Outcomes in Adolescents From Sequential vs Bilateral Cochlear Implantation in Young Children

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abstract

OBJECTIVE: To investigate whether early simultaneous vs sequential bilateral cochlear implantation affects long-term hearing outcomes into adolescence and early adulthood.

METHODS: In this cross-sectional study, we compared performance in sound localization and speech recognition in quiet and in masking speech between adolescents with simultaneous or sequential bilateral cochlear implantation using linear mixed modeling. Participants were required to be aged 12 to 21 years, have received at least 1 cochlear implant before age 2.5 years, have an interval between the first and second cochlear implantation less than 4 years, attend a standard school curriculum, and have no cochlear malformation. Fifteen adolescents with normal hearing provided normative data.

RESULTS: Of 109 individuals from the Karolinska University Hospital medical records who were eligible based on the age and age at implantation criteria, 37 (34%) met all inclusion criteria and were willing to participate. Simultaneously implanted participants ($n = 17$) achieved higher sound localization accuracy than those who were sequentially implanted ($n = 20$) ($P < .001$; Cohen's $d = 0.58$), whereas recognition of speech was comparable. Because both implant groups were consistent users of bilateral implants for on average 15 years, the interimplant delay was short for participants with sequential implants (mean = 1.2 years; 95% confidence interval, 0.29–3.5 years), and the groups were similar on a large number of social, environmental, and auditory factors before and after implantation; the higher localization accuracy is likely the result of simultaneous implantation. Both implant groups performed worse than adolescents with normal hearing.

CONCLUSION: Simultaneous bilateral cochlear implantation in early childhood supports better long-term spatial hearing than sequential implantation.

WHAT'S KNOWN ON THIS SUBJECT: Bilateral cochlear implantation in children enhances language, speech recognition, and sound localization compared with unilateral implantation. Although sequential implantation is associated with decreased performance compared with simultaneous implantation, the long-term impact of interimplant delay remains unclear.

WHAT THIS STUDY ADDS: Simultaneous bilateral cochlear implantation in early childhood improves spatial hearing into adolescence and young adulthood compared with sequential implantation, even with short interimplant delays, whereas speech recognition remains similar between groups.

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Dr Asp conceptualized and designed the study, designed the data collection instruments, coordinated and supervised data collection, collected the data, carried out the initial analyses, drafted the initial manuscript, and critically reviewed and revised the manuscript. Dr Eklöf designed the data collection instruments, collected the data, carried out the initial analyses, and critically reviewed and revised the manuscript. Dr Moumèn-Denanto collected the data and critically reviewed and revised the manuscript for important intellectual content. Dr Kral critically reviewed and revised the manuscript for important intellectual content. Dr Karltorp conceptualized and designed the study and critically reviewed and revised the manuscript for important intellectual content. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

INTRODUCTION

Cochlear implantation enables speech understanding and language development in children with severe-to-profound bilateral hearing loss.[1–4] Early implantation and family-centered intervention further support language outcomes,[5,6] and cochlear implant (CI) users generally show better educational and quality of life outcomes than nonusers.[7] Bilateral implantation enhances speech perception, language development, and sound localization compared with unilateral implantation.[3,8–12] In sequential bilateral implantation, speech recognition is typically poorer in the second ear,[13–15] and brainstem response latencies are prolonged when the delay exceeds 1.5 years.[16] For speech-in-noise recognition and sound localization, shorter interimplant intervals improve outcomes when using both implants.[9,14,17,18] Animal and human studies suggest that cortical asymmetry and "aural preference" for the first ear arise from delayed second implantation, emphasizing the need to minimize interimplant delay to prevent maladaptive brain reorganization.[19] However, the long-term effects of interimplant delay in children implanted bilaterally before age 6 years, within the sensitive period for auditory development,[20] remain unclear. Existing studies have limited follow-up durations for cortical, subcortical, and behavioral outcomes.

This study investigates whether early simultaneous vs sequential implantation differentially affects sound localization and speech recognition in quiet and adverse conditions after extended bilateral CI use. The Teenagers and Young Adults with CIs cohort represents a cross-sectional sample of Swedish pediatric CI users.[21] We evaluated horizontal sound localization accuracy and speech recognition in children with simultaneous or sequential bilateral CIs, with a mean of 15 years of bilateral experience.

METHODS

The study was approved by the Regional Ethical Review Board in Umeå on December 21, 2019. Participants received oral and written information about the study and gave their written informed consent. Parents to participants younger than age 18 years gave written consent.

Inclusion Criteria and Study Design

In this cross-sectional cohort study on long-term communication and quality of life outcomes in adolescents and young adults using CIs since early childhood,[21] 135 individuals from the Karolinska University Hospital medical records were assessed for eligibility based on the criteria of being aged 12 to 21 years, receiving a CI when aged less than 2.5 years, and attending a standard school curriculum (any school attendance was allowed as long as the national standard curriculum was followed). No specific comorbidity was an exclusion criterion. The criteria resulted in a study invitation to 109 individuals, and 26 were excluded because of not meeting the requirements of attending the national standard school curriculum. Fifty-one individuals agreed to participate in all parts of the study (language, hearing, balance, quality of life, and genetics; see Löfkvist et al[21]), 12 declined, and 46 did not respond. For the present study on the long-term effects of simultaneous or sequential implantation, additional inclusion criteria were no cochlear malformations and an interimplant interval of no more than 4 years to allow evaluation of performance in individuals for whom there allegedly was minimal brain reorganization because of a period of unilateral CI stimulation[19,22], which may result in an "aural preference" for the first implanted side.[15,22]

Fifteen individuals (8 female) with normal hearing participated in the study to provide normative data. Inclusion criteria were ages 12–21 years, hearing thresholds less than or equal to 20 dB hearing level at octave frequencies from 0.125 to 8 kHz, and threshold asymmetry less than or equal to 10 dB across frequencies.

The participants took part in 3 auditory tasks. Localization accuracy was measured repeatedly using 4 different stimuli. The test order of the stimuli was pseudorandomized. Recognition of speech in quiet was measured at a presentation level normally used for clinical evaluation of CI performance in Sweden (65 dB sound pressure level [SPL]) and at a relatively soft presentation level (50 dB SPL). Recognition of speech in adverse listening conditions was measured in an adaptive speech-in-speech task. The total time for the measurements was approximately 60 minutes.

Sound Localization

The test setup, procedure, and behavioral response acquisition have been described previously.[24] The method demonstrates high reliability,[24] demonstrates sensitivity to both simulated and congenital asymmetric hearing in children and adults,[25–29] and has been applied in studies of spatial hearing development in infants with normal hearing and CIs.[24,30,31]

Participants were seated in front of 12 active loudspeakers (ARGON 7340A; Argon Audio, Sweden) arranged in a 110° arc in the frontal horizontal plane within an audiometric test room ($4.1 \times 3.3 \times 2.1$ m; quasi-free field; ambient noise: 25 dB[A] over 15 seconds; reverberation time $T30 = 0.11$ seconds at 500 Hz, measured with B&K 2238 Mediator and 2260 Investigator, Brüel & Kjær, Denmark). Loudspeakers were spaced at 10° intervals (±5° to ±55° azimuth) and positioned at ear level. Each loudspeaker was paired with a 7-in thin-film transistor display, forming 12 loudspeaker/display (LD) pairs. Eye tracking (Smart Eye Pro; Smart Eye AB, Sweden) was used to record pupil position relative to LD pairs.

The localization task involved 24 azimuthal shifts of a continuous auditory-visual stimulus. At each shift (every

5–9 seconds, mean 7 seconds), the sound moved to a randomly selected loudspeaker, and the visual stimulus ceased. After 1.6 seconds, the visual stimulus resumed at the new sound source. This interval enabled measurement of gaze accuracy and latency in response to spatial auditory changes. Each test lasted approximately 3 minutes.

Participants were instructed to direct and maintain gaze toward the perceived sound source and adjust if the visual stimulus reappeared elsewhere. Head movement was permitted. No information was given about the 1.6-second sound-only interval, and saccades were neither encouraged nor discouraged.

Four auditory stimuli were used (63 dB SPL) to assess spatial cue contributions. Two broadband stimuli (female voice-like spectrum) provided both interaural time difference (ITD) and interaural level difference (ILD) cues: a musical melody with minimal monaural cues because of amplitude modulation and stationary noise with enhanced monaural cues. Two octave-filtered noises (center frequencies: 0.5 kHz and 4 kHz) were used to isolate ITD and ILD contributions. The 4-kHz stimulus also provided monaural cues, whereas the 0.5-kHz stimulus minimized both monaural and ILD cues.

Recognition of Speech in Quiet

Speech recognition in quiet was assessed using a standardized and validated Swedish clinical speech audiometry test.[32] The test material consisted of phonemically balanced lists of 50 monosyllabic words. Two different lists were presented in sound field at 65 dB SPL and at 50 dB SPL. Participants were seated 1 m from the loudspeaker presenting the words at 0° azimuth and were instructed to repeat the words as accurately as possible. Guessing was encouraged, and no feedback was provided. The test administrator listened to the target signal and the participant's responses through a feedback system and scored the responses after each word. Words had to be repeated grammatically correct to be scored as correct.

Recognition of Speech-in-Speech

The experimental setup, speech material, and procedures have been detailed previously.[28,29] Speech recognition in the presence of competing speech was evaluated using Swedish Hagerman sentences,[33] presented in a calibrated sound field within an audiometric test room (dimensions: $4.0 \times 2.6 \times 2.1$ m; ambient noise: 20 dB[A] over 15 seconds; reverberation time $T30 = 0.09$ seconds at 500 Hz, measured with B&K 2238 Mediator and 2260 Investigator). The Hagerman corpus comprises grammatically correct 5-word sentences with fixed syntax and low semantic predictability. Twelve test lists and 1 training list (10 sentences each) were employed.

Target speech (female voice) was delivered from a frontal loudspeaker (0° azimuth). The maskers consisted of 4 noncorrelated speech streams (1 male voice reading a novel), either colocated (0°) or spatially separated (±30° and ± 150° azimuth). Loudspeakers were positioned at ear level. Masker level was fixed at 63 dB SPL (measured for 12-minute duration), measured at the participant's head position in absentia.

An adaptive psychoacoustic procedure estimated the speech recognition threshold (SRT) corresponding to 40% correctly repeated words, using a level adjustment algorithm optimized via simulations and psychometric function analysis.[33–35]

Participants were seated 1.8 m from the frontal speaker and were instructed to face forward and repeat each sentence as accurately as possible. Guessing was encouraged; no feedback was provided. A test administrator, located outside the room, monitored responses via a feedback system and scored them in real time. Only grammatically correct word repetitions were accepted as correct.

Main Outcomes

Localization accuracy was quantified by an error index (EI),[36,37] which was calculated as

$$EI = \frac{\sum_{p=1}^{P} |i_p - k_p|}{\left(\sum_{p=1}^{P} \sum_{j=1}^{n} |i_p - j|\right)/\mathrm{n}} \tag{1}$$

where P was the number of presentations with a valid response ($P \leq 24$ in the current test paradigm), i_p was the presenting loudspeaker (1 to 12) and k_p was the perceived loudspeaker (1 to 12) at the pth presentation, and n was the number of loudspeakers. An EI of 0 corresponded to perfect performance, whereas an EI of 1 corresponded to average random performance. In addition to accuracy, saccadic latency was quantified by fitting an arctangent function to the gaze samples during a 4.1 analysis window for each trial, starting 2.5 seconds (50 samples) before each azimuthal sound shift and ending when the visual stimulus was reintroduced.[30,38]

Recognition of speech in quiet was quantified as the proportion of correctly identified words. This score was transformed into rationalized arcsine units (RAUs) to avoid statistical problems inherent in proportional scales.[39] In the current test paradigm, test scores could range from −16.47 to 116.47 RAUs.

Recognition of speech in competing speech was quantified by an SRT (expressed in dB), defined as the mean of the signal-to-noise ratios for the last 10 presented sentences of the adaptive procedure.[35,40]

Statistical Analysis

Sound localization performance was analyzed using a linear mixed model with group (simultaneous CI, sequential CI, and normal hearing) and stimulus (4 levels) as fixed effects and participants as random effects. Linear regression assessed relationships between localization accuracy and saccadic latency across groups. Speech recognition in quiet and in competing speech was also analyzed using mixed models, with group (3 levels) and either presentation level (2 levels) or spatial condition (2 levels) as fixed effects and participants as random effects. Post hoc analyses were performed for any significant main effects or interactions by comparing estimated marginal means with Bonferroni correction. Differences between marginal means are abbreviated with "Δ" in the Results section. Effect sizes (Cohen's d, abbreviated with "d" in the Results section) were computed by subtracting estimated marginal means for specific levels within a fixed effect divided by the pooled SD across levels. *P* values less than 0.05 were considered statistically significant. Assumptions of the mixed models were validated by a Kolmogorov-Smirnoff test of normality and Levene test of homogeneity of variance for the dependent variables. Statistical analyses were performed using Statistica version 13 (Statsoft, Inc., Tulsa, OK) and JASP (version 0.19.3).

RESULTS

Participants With CIs

Table 1 summarizes participant demographics, hearing thresholds, etiology, preoperative hearing, hearing aid use, and parental education, stratified by implantation type. The final sample included 37 individuals (mean ± SD age = 16.8 ± 2.6 years; 22 male participants), all using bilateral CIs more than 10 hours/day, confirmed via data logs.

Twenty participants (54%, 13 male participants) received sequential implants at mean ± SD ages of 1.4 ± 0.6 years (CI-1) and 2.6 ± 0.9 years (CI-2), with a mean interimplant interval of 1.2 years. Seventeen participants (46%, 9 male participants) received simultaneous implants at a mean ± SD age of 1.2 ± 0.5 years. Age at CI-1 was comparable between groups ($P = .27$), whereas age at CI-2 differed significantly (mean difference: 1.4 years; $P < .001$). All participants failed newborn hearing screening bilaterally and were subsequently diagnosed with bilateral sensorineural hearing loss. Screening of medical records revealed that sequential instead of simultaneous implantation occurred for the following reasons: regulatory (35%, n = 7; bilateral implantation not reimbursed by the publicly funded health care system in Sweden until 2006), medical (25%, n = 5; eg, excessive bleeding during surgery), parental decision (5%, n = 1), clinical uncertainty of the degree of hearing loss in 1 ear (10%, n = 2), and progressive hearing loss in 1 ear (25%, n = 5). Decisions on CI-2 for participants

TABLE 1. Participant Characteristics, Hearing Before and After Implantation, Cause of Hearing Loss, and Parental Education Level

	Simultaneous (n = 17)	Sequential (n = 20)
Characteristic		
Sex, male/female, n	8/9	9/11
Age, mean (SD; range), years	16 (2.0; 13–20)	17 (2.9; 13–22)
Age first implant, mean (SD; range), years	1.2 (0.48; 0.61–2.2)	1.4 (0.56; 0.67–2.4)
Age second implant, mean (SD; range), years	1.2 (0.48; 0.61–2.2)	2.6 (0.93; 1.1–5.5)
Interimplant interval, mean (SD; range), years	0	1.2 (0.83; 0.29–3.5)
Bilateral CI experience, mean (SD; range), years	15 (1.7; 12–18)	15 (3.1; 10–19)
Hearing with CI, mean (SD)[a]		
Right ear hearing thresholds, dB HL		
0.125 kHz	29 (9)	28 (6)
0.25 kHz	26 (8)	26 (6)
0.5 kHz	28 (5)	27 (7)
1 kHz	27 (4)	27 (6)
2 kHz	23 (5)	24 (7)
3 kHz	25 (6)	26 (8)
4 kHz	25 (6)	28 (6)
6 kHz	20 (7)	19 (6)
8 kHz	17 (10)	17 (12)
Left ear hearing thresholds, dB HL		
0.125 kHz	29 (9)	28 (8)
0.25 kHz	25 (7)	26 (7)
0.5 kHz	29 (5)	30 (6)
1 kHz	27 (6)	28 (6)
2 kHz	23 (5)	27 (6)
3 kHz	26 (6)	26 (5)
4 kHz	26 (7)	29 (6)
6 kHz	18 (6)	18 (7)
8 kHz	17 (13)	15 (10)
Right ear speech recognition, %	76 (10)[b]	74 (14)
Left ear speech recognition, %	78 (14)[b]	74 (12)
Hearing before implantation		
Hearing aid use, n		
Yes	12	18
No	5	2
Pure-tone average, mean (SD), dB HL[c]		
Right ear	110 (15)	105 (19)
Left ear	117 (12)	109 (16)
Cause, n		
Connexin 26	4	2
Unknown	7	6

(Continued on next page)

TABLE 1. Participant Characteristics, Hearing Before and After Implantation, Cause of Hearing Loss, and Parental Education Level (Continued)

	Simultaneous (n = 17)	Sequential (n = 20)
Congenital cytomegalovirus	1	5
Meningitis	2	0
Waardenburg syndrome	1	1
Pendred	0	2
Hereditary	1	1
Jervell and Lange-Nielsen syndrome	1	1
Usher syndrome	0	2
Education level of mother, n		
University	10	13
High school	3	3
Other education after high school	3	4
Education level of father, n		
University	7	9
High school	6	6
Other education after high school	2	4
Elementary school	1	1

Abbreviations: CI, cochlear implant; HL, hearing level.

[a] Sound-field hearing thresholds measured according to International Organization for Standardization 8253-2:2009, and recognition of speech measured by a standardized and validated Swedish clinical speech audiometry test (Liden and Fant)[32] consisting of lists of phonemically balanced monosyllabic words.

[b] Speech recognition scores for 13 of 17 (76%) individuals with simultaneous bilateral implantation were available.

[c] Measured according to International Organization for Standardization 8253-1:2010. Value calculated from the last audiogram before implantation for a specific ear.

with a progressive or uncertain degree of hearing loss were made based on repeated measurements of behavioral hearing thresholds with and without hearing aids for the unimplanted ear during follow-up within the Hearing Implant Programme at Karolinska University Hospital.

The mean ± SD age at testing was 17.4 ± 2.9 years (sequential) and 16.1 ± 2.0 years (simultaneous) ($P = .12$). Hearing thresholds and speech recognition scores for both ears were similar across groups. No significant group differences were found in etiology of hearing loss ($P = .98$), maternal ($P = .96$) or paternal education ($P = .92$), special school attendance (15% vs 24%; risk ratio [RR], 0.64 [95% confidence interval, 0.17–2.5], $P = .51$), or self-reported learning disabilities (25% vs 18%; RR, 1.1 [95% confidence interval, 0.31–4.1], $P = .85$).

Participants With Normal Hearing

The age range of the participants with normal hearing was 13.8–20.8 years (mean [SD], 16.1 [2.4] years). All 15 participants provided normative data for the sound localization test, whereas only 10 of 15 participants provided data for the speech recognition tests because of limited time availability on the participants' part.

Sound Localization Accuracy and Latency

Main effects of group (simultaneous implants, sequential implants, and normal hearing) ($P < .001$) and stimulus (4 different stimuli) ($P < .001$) on localization accuracy existed (Figure 1). There was no interaction between stimulus and group. The simultaneous group showed higher localization accuracy than the sequential group ($\Delta = 0.071$; 95% confidence interval, 0.110–0.031; d = 0.58). Normal hearing participants showed higher accuracy than the group with simultaneous ($\Delta = 0.139$; 95% confidence interval, 0.181–0.096; d = 1.1) and sequential ($\Delta = 0.209$; 95% confidence interval, 0.169–0.250; d = 1.7) implants. Simple linear regression analyses in the sequential group did not reveal any association between sound localization accuracy and interimplant interval (0.5 kHz: $r = -0.34$, $P = .15$; 4 kHz: $r = -0.03$, $P = .90$; musical melody: $r = -0.31$, $P = .19$; and speech-weighted noise: $r = -0.19$, $P = .42$) (Supplemental Figure 1). Individual data in Supplemental Figure 1 indicate that individuals with relatively short interimplant intervals (eg, <1 year) showed similar localization accuracy as individuals with longer intervals but worse than most of the individuals with simultaneous implantation (please see Supplemental Figure 1). Similarly, there was no association between sound localization accuracy and age at second implantation (0.5 kHz: $r = -0.22$, $P = .35$; 4 kHz: $r = 0.17$, $P = .47$; musical melody: $r = -0.15$, $P = .53$; and speech-weighted noise: $r = -0.01$, $P = .96$) across stimuli.

Localization accuracy was higher for speech-weighted noise than for octave-filtered noises (0.5 kHz: $\Delta = 0.080$, 95% confidence interval, 0.055–0.105, d = 0.65; 4 kHz: $\Delta = 0.053$, 95% confidence interval, 0.028–0.078, d = 0.43) and higher for the musical melody than the 0.5 kHz stimulus ($\Delta = 0.054$, 95% confidence interval, 0.029–0.078, d = 0.43).

Figure 2 illustrates the relationship between sound localization accuracy and saccadic latency for participants with implants. For the simultaneously implanted group, statistically significant correlations between localization accuracy and saccadic latency existed across stimuli, corresponding to decreased accuracy as a function of increased latency. No relationship between accuracy and latency existed for the sequential group. A corresponding analysis for trial-by-trial sound localization accuracy and latency (ie, the accuracy and latency for each trial per sound localization test where latency could be determined) confirmed the accuracy-latency relationship for the simultaneous group for 2 of the stimuli (0.5 kHz octave-filtered noise: $r = 0.17$, $P = .008$, $n = 255$; musical melody: $r = 0.16$, $P = .008$, $n = 269$). No trial-by-trial relationship existed for the sequential group. Because of ceiling effects for the

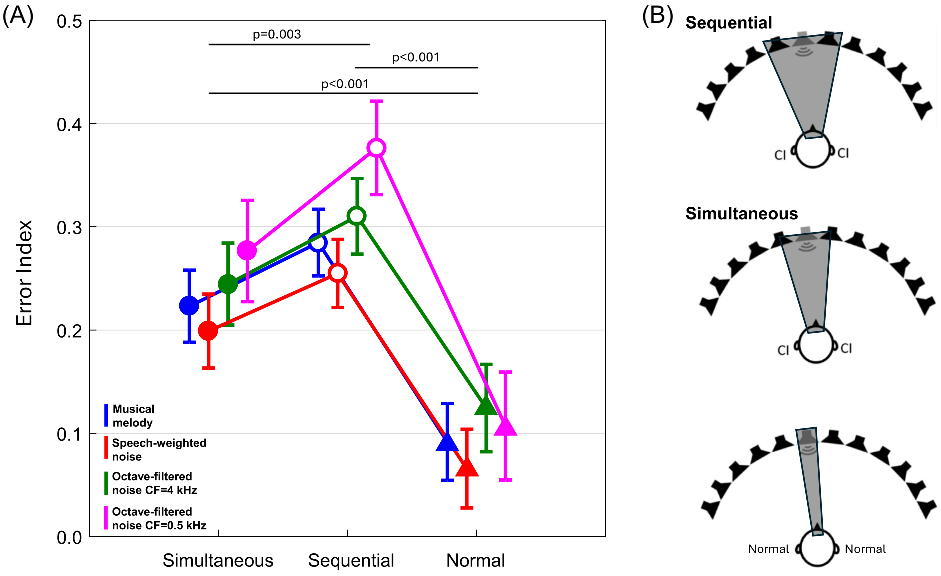

FIGURE 1.

(A) Means and 95% confidence intervals (whiskers) for the error index (ie, horizontal sound localization accuracy) for the simultaneous (filled circles), sequential (open circles), and normal hearing (triangles) group across 4 different stimuli. There was a main effect of group, where the simultaneous group achieved higher localization accuracy than the sequential group. (B) Graphical illustration of the angular resolution achieved by the 3 different groups for the octave-filtered noise with a CF of 0.5 kHz. The shaded areas are based on group averages of the error index, recalculated as a mean absolute angular error (14.5°, 10.7°, and 4.1° for the sequential, simultaneous, and normal groups, respectively). The boundaries of the shaded areas that are at the level of the loudspeakers in the figure are depicted with the midpoint of the loudspeaker presenting the sound ± the group average of the mean angular error.

Abbreviations: CF, center frequency; CI, cochlear implant.

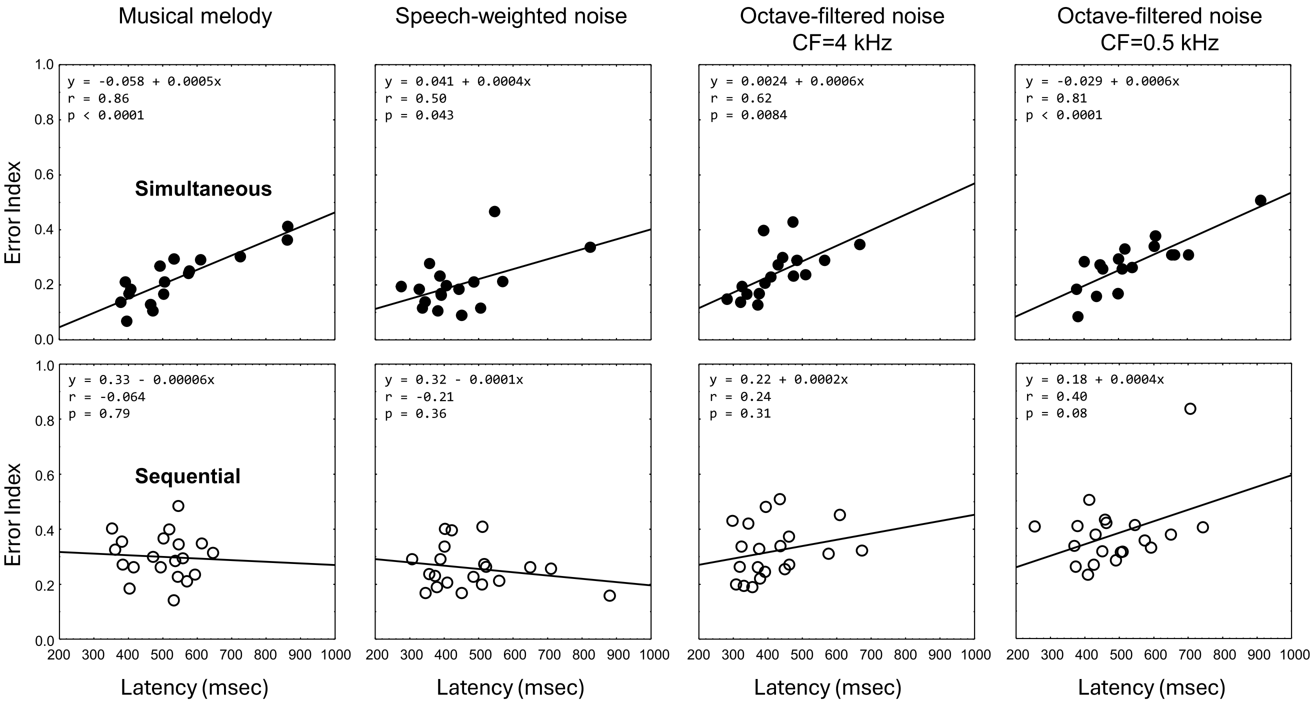

FIGURE 2.

Sound localization accuracy as a function of sound localization latency across 4 different stimuli for simultaneous implantation (top row) and sequential implantation (bottom row). Each marker represents a participant (filled markers simultaneous and open markers sequential). Diagonal lines depict the linear regression line.

Abbreviation: CF, center frequency.

localization accuracy, data from the normal hearing group were not suitable for analysis.

Speech Recognition in Quiet

Main effects of group (simultaneous implants, sequential implants, and normal hearing) ($P < .001$) and presentation level (65 dB SPL and 50 dB SPL) ($P < .001$) existed, with a significant interaction between the main effects ($P < .001$).

Speech recognition scores were similar for simultaneous and sequential participants for the 65 dB SPL ($\Delta = 1.4$ RAUs, 95% confidence interval, −7.4 to 10.1, $d = 0.064$) and the 50 dB SPL ($\Delta = 6.5$ RAUs, 95% confidence interval, −15.2 to 2.3, $d = 0.31$) presentation levels (Figure 3). As reflected in the significant interaction, both groups with implants showed a large effect of decreased presentation level on the speech score (simultaneous: $\Delta = 18.5$ RAUs, 95% confidence interval, 13.8–23.8, $d = 0.88$; sequential: $\Delta = 23.6$ RAUs, 95% confidence interval, 18.6–28.1, $d = 1.12$), whereas participants with normal hearing showed similar scores across presentation levels ($\Delta = 2.2$ RAUs, 95% confidence interval, −4.7 to 9.2, $d = 0.11$) (Figure 3). Across presentation levels, participants with normal hearing showed higher scores than participants with sequential implants (65 dB SPL: $\Delta = 21.2$ RAUs, 95% confidence interval, 10.9–31.4, $d = 1.0$; 50 dB SPL: $\Delta = 47.0$ RAUs, 95% confidence interval, 36.8–47.3, $d = 2.2$) and simultaneous implants (65 dB SPL: $\Delta = 19.8$ RAUs, 95% confidence interval, 9.4–30.3, $d = 0.94$; 50 dB SPL: $\Delta = 40.6$ RAUs, 95% confidence interval, 30.1–51.0, $d = 1.93$) (Figure 3).

Speech Recognition in Noise

Main effects of group ($P < .001$) and spatial condition (separated and colocated) ($P < .001$) existed, with a significant interaction between the main effects ($P = .002$) (Figure 4).

Across spatial conditions, the sequential and simultaneous implant groups showed similar speech-in-speech scores (separated maskers: $\Delta = 0.4$ dB, 95% confidence interval, −7.4 to 10.1, $d = 0.07$; colocated maskers: $\Delta = 0.04$ dB, 95% confidence interval, −2.0 to 2.1, $d = 0.006$) (Figure 4). Both implant groups achieved lower SRTs in the separated condition than in the colocated condition, corresponding to a spatial release from masking of 5.9 dB in the sequential group (95% confidence interval, 5.0–6.7; $d = 0.92$]) and 6.3 dB in the simultaneous group (95% confidence interval, 5.3–7.2; $d = 0.99$]). Participants with normal hearing showed lower SRTs than the simultaneous (colocated: $\Delta = 9.4$ dB, 95% confidence interval, 7.0–11.9, $d = 1.5$; separated: $\Delta = 11.8$ dB, 95% confidence interval, 9.3–14.2, $d = 1.9$) and the sequential (colocated: $\Delta = 9.5$ dB, 95% confidence interval, 7.1–11.8, $d = 1.5$; separated: $\Delta = 12.2$ dB, 95% confidence interval, 9.9–14.6, $d = 1.9$) implant groups. The significant interaction between

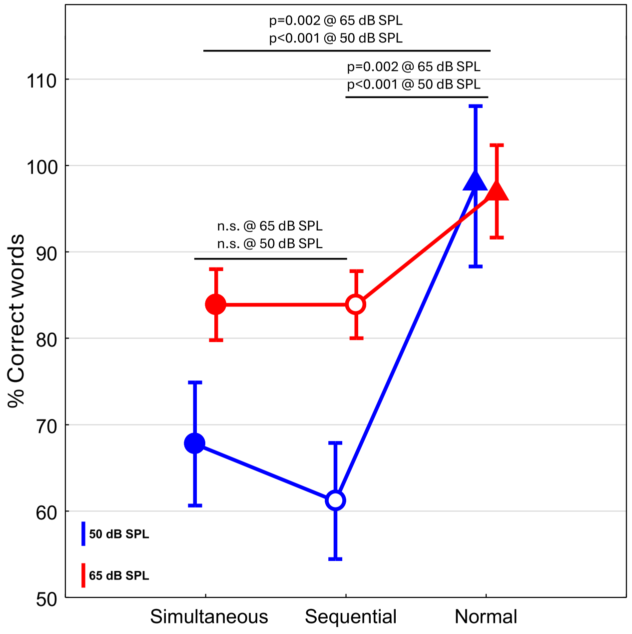

FIGURE 3.

Means (circular markers) and 95% confidence intervals (whiskers) for recognition of speech in quiet for the simultaneous (filled circles), sequential (open circles), and normal hearing (triangles) groups at 2 presentation levels. Blue depicts the 50 dB SPL and red depicts 65 dB SPL presentation level of the speech signal.

Abbreviations: n.s., not significant; SPL, sound pressure level.

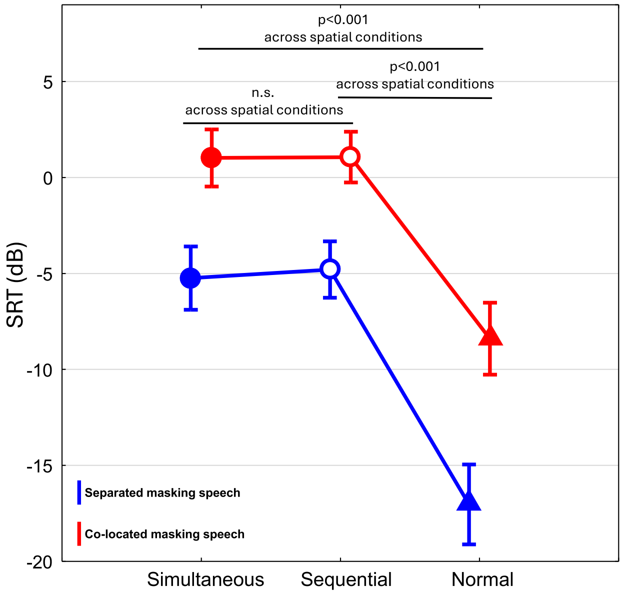

FIGURE 4.

Means (circular markers) and 95% confidence intervals (whiskers) for recognition of speech in competing speech for the simultaneous, (filled circles), sequential (open circles), and normal hearing (triangles) groups for 2 spatial configurations of the competing speech. Blue depicts masking speech that is spatially separated from target sentences and red depicts masking speech that is colocated with the target sentences.

Abbreviations: n.s., not significant; SRT, speech recognition threshold.

group and spatial condition corresponded to a larger spatial release from masking for normal hearing (estimated spatial release = 8.6 dB, 95% confidence interval, 7.5–9.8) than for simultaneous implants ($\Delta = 2.4$ dB, 95% confidence interval, 1.3–4.3) and sequential implants ($\Delta = 2.8$ dB, 95% confidence interval, 1.5–3.9) (Figure 4).

DISCUSSION

This study compared long-term sound localization accuracy and recognition of speech for adolescents and young adults with either simultaneous or sequential bilateral cochlear implantation on average 15 years after the second implantation. Results were compared with normal hearing. Sound localization accuracy was higher for the simultaneous than the sequential bilateral cochlear implantation group, whereas speech recognition in quiet and in masking speech was similar. The group with normal hearing showed higher localization accuracy and recognition of speech than the groups with implants, and speech in quiet performance was, unlike the groups with implants, unaffected by reduced presentation level.

The CI groups were comparable across several demographic, environmental, and auditory variables, suggesting that the observed localization differences are attributable to implantation timing. However, the absence of prematching limits causal inference, and differences between groups are likely to remain. For instance, although hearing aid use before implantation was similar, age at fitting was inconsistently reported and could not be analyzed. A further limitation of the present study is the requirement for participants to follow the national standard school curriculum, which likely led to the exclusion of individuals with severe comorbidities. Consequently, the observed differences related to the timing of implantation may not be generalizable to this subgroup.

Sound localization is a fundamental auditory ability, allowing the listener to have a sense of space through hearing, avoid safety hazards, navigate in conditions where vision is limited, and direct attention to sounds of interest. High localization accuracy is reliant on central processing of interaural differences in time and level.[41] Although monaural sound localization may be achievable for listeners with 1 normal hearing ear,[42,43] it is generally poor using a unilateral implant regardless of if the listener is used to bilateral[2,3,44] or unilateral stimulation.[45] Technological limitations, such as unsynchronized bilateral stimulation[46] disrupting ITD cues[47], contribute to reduced localization accuracy. Our findings highlight that nontechnological factors, such as implantation timing, also have lasting effects and should be considered in clinical decision-making. Expressed as an average angular deviation between presented sound source azimuths and the perceived azimuths, the simultaneous group showed approximately 6° higher accuracy than the sequential group, and 10° lower accuracy than the normal group. Although the difference between the groups with implants was relatively small, probably permitting individuals with sequential implantation to make reasonably correct judgments of the spatial origin of a sound in daily life, it holds clinical significance because deficits in spatial hearing contribute to perceived disability for individuals with hearing impairment.[48]

The absence of a relationship between localization accuracy and the interimplant interval in the sequential group suggests that even brief early asymmetry during development may have enduring effects on spatial hearing. Whereas congenital binaural deafness reduces the sensitivity to binaural cues, it is rudimentarily present even in congenital deafness.[49,50] Asymmetry in hearing during an early critical period[22,51] further degrades ITD sensitivity[52] and extensively reorganizes ILD sensitivity[50] so that binaural cues do not provide consistent information on sound source anymore. Under such conditions, the cue representation for auditory source localization is not effectively useful. The spatial maps of hearing and vision are normally congruent at the level of superior colliculus,[53] where saccadic control is automatized and vision normally supports and guides the auditory localization.[54] The present data suggest that periods of single-sided hearing, as for the sequentially implanted group, detach the auditory and visual maps and affect auditory-visual integration. Previous studies have reported effects of deafness on saccadic control.[55] The relation between saccadic accuracy and latency could not be studied in the normal hearing participants, but acutely altering interaural cues in normal hearing show a similar relationship.[38] Although our saccade measures were sensory-driven, the potential role of vestibular dysfunction warrants further investigation.

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ABBREVIATIONS

CI: cochlear implant
EI: error index
ILD: interaural level difference
ITD: interaural time difference
LD: loudspeaker/display
RAU: rationalized arcsine unit
RR: risk ratio
SPL: sound pressure level
SRT: speech recognition threshold

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