Factors Associated with Speech-Recognition Performance in School-Aged Children with Cochlear Implants and Early Auditory-Verbal Intervention

Jace Wolfe[1] Mickael Deroche[2] Sara Neumann[1] Lindsay Hanna[1] Will Towler[1] Caleb Wilson[3]
Alexander G. Bien[4] Sharon Miller[5] Erin C. Schafer[5] Vincent Gracco[6,7]

[1] Hearts for Hearing Foundation, Oklahoma City, Oklahoma
[2] Department of Psychology, Concordia University, Montreal, Canada
[3] University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma
[4] Department of Otolaryngology – Head & Neck Surgery, University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma
[5] Department of Audiology & Speech-Language Pathology, University of North Texas, Denton, Texas
[6] Haskins Laboratories, Yale University, New Haven, Connecticut
[7] School of Communication Sciences & Disorders McGill University, Montreal, Canada

Address for correspondence Jace Wolfe, PhD,
Jace.wolfe@heartsforhearing.org

J Am Acad Audiol 2021;32:433–444.

Abstract

Background Considerable variability exists in the speech recognition abilities achieved by children with cochlear implants (CIs) due to varying demographic and performance variables including language abilities.

Purpose This article examines the factors associated with speech recognition performance of school-aged children with CIs who were grouped by language ability.

Research Design This is a single-center cross-sectional study with repeated measures for subjects across two language groups.

Study Sample Participants included two groups of school-aged children, ages 7 to 17 years, who received unilateral or bilateral CIs by 4 years of age. The *High Language* group ($N = 26$) had age-appropriate spoken-language abilities, and the *Low Language* group ($N = 24$) had delays in their spoken-language abilities.

Data Collection and Analysis Group comparisons were conducted to examine the impact of demographic characteristics on word recognition in quiet and sentence recognition in quiet and noise.

Results Speech recognition in quiet and noise was significantly poorer in the *Low Language* compared with the *High Language* group. Greater hours of implant use and better adherence to auditory-verbal (AV) therapy appointments were associated with higher speech recognition in quiet and noise.

Conclusion To ensure maximal speech recognition in children with low-language outcomes, professionals should develop strategies to ensure that families support full-time CI use and have the means to consistently attend AV appointments.

Keywords
- cochlear implant
- children
- speech perception
- data logging

Significant variability exists in the speech recognition abilities of children with cochlear implants (CIs).[1–4] As summarized in ►**Table 1**, multiple variables influence the speech recognition abilities of children with CIs including age at implantation,[1,2] duration of CI use,[3,5] the child's language abilities,[3,5] and factors related to education/therapy approaches.[4]

received
February 8, 2021
accepted after revision
March 22, 2021

Thieme Medical Publishers, Inc.,
333 Seventh Avenue, 18th Floor,
New York, NY 10001, USA

DOI https://doi.org/10.1055/s-0041-1730413.
ISSN 1050-0545.

Table 1 Sample studies demonstrating factors influencing (CI) speech recognition outcomes

Factor	Authors (year)	Sample size, age	Subject description	Test results and interpretation
Age at implant	Geers, Brenner, and Davidson (2003)[23]	$N = 181$, 8–9 y	Implanted by 6 y (M: 3; 5 y, SD: 10 mo)	• 48.3% (SD: 29) on easy version of LNT • 44.2% (SD: 27) on hard version of LNT • Late age at CI may explain poor scores
	Davidson et al (2011)[5]	$N = 112$, 15–18 y	Subset of children from Geers and Brenner (2003) to examine increased duration of CI	Higher average scores in high school vs. elementary school • 60.1% (SD: 23) on LNT • 80.3% (SD: 27) on BKB-SIN in quiet • 52.0% (SD: 26) on BKB-SIN in noise (+10 dB SNR)
	Dettman et al (2016)[2]	$N = 403$, 8–10 y	Range of implantation ages	CNC score decreases as implant age increases: • 85% at 12 mo; 75% at 13–18 mo • 76% at 19–24 mo; 52% at 25–42 mo • 45% at 43–72 mo
	Tajudeen et al (2010)[24]	$N = 110$	Range of implantation ages	• LNT mean significantly better if implant by 12 mo compared with 13–24 mo • 13–24 mo better than 25–36 mo ($N = 33$) • When adjusting for hearing age (mo after implant), no group differences
Language abilities	Eisenberg et al (2016)[3]	$N = 188$, testing at 48-, 60-, and 72-mo postimplant	Implanted by 5 y (M: 29.4 mo). Enrolled in CDaCI study	• Linear relationship: HINT-C in quiet and at +10 dB SNR and language scores • Poor HINT-C scores associated with language decrements at 48–72 mo • HINT-C scores ≥ 50% showed improved language scores over time
	Davidson et al (2011)[5]	$N = 112$, 15–18 y	Compared scores from 8–9 y with those as a teen	• Word and sentence recognition scores increased linearly until a language age 10–11 y
	Caldwell and Eisenberg (2013)[25]	$N = 19$ normal hearing; $N = 27$ CI; $N = 8$ HA	Age at implant: M = 21 mo (SD = 13); age at test: 81 mo (SD = 5)	• Age at implant and expressive vocabulary significantly related to speech recognition • Those with typical hearing and CI had similar reductions in speech recognition from the quiet to noise condition
Communication mode	Dettman et al (2013)[25]	$N = 31$	23 in auditory–oral;8 in bilingual–bicultural	• Children educated in auditory-verbal and auditory-only settings had better word and sentence recognition than those in bilingual–bicultural programs
	Geers, Brenner, and Davidson (2003)	$N = 181$, 8–9 y	Implanted by 5 y	• Children in classrooms focused on listening and spoken language had better speech recognition than those in total communication
	Geers et al (2017)[4]	$N = 97$	Grouped based on sign language exposure	• Children in families who did not use sign had better speech recognition than those who did

Abbreviations: BKB-SIN, Bamford–Kowal–Bench sentence recognition; CDaCI, Childhood Development after Cochlear Implantation study; CI, cochlear implant; CNC, consonant–nucleus–consonant word recognition; HA, hearing aid; HINT-C, Hearing In Noise Test – Children; M, mean; LNT, Lexical Neighborhood Test; SD, standard deviation; SNR, signal-to-noise ratio.

In addition to these factors, consistency of daily implant use is critical to successful CI outcomes. Park et al[6] reported better receptive and expressive language outcomes for 3-year-old children who used their CIs during all waking hours as compared with those who used their CIs only part of the day. In fact, full-time device use was a better predictor of language outcomes than age at implantation. Gagnon et al[7] and Easwar et al[8] reported similar findings to support the importance of consistent device use with the latter study finding a significant correlation between daily duration of implant use and monaural speech recognition in quiet.

Study Rationale

The objective of the present study was to explore behavioral and demographic differences in groups of school-aged children with CIs who had low or high scores on a commonly used language test. Separate language groups were defined to examine how demographic variables, including age at CI, age at testing, data logging hours, and percentage of speech–language and audiology appointments attended, support successful speech and language outcomes. Children with lower language scores or inconsistent implant use were hypothesized to have poorer speech recognition outcomes. Findings of this study will be valuable to pediatric hearing health care professionals to better understand the influence of language and demographic factors on the speech recognition of school-aged children with CIs when evaluated with commonly used tests. Moreover, study results will determine how consistent implant use and attendance to audiology and speech–language therapy appointments contribute to variability in speech recognition outcomes.

Methods

Subjects

Children with congenital bilateral severe to profound hearing loss and CIs were divided into two groups based on their standard scores from the Core Language scale of the *Clinical Evaluation of Language Fundamentals – Fifth Edition* (CELF-5).[9] The *High Language* group had a composite score of 100 or more on the CELF-5, whereas the *Low Language* group had a composite score of 85 or less on the CELF-5. The CELF-5 was selected because it is commonly used to determine language aptitude in children with hearing loss.[10] Additional inclusion criteria were as follows:

- At least one CI by 4 years of age
- Primary communication via listening and spoken language in American English (i.e., limited use of sign language in most daily listening settings)
- Minimum of 6 hours of CI use per day as indicated by data logging or parent's report for one participant for whom data logging was unavailable.

Exclusion criteria were as follows:

- No additional disabilities that could induce delays in language development
- No anatomical abnormalities that could cause delays in language development such as ossification after bacterial meningitis, cochlear nerve deficiency, or significant cochlear deformities.

Licensed speech–language pathologists reviewed the clinical database from one speech and hearing center to identify children who met the inclusion criteria and recruited 26 children who qualified for the *High Language* group and 24 who qualified for the *Low Language* group. The demographics of these study participants are provided in ►**Tables 2** and **3**.

Table 2 Demographic information for the *Low Language* group

Subject	CI side	Age (y)	Age at first HA (mo)	Age at first CI (mo)	CELF	Sound processor R/L	Hrs data logging	% therapy attended	% audiology attended
1A	Seq Bil	15.4	19	26	58	Nuc CP1000/CP1000	11.4	78.2	100
2A	Seq Bil	11.3	2	15	75	Nuc CP1000/CP1000	13.9	73.5	50
3A	Seq Bil	16.0	24	48	84	Nuc Freedom/CP910	14	80.6	95.7
4A	Seq Bil	10.9	24	26	76	Nuc CP910/CP910	12.9	49.2	88.9
5A	Seq Bil	16.7	24	48	58	Nuc CP1000/CP1000	13.7	70.2	80
6A	Seq Bil	16.7	24	48	61	Nuc CP1000/CP1000	13.9	70.2	80
7A	Seq Bil	17.0	29	33	52	Nuc CP1000/CP910	10.8	40.0	76.9
8A	Seq Bil[a]	17.5	29	50	50	Nuc CP1000/CP100	12.9	CNE	64.7
9A	Left	8.7	10	13	73	NA/Nuc CP1000	15.4	69.2	77.8
10A	Sim Bil	14.1	19	22	45	Nuc CP1000/CP1000	14.2	CNE	80
11A	Seq Bil	15.9	12	14	77	Nuc CP910/CP910	15	85.1	86.2
12A	Right	11.6	31	39	57	Nuc CP950/NA	6	54.5	83.3
13A	Seq Bil	17.1	17	21	75	Nuc CP1000/Naida Q90	15.6	86.7	87.0
14A	Seq Bil	14.7	8	20	61	Nuc CP910/CP910	12	25.0	74.1
15A	Seq Bil	12.9	19	24	85	Nuc CP1000/CP1000	13.2	CNE	93.1
16A	Seq Bil	13.5	2	13	57	Nuc CP910/CP1000	12	83.3	72.2
17A	Seq Bil	12.2	13	16	76	Nuc CP1000/CP1000	11.7	70.5	87.2
18A	Seq Bil	9.8	22	26	40	Nuc CP1000/CP1000	CNE	66.1	75.0
19A	Seq Bil	13.0	33	40	67	Nuc CP1000/CP1000	9.3	59.1	86.7
20A	Seq Bil	13.2	2	15	45	Nuc CP910/CP910	10	68.8	84.6
21A	Seq Bil	16.6	1	32	62	Nuc CP1000/CP1000	13.5	48.7	66.7
22A	Sim Bil	14.1	24	24	70	Naida Q70 /Naida Q70	12	CNE	87.0
23A	Right	10.1	21	33	62	Nuc CP910/CP910	14.6	64.5	38.9
24A	Right	14.1	4	15	73	Nuc CP910/NA	12.9	CNE	94.1
Mean (SD)		13.9 (2.6)	17.2 (10.0)	27.5 (12.3)	64.1 (12.5)		12.6 (2.2)	65.4 (16.2)	79.6 (14.0)

Abbreviations: Bil, bilateral; CELF-5, *Clinical Evaluation of Language Fundamentals – Fifth Edition* standard score; CI, cochlear implant; CNE, could not evaluate; HA, hearing aid; Hrs, average hours per day; L, left ear; NA, not applicable; Nuc, Nucleus; R, right ear; Seq, sequential; Sim, simultaneous.

[a] Tested with only left implant due to malfunctioning right processor. Percentage of therapy and audiology refer to the percentage of scheduled visits that were attended.

Table 3 Demographic information for the *High Language* group

Subject	CI Side	Age (y)	Age at first HA (mo)	Age at first CI (mo)	R/L PTA dB HL	CELF	Sound processor R/L	Hrs data logging	% therapy attended	% audiology attended
1B	Seq Bil	13.4	12	25	25/22	108	Nuc CP1000/CP1000	13	53.1	87.5
2B	Seq Bil	14.8	3	13	22/20	100	Nuc CP910/CP910	15.2	85.1	93.8
3B	Sim Bil	10.3	9	17	30/27	100	Nuc CP950/CP950	10.9	94.1	100.0
4B	Seq Bil	10.0	1.5	32	27/28	100	Nuc CP910/CP910	14.4	96.7	93.9
5B	Seq Bil	12.5	16	40	23/22	116	Nuc CP910/CP800	15	88.4	88.9
6B	Seq Bil	13.1	13	17	27/32	120	Sonnet 2/Sonnet 2	12[a]	CNE	85.7
7B	Seq Bil	7.5	1	13	23/23	111	Nuc CP910/CP910	14	87.6	95.1
8B	Seq Bil	8.0	4	41	25/22	133	Nuc CP910/CP910	14	88.7	88.9
9B	Seq Bil	9.6	26	30	28/27	107	Nuc CP1000/CP1000	14.5	89.8	96.8
10B	Seq Bil	8.7	1	14	28/27	120	Nuc CP1000/CP1000	12	83.9	94.1
11B	Sim Bil	12.5	15	28	25/28	103	Naida Q70/Naida Q70	12.2	CNE	88.9
12B	Seq Bil	7.5	1	12	22/23	111	Nuc CP1000/CP1000	12.8	93.8	100.0
13B	Seq Bil	9.6	16	20	22/23	117	Nuc CP910/CP910	14.9	58.2	88.9
14B	Seq Bil	8.3	28	30	23/23	100	Nuc CP910/CP910	14	86.1	100.0
15B	Sim Bil	12.5	1	10	32/28	102	Nuc CP1000/CP1000	14	72.4	92.9
16B	Seq Bil	9.3	3	10	28/33	120	Nuc CP1000/CP1000	14		100.0
17B	Seq Bil	14.5	3	10	22/25	108	Nuc CP1000/CP1000	12.7	89.7	75.0
18B	Seq Bil	11.2	3	13	23/22	100	Nuc CP910/CP910	13	CNE	94.4
19B	Seq Bil	15.3	2	35	27/22	106	Nuc CP910/CP910	13	86.4	90.6
20B	Sim Bil	10.4	2	14	22/27	111	Nuc CP910/CP910	11.8	CNE	82.4
21B	Seq Bil	14.3	1.5	13	25/23	120	Nuc CP950/CP950	13.2	89.7	95.8
22B	Seq Bil	16.0	2	12	28/27	132	Naida Q70/Naida Q70	14	92.0	76.5
23B	Seq Bil	16.0	1	22	25/25	100	Nuc CP1000/CP1000	CNE	85.7	88.2
24B	Seq Bil	14.0	10	34	27/22	106	Nuc CP910/CP910	14	94.7	80.0
25B	Sim Bil	8.0	0.75	9	27/28	109	Nuc CP1000/CP1000	12.2	83.3	92.6
26B	Sim Bil	11.2	12	15	22/18	111	Nuc CP910/CP910	13	81.6	97.1
Mean (SD)		11.5 (2.8)	7.2 (7.9)	20.3 (10.1)	25/25 (3/4)	110.4 (9.5)		13.4 (1.1)	84.8 (11.1)	91.1 (7.0)

Abbreviations: Bil, bilateral; CELF, *Clinical Evaluation of Language Fundamentals – Fifth Edition* standard score; CI, cochlear implant; CNE, could not evaluate; HA, hearing aid; Hrs, average hours per day; L, left ear; Nuc, nucleus; R/L PTA, right and left ear pure tone average at 500, 1,000, and 2,000 Hz with the CIs; R, right ear; Seq, sequential; Sim, simultaneous.

[a] Hours of CI use were estimated because data logging records were unavailable. Percentage of therapy and audiology refer to the percentage of scheduled visits that were attended.

Study Design and Test Measures

This study included a review of patient records and a series of behavioral measures approved by the Western Institutional Review Board. Demographic variables were collected through retrospective chart review and included: chronological age at test, age at implantation, age at first hearing aid, percentage of auditory-verbal (AV) therapy appointments kept, percentage of audiology appointments kept, and daily data logging information.

As recommended by the working group that developed the Pediatric Minimum Speech Test Battery (PMSTB) protocol,[11] word recognition in quiet was evaluated with the consonant–nucleus–consonant (CNC) test[12] at a presentation level of 60 dBA (decibels A-weighted) in each unilateral CI condition and also in the bilateral CI condition, when applicable. Although the PMSTB suggests the use of the BabyBio or AzBio for speech recognition in noise, the AzBio was selected to avoid ceiling effects in quiet and noise that occur in some 5- to 6-year-old children.[13–16] Sentences were presented at 60 dBA in quiet and at two signal-to-noise ratios (SNRs) in multitalker babble with speech at 65 dBA and babble at 55 dBA (+10 dB SNR) or babble at 60 dBA (+5 dB SNR). AzBio sentence recognition testing was only completed in the bilateral CI condition for bilateral users and in the unilateral condition for the bimodal and unilateral CI users. The hearing aid was removed for all testing, and the nonimplanted ear was occluded with a foam ear plug.

Additionally, to ensure each group had sufficient and similar audibility of the speech stimuli presented in this study, all the children's aided sound-field detection thresholds for warble tones at octave frequencies from 250 to 6,000 Hz were measured for each implanted ear using a modified Hughson–Westlake method-of-limits procedure. Warble tones were delivered from a Grason Stadler Industries (GSI) 61 audiometer and presented from a GSI sound-field loudspeaker located 1 m directly in front of the participant (0 degree azimuth) while the participants used their CIs.

Results

Sample Characteristics Differentiating Low and High Language Groups

As shown in ►**Tables 2** and **3**, average demographic characteristics between groups differed for some variables, and statistical analyses with independent samples *t*-tests (two-tailed) yielded several significant findings. First, as expected given the group cutoff score, the *Low Language* group exhibited poorer CELF scores than children in the *High Language* group ($t[48] = -14.6$, $p < 0.001$), a large difference of ~46 points. In addition, children in the *Low Language* group were older than children in the *High Language* group ($t[48] = 3.1$, $p = 0.003$).

The *Low Language* group was fitted with hearing aids at a later age than children in the *High Language* group ($t[48] = 3.9$, $p < 0.001$), a difference of ~10 months. The *Low Language* group also had a later age at first CI than children in the *High Language* group ($t[48] = 2.3$, $p = 0.028$) by ~7 months. CI experience (i.e., age at testing − age at implant) also was significantly different between the *Low Language* (mean [M] = 11.6 years; standard deviation [SD] = 2.3) and *High Language* groups (M = 9.7 years; SD = 2.9) groups ($t[48] = 2.4$, $p = 0.019$). In the children with bilateral implants, there was no significant group difference in the time interval between implants ($t[45] = 0.2$, $p = 0.814$).

Duration of daily implant use (~13 hours per day) was not significantly different between the groups ($t[46] = -1.4$, $p = 0.161$). The *High Language* group had more assiduous attendance to both AV therapy ($t[38] = -4.5$, $p < 0.001$) and audiology appointments ($t[48] = -3.7$, $p = 0.001$). Finally, aided sound-field warble tone threshold data were analyzed with a repeated measures analysis of variance (ANOVA). There was no significant main effect of group ($F[1, 570] = 0.96$, $p = 0.33$) or ear ($F[1, 570] = 0.24$, $p = 0.63$), suggesting similar hearing thresholds for the two groups.

Speech Recognition of the Low and High Language Groups

Average per cent-correct speech recognition performance in the CNC and AzBio test conditions is shown in ►**Figs. 1** and **2**, respectively, and individual data are provided in ►**Appendices A** and **B**. Given that some participants achieved ceiling effects and data from some of the test conditions were not normally distributed according to a Shapiro–Wilk's test, all data were arcsine transformed prior to analysis.

Word Recognition Results

The CNC data (►**Fig. 1**) were analyzed with three separate Kruskal–Wallis' nonparametric tests to compare the scores in the two groups because, even after the data were acrsine transformed, several conditions had nonnormal distributions. Ten of the data points were missing due to the four unilateral participants and missing scores from one participant in the *Low Language* group (8A). These analyses suggested significantly higher word recognition for the *High Language* group in the right ear ($H[1] = 7.3$, $p < 0.01$), left ear ($H[1] = 18.8$, $p < 0.0001$), and bilateral condition ($H[1] = 20.3$, $p < 0.0001$).

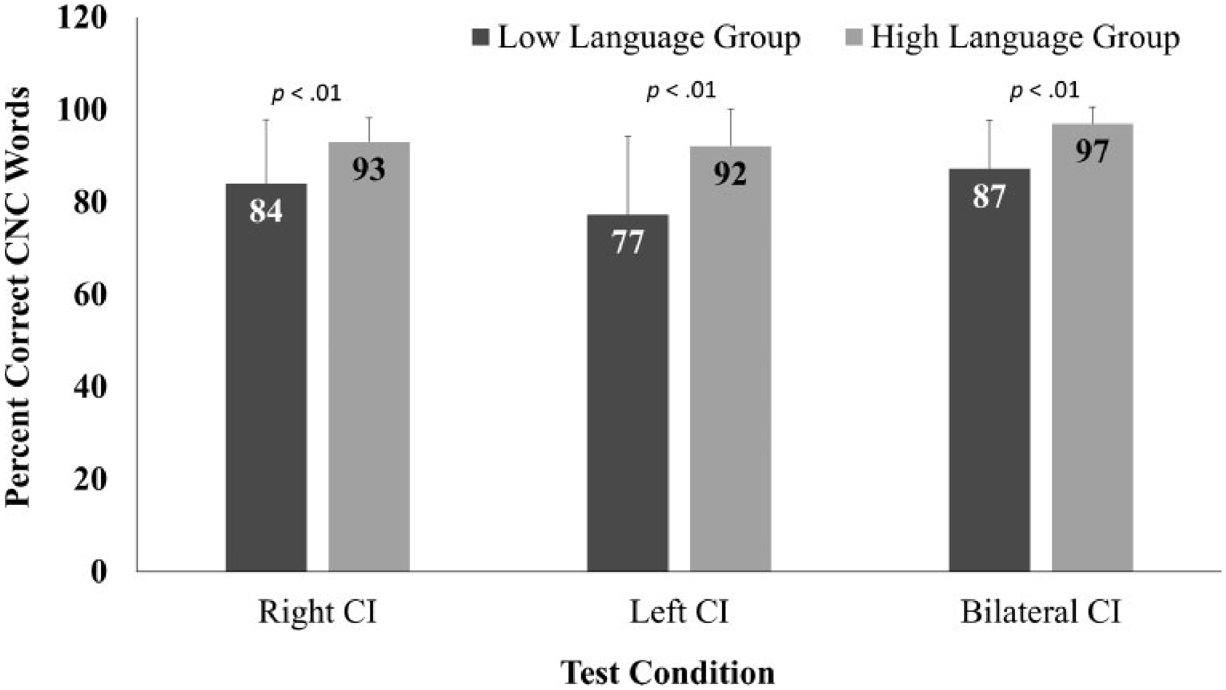

Fig. 1 Average speech recognition on the CNC word recognition test. Vertical lines represent one standard deviation and *p*-values denote significance. CI, cochlear implant; CNC, consonant–nucleus–consonant.

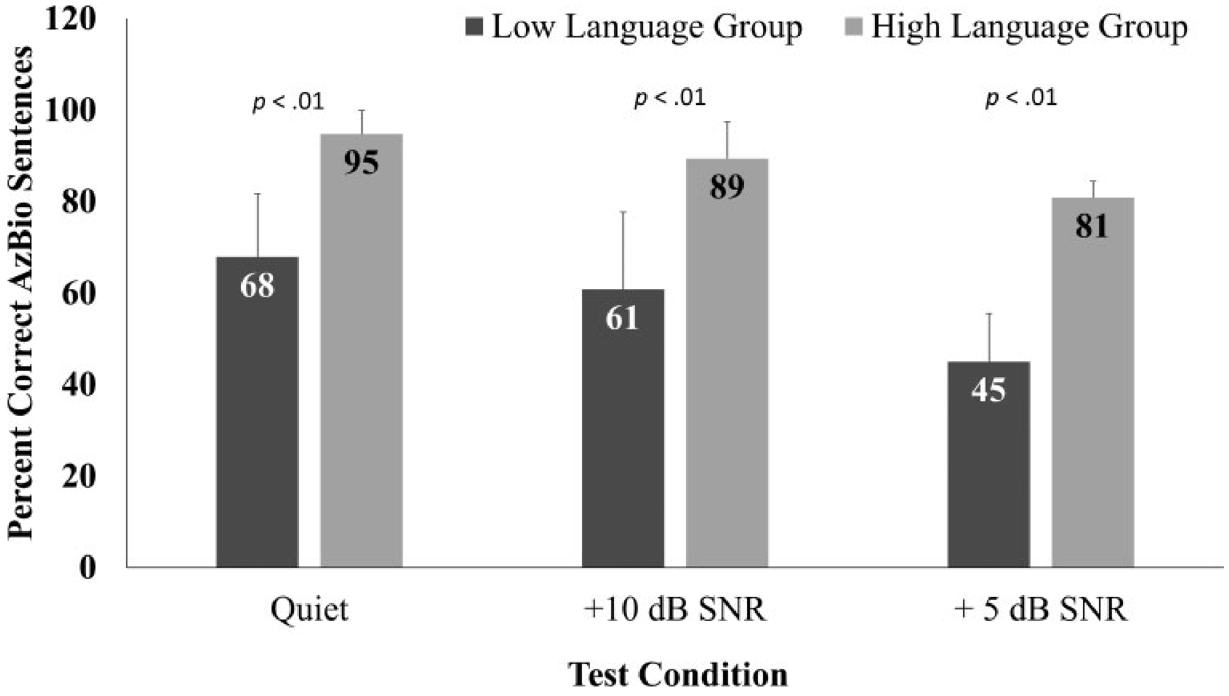

Fig. 2 Average speech recognition on the AzBio Sentence test. Vertical lines represent one standard deviation and *p*-values denote significance. SNR, signal-to-noise ratio.

Sentence Recognition Results

Data in the AzBio conditions (►**Fig. 2**) yielded normal distributions after the arcsine transform and were analyzed with a repeated measures ANOVA. This analysis yielded a significant main effect of *language group* ($F[1, 149] = 49.3, p < 0.0001$) and a significant main effect of *test condition* ($F[2, 149] = 83.5, p < 0.0001$) with no significant interaction effect between *language group* and *test condition* ($F[2, 149] = 0.54, p > 0.05$). Post hoc analyses with the Bonferroni's test revealed significant differences between the groups with the *High Language* group showing higher scores across conditions. In addition, significant differences were found across all conditions with best scores in the quiet condition followed by the +10 dB SNR and +5 dB SNR conditions (►**Fig. 2**).

Intervention and Demographic Factors Associated with Speech Recognition

Separate linear mixed effects regression analyses were performed to examine whether (1) performance on the CELF-5 is predictive of best CNC word recognition in quiet and AzBio sentence recognition in quiet and noise or (2) adherence to programming and therapy schedules affects speech recognition outcomes in pediatric CI recipients. In all analyses, regression assumptions were met, and all variables were entered simultaneously. Statistical analyses are summarized in ►**Tables 3** and **4**, including beta and significance values.

In the regression models, CI recipient was treated as a random effect using a random intercept to control for baseline differences across pediatric patients. *Age at first hearing aid* (in months), *age at first CI* (in months), and *age at test* (in months) were included as block variables in all models to control for auditory experience and developmental factors known to contribute to speech recognition outcomes (Davidson et al, 2019[21]). *CELF-5 language score*, *percentage of AV therapy* and *percentage of audiology appointments kept*, and *data logging hours* (►**Table 4**) were also included as fixed effects.

CNC Regression Results

Regression results predicting best CNC score are displayed in ►**Table 4**. When controlling for *age at test*, *age at first hearing aid*, and *age at first CI*, *CELF-5 language score* and *data logging hours* were significant predictors of CNC scores in quiet. Results indicate that CNC scores are expected to increase by 0.11% for every unit increase in CELF score (►**Fig. 3**). Likewise, CNC scores are expected to increase by 2.1% for every additional hour of processor usage time.

Examination of the CNC scores in each language group suggests that children in the *High Language* group perform near ceiling on the measure (►**Fig. 3**). Thus, post hoc regression analyses were performed on CNC scores separately for children in the *Low Language* and *High Language* groups with only *CELF-5 score* as a fixed effect in the models. Results suggest CNC scores significantly increased by 0.58% per CELF-5 unit in the *Low Language* group, while CELF-5 had no significant effect (0.01% change in CNC score per CELF-5 unit) in the *High Language* group (►**Table 5**).

AzBio Regression Results

Linear mixed effects regression results predicting best AzBio score in quiet and noise are displayed in ►**Table 4**. In quiet, when controlling for *age at test*, *age at first hearing aid*, and *age at first CI*, *CELF-5 language score* was a significant predictor of AzBio sentence scores. Sentence recognition scores in quiet are expected to increase by 0.5% for every unit increase in CELF score (►**Fig. 4A**). *Data logging hours* were not a significant predictor of AzBio scores in quiet.

Table 4 Results of full model regression analyses

Variable	CNC ($R^2 = 0.60$)		AzBio quiet ($R^2 = 0.79$)		AzBio + 10 SNR ($R^2 = 0.77$)		AzBio + 5 SNR ($R^2 = 0.75$)	
	β	*F*	β	*F*	β	*F*	β	*F*
Intercept	–	5,276.8[a]	–	3,386.1[a]	–	1,896.6[a]	–	782.4[a]
Age at test	0.18	3.2	0.16	0.07	0.19	1.03	0.18	1.3
Age at first CI	0.09	0.53	0.05	1.29	0.06	0.17	0.09	2.1
Age at HA	−0.15	5.4[a]	0.03	3.9[a]	−0.06	6.9[a]	−0.17	7.7[a]
CELF-5 score	0.11	10.4[a]	0.5	64.2[a]	0.56	45.9[a]	0.68	37.12[a]
% therapy attended	0.05	10.8[a]	0.07	36.9[a]	0.15	36.4[a]	0.26	34.9[a]
% audiology attended	0.27	3.3	0.1	0.40	0.3	1.06	0.29	0.6
Data logging hours	2.1	10.4[a]	0.46	0.41	2.8	6.7[a]	3.04	4.6[a]

Abbreviations: CI, cochlear implant; CNC, consonant–nucleus–consonant; HA, hearing aid; CELF-5, *Clinical Evaluation of Language Fundamentals – Fifth Edition*; SNR, signal-to-noise ratio.

[a] $p < 0.05$.

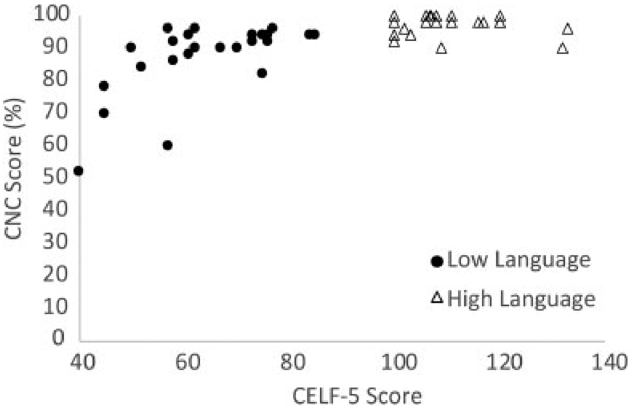

Fig. 3 CNC performance in quiet as a function of CELF-5 score ($R^2 = 0.60$) in the *Low Language* (filled circles) and *High Language* (open triangles) groups. CELF-5, *Clinical Evaluation of Language Fundamentals – Fifth Edition*; CNC, consonant–nucleus–consonant.

However, the regression results indicate scores in quiet would increase by 0.41% for every additional hour of wear time.

In both noise conditions, when controlling for *age at test*, *age at first hearing aid*, and *age at first CI*, the following variables were significant predictors of sentence recognition in noise scores: *CELF-5 language score*, *percentage of AV therapy*, and *data logging hours*. For the +10 (►**Fig. 4B**) and +5 dB (►**Fig. 4C**) SNR conditions, AzBio scores are expected to increase by 0.56 and 0.68% for every one unit increase in CELF unit, respectively. Sentence in noise scores are predicted to increase by 3% for every additional hour of wear time (►**Fig. 5A**). Finally, higher percentage of therapy appointments kept is also estimated to produce higher AzBio in noise scores (►**Fig. 5B**).

Similar to the CNC analysis, post hoc linear mixed effects analyses were performed on each language group separately to examine more closely the increase in AzBio sentence scores in quiet and noise as a function of CELF unit. In the separate *Low Language* group analyses, the rise in AzBio score per CELF-5 unit were as follows: 1.44% per CELF-5 unit in quiet, 1.5% per CELF-5 in +10 dB SNR, and 1.4% per CELF-5 unit in +5 dB SNR (►**Table 5**). In the *Low Language* group, CELF-5 scores ranged from 40 to 85 which is associated with approximately 65% increase in AzBio score over this range, regardless of test condition (quiet vs. noise). In contrast, for the *High Language* group, *CELF-5 score* had practically no

Table 5 Results of secondary regression analyses for children in the *Low Language* (top) and *High Language* (bottom) groups

Low Language group	CNC ($R^2 = 0.55$)		AzBio quiet ($R^2 = 0.53$)		AzBio + 10 SNR ($R^2 = 0.55$)		AzBio + 5 SNR ($R^2 = 0.49$)	
Variable	β	*F*	β	*F*	β	*F*	β	*F*
Intercept	–	2,230.7[a]	–	342.58[a]	–	276.8[a]	–	146.4[a]
CELF-5 score	0.58	14.94[a]	1.44	23.2[a]	1.5	26.02[a]	1.4	19.9[a]
***High Language* group**	**CNC ($R^2 = 0.05$)**		**AzBio quiet ($R^2 = 0.04$)**		**AzBio + 10 SNR ($R^2 = 0.05$)**		**AzBio + 5 SNR ($R^2 = 0.0002$)**	
Variable	β	*F*	β	*F*	β	*F*	β	*F*
Intercept	–	26,376[a]	–	15,786.4[a]	–	4,864.7[a]	–	1,192.4
CELF-5 score	0.001	1.25	0.04	1.02	0.08	1.12	0.01	0.005

Abbreviations: CI, cochlear implant; CNC, consonant–nucleus–consonant; HA, hearing aid; CELF-5, *Clinical Evaluation of Language Fundamentals – Fifth Edition*; SNR, signal-to-noise ratio.

[a] $p < 0.05$.

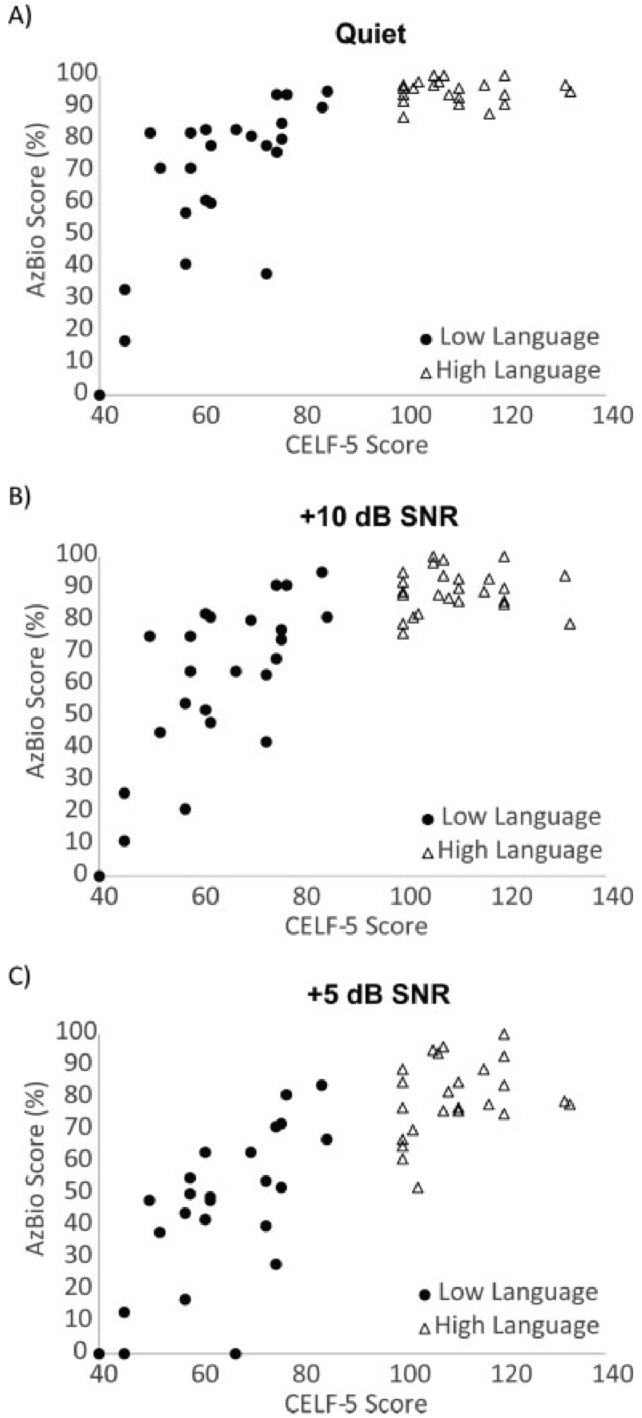

Fig. 4 AzBio sentence recognition performance as a function of CELF-5 score in (**A**) quiet ($R^2 = 0.79$); (**B**) +10 dB SNR ($R^2 = 0.77$); and (**C**) +5 dB SNR ($R^2 = 0.75$) for individual participants in the *Low Language* (filled circles) and *High Language* (open triangles) groups. CELF-5, *Clinical Evaluation of Language Fundamentals – Fifth Edition*; SNR, signal-to-noise ratio.

effect on AzBio score in quiet (+0.04% per CELF-5 unit), + 10 dB SNR (+0.08% per CELF-5 unit), or +5 dB SNR (+0.01% per CELF-5 unit) (►**Table 5**).

Discussion

This study compared speech recognition in quiet and noise in children with higher and lower language scores and explored how demographic impacted performance. Overall, significant group differences were found for all speech recognition conditions (►**Figs. 1** and **2**). In particular, the children in the *High Language* group showed resistance to the presence of competing noise as evidenced by their high average sentence recognition at both the +10 and +5 dB SNRs. Conversely, the sentence recognition of the children in the *Low Language* group decreased considerably in the presence of noise. In addition to the language differences, these findings may be related to the earlier age at first hearing aid, duration of deafness, and earlier age at implantation (i.e., age at first CI) in the *High Language* group. For the *Low Language* group, the average age of hearing aid fitting was 10 months later and age at first CI was 7 months later. This longer period of auditory deprivation during the critical period of language development may have resulted in greater speech-in-noise processing deficits. Alternatively, it is possible that children whose implant allowed them to perceive speech in the presence of noise helped them to develop better language.

Regarding the language disparities between the groups, Caldwell and Nittrouer (2013)[22] and Davidson et al[5] reported higher word recognition scores for pediatric implant recipients with higher language abilities. Davidson et al (2011) also found that children with CIs experienced a subceiling plateau in their word recognition scores at a language age of 10 to 11 years. Similarly, in the present study, children with poorer word and sentence recognition performance in quiet also had poorer CELF-5 scores even though *Low Language* group had a longer average duration of implant use (►**Table 2**).

Children in the *High Language* group attended significantly more AV therapy appointments (85 vs. 66% attendance) and audiology appointments (91 vs. 80% attendance) than the children in the *Low Language* group. Although audiology appointments attendance was not a significant predictor, AV therapy attendance significantly predicted speech recognition performance in all testing conditions. As the *High Language* group had higher AV therapy attendance, the speech recognition results could be a byproduct of group or an associated variable such as family support, socioeconomic status, richness of language environment at home, and participation in other types of early invention. While this study cannot determine if higher AV therapy attendance rates lead to better language outcomes, it is important not to discount the positive effects parental involvement (i.e., higher attendance of therapy and programming appointments) has in the hearing habilitation process.

Average hours of implant use per day (data logging) was a significant predictor of word recognition and of sentence recognition in noise, with longer usage predicting better outcomes. Data logging records obtained from the participants' most recent audiology appointments indicated that the children in the *Low and High Language* groups used their CIs for a similar number of hours of per day (►**Tables 2** and **3**). As the two language groups did not significantly differ in processor wear time, daily use of the CI appears to be a factor independent of language group allocation. Although no group difference was found in the present study, Busch et al[17] and Park et al[6] reported

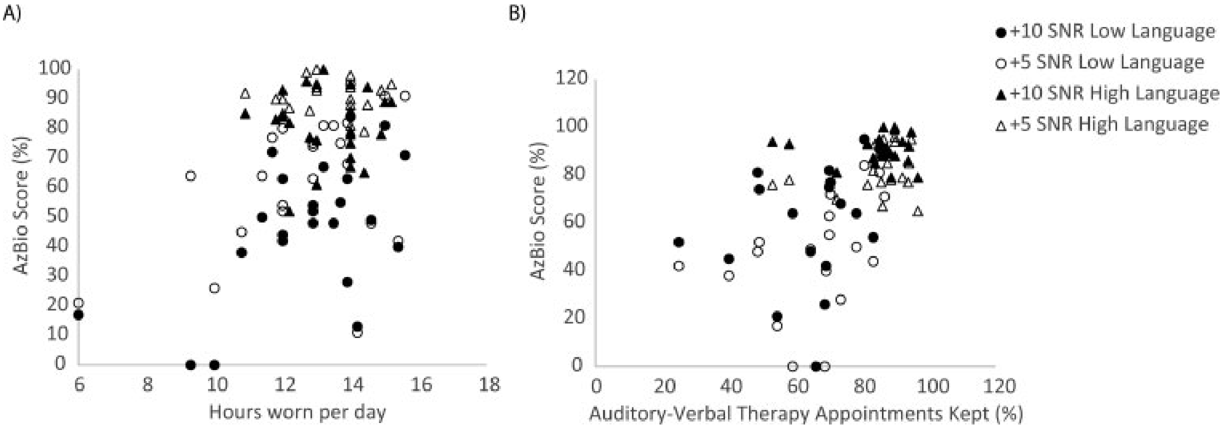

Fig. 5 AzBio sentence recognition performance in noise at +10 dB SNR (filled symbols) and +5 dB SNR (open symbols) as a function of (**A**) hours of daily processor use and (**B**) percentage of auditory-verbal therapy appointments kept for individual participants in the *Low Language* (circles) and *High Language* (triangles) groups. SNR, signal-to-noise ratio.

better receptive vocabulary and language abilities, respectively, for children whose data logging records indicated more hours of CI use during their early years of life. However, it should be noted that the impact of individual wear time hours (►**Tables 2** and **3**) varies across patients and likely relates to other demographic factors.

Additionally, it should be noted that differences in speech recognition between the children in the *Low Language* group versus those in the *High Language* group may be due to greater use of bilateral CIs by the *High Language* group. Specifically, five of the children in the *Low Language* group were tested with use of only a unilateral CI, whereas all the children in the *High Language* group used bilateral CIs. Previous research has shown better speech recognition in quiet and in noise with the use of bilateral CIs relative to unilateral CI use.[18] Furthermore, six of the children in the *High Language* group were simultaneously implanted, whereas only three of the bilateral CI users from the *Low Language* group were simultaneously implanted. Previous studies have found better speech recognition in noise for children who receive bilateral CIs in a simultaneous procedure relative to those who receive bilateral CIs in sequential procedures, particularly when there is a longer delay between implantation of the two ears (e.g., more than 12 months elapses between implantation of first and second implanted ears).[18–20] It should, however, be noted that there was not a statistically significant difference between the *Low Language* and *High Language* groups in the mean time interval between implantation of the first and second ears.

Limitations to this study are related primarily to the ceiling effects measured in the quiet test conditions in the *High Language* group. As a result, group differences may be even larger than could be measured in the present study. Also, data were missing for some participants (e.g., hours of CI use, percentage of AV therapy sessions attended, etc.). Other limitations relate to small sample size and demographic differences between the two groups. We analyzed percentage of AV therapy appointments attended because it likely relates to the family's adherence to intervention recommendations, although this may not be a perfect predictor of family support. Additional research is needed to explore the relationship of intervention dosage and CI outcomes.

Clinical Implications

The results of this study are relevant to all professionals who serve children with CIs because they highlight the importance of language ability, consistent CI use, and participation in AV therapy. A team approach, including the family, will ensure that all the necessary counseling, recommendations, and therapies are provided to the child to ensure optimal outcomes. The team may need to consider individualized accommodations to support success such as a child-focused reward system for consistent CI use, transportation to and from appointments, and educational accommodations (e.g., remote microphone technology). Additionally, performance on commonly used sentence recognition-in-noise tests are influenced by language aptitude, with poorer performance observed for school-aged children with low language aptitude.

Conclusion

Children's language abilities and demographic factors explain significant variability in speech recognition in quiet and noise outcomes in children with CIs. Factors associated with speech recognition include language aptitude, attendance to AV therapy appointments, and consistent use of the CI during all waking hours.

Conflict of Interest
None declared.

Acknowledgement
This work was supported by a grant from the Oberkotter Foundation. We would like to thank Teresa Caraway and Bruce Rosenfield for their support and would also like to thank the reviewers of this manuscript for their helpful comments regarding an earlier version of this paper.

References

1 Ching TYC, Dillon H, Leigh G, Cupples L. Learning from the Longitudinal Outcomes of Children with Hearing Impairment (LOCHI) study: summary of 5-year findings and implications. Int J Audiol 2018;57(sup2):S105–S111

2 Dettman SJ, Dowell RC, Choo D, et al. Long-term communication outcomes for children receiving cochlear implants younger than 12 months: a multicenter study. Otol Neurotol 2016;37(02):e82–e95

3 Eisenberg LS, Fisher LM, Johnson KC, Ganguly DH, Grace T, Niparko JKCDaCI Investigative Team. Sentence recognition in quiet and noise by pediatric cochlear implant users: relationships to spoken language. Otol Neurotol 2016;37(02):e75–e81

4 Geers AE, Mitchell CM, Warner-Czyz A, Wang NY, Eisenberg LSCDaCI Investigative Team. Early sign language exposure and cochlear implantation benefits. Pediatrics 2017;140(01):e20163489

5 Davidson LS, Geers AE, Blamey PJ, Tobey EA, Brenner CA. Factors contributing to speech perception scores in long-term pediatric cochlear implant users. Ear Hear 2011;32(1, Suppl):19S–26S

6 Park LR, Gagnon EB, Thompson E, Brown KD. Age at full-time use predicts language outcomes better than age of surgery in children who use cochlear implants. Am J Audiol 2019;28(04):986–992

7 Gagnon EB, Eskridge H, Brown KD. Pediatric cochlear implant wear time and early language development. Cochlear Implants Int 2020;21(02):92–97

8 Easwar V, Sanfilippo J, Papsin B, Gordon K. Impact of consistency in daily device use on speech perception abilities in children with cochlear implants: datalogging evidence. J Am Acad Audiol 2018; 29(09):835–846

9 Wiig EH, Semel E, Secord WA. Clinical Evaluation of Language Fundamentals – Fifth Edition (CELF-5). Bloomington, MN: NCS Pearson; 2013

10 Geers AE, Moog JS, Rudge AM. Effect of frequency of early intervention on spoken language and literacy levels of children who are deaf or hard of hearing in preschool and elementary school. J Early Hear Detect Interv 2019;4(01):15–27

11 Uhler K, Warner-Czyz A, Gifford R, Working Group P. Pediatric minimum speech test battery. J Am Acad Audiol 2017;28(03):232–247

12 Peterson GE, Lehiste I. Revised CNC lists for auditory tests. J Speech Hear Disord 1962;27:62–70

13 Holder JT, Sheffield SW, Gifford RH. Speech understanding in children with normal hearing: sound field normative data for BabyBio, the BKB-SIN, and QuickSIN. Otol Neurotol 2016;37(02): e50–e55

14 Spahr AJ, Dorman MF, Litvak LM, et al. Development and validation of the pediatric AzBio sentence lists. Ear Hear 2014;35(04): 418–422

15 Spahr AJ, Dorman MF, Litvak LM, et al. Development and validation of the AzBio sentence lists. Ear Hear 2012;33(01): 112–117

16 Wolfe J, Neumann S, Schafer E, Marsh M, Wood M, Baker RS. Potential benefits of an integrated electric-acoustic (EAS) sound processor with children: a preliminary report. J Am Acad Audiol 2017;28(02):127–140

17 Busch T, Vermeulen A, Langereis M, Vanpoucke F, van Wieringen A. Cochlear implant data logs predict children's receptive vocabulary. Ear Hear 2020;41(04):733–746

18 Sharma SD, Cushing SL, Papsin BC, Gordon KA. Hearing and speech benefits of cochlear implantation in children: a review of the literature. Int J Pediatr Otorhinolaryngol 2020; 133:109984

19 Chadha NK, Papsin BC, Jiwani S, Gordon KA. Speech detection in noise and spatial unmasking in children with simultaneous versus sequential bilateral cochlear implants. Otol Neurotol 2011;32(07):1057–1064

20 Gordon KA, Papsin BC. Benefits of short interimplant delays in children receiving bilateral cochlear implants. Otol Neurotol 2009;30(03):319–331

21 Davidson LS, Geers AE, Uchanski RM, et al. Effects of early acoustic hearing on speech perception and language for pediatric cochlear implant recipients. Journal of Speech, Language, and Hearing Research 2019;62(09):3620–3637

22 Caldwell A, Nittrouer S. Speech perception in noise by children with cochlear implants. Journal of Speech, Language, Hearing Research 2013;56:13–30

23 Geers A, Brenner C, Davidson L. Factors associated with development of speech perception skills in children implanted by age five. Ear and Hearing 2003;24:24S–35S

24 Tajudeen BA, Waltzman SB, Jethanamest D, Svirsky MA. Speech perception in congenitally deaf children receiving cochlear implants in the first year of life. Otology & Neurotology 2010; 31:1254–1260

25 Dettman S, Wall E, Constantinescu G, Dowell R. Communication outcomes for groups of children using cochlear implants enrolled in auditory-verbal therapy, aural-oral, and bilingual-bicultural early intervention programs. Otology and Neurotology 2013; 34:451–459

Appendix A Individual speech recognition data for the *Low Language* group

Subject	CNC word recognition results			AzBio sentence recognition results		
	Right CI	Left CI	Bilateral CI	Bilateral CI	Bilateral CI	Bilateral CI
1A	92	88	92	71	64	50
2A	72	82	82	76	68	28
3A	92	90	94	90	95	84
4A	90	84	92	80	74	52
5A	80	72	86	82	75	55
6A	92	60	94	83	82	63
7A	88	70	84	71	45	38
8A	.	90	.	82	75	48
9A	.	94	.	38	42	40
10A	82	84	78	17	11	13
11A	92	92	96	94	91	81
12A	60	.	.	41	21	17
13A	88	26	94	94	91	71
14A	76	82	88	61	52	42
15A	90	86	94	95	81	67
16A	96	84	96	57	54	44
17A	94	92	94	85	77	72
18A	46	44	52	0	0	0
19A	90	82	90	83	64	0
20A	54	58	70	33	26	0
21A	94	78	90	78	81	48
22A	92	86	90	81	80	63
23A	96	.	.	60	48	49
24A	92	.	.	78	63	54
Mean (SD)	84 (14)	77 (17)	87 (11)	68 (25)	61 (26)	45 (25)

Abbreviations: CI, cochlear implant; CNC, consonant–nucleus–consonant; SD, standard deviation.
Note: Period (.) indicates missing data due to unilateral implantation.

Appendix B Individual speech recognition data for the *High Language* group

Subject	CNC word recognition results			AzBio sentence recognition results		
	Right CI	Left CI	Bilateral CI	Bilateral CI	Bilateral CI	Bilateral CI
1B	84	96	100	100	94	76
2B	100	98	100	96	95	89
3B	94	94	92	94	92	85
4B	100	96	100	87	79	65
5B	98	96	98	97	89	89
6B	88	92	100	91	90	84
7B	92	96	98	93	90	85
8B	90	94	96	95	79	78
9B	95	93	100	98	88	94
10B	98	94	94	94	85	93
11B	92	84	94	98	82	52
12B	92	88	100	91	86	77
13B	96	90	98	88	93	78
14B	98	58	96	92	88	67
15B	85	90	96	96	81	70
16B	89	92	98	91	86	75
17B	96	94	98	100	99	96
18B	84	82	92	92	76	61
19B	98	94	98	97	100	95
20B	88	90	100	88	90	83
21B	100	100	100	100	100	100
22B	90	88	86	97	94	79
23B	94	98	96	97	89	77
24B	96	100	100	100	98	95
25B	84	98	90	94	87	82
26B	98	98	100	96	93	76
Mean (SD)	93 (5)	92 (8)	97 (4)	95 (4)	89 (6)	81 (12)

Abbreviations: CI, cochlear implant; CNC, consonant–nucleus–consonant; SD, standard deviation.