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Early Bimodal Stimulation Benefits Language Acquisition for Children with Cochlear Implants

Aaron C. Moberly, M.D., **Joanna H. Lowenstein, Ph.D.**, and **Susan Nittrouer, Ph.D.**

The Ohio State University Wexner Medical Center

Abstract

Hypothesis—Adding a low-frequency acoustic signal to the cochlear implant (CI) signal (i.e., bimodal stimulation) for a period of time early in life improves language acquisition.

Background—Children must acquire sensitivity to the phonemic units of language to develop most language-related skills, including expressive vocabulary, working memory, and reading. Acquiring sensitivity to phonemic structure depends largely on having refined spectral (frequency) representations available in the signal, which does not happen with CIs alone. Combining the low-frequency acoustic signal available through hearing aids with the CI signal can enhance signal quality. A period with this bimodal stimulation has been shown to improve language skills in very young children. This study examined whether these benefits persist into childhood.

Methods—Data were examined for 48 children with CIs implanted under age 3 years, participating in a longitudinal study. All children wore hearing aids prior to receiving a CI, but upon receiving a first CI, 24 children had at least one year of bimodal stimulation (Bimodal group), and 24 children had only electric stimulation subsequent to implantation (CI-only group). Measures of phonemic awareness were obtained at second and fourth grade, along with measures of expressive vocabulary, working memory, and reading.

Results—Children in the Bimodal group generally performed better on measures of phonemic awareness, and that advantage was reflected in other language measures.

Conclusions—Having even a brief period of time early in life with combined electric-acoustic input provides benefits to language learning into childhood, likely due to the enhancement in spectral representations provided.

Introduction

Bilateral simultaneous pediatric cochlear implantation is commonly being performed for infants with profound sensorineural hearing loss, and some clinicians and researchers would now consider simultaneous implantation to be standard of care (1–2). This push to implant bilaterally early in life stems from studies suggesting that restoring binaural auditory input through bilateral implantation, or implanting sequentially with only a short delay between implants, optimizes the chances for normal auditory cortical development and use of

Address correspondence to and request reprints from: Aaron Moberly, Otolaryngology – Head & Neck Surgery, The Ohio State University, 915 Olentangy River Road, Suite 4000, Columbus, OH 43212; Aaron.Moberly@osumc.edu, Phone: 614-366-3687, Fax: 614-293-7292.

binaural cues in the service of recognizing speech in noise and localizing sound sources (1,3–5).

But it is not clear whether or not there are advantages of bilateral simultaneous implantation to language learning. Because there are only a limited number of stimulating electrodes (22 or fewer), with overlapping regions of neural stimulation (6–7), cochlear implants (CIs) provide only poorly preserved spectrotemporal structure (the detailed representations of frequencies over time). Consequently, children with 2 CIs receive bilateral *degraded* input, and that may not necessarily support language acquisition to a greater extent than one implant alone. In sum, even if early bilateral implants facilitate binaural processing, that may not directly translate to improved language development.

This degradation in spectrotemporal structure available through CIs undoubtedly contributes to the continuing gap in language performance observed between children with CIs and their normal-hearing (NH) peers. Children with CIs perform, on average, one standard deviation below children with NH on standard measures of language. These measures have included comprehension of spoken sentences or understanding relationships between words (e.g., using subtests of the Clinical Evaluation of Language Fundamentals – CELF) (8), or children's knowledge or understanding of syntax (e.g., using subtests of the Comprehensive Assessment of Spoken Language – CASL) (9). These measures largely evaluate morphosyntactic skills, which relate to word formation and how words are combined into phrases and sentences. However, the degradation in spectrotemporal structure imposed by hearing loss and CI processing would be expected to have more deleterious effects on processing phonological structure (relating to syllables within words), and especially phonemic structure (relating to the individual sound units of words), because recognizing phonemic units depends strongly on spectral cues. And, in fact, investigations of sensitivity to phonemic structure show that children with CIs are closer to two standard deviations below children with NH on these tasks (10–11). This lack of sensitivity to phonemic structure could be expected to disproportionately affect language skills that depend on that structure. This has been observed using non-standardized measures of phonemic processing, as well as tasks assessing skills that presumably depend on that level of structure. For example, vocabulary knowledge would be expected to depend on sensitivity to phonemic structure because the lexicon (an individual's store of words) is commonly modeled as being organized phonemically (12). Working memory, a short-term memory mechanism that stores and processes information, would be expected to suffer for children with CIs, as they have more difficulty representing phonemes robustly in working memory storage (13–14). Finally, word reading would likely suffer as a result of poor sensitivity to phonemic structure, because reading acquisition depends strongly on the ability to recover phonemic structure from the visual input (15).

Examining methods to enhance the delivery of more detailed spectral structure, which should support processing of phonemic structure and likely better facilitate early language development, is essential. Many children who receive CIs have some degree of residual low-frequency hearing that could benefit from a powerful hearing aid. While this small amount of low-frequency hearing alone is certainly not sufficient for speech and language acquisition, it is richer in its acoustic details than the signals transmitted through the CI, both by extending the range of frequencies represented and by enhancing the resolution of the signal, at least in that limited frequency range. Thus, the signal provided through the hearing aid is complementary to the signal provided through the CI, rather than redundant to it. Providing this enhanced signal could aid in closing the gap in language abilities between children with CIs and those with normal hearing.

These predicted benefits of early bimodal stimulation for children with CIs were observed in a report by Nittrouer and Chapman (16). That study of 58 children with CIs tested at 48 months of age, 29 of whom had some bimodal experience, revealed that the children with a period of bimodal stimulation performed better than children with electric-only stimulation subsequent to receiving a first CI. The purpose of this report is to review findings regarding language development through early elementary school for children with a period of bimodal stimulation compared to those children who had CI-only experience, during assessments at second and fourth grade, by longitudinally examining language measures for the same children from the Nittrouer and Chapman (16) report. Sensitivity to phonemic structure, and language functions dependent on that structure, served as the outcome measures. The hypothesis was that having access to low-frequency information through a hearing aid early in life would provide acoustic structure that assisted children with CIs in acquisition of phonemic sensitivity. To test this hypothesis, data were compared for the group of children who had a period of bimodal stimulation after receiving a CI and the group of children who had CI-only experience on these phonemically based skills. In addition, phonemic awareness at second and fourth grade was examined as a predictor of the other measures. Evidence of a benefit of a period of bimodal stimulation on scores of phonemic awareness, along with evidence that phonemic awareness predicts other language measures, would suggest that early bilateral simultaneous implantation of infants as standard of care ought to be reconsidered carefully, and that a period of bimodal stimulation may provide an advantage to language acquisition.

Materials and Methods

Participants

Participants were 48 children with CIs and 48 children with normal hearing (NH) from an ongoing longitudinal study of children learning American English (17). All children with CIs included in the current report had congenital, profound sensorineural hearing loss, identified before age 24 months. Those children received their CIs early, which for most meant by the age of two years. See Supplemental Digital Content for further participant details. All children came from middle-class families, suggesting reasonably rich language environments at home. Thirty-two children had bilateral implants by the time of the fourth grade language assessment. Of these, 3 had undergone simultaneous bilateral implantation. At the time of implantation, 24 children continued to use a hearing aid on the non-implanted ear for at least 11 months (hereafter, “Bimodal” participants), and 24 did not (hereafter, “CI-only” participants). Table 1 shows means (and SDs) between the two groups of children, Bimodal and CI-only, for each of the following: Socioeconomic status (SES) (as defined by Nittrouer and Burton) (20), age of identification of hearing loss, age at first implant, pre-implant hearing status (better-ear pure tone average across the frequencies, 500, 1000, and

2000 Hz - PTA), as well as word recognition (using a CID word list). The only statistically significant differences found between the Bimodal and CI-only groups for any demographic or audiologic factors were earlier age at first implant for the CI-only group, and a better mean pre-op better-ear PTA for the Bimodal group. However, the ranges in both measures were large. Data collected from these children at second and fourth grade are reported here.

General Procedures

Testing at each grade took place at The Ohio State University Wexner Medical Center, as part of an ongoing longitudinal study (10,17). Institutional Review Board approval was obtained for the study, and participants' parents provided informed written consent. Measures reported here include phonemic awareness, working memory, expressive vocabulary, and word reading ability. Details of equipment used can be found in the Supplemental Digital Content.

Task-Specific Procedures

Phonemic Awareness—Evaluating children's sensitivity to the phonemic structure of speech can be accomplished with a variety of tasks. These tasks usually consist of asking children to explicitly identify words that share phonemes or manipulate phonemes within words, and several tasks of varying, age-appropriate difficulty were used. At second grade, participants completed an Initial Consonant Choice task (ICC), a Final Consonant Choice task (FCC), and a Phoneme Deletion task (PD). In fourth grade, participants again completed the FCC task, along with a Backwards Words task (BW) and a Pig Latin task (PL), which were more difficult. Details of these tasks can be found in the Supplemental Digital Content.

The percent correct scores for each phonemic awareness task at each grade were used to develop a latent phonemic awareness score, representing a single measure of phonemic awareness ability at each grade. These latent scores were then converted to standard scores, which served as the dependent measures reported. Standard scores are typically computed using a normative sample. Because scores for these tasks have not previously been standardized, data from the children with normal hearing in this study were used to establish standard scores of phonemic awareness, with the mean for the NH group assigned a value of 100 and the standard deviation given a value of 15.

Working Memory—The same serial-recall task was used to assess working memory at both second and fourth grade. Six nouns served as stimuli. Details of this task can be found in the Supplemental Digital Content. Standard scores were derived, again using the NH children in this study as the basis for these scores, such that the mean standard score for NH children was 100 with a standard deviation of 15.

Expressive Vocabulary—The Expressive One Word Picture Vocabulary Test (EOWPVT) (18) was used to assess children's vocabulary skills at both second and fourth grade. This task required participants to provide words to label a series of pictures shown one at a time on separate pages of an easel. Standard scores were used as the dependent measures. Because a normative sample was already available for this measure (18), these standard scores were used. As a result, the mean and standard deviation for the children with NH in this study were not necessarily 100 and 15, respectively.

Word Reading Ability—The Wide Range Achievement Test 4 (WRAT) (19) is a standardized measure of reading skills, and was used at second and fourth grade. The participant was asked to read the words presented on a single page. Participants were video- and audio-recorded, and responses were scored later for words correctly read aloud. Standard scores are reported, again relative to a published normative sample (19).

Data Analyses

Examination of language measures for Bimodal and CI-only groups—In order to examine the effects of a period of bimodal stimulation after receiving a CI on phonemic awareness and related language measures, a series of independent samples *t*-tests was performed comparing scores between the Bimodal group and the CI-only group.

Examination of phonemic awareness scores as predictors of other language measures—In order to examine sensitivity to phonemic structure as a predictor of working memory, expressive vocabulary, or word reading ability, a series of linear regression analyses was performed, with working memory, expressive vocabulary, and word reading scores at second or fourth grade as dependent measures and standard scores on phonemic awareness tasks at each grade as predictor variables.

Results

The reported analyses examined phonemic awareness, working memory, expressive vocabulary, and word reading for two groups of pediatric CI users, one with CI-only experience, and one with at least 11 months of Bimodal stimulation after implantation. For an in-depth analysis of the outcomes of these two groups of patients as compared with children with NH or hearing aids, the reader is encouraged to review the results of the ongoing longitudinal study (10,17). Specifically on the measures included here, results for the NH children in the study are included in Table 2 to give a perspective of performance by the children with CIs. One child in the Bimodal group was not tested at second grade, so the sample size for that group is 23 at second grade. One child in the CI-only group was unable to complete the ICC and PD tasks at second grade. Thus, the sample size for that task and group is 23 at second grade.

Before analyzing data for the children with CIs, some general impressions can be gathered from Table 2 regarding their performance relative to that of the children with NH. First, on most measures, the children with CIs were performing approximately one standard deviation below the mean for the children with NH. An even greater deficit was found for the children with CIs on phonemic awareness at second grade, with an average standard score of 72.7, close to two standard deviations below the mean standard score of children with NH. At first glance, the children with CIs appeared to be performing closer to the mean performance of the normative samples for expressive vocabulary and word reading because their standard scores are near 100; however, it should be noted that all children in this study came from families with relatively high (middle-class) SES, and so the NH children tested in this study performed almost one standard deviation above the mean for the normative samples. That means that the children with CIs in this study, who were matched on SES to the NH children, still performed approximately one standard deviation below the children with NH on expressive vocabulary, and approximately one-half standard deviation below the NH children for word reading.

Language Skills for Bimodal versus CI-only Groups

The main question of interest was whether language skills (phonemic awareness, working memory, expressive vocabulary, and word reading ability) for the Bimodal and CI-only groups would differ at second and fourth grade. Separate independent samples *t*-tests were performed comparing the Bimodal and CI-only groups for each measure examined. For all measures, the Bimodal group showed better mean scores than the CI-only group (Table 2); however, not all differences were statistically significant. By examining Table 2, it is apparent that standard deviations (SDs) were larger for most measures for the children with CIs than for those with NH. Had these SDs been more similar to the NH group, it is likely that group differences would have been significant. Moreover, effect sizes were computed as Cohen's d scores (Table 3), and medium effect sizes were seen for the Bimodal condition over the CI-only condition for phonemic awareness standard scores, working memory, and expressive vocabulary.

Phonemic Awareness Scores as Predictors of Other Language Measures

The second question of interest in evaluating the benefit of a period of bimodal stimulation was whether better phonemic awareness at second or fourth grade would predict better working memory, expressive vocabulary, or word reading ability. Evidence of these relationships would further support the notion that by assisting in the development of phonemic sensitivity, a period of bimodal stimulation would contribute to better language skills over electric-only stimulation. To examine these relationships, separate linear regression analyses were performed for all children with CIs, with either working memory, expressive vocabulary, or word reading scores at second or fourth grade as dependent measures, and phonemic awareness standard scores at that grade as predictor variables. The β coefficients are shown in Table 4. Indeed, phonemic awareness scores strongly predicted almost all measures of working memory, expressive vocabulary, and word reading.

One-CI versus Two-CI patients

Another question that is relevant to the interpretation of the data presented here concerns the effect of having one or two CIs. Specifically, the question is whether bimodal experience or number of CIs accounts for the most variability in outcomes. To help answer that question, standard scores for phonemic awareness for children, divided into those groups, are shown in Figure 1. Two-way ANOVAs were performed for phonemic awareness scores for each grade separately, with group (CI-only versus Bimodal) and number of CIs (1 or 2) as factors. No main effects were seen in second grade for either group (p = 0.380) or number of CIs (p = 0.283). A main effect was seen for fourth grade phonemic awareness for group, with Bimodal outperforming CI-only (p = 0.050), but not for number of CIs (p = 0.507).

Therefore, simply having bilateral implants did not necessarily provide an advantage in language acquisition over one implant. Rather, having a period of bimodal experience did.

Preoperative PTA and Language Scores

A final question arises that must be addressed, and that is whether the better mean preoperative PTA seen for the Bimodal group as compared with the CI-only group could explain the benefits in phonemic awareness and language scores seen for the Bimodal group. Figure 2 shows, as an example, second grade phonemic awareness standard scores as a function of preoperative better-ear PTA, plotted separately for the Bimodal group and for the CI-only group. This figure illustrates that the phonemic awareness scores at second grade were not related to preoperative PTA for either group. Similar-appearing plots were seen for the other language scores versus preoperative better-ear PTA. Thus, it is reasonable to conclude that the advantages observed in phonemic awareness and language scores for the Bimodal group over the CI-only group were not attributable to differences in preoperative audiologic status.

Discussion

This report reviews data from a longitudinal study of children with hearing loss. The aim of the current study was to examine whether a persistent benefit to language development exists for children, beyond 48 months of age, who undergo cochlear implantation followed by a period (approximately a year or more) of bimodal stimulation, as compared with children who do not experience bimodal stimulation. Data from 48 children with CIs participating in an ongoing longitudinal study were examined. Measures of phonemic awareness in 2nd grade and 4th grade were examined for a Bimodal group and a CI-only group, along with measures of skills that should depend heavily on sensitivity to phonemic structure: working memory, expressive vocabulary, and word reading ability. Results revealed that the Bimodal group outperformed the CI-only group, with medium effect sizes, for most measures.

A second important finding was that phonemic awareness strongly predicted the acquisition of other language skills for children with CIs. This point is worth emphasizing, because the largest language deficits that continue to be seen for children with CIs relative to their NH peers are for those language skills that require explicit sensitivity to the phonemic structure of language. Currently, these are not skills that are routinely assessed in clinical settings, but they are foundational to the development of other language abilities, such as working memory, vocabulary, and reading. Therefore, the addition of clinical tools to assess phonemic awareness should be considered for monitoring the progress of language development by pediatric CI users.

A striking additional finding, which relates directly to the increasing practice of simultaneous bilateral cochlear implantation, was that children with two CIs did not necessarily perform better on language measures than those with one CI. Rather, it was those children who experienced a period of bimodal stimulation who outperformed the others. Any appearance of an advantage of two CIs over just one CI could be accounted for by the better scores observed for children with two CIs who had a period of bimodal stimulation. This is likely a result of the complementary nature of the acoustic and electric stimulation provided to these children. The addition of a powerful hearing aid to the signals delivered through a CI provides access to extended low-frequency information with more detailed spectrotemporal resolution. Consequentially, this combination of both electric (CI) and acoustic (contralateral hearing aid) stimulation appears to support development of better sensitivity to phonemic structure and, thus, better language skills.

While findings of this study suggest that a period of bimodal stimulation may benefit language acquisition for children receiving CIs, conclusions should be made cautiously, and questions remain. First, as is commonly seen in studies of clinical populations of CI users, large standard deviations existed for most language measures reported here. As such, trends were seen towards better performance by the Bimodal group over the CI-only group on most measures with medium effect sizes, but not all differences were statistically significant. Second, the data presented were prospectively collected for pediatric patients who received surgical and rehabilitative interventions at well-respected CI programs throughout the country, but patients were not randomized to treatment arms. Children in the Bimodal and CI-only groups appeared equivalent based on demographics and SES; moreover, preoperative hearing status (PTA) did not appear to have a significant effect on language measures. However, a definitive study of the benefits of a period of bimodal stimulation would require a controlled trial with patients randomized to Bimodal or CI-only intervention groups. Third, it is unclear what the duration of an adequate period of bimodal stimulation would entail. The authors posit that the eventual benefits of having bilateral CIs likely outweigh the benefits achieved through bimodal stimulation long term, especially with regard to hearing in noise and sound localization. Evidence suggests that a long delay between sequential implants portends impaired use of binaural cues and abnormal auditory cortical development (1,4). Thus, an appropriate period of bimodal stimulation early in life could optimize children’s development of language, especially where phonological structure is concerned. Following that bimodal stimulation with sequential implantation of the second side would provide greater assistance in hearing in noise and sound localization.

Conclusion

A period of early bimodal stimulation provides a benefit to early language acquisition for children undergoing cochlear implantation. These early benefits translate into later benefits in phonemic awareness, working memory, expressive vocabulary, and reading ability. While prior evidence suggests that early bilateral simultaneous implantation may optimize bilateral auditory processing for these children, the results of this study reveal that clinicians should consider offering pediatric patients a period of bimodal stimulation to optimize language acquisition. Moreover, future studies should be designed to more definitively examine the benefits of combined electric-acoustic stimulation (whether bimodal or in the same ear) for language acquisition by children with hearing loss.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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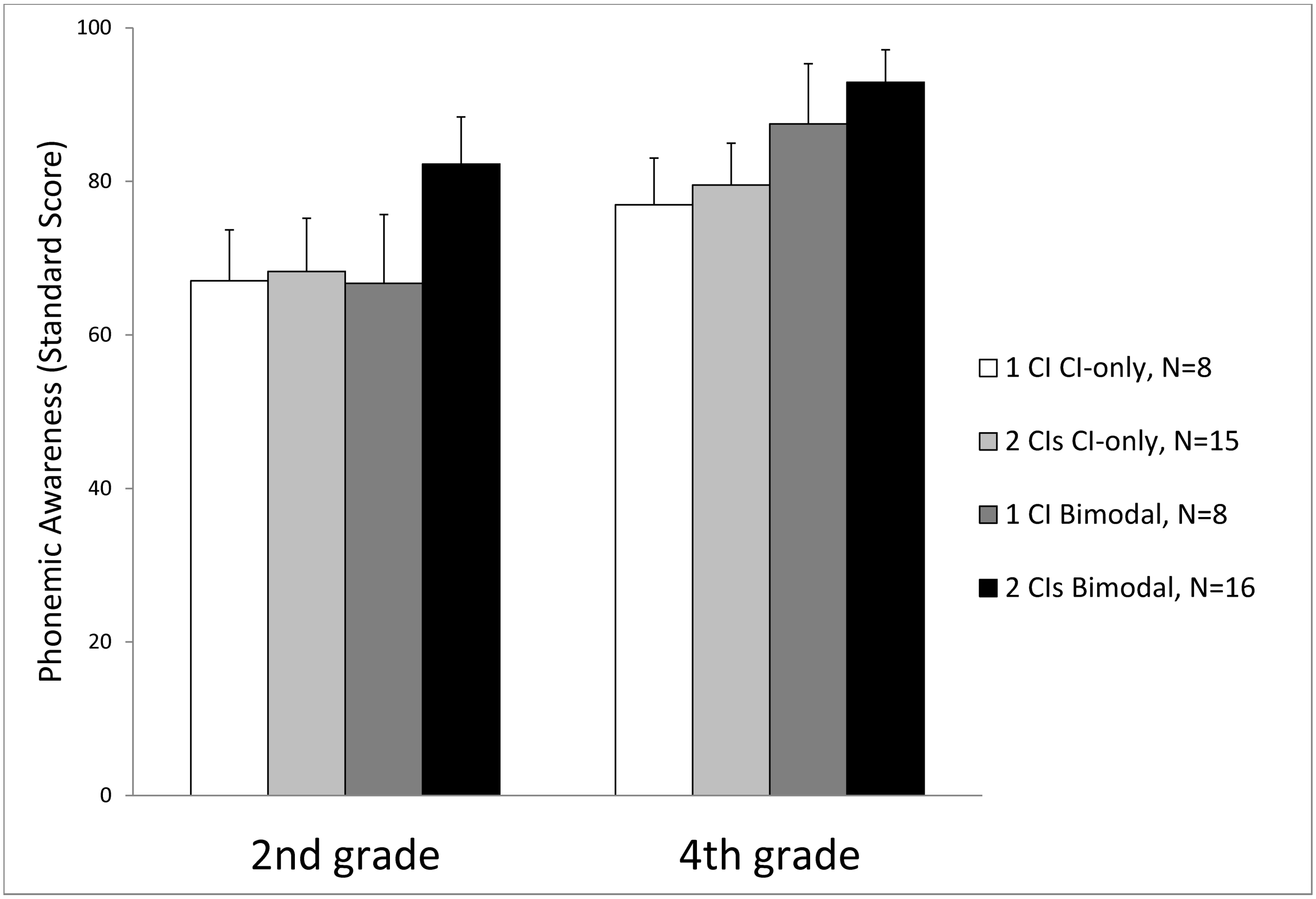

Figure 1.

Phonemic awareness standard scores for 2nd and 4th grade for children with CIs, divided into groups based on having one or two CIs, with or without some bimodal experience. Error bars represent standard errors of the mean.

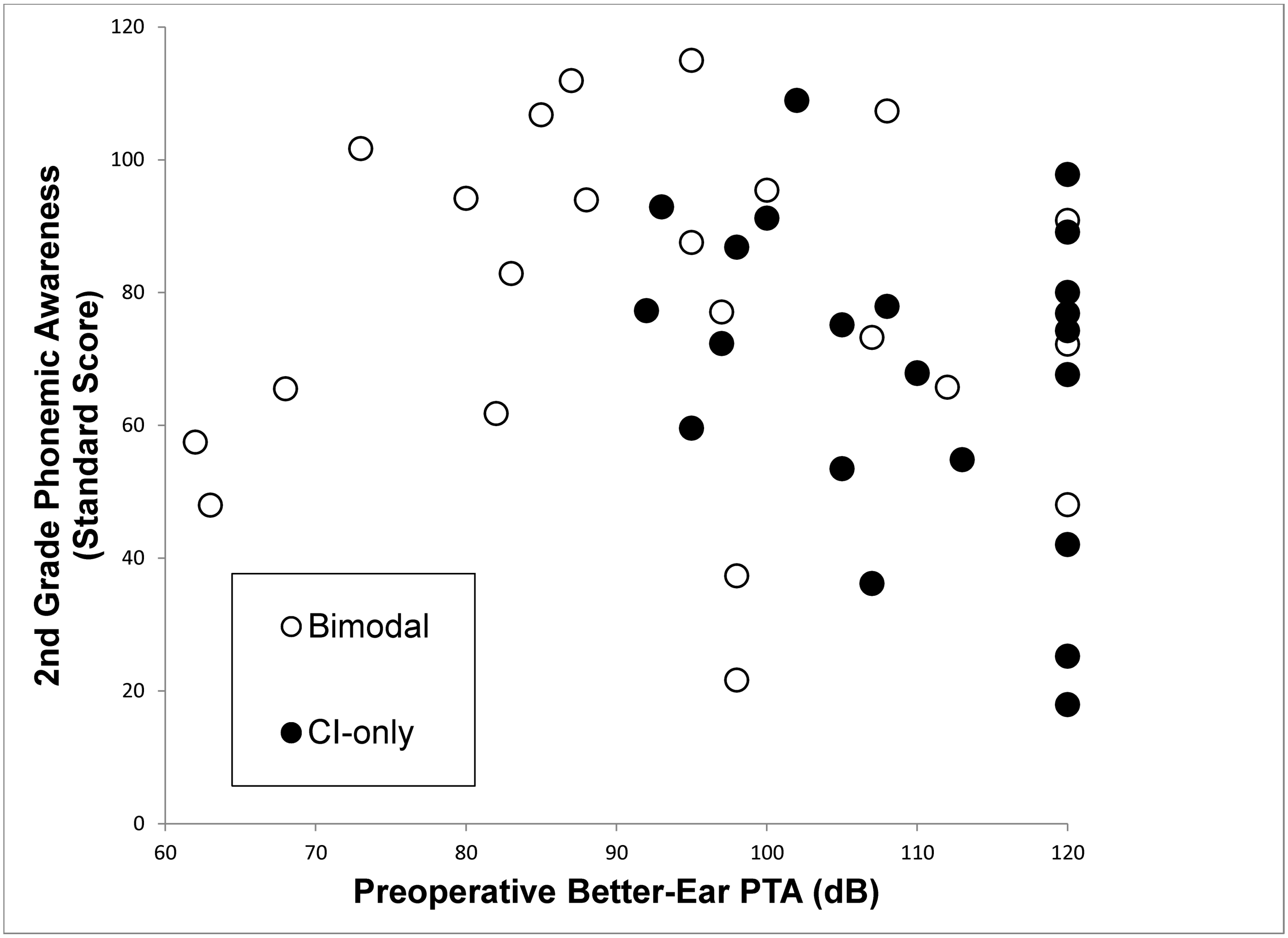

Figure 2.

Scatter plot of 2nd grade phonemic awareness standard scores versus preoperative better-ear pure tone average (PTA) at 500, 1000, and 2000 Hz in dB HL. Scores are plotted separately for Bimodal participants (open circles) and CI-only participants (solid circles).

Table 1

Participant demographics of the Bimodal and CI-only groups included at fourth grade. Pure tone average is for 500, 1000, and 2000 Hz.

	Groups					
	Bimodal		**CI-only**			
	Mean	**(SD)**	**Mean**	**(SD)**	***t***	***p***
N	*24*		*24*			
SES (score)	32.8	10.9	34.4	11.4	0.51	0.616
Age of identification of hearing loss (months)	6.9	6.8	4.6	6.5	1.19	0.240
Age at first implant (months)	28.2	23.9	14.6	5.4	2.72	**0.009**
Pre-op better ear pure tone average (dB HL)	93.5	17.6	109.7	11.4	3.89	**0.001**
Word recognition 4th grade (percent correct)	73.9	10.0	69.6	18.2	1.02	0.311
Unilateral CI						
N	*8*		*8*			
Bilateral simultaneous CI						
N	*NA*		*3*			
Bilateral sequential CI						
N	*16*		*13*			
Interimplant interval (months)	29.7	23	36.1	27	0.68	0.501

Degrees of freedom for all *t*-tests are 47. Bolded *p* values are for those less than or equal to 0.05. SES: Socioeconomic status

Table 2

Phonemic awareness and language scores for the normal-hearing (NH), Bimodal, and CI-only groups. Results of *t* tests are between the Bimodal and CI-only groups. Results are shown for the NH group for comparison.

	Groups										
	NH			Bimodal			CI-only				
	N	Mean	(SD)	*N*	Mean	(SD)	*N*	Mean	(SD)	*t*	*p*
Phonemic Awareness (standard score)											
2nd grade	*46*	100	15	*23*	77.5	24.9	*23*	67.9	23.9	1.34	0.186
4th grade	*46*	100	15	*24*	91.1	18.5	*24*	78.6	20.0	2.26	**0.031**
Working Memory (standard score)											
2nd grade	*46*	100	15	*23*	91.6	17.1	*24*	84.7	9.4	1.73	0.091
4th grade	*46*	100	15	*24*	90.1	15.1	*24*	85.0	14.2	1.21	0.233
Expressive Vocabulary (standard score)											
2nd grade	*46*	110.2	13.8	*23*	100.4	20.1	*24*	91.5	16.4	1.67	0.101
4th grade	*46*	107.1	11.3	*24*	101.8	17.8	*24*	91.9	15.8	2.05	**0.047**
Word Reading (standard score)											
2nd grade	*46*	109.8	11.5	*23*	103.4	14.5	*24*	100.7	16.4	0.13	0.562
4th grade	*46*	111.2	12.1	*24*	105.8	17.1	*24*	101.6	19.0	0.64	0.425

Degrees of freedom for *t*-tests are $N - 1$. Bolded *p* values are for those less than or equal to 0.05.

Table 3

Cohen's d effect sizes for the Bimodal over the CI-only condition, examining phonemic awareness and language scores.

	Cohen's d
Phonemic Awareness (standard score)	
2nd grade	0.396
4th grade	0.645
Mean	**0.521**
Working Memory (standard score)	
2nd grade	0.536
4th grades	0.349
Mean	**0.443**
Expressive Vocabulary (standard score)	
2nd grade	0.487
4th grade	0.588
Mean	**0.538**
Word Reading (standard score)	
2nd grade	0.174
4th grade	0.232
Mean	**0.203**

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Table 4

β coefficients, representing results of linear regression analyses for all children with CIs, with phonemic awareness standard scores at second and fourth grade as predictor variables, and language measures (working memory, expressive vocabulary, and word reading) at the same grade as dependent measures.

Phonemic awareness	Memory	Vocabulary	Word reading
2nd grade	0.54	0.74	0.73
4th grade	0.40	0.60	0.67

Degrees of freedom for all analyses are (1,44) and (1,46) at second and fourth grade, respectively. All β coefficients have *p* values less than or equal to 0.01.