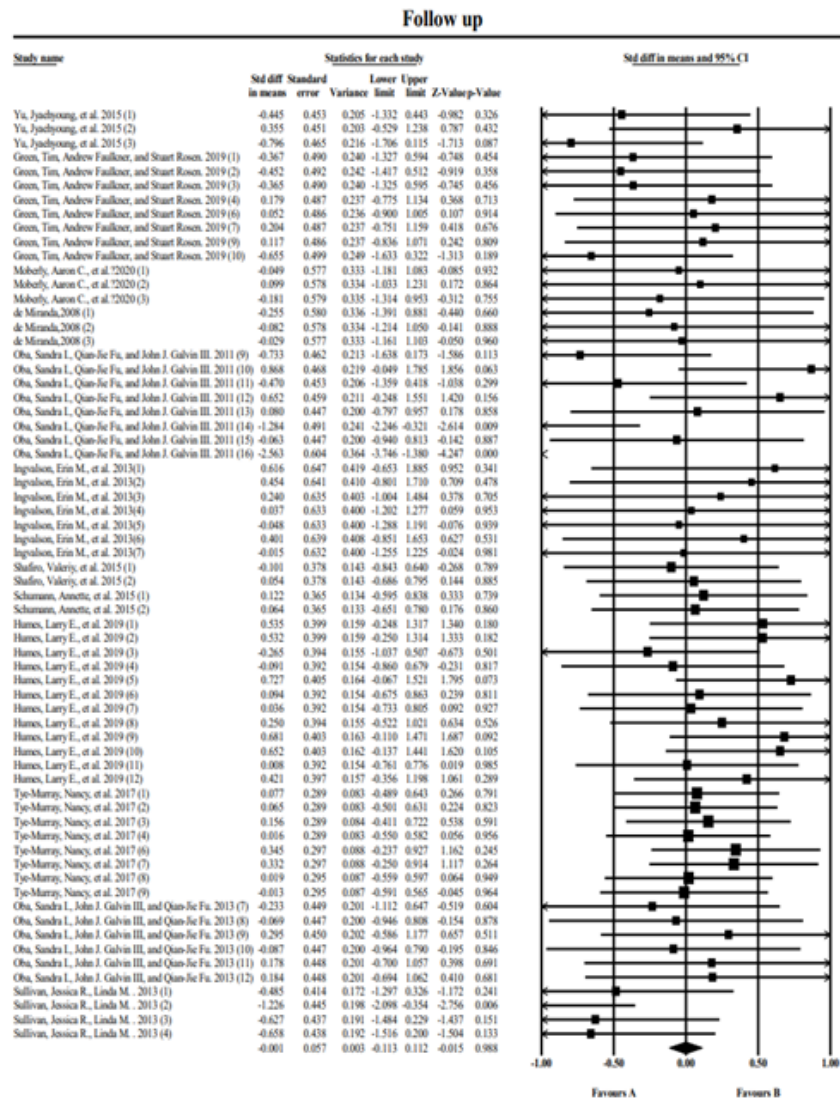


Figure 5. Meta-analysis according to the training retention.

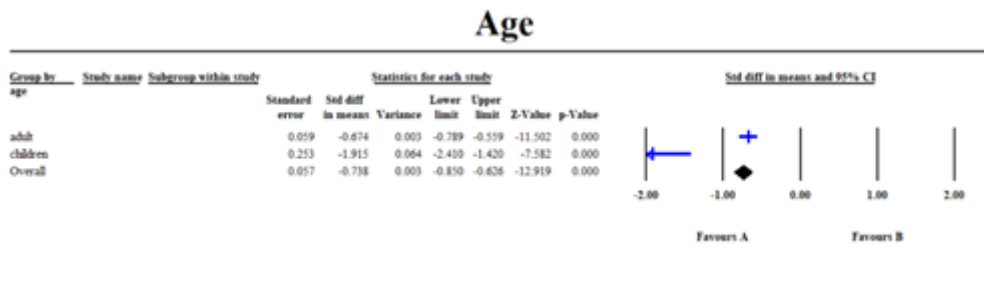


Figure 6. Meta-analysis according to the age.

is a crucial indicator of its benefits [19]. Previous studies have measured the retention of improved performance by comparing subjects' performance at baseline to their performance after completion of training [14,30,38,48].

In this study, we analyzed 11 out of 24 studies that included follow-up evaluations ranging from 4 days post-training [24] to 34 months [22]. Our analysis showed that auditory training benefits appeared to have been maintained with a non-significant

decrease in performance when comparing post-training and follow-up assessments. These results suggest that auditory training may provide lasting benefits beyond any naturally occurring learning effects.

Does auditory training affect adults and children differently?

To investigate whether the benefits of auditory training differ between “adults (> 18 years of age)” and “children (< 18 years of age)”, we conducted a subgroup analysis of the included studies. Our analysis revealed that auditory training had a significant positive effect on speech perception in both adult and child populations. Specifically, in adults, a medium effect size was found, whereas in children, a large effect size was observed [8,22,24,49,50,61,62].

Auditory training has been shown to induce anatomical and functional neuroplasticity in children [52]. Based on the principle of neuroplasticity, it is plausible that children who wear hearing aids or cochlear implants may benefit more than adults [16].

In addition to age, it would have been desirable to examine the effect of hearing aids versus cochlear implants in this study. However, most of the children in the study used cochlear implants, and the limited data precluded further subdivision of participants based on hearing aid use or cochlear implant use.

What is the most effective condition for auditory training?

Auditory training has been shown to improve speech recognition in noise conditions for individuals with hearing loss [6,59], including children with hearing loss [58], and cochlear implant users in noisy environments [14].

The results of this study indicate that the “in quiet” training group had a higher effect size in the “in quiet” condition than in the “in noise” condition, whereas the “in noise” training group had a higher effect size in the “in noise” condition than in the “in quiet” condition. This finding suggests that the training effect is stronger when the training and measurement conditions match. However, even when auditory training was conducted in both quiet and noise conditions, speech perception improved in both conditions.

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