The Laryngoscope

Longitudinal Speech Recognition Changes After Cochlear Implant: Systematic Review and Meta-analysis

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Objectives: To examine patterns of change and plateau in speech recognition scores in postlingually hearing impaired adult cochlear implant recipients. The study also examines variations in change patterns for different speech materials and testing conditions.

Study Design: Used systematic review with meta-analysis.

Methods: Articles in English reporting speech recognition scores of adults with postlingual hearing loss at pre-implantation and at least two post-implantation time points were included. Statistically significant changes were determined by meta-analysis and the 95% confidence interval.

Results: A total of 22 articles representing 1954 patients were included. Meta-analysis of mean difference demonstrated significant improvements in speech recognition score for words in quiet (37.4%; 95% confidence interval [34.7%, 40.7%]), sentences in quiet (49.4%; 95% confidence interval [44.9%, 53.9%]), and sentences in noise (30.8%; 95% confidence interval [25.2%, 36.4%]) from pre-op to 3 months. Scores continued to increase from 3 to 12 months but did not reach significance. Similarly, significant improvements from pre-op to 3 months were observed for consonant nucleus consonant (CNC) words in quiet (37.1%; 95% confidence interval [33.8%, 40.4%]), hearing in noise test (HINT) sentences in quiet (46.5%; 95% confidence interval [37.0%, 56.0%]), AzBio sentences in quiet (45.9%; 95% confidence interval [44.2%, 47.5%]), and AzBio sentences in noise (26.4%; 95% confidence interval [18.6%, 34.2%]). HINT sentences in noise demonstrated improvement from pre-op to 3 months (35.1%; 95% confidence interval [30.0%, 40.3%]) and from 3 to 12 months (15.5%; 95% confidence interval [7.2%, 23.8%]).

Conclusions: Mean speech recognition scores demonstrate significant improvement within the first 3 months, with no further statistically significant improvement after 3 months. However, large individual variation should be expected and future research is needed to explain the sources of these individual differences.

Key Words: cochlear implants, longitudinal, meta-analysis, postlingual hearing loss, speech recognition, systematic review.

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INTRODUCTION

Cochlear implants (CIs) are Food and Drug Administration approved devices for the treatment of moderate-to-profound sensorineural hearing loss in adults.[1] During the CI evaluation process to determine candidacy, patients are counseled regarding the magnitude and progression of communication improvement after implantation. This involves setting realistic expectations on their ability, for example, to understand speech when conversing in noisy listening environments. Patients whose post-implantation experiences fall in line with their pre-implantation expectations report improved CI-related quality of life (QOL), however, this counseling process is not standardized and research is required to guide informed expectation setting.[2,3]

Speech recognition is one of the primary outcome measures for cochlear implantation.[4] In general, speech recognition improves rapidly in the early post-implantation period and stabilizes over time.[5–10] Following implantation, patients continue to demonstrate performance improvements with improved loudness tolerance, expanded electrical dynamic range, and regular device adjustments.[11–13] Patients must also learn to interpret the degraded auditory signal from the CI and recognize sounds as speech and words. At some time point following implantation, speech recognition no longer improves as the limits of the relatively poor quality of the auditory input provided by the CI are reached.[14] In addition, chronic hearing deprivation weakens the connectivity of central neuronal networks in the auditory cortex. This is especially limiting for older adults with reduced cortical plasticity and a limited capacity to rebuild lost connections.[15,16]

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Patterns of change in speech recognition scores have been studied extensively; however, there is limited agreement on the timing of these changes. In addition, few studies have explored the direction and magnitude of speech recognition scores following cochlear implantation and how early scores impact long-term outcomes. Current studies have noted that speech recognition scores could reach a plateau anywhere from 3 months to over 3 years post-implantation, however, there is much variability in these estimates.[6,8–10,17] The vast majority of these studies are single-center retrospective studies with small study populations (fewer than 150 participants). In addition, most studies tend to report speech recognition changes based on statistical differences, but fail to consider whether the observed change is beyond the measurement error of the speech recognition test.[18]

The aim of this systematic review and meta-analysis is to examine patterns of change and determine the timing of plateau for speech recognition scores in the first 2 years following CI activation in adults with postlingual hearing loss. The study also examines how different speech recognition materials and listening conditions impact patterns of change in speech recognition scores. Systematic review and meta-analysis address the limitations of individual studies and is able to demonstrate associations in a large study population by aggregating data from existing smaller studies to maximize statistical power and more precisely measure intervention effects.[19,20] In addition, variability in outcome reporting between studies can be analyzed and addressed. With a better understanding of when and to what extent speech recognition scores change after CI, providers can offer better pre-operative counseling and guidance on how much speech recognition might improve after implantation and when patients are likely to achieve these outcomes. These results could also provide clinicians with a more specific timeframe of when to seek additional support for CI users who do not achieve the expected goals.

MATERIALS AND METHODS

Search Criteria

The research objective for this systematic review and meta-analysis was developed in accordance to population, intervention, vomparison, outcome (PICO) criteria.[21] The study seeks to explore speech recognition score changes (outcome) following cochlear implantation (intervention) across pre- and different post-implantation timepoints (comparison) in adults with post-lingual hearing loss (population). To identify studies for inclusion in this review, detailed search strategies were developed for the following three databases: PubMed (U.S. National Library of Medicine, National Institutes of Health), Scopus (Elsevier), and Embase (Elsevier). Databases were searched from the date of inception through January 2022. Search strategies were developed using combinations of subject headings and MeSH terms (e.g., "cochlear implant" [MeSH Terms], "speech recognition" [MeSH Terms], and "postlingual" [MeSH Terms]) for topics related to speech recognition outcomes after CI in adults with postlingual hearing loss. The PubMed search strategy was modified for the other two databases, replacing MeSH terms with appropriate subject headings, when available, and maintaining similar keywords. Detailed search strategies for each database are listed in Appendix S1. To identify additional articles, the reference lists of relevant articles were hand-searched. References were exported into the review management software, Covidence (Veritas Health Innovation Ltd, Melbourne, Australia), for study selection. Reporting of systematic review and meta-analysis results was performed in accordance with PRISMA reporting guidelines.[22]

Selection Criteria

Studies assessing long-term speech recognition outcomes in adults with postlingual hearing loss were included. Studies were considered for inclusion if they were: (1) double- or single-blinded randomized controlled trials, (2) double- or single-blinded randomized comparison trials, (3) non-randomized controlled trials, and (4) prospective or retrospective observational studies with pre-operative and at least two follow-up speech recognition data points at either 3, 6, 12, or 24 months post-implantation. Exclusion criteria included: pediatric study population, non-English language, non-human studies, review articles, case reports, case series (<10 patients), duplicates, inaccessible articles, incomplete or missing statistical data (e.g., did not report mean and standard deviation), articles studying bilaterally implanted patients, participants whose hearing loss occurred prelingually, and non-reporting of pre-operative or post-operative speech recognition outcomes. Abstracts were first independently assessed by two authors (C.M. and J.F.) to identify all articles that met the inclusion criteria. Conflicts were resolved by a third author (S.A.N.).

Included articles were critically appraised to assess the level of evidence using the Oxford Center for Evidence-Based Medicine criteria.[23] The risk of bias was assessed according to the Cochrane Handbook for Systematic Reviews of Interventions version 6.0.[24] The Risk of Bias in Non-Randomized Studies—of Interventions tool was used specifically to evaluate non-randomized studies.[25] Two authors (C.M. and J.F.) performed a pilot assessment on three studies to check for consistency of assessment. Both then performed independent risk assessments on the remaining studies. All disagreements were resolved by the way of discussion with a third author (S.A.N.). Risk of bias items included the following: bias due to confounding, bias in the selection of participants into the study, bias in classification of interventions, bias due to deviations from intended interventions, bias due to missing data, bias in the measurement of outcomes, and bias in the selection of the reported results. The risk of bias for each aspect was graded as low, unclear, or high.

Data Extraction

Data extraction was performed by two authors (C.M. and J.F.) independently. Data extracted from studies included: author, year of publication, patient demographics (age, sex), etiology of hearing loss, age at hearing loss onset, duration of hearing loss prior to implantation, age at implantation, history and duration of hearing aid use, follow-up period, and speech recognition outcomes at follow-up. Post-implantation speech recognition scores, including open-set word recognition in quiet and open-set sentence recognition in quiet and in noise, were collected as the primary outcome measures for meta-analysis. In instances of incomplete data, two attempts were made to contact the primary author via email for clarification or sharing of primary data.

Statistical Analysis

Continuous variables were summarized using means and standard deviations. Pre-operative characteristics of the study population were analyzed using a meta-analysis of single proportions for gender and a meta-analysis of single means for age, which were reported as an overall mean with a 95% confidence interval. To produce overall estimates of speech recognition at each time point (pre-op, 3, 6, 12, 24 months), a meta-analysis of single means was performed with Open Meta Analyst (Brown University, 2014). These estimators were used to examine the change over time for each speech recognition measure.

To determine statistically significant differences in speech recognition between two-time points (e.g., pre-op vs. 3 months, 3 vs. 6 months, etc.), the meta-analysis of continuous measures for mean difference was performed using Cochrane Review Manager (RevMan) version 5.4 (The Cochrane Collaboration, 2020). The mean, standard deviation, and sample size of each included study from two separate time points were used for each comparison. A DerSimonian-Laird random-effects model was used, which provides a more conservative estimate compared to a fixed-effects model, but better accounts for between-study variability in subject sampling and heterogeneity. Heterogeneity was assessed using the I^2-statistic and reported as being absent, mild, moderate, or high. Publication bias of included studies was assessed by examining generated funnel plots for asymmetry and performing Egger's linear regression test. A p-value of <0.05 was considered to indicate a statistically significant difference for all statistical tests.

For the current study, significant changes in speech recognition scores between two time periods were defined as those that demonstrated both (1) statistically significant differences and (2) change beyond the previously established 95% confidence interval for word or sentence recognition tests.[18,26,27] Each response to an item from a speech recognition test list produces a binomial outcome (correct or incorrect), with the final result expressed as a percentage of correct responses from the list. Based on this, speech recognition scores follow a binomial model with each outcome centered within a 95% confidence interval. Score changes that fall within this measurement error are likely due to chance as opposed to significant improvement in speech recognition ability.[26] These comparisons were made using group mean estimates at each timepoint obtained by meta-analysis of single means. A large number of patients in this meta-analysis ensure that changes within the measurement error for word and sentence recognition are not erroneously considered true differences solely based on statistical significance.[28]

RESULTS

A total of 1544 unique publications were collected in the search. Screening by title and abstract excluded 1263 articles. Full-text review of the remaining articles excluded 259 publications, resulting in 22 articles being included in the final analysis.[29–50] The search process is summarized in Figure 1. The risk of bias graph is presented as percentages across all included studies and summarized in Figure S1. Bias across all studies ranged from low to high. The included studies were all published between 2001 and 2021 The characteristics of the

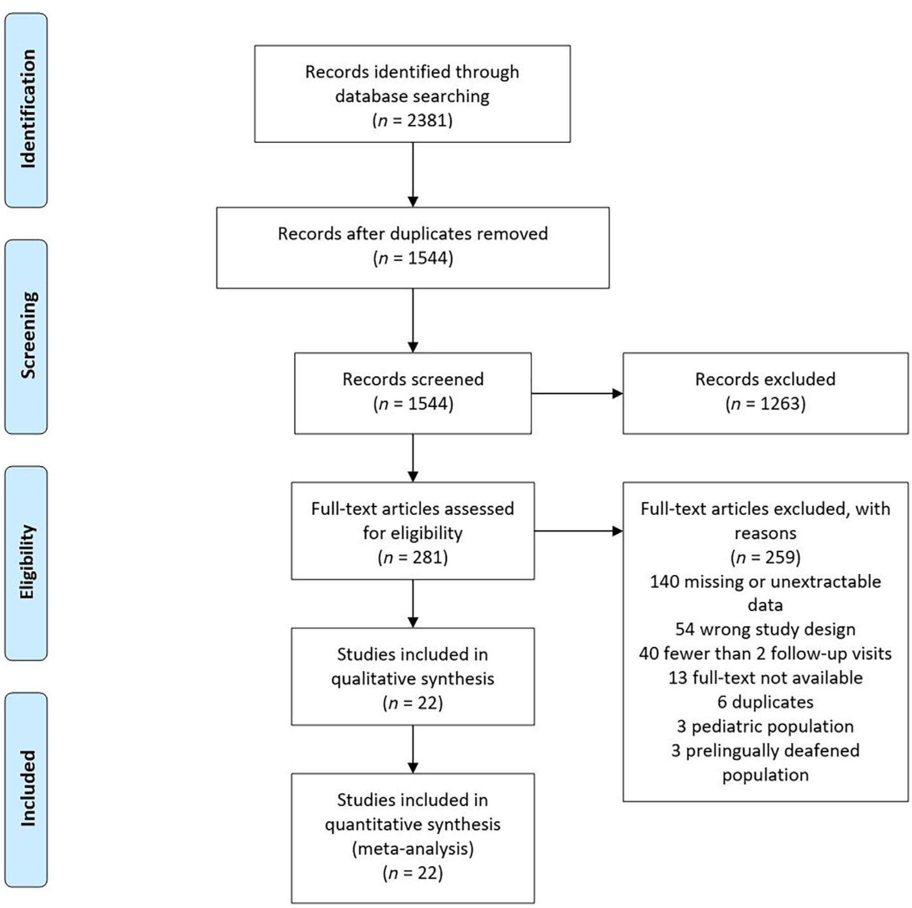


Fig. 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow diagram. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

TABLE I.
Study Design.

Author (Year)	Study Design	Patients (n)	Mean Age at CI in Years (SD)	Male (n)	Female (n)	Mean Age at HL Onset in Years (SD)	Mean Duration of HL in Years* (SD)	Speech Instruments Tested	Follow-Up Length in Months
Adunka (2008)	RCo	50	62.3	17	33	52.2	9.9	Words: CNC	12
Bergman (2020)	PCo	40	71 (11.3)	16	24	-	-	Sentences: CUNY, HINT Words: Unspecified	36
Borger (2015)	PCo	10	55.9 (11.1)	4	6	-	3.6 (3.1)	Words: Fournier List	12
Cooper (2020)	RCo	14	61.7 (15.7)	8	6	-	-	Sentences: Unspecified Sentences: HINT	12
Dalbert (2016)	RCo	91	-	41	50	-	22	Words: Freiburger	18
Deep (2021)	RCo	53	53.2 (11.9)	23	30	49.2 (13.1)	4 (7.8)	Words: CNC	24
Firszt (2018)	PCo	47	62.8 (14.6)	27	20	-	-	Words: CNC	12
Friedland (2021)	RCo	50	69.7 (13.7)	33	17	-	-	Sentences: TIMIT Words: CNC	24
Grisel (2021)	RCo	805	-	-	-	-	-	Sentences: AzBio Words: CNC	24
Kelsall (2021)	PCo	100	-	63	37	-	8 (6)	Words: CNC	12
Knopke (2019)	PCo	86	76.2	41	45	-	17.3	Sentences: AzBio Words: Freiburger	12
Knopke (2021)	PCo	49	67.3 (8.7)	20	29	-	22.9 (22.9)	Words: Freiburger	12
Lee (2021)	RCo	18	58.8 (12)	8	10	51.6 (16.2)	7.3 (11.9)	Words: Unspecified	12
Moberly (2020)	PCo	19	67.2 (10.4)	12	7	-	31.3 (18.6)	Sentences: Unspecified Words: CNC	6
Plontke (2020)	PCo	16	55 (14)	10	6	-	7.2 (6)	Sentences: AzBio Words: Freiburger	12
Runge (2016)	PCo	38	63.6	-	-	40.8	22.8	Words: CNC	12
Schramm (2020)	PCo	31	-	19	12	-	8.6	Sentences: AzBio Sentences: HINT	12
Sladen (2017)	PCo	61	67	22	39	-	12.6 (9.2)	Words: CNC	12
Sturm (2021)	RCo	119	-	52	67	-	-	Words: CNC	24
Wang (2010)	RCo	50	45.8	14	36	-	-	Sentences: CUNY, HINT	48
Yang (2016)	RCo	95	48 (14)	58	37	-	13 (13)	Words: Unspecified	36
Zwolan (2001)	PCo	112	57.3	-	-	45.7	11.7	Sentences: Unspecified Words: CNC Sentences: CID, HINT	6

*Duration of hearing loss prior to implantation.

CI = cochlear implant; CID = Central Institute for the Deaf; CNC = Consonant Nucleus Consonant; CUNY = City University of New York; HINT = hearing in noise test; HL = hearing loss; PCo = prospective cohort study; RCo = retrospective cohort study; TIMIT = Texas Instruments and Massachusetts Institute of Technology.

included studies are shown in Table I. Based on the Oxford Center for Evidence-Based Medicine criteria, all studies were considered level 3 evidence.[23]

Patient Characteristics

In total, 1954 patients are represented in the included studies. Sex was reported in 19 studies ($n = 999$) with 488 men and 511 women; based on the meta-analysis of single proportions, the overall proportion of men was 47.6% (95% confidence interval [42.7%, 52.4%]) and of women was 52.4% (95% confidence interval [47.6%, 57.3%]) (Figures S2 and S3). Mean age at implantation was reported in 17 studies ($n = 808$) and ranges from 45.8 to 76.2 years with an overall mean age of 58.5 years (95% confidence interval [53.9, 63.2]) based on a meta-analysis of single means (Figure S4). The mean age of hearing loss onset was reported by five studies ($n = 271$) and ranges from 40.8 to 52.2 years with an overall mean age of 46.8 years (95% confidence interval [43.8, 49.8]) based on a meta-analysis of single means (Figure S5). Mean duration of hearing loss prior to implantation as reported by 15 studies ($n = 809$) ranged from 3.6 to 31.3 years with an overall mean of 12.3 years (95% confidence interval [9.2, 15.4]) based on a meta-analysis of single means (Figure S6). Hearing aid use was rarely reported; three studies ($n = 179$) reported that 77.4% (24 of 31 patients), 33% (31 of 95 patients), and 41.5% (22 of 53 patients) had used hearing aids prior to implantation.[37,40,42] The length of follow-up varied greatly across all studies and ranged from 6 to 48 months post-implantation.

Speech Recognition Score Changes

Mean speech recognition scores were reported for word recognition in quiet (18 studies, $n = 1860$), sentence

TABLE II.
Meta-Analysis of Single Means for Words In Quiet, Sentences In Quiet, and Sentences In Noise at Each Time Point.

Follow-Up	Words In Quiet Score				Sentences In Quiet Score				Sentences In Noise Score			
	Mean (%)	95% CI (%)	SE (%)	*N*	Mean (%)	95% CI (%)	SE (%)	*N*	Mean (%)	95% CI (%)	SE (%)	*N*
Pre-op	9.8	(7.6, 12.0)	1.1	1675	18.9	(13.9, 23.8)	2.5	491	14.8	(11.2, 18.4)	1.8	275
3 Months	48.4	(45.5, 51.5)	1.6	1161	70.2	(62.2, 78.1)	4.1	385	46.2	(40.0, 52.4)	3.2	304
6 Months	53.7	(50.5, 56.9)	1.6	1173	74.1	(67.5, 80.6)	3.3	482	50.8	(45.1, 56.6)	2.9	351
12 Months	60.0	(56.4, 63.6)	1.8	1073	80.9	(71.0, 90.9)	5.1	295	62.1	(48.3, 76.0)	7.1	191
24 Months	60.3	(53.9, 66.8)	3.3	529	83.8	(74.9, 92.6)	4.5	185	-	-	-	-

CI = confidence interval; *N* = sample size; SE = standard error.

recognition in quiet (12 studies, $n = 541$), and sentence recognition in noise at +10 dB signal-to-noise ratio (SNR) (6 studies, $n = 275$). Outcomes using sentence recognition in noise at +5 dB SNR were not included as only one study using this measure met inclusion criteria.[43] Table II and Figure 2 summarize the mean estimates as determined by a meta-analysis of single means, 95% confidence interval, and pooled standard error for all speech recognition scores at each time point. Forest plots for meta-analysis of single means for words in quiet, sentences in quiet, and sentences in noise are included in Figures S7–S9, respectively. There were no available data on sentence recognition in noise (+10 dB SNR) beyond 12 months. Higher mean speech recognition values (as compared to pre-op) were observed at each subsequent follow-up through the first 2 years for words and sentence recognition in quiet, and through the first 12 months for sentence recognition in noise. The significance of these changes is discussed later.

Meta-Analysis Results

The meta-analysis of continuous measures for mean difference was used to detect significant changes in mean scores between two-time points (Table III). Examination

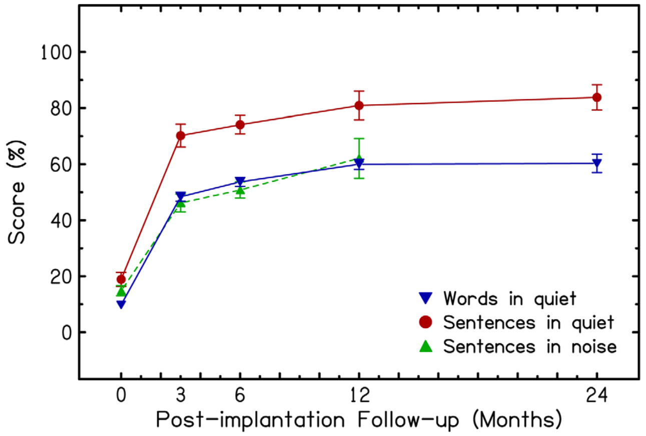


Fig. 2. Meta-analysis of single means and pooled standard error for words in quiet, sentences in quiet, and sentences in noise for pre-implant (0) and various post-implantation time points. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

of funnel plots showed no evidence of significant publication bias (Figures S10–S12). Forest plots for words in quiet are shown in Figure 3, and for sentences in quiet and sentences in noise in Figures S13 and S14, respectively. Our findings demonstrated that significant improvements in mean words in quiet, sentences in quiet, and sentences in noise scores occurred from pre-op to 3 months post-op. Mean speech recognition scores continued to demonstrate a statistical difference between time points (as defined previously) through 2 years for word recognition, 12 months for sentence recognition in quiet, and 6 months for sentence recognition in noise. However, these changes were not beyond the preceding mean score's 95% confidence interval and thus not considered significant. Further analysis of 3- to 12-month changes in mean score also demonstrated non-significant increases. Thus, based on mean scores, significant improvement in speech recognition occurred within the first 3 months following implantation, with no additional statistically significant improvement after 3 months.

Meta-analysis was also performed on speech recognition scores to determine whether post-implantation score improvement trajectories varied depending on the specific test instrument (Table IV). Forest plots for Consonant Nucleus Consonant (CNC) word recognition are shown in Figure 4 and for Hearing in Noise Test (HINT) in quiet, AzBio sentences in quiet, and HINT sentences in noise in Figures S15–S17, respectively. There were insufficient data to perform similar analyses for AzBio sentences in noise. The post-implantation mean score improvement for all word recognition material and for CNC word recognition was similar with the only significant improvement occurring from pre-op to 3 months post-CI. For sentence recognition in quiet, notable differences were seen between the mean score improvement trajectories as measured by HINT compared to AzBio sentences. Both instruments demonstrated significant improvements from pre-op to 3 months. HINT mean scores continued to show statistical differences from 3 to 6 months, but this was within the measurement error of the speech material. AzBio scores failed to reach statistical significance past 3 months. For sentence recognition in noise at +10 dB SNR, HINT sentences demonstrated significant improvement from 3 to 12 months.

As noted earlier, all instrument scores demonstrated significant improvements from pre-op to 3 months. As

TABLE III.
Meta-Analysis of Continuous Measures for Words In Quiet, Sentences In Quiet, and Sentences In Noise.

Speech Recognition Test	Mean Difference of Percentage (%) Correct (95% Confidence Interval) Pre-Op to 3 Months	3 to 6 Months	6 to 12 Months	3 to 12 Months	12 Months to 2 Years
Words (in quiet)	37.4 (34.7, 40.7)	4.2 (3.0, 5.5)	4.2 (2.9, 5.5)	7.7 (6.4, 9.1)	2.6 (0.1, 5.0)
Sentences (in quiet)	49.4 (44.9, 53.9)	5.3 (3.5, 7.1)	5.3 (3.4, 7.2)	11.8 (9.7, 13.8)	0.0 (−2.7, 2.7)
Sentences (in noise)	30.8 (25.2, 36.4)	5.4 (1.5, 9.2)	4.6 (−0.3, 9.5)	14.0 (8.5, 19.5)	-

Light shade, Statistically significant change beyond the preceding score's measurement error interval; medium shade, statistically significant change within the preceding score's measurement error interval; dark shade, non-statistically significant change.

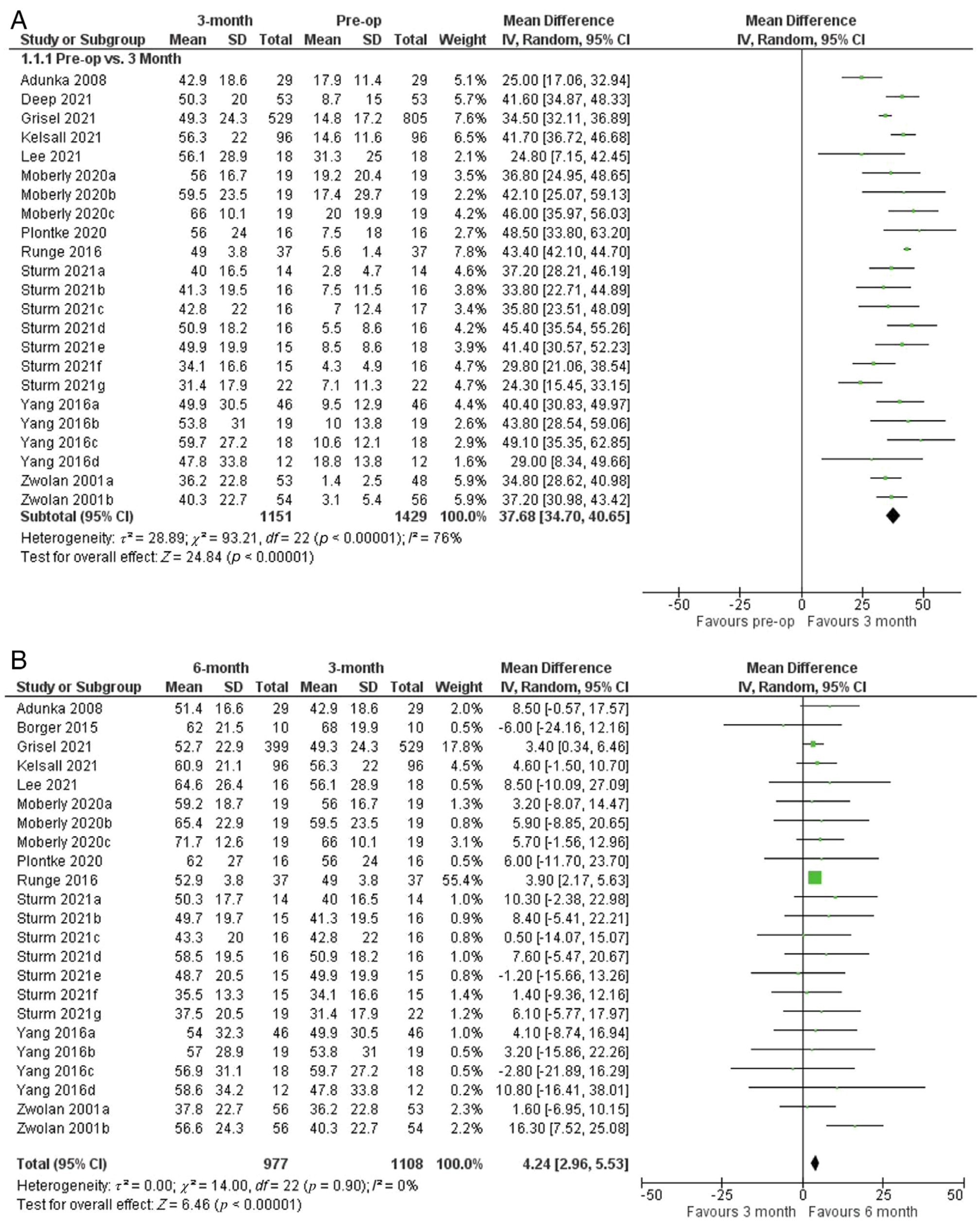
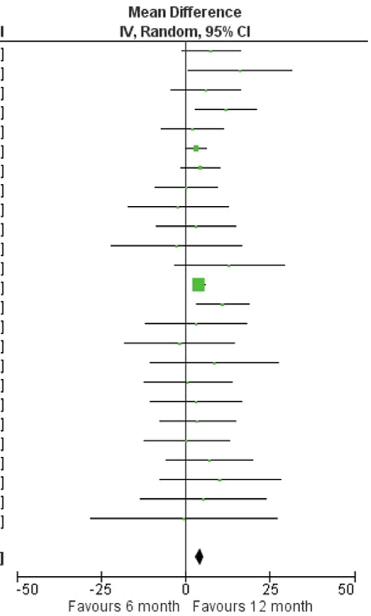


Fig. 3. Forest plots for meta-analysis of continuous measures for mean difference of words in quiet from (A) pre-op to 3 months, (B) 3 to 6 months, (C) 6 to 12 months, (D) 3 to 12 months, and (E) 12 months to 2 years. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

C

Study or Subgroup	12-month Mean	12-month SD	12-month Total	6-month Mean	6-month SD	6-month Total	Weight	Mean Difference IV, Random, 95% CI
Adunka 2008	59	16.6	29	51.4	16.6	29	2.3%	7.60 [-0.94, 16.14]
Borger 2015	78	12.3	10	62	21.5	10	0.7%	16.00 [0.65, 31.35]
Dalbert 2016a	71	25	46	65	25	46	1.6%	6.00 [-4.22, 16.22]
Dalbert 2016b	79	22	50	67	24	50	2.0%	12.00 [2.98, 21.02]
Firszt 2018	51	22	39	49	20	39	1.9%	2.00 [-7.33, 11.33]
Grisel 2021	55.8	23.4	426	52.7	22.9	399	16.6%	3.10 [-0.06, 6.26]
Kelsall 2021	65.2	18.8	91	60.9	21.1	96	5.1%	4.30 [-1.42, 10.02]
Knopke 2019a	35.4	25.5	62	35.2	27.3	62	1.9%	0.20 [-9.10, 9.50]
Knopke 2019b	32.1	25.1	24	34.2	27.2	24	0.8%	-2.10 [-16.91, 12.71]
Knopke 2021	39.2	28.2	49	36.1	31.3	49	1.2%	3.10 [-8.70, 14.90]
Lee 2021	61.9	26.8	13	64.6	26.4	16	0.4%	-2.70 [-22.18, 16.78]
Plontke 2020	75	19	16	62	27	16	0.6%	13.00 [-3.18, 29.18]
Runge 2016	56.8	3.9	37	52.9	3.8	37	53.8%	3.90 [2.15, 5.65]
Sladen 2017	67	19	61	56	24	61	2.8%	11.00 [3.32, 18.68]
Sturm 2021a	53.4	21.3	13	50.3	17.7	14	0.8%	3.10 [-11.73, 17.93]
Sturm 2021b	48	18.4	8	49.7	19.7	15	0.6%	-1.70 [-17.89, 14.49]
Sturm 2021c	51.8	23.2	8	43.3	20	16	0.5%	8.50 [-10.33, 27.33]
Sturm 2021d	59.2	17.4	15	58.5	19.5	16	1.0%	0.70 [-12.29, 13.69]
Sturm 2021e	51.9	16	13	48.7	20.5	15	0.9%	3.20 [-10.34, 16.74]
Sturm 2021f	39.1	16.1	13	35.5	13.3	15	1.4%	3.60 [-7.44, 14.64]
Sturm 2021g	37.8	13.3	9	37.5	20.5	19	1.0%	0.30 [-12.37, 12.97]
Yang 2016a	61	29.7	46	54	32.3	46	1.0%	7.00 [-5.68, 19.68]
Yang 2016b	67.2	27.5	19	57	28.9	19	0.5%	10.20 [-7.74, 28.14]
Yang 2016c	62.1	25.3	18	56.9	31.1	18	0.5%	5.20 [-13.32, 23.72]
Yang 2016d	58.2	34.9	12	58.6	34.2	12	0.2%	-0.40 [-28.05, 27.25]
Total (95% CI)			**1127**			**1139**	**100.0%**	**4.18 [2.90, 5.47]**

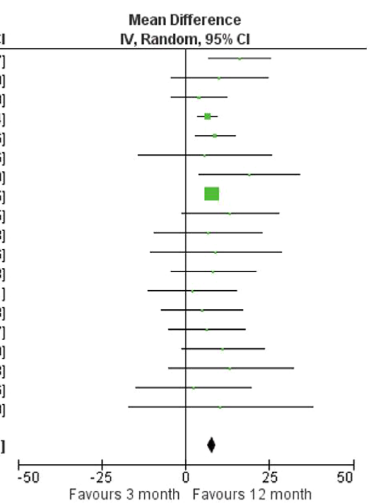
Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 14.87$, $df = 24$ ($p = 0.92$); $I^2 = 0\%$
Test for overall effect: $Z = 6.37$ ($p < 0.00001$)



D

Study or Subgroup	12 Month Mean	12 Month SD	12 Month Total	3 Month Mean	3 Month SD	3 Month Total	Weight	Mean Difference IV, Random, 95% CI
Adunka 2008	59	16.6	29	42.9	18.6	29	2.2%	16.10 [7.03, 25.17]
Borger 2015	78	12.3	10	68	19.9	10	0.9%	10.00 [-4.50, 24.50]
Deep 2021	54.3	21	41	50.3	20	53	2.6%	4.00 [-4.39, 12.39]
Grisel 2021	55.8	23.4	426	49.3	24.3	529	19.6%	6.50 [3.46, 9.54]
Kelsall 2021	65.2	18.8	91	56.3	22	96	5.3%	8.90 [3.04, 14.76]
Lee 2021	61.9	26.8	13	56.1	28.9	18	0.5%	5.80 [-13.96, 25.56]
Plontke 2020	75	19	16	56	24	16	0.8%	19.00 [4.00, 34.00]
Runge 2016	56.8	3.9	37	49	3.8	37	58.8%	7.80 [6.05, 9.55]
Sturm 2021a	53.4	21.3	13	40	16.5	14	0.9%	13.40 [-1.05, 27.85]
Sturm 2021b	48	18.4	8	41.3	19.5	16	0.7%	6.70 [-9.23, 22.63]
Sturm 2021c	51.8	23.2	8	42.8	22	16	0.5%	9.00 [-10.36, 28.36]
Sturm 2021d	59.2	17.4	15	50.9	18.2	16	1.2%	8.30 [-4.23, 20.83]
Sturm 2021e	51.9	16	13	49.9	19.9	15	1.0%	2.00 [-11.31, 15.31]
Sturm 2021f	39.1	16.1	13	34.1	16.6	15	1.2%	5.00 [-7.13, 17.13]
Sturm 2021g	37.8	13.3	9	31.4	17.9	22	1.4%	6.40 [-5.07, 17.87]
Yang 2016a	61	29.7	46	49.9	30.5	46	1.2%	11.10 [-1.20, 23.40]
Yang 2016b	67.2	27.5	19	53.8	31	19	0.5%	13.40 [-5.23, 32.03]
Yang 2016c	62.1	25.3	18	59.7	27.2	18	0.6%	2.40 [-14.76, 19.56]
Yang 2016d	58.2	34.9	12	47.8	33.8	12	0.2%	10.40 [-17.09, 37.89]
Total (95% CI)			**837**			**997**	**100.0%**	**7.77 [6.42, 9.11]**

Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 9.76$, $df = 18$ ($p = 0.94$); $I^2 = 0\%$
Test for overall effect: $Z = 11.32$ ($p < 0.00001$)



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Study or Subgroup	2 Year Mean	2 Year SD	2 Year Total	12 Month Mean	12 Month SD	12 Month Total	Weight	Mean Difference IV, Random, 95% CI
Dalbert 2016a	72	25	46	71	25	46	5.8%	1.00 [-9.22, 11.22]
Dalbert 2016b	83	17	50	79	22	50	10.2%	4.00 [-3.71, 11.71]
Deep 2021	61.8	20	27	54.3	21	41	6.2%	7.50 [-2.41, 17.41]
Friedland 2021a	53.1	21.5	30	55.8	22.7	30	4.8%	-2.70 [-13.89, 8.49]
Friedland 2021b	54.9	14.8	20	53	13.4	20	7.9%	1.90 [-6.85, 10.65]
Grisel 2021	57.3	22.6	176	55.8	23.4	426	37.7%	1.50 [-2.51, 5.51]
Knopke 2021	38.7	24.2	49	39.2	28.2	49	5.6%	-0.50 [-10.90, 9.90]
Sturm 2021a	60.7	12.8	6	53.4	21.3	13	2.5%	7.30 [-8.16, 22.76]
Sturm 2021b	58.8	18.4	10	59.2	17.4	15	2.9%	-0.40 [-14.81, 14.01]
Sturm 2021c	58.8	22.2	10	51.9	16	13	2.3%	6.90 [-9.38, 23.18]
Sturm 2021d	52.2	12.3	10	39.1	16.1	13	4.5%	13.10 [1.49, 24.71]
Yang 2016a	63.3	25.7	46	61	29.7	46	4.7%	2.30 [-9.05, 13.65]
Yang 2016b	70.6	24.8	19	67.2	27.5	19	2.2%	3.40 [-13.25, 20.05]
Yang 2016c	58.1	29.7	18	62.1	25.3	18	1.9%	-4.00 [-22.02, 14.02]
Yang 2016d	62.3	32.2	12	58.2	34.9	12	0.8%	4.10 [-22.77, 30.97]
Total (95% CI)			**529**			**811**	**100.0%**	**2.55 [0.09, 5.01]**

Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 7.15$, $df = 14$ ($p = 0.93$); $I^2 = 0\%$
Test for overall effect: $Z = 2.03$ ($p = 0.04$)

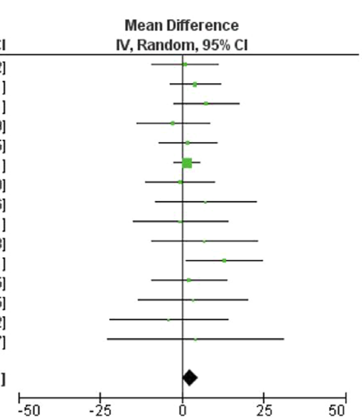

Fig. 3 (Continued)

TABLE IV.
Meta-Analysis of Continuous Measures for Different Speech Recognition Instruments.

Speech Recognition Instrument	Mean Difference of Percentage (%) Correct (95% Confidence Interval)			
	Pre-op to 3 Months	3 to 6 Months	6 to 12 Months	3 to 12 Months
CNC words (in quiet)	37.1 (33.8, 40.4)	4.3 (3.0, 5.6)	3.9 (2.6, 5.3)	7.6 (6.2, 9.0)
HINT sentences (in quiet)	46.5 (37.0, 56.0)	5.7 (0.1, 11.4)	4.4 (−1.1, 9.9)	11.5 (4.0, 18.9)
AzBio sentences (in quiet)	45.9 (44.2, 47.5)	3.4 (−1.9, 8.6)	-	-
HINT sentences (in noise)	35.1 (30.0, 40.3)	6.1 (0.1, 12.1)	7.4 (−0.9, 15.6)	15.5 (7.2, 23.8)
AzBio sentences (in noise)	26.4 (18.6, 34.2)	4.9 (−0.2, 9.9)	-	-

Light shade, Statistically significant change beyond the preceding score's measurement error interval; medium shade, statistically significant change within the preceding score's measurement error interval; dark shade, non-statistically significant change.
CNC = Consonant Nucleus Consonant; HINT = hearing in noise test.

expected, this time period also represents the highest degree of between-study heterogeneity. From pre-op to 3 months, all study comparisons demonstrated moderate-to-high degrees of heterogeneity based on the I^2-statistic (range, 52%–81%) except those examining AzBio sentences in quiet and HINT sentences in quiet, both without heterogeneity ($I^2 = 0\%$). None of the study comparisons demonstrated between-study heterogeneity beyond 3 months ($I^2 = 0\%$) except those examining AzBio sentences in quiet, which demonstrated moderate heterogeneity ($I^2 = 59\%$) from 3 to 12 months. This indicates that there is a wide range of changes in speech recognition scores from pre-op to 3 months, suggesting that although significant improvements are expected based on mean score, individual patient performance varies.

DISCUSSION

In the current study, pre- and post-CI speech recognition data from adults with postlingual hearing loss from multiple studies were analyzed to identify longitudinal patterns of change. When grouped by speech recognition measure, significant improvements in scores were observed only in the immediate post-implantation period from pre-op to 3 months (Table III). Statistically significant differences were detected beyond 3 months for each speech recognition measure, but these differences were not beyond the measurement error of the speech material and, therefore, were not considered significant changes.[26,27] No statistically significant changes in speech recognition scores were observed from 3 to 6 months, 6 to 12 months, or 3 to 12 months.

Similar results were found when studies were grouped by the speech recognition material. All tests demonstrated significant improvement from pre-op to 3 months, but no significant changes beyond 3 months on consecutive testing intervals were observed (Table IV). Of note, from 3 to 12 months, only scores for HINT sentences in noise demonstrated significant improvement, whereas scores for HINT sentences in quiet showed no significant change. These differences reflect how the testing environment can impact speech recognition ability and highlight the potential importance of speech recognition testing in multiple settings. In CI users, scores obtained with background noise generally demonstrate more modest improvements compared to scores obtained in quiet.[51,52] In addition, scores obtained in noise are also known to improve at a slower rate compared to scores obtained in quiet.[35,37,41] A major motivator for patients pursuing CIs is the desire to improve communication and social independence, especially in challenging listening environments.[53,54] The present findings support the importance of pre-operative discussions on the maximum speech recognition benefit patients can expect to obtain from CI in noisy settings, which is significantly less when compared to quiet settings. Patients who understand the potential limitation in speech recognition in noise improvements provided by CI prior to implantation may have clearer expectations of their long-term outcome.[2,3]

Overall, the meta-analysis suggests that the most critical time period for improvements in speech recognition occurs in the early post-implantation period (up to three months). Afterward, scores, on average, might undergo small incremental changes, but are less likely to demonstrate any further significant improvements. These trends are observed regardless of which measures are being analyzed and are consistent with findings from previous studies.[5–10] In other words, on average, a newly implanted CI user's speech recognition ability at 3 months likely represents a plateau in their abilities and their maximum level of improvement achieved. Similar conclusions have been reported by previous studies. For example, Spivak et al. found that patients with good speech recognition ability in the first 3 months were more likely to demonstrate continued improvement at 12 months compared to patients who performed poorly.[55] For clinicians, these findings underscore the importance of regular use of the device and repeated evaluation in the early post-operative period. Patients who demonstrate little improvement in speech recognition in the early post-operative period might require additional interventions such as speech-language pathologist-led auditory rehabilitation and computer-based auditory training activities, which have been demonstrated to improve speech recognition in the early post-implantation period.[56–60] Long-term evaluation of speech recognition is necessary for all patients as individual patient outcomes may demonstrate wide variation from group means.[61,62]

Although speech recognition is considered to be the standard for measuring outcomes in CI users, word and

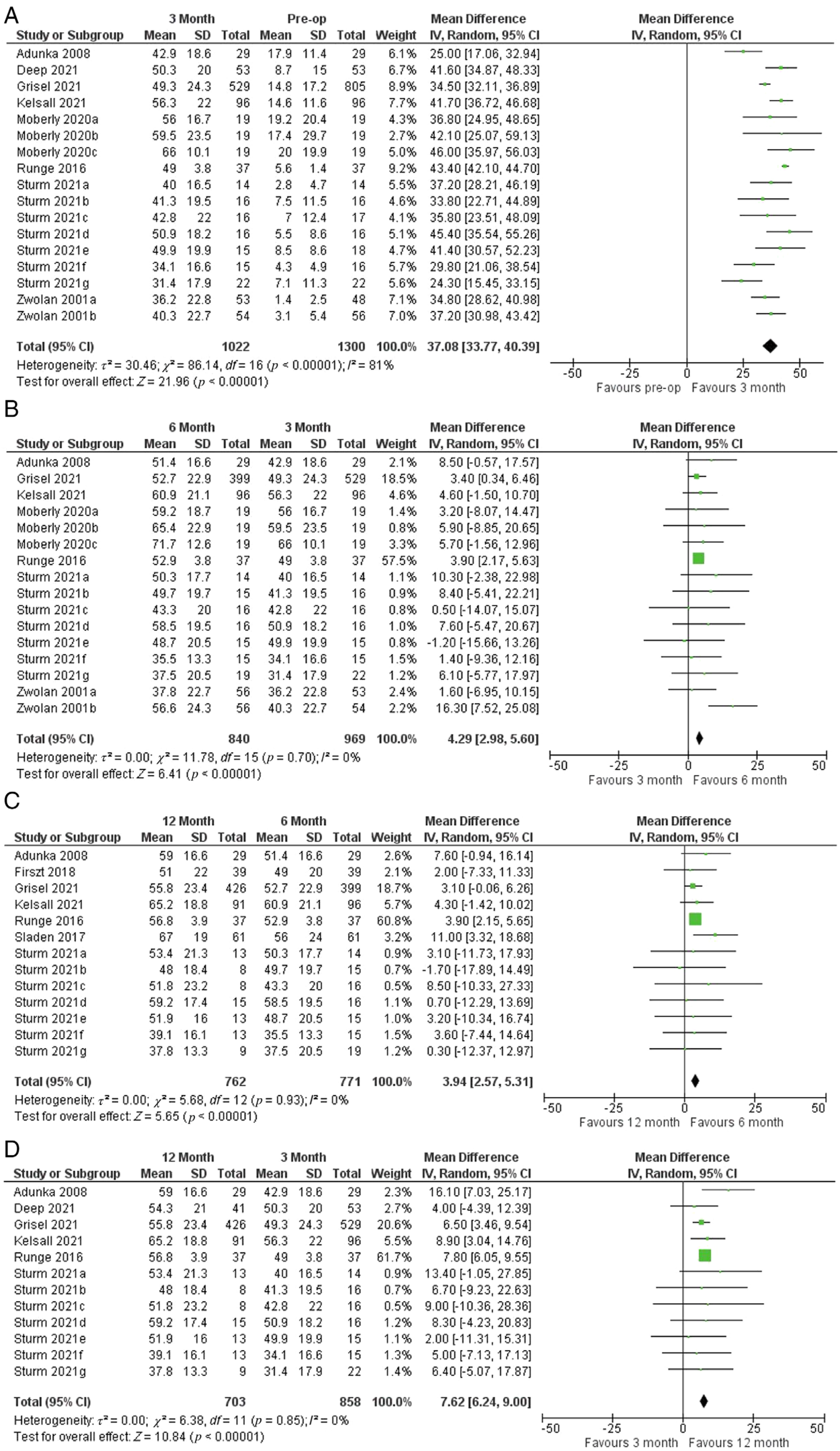

Fig. 4. Forest plots for meta-analysis of continuous measures for mean difference of Consonant-Nucleus-Consonant (CNC) word recognition in quiet from (A) pre-op to 3 months, (B) 3 to 6 months, (C) 6 to 12 months, and (D) 3 to 12 months. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

sentence recognition measured in a controlled environment does not assess communication abilities in more complex environments and, therefore, does not reflect CI users' abilities in real-world listening situations.[63–66] Multiple studies show that QOL, as assessed by patient-reported outcome measures (PROMs), improves significantly after CI and that there is a poor correlation between speech recognition and patient-reported functional abilities across multiple domains.[63,65–67] However, very few studies have reported longitudinal changes in PROM scores and the extent to which changes in PROM scores mirror changes in speech recognition.[67–69] Given that PROMs are more direct measures of the functional abilities of CI patients, additional studies of post-CI patterns of change in PROMs are necessary to determine when and how much QOL improvement occurs following cochlear implantation.

LIMITATIONS

These meta-analysis results reflect the trends in mean scores observed in a large cohort of CI users. However, the results of previous studies demonstrate that for a sizeable group of CI users, individual speech recognition scores can fall within a wide range of outcomes that are very different from the mean.[17,70] As such, our findings cannot capture the wide range of individual CI outcomes and might not be representative of every CI user's experience. This limits the utility of using mean speech recognition scores to guide pre-operative counseling discussions. In practice, patients should be made aware of this variability and group mean scores should only be used as a general guideline of expected post-implantation speech recognition change. Future studies focusing on changes in speech recognition by individual CI users can be helpful in personalized counseling and setting expectations for patients whose performance deviates from those of the average patient.

Being a systematic review, data are drawn from previously published studies. As such, there is an inherent risk of bias associated with such data. For example, we are unable to control for pre-operative factors or testing conditions in our included studies. In addition, several relevant studies were excluded from quantitative analysis due to missing key data metrics (e.g., standard deviation values), being unavailable for full-text review, or being published in a language other than English. Our analysis of overall mean scores features multiple different speech recognition measures including CNC, HINT, and AzBio. The current standard for speech testing includes CNC and AzBio due to known ceiling effects associated with the HINT, which is part of an older battery of tests.[71,72] Given this, our aggregate results likely include a subset of CI users from earlier time periods assessed with a speech recognition measure no longer widely used. Finally, our analysis of significant changes in speech recognition is limited to the first 12 months post-CI. A previous study confirmed that speech recognition could continue to improve beyond 12 months.[6] While the included studies reported some speech recognition data after 12 months, meta-analysis was not possible due to the low number of contributing studies and limited quantitative data. Future studies are necessary to better understand whether any significant changes occur beyond 12 months.

CONCLUSIONS

Cochlear implantation has established benefits for speech recognition ability in adults with severe to profound hearing loss. Mean scores demonstrate rapid and significant improvement within the first 3 months, with no further statistically significant improvement for the average patient after 3 months. Longitudinal changes in average scores are important discussion points that can facilitate pre-operative counseling and setting of expectations, but large individual variation in scores should be anticipated. Future research that focuses on explaining the sources of these individual differences is warranted to develop a more complete understanding of longitudinal changes in speech recognition outcomes for individual patients.

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