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Research Article

Early Postimplant Speech Perception and Language Skills Predict Long-Term Language and Neurocognitive Outcomes Following Pediatric Cochlear Implantation

Cynthia R. Hunter,[a] William G. Kronenberger,[a,b,c] Irina Castellanos,[d] and David B. Pisoni[a,b]

Purpose: We sought to determine whether speech perception and language skills measured early after cochlear implantation in children who are deaf, and early postimplant growth in speech perception and language skills, predict long-term speech perception, language, and neurocognitive outcomes.
Method: Thirty-six long-term users of cochlear implants, implanted at an average age of 3.4 years, completed measures of speech perception, language, and executive functioning an average of 14.4 years postimplantation. Speech perception and language skills measured in the 1st and 2nd years postimplantation and open-set word recognition measured in the 3rd and 4th years postimplantation were obtained from a research database in order to assess predictive relations with long-term outcomes.
Results: Speech perception and language skills at 6 and 18 months postimplantation were correlated with long-term outcomes for language, verbal working memory, and parent-reported executive functioning. Open-set word recognition was correlated with early speech perception and language skills and long-term speech perception and language outcomes. Hierarchical regressions showed that early speech perception and language skills at 6 months postimplantation and growth in these skills from 6 to 18 months both accounted for substantial variance in long-term outcomes for language and verbal working memory that was not explained by conventional demographic and hearing factors.
Conclusion: Speech perception and language skills measured very early postimplantation, and early postimplant growth in speech perception and language, may be clinically relevant markers of long-term language and neurocognitive outcomes in users of cochlear implants.
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Cochlear implants (CIs) provide children who have prelingual deafness with access to sound that is sufficient in many cases to support the acquisition of spoken language (Geers, Brenner, & Davidson, 2003; Geers, Nicholas, & Sedey, 2003; Meyer, Svirsky, Kirk, & Miyamoto, 1998). By elementary school, more than half of pediatric CI users can be expected to score in the average range on assessments of spoken language skills (Geers, Brenner, & Tobey, 2011; Geers, Nicholas, & Sedey, 2003), and this percentage increases with more experience by high school age (Geers & Sedey, 2011). However, the effectiveness of CIs in supporting speech and language development is highly variable. Although variability in outcomes has been identified as a major target for research by the National Institutes of Health, individual outcomes remain extremely difficult to predict (National Institutes of Health, 1995; Niparko et al., 2010; N. R. Peterson, Pisoni, & Miyamoto, 2010; Pisoni et al., 2008; Svirsky, Teoh, & Neuburger, 2004). Individual outcomes after several years of implant experience range from minimal benefit and awareness of environmental sounds to robust speech perception and language (SP-L) skills that are on par with peers with normal hearing (NH; Barnard et al., 2015; Cooper, 2006; Gantz, Woodworth, Fryauf-Bertschy, Kelsay, & Tyler, 1997; Geers, Brenner, &

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[a]Speech Research Laboratory, Department of Psychological and Brain Sciences, Indiana University, Bloomington
[b]Riley Child and Adolescent Psychiatry Clinic, Department of Psychiatry, Indiana University School of Medicine, Indianapolis
[c]DeVault Otologic Research Laboratory, Department of Otolaryngology—Head and Neck Surgery, Indiana University School of Medicine, Indianapolis
[d]Department of Otolaryngology—Head and Neck Surgery, The Ohio State University, Columbus

Correspondence to Cynthia R. Hunter: cynthunt@indiana.edu

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Davidson, 2003). The identification of children who are at risk for a poor outcome is a high research priority, because early identification may inform clinical decisions about habilitation and intervention, potentially increasing the benefits children receive from their CIs.

To date, the relations of speech and language measures taken in the first few years of implant use to long-term outcomes after a decade or more of CI use have been examined by only a small handful of studies, some of which have used data from a larger study of long-term outcomes at the Indiana University School of Medicine (Castellanos et al., 2014; Castellanos, Pisoni, Kronenberger, & Beer, 2016; Hay-McCutcheon, Kirk, Henning, Gao, & Qi, 2008). Hay-McCutcheon et al. found that receptive language scores obtained when children were in preschool and kindergarten were significantly correlated with language scores in the teenage years. The observed relations between early receptive language and long-term language outcomes are similar to those found by Geers and colleagues in a separate, large-scale study of long-term CI users (Geers & Sedey, 2011; Tobey, Geers, Sundarrajan, & Lane, 2011). They observed that language scores measured in elementary school after several years of CI use were highly predictive of language scores in high school. Low receptive and productive language scores of CI users in preschool have also been associated with persistent language delays from elementary through the high school years (Geers, Nicholas, Tobey, & Davidson, 2016). These findings suggest that the relation between early and long-term language outcomes is present as early as the preschool period.

A more recent study by Castellanos et al. (2014) provides support for this conclusion. That study examined whether speech intelligibility and receptive vocabulary sampled in preschool after participants had used their implant for nearly 2 years on average would predict long-term outcomes for speech perception, language, and verbal working memory. The authors found that CI users whose speech was more intelligible in preschool scored higher on assessments of speech perception, language, and verbal working-memory capacity taken approximately a decade later. Children who scored higher on vocabulary in preschool also had significantly better long-term outcomes for SP-L. The relations between early language and long-term outcomes were not accounted for by conventional demographic and hearing-history variables, although age at onset of deafness and age at implantation were related to several long-term outcomes. These findings indicate that CI users who are at risk for suboptimal long-term outcomes for speech, language, and verbal working memory may be identified during the preschool period.

Current clinical guidelines recommend cochlear implantation in children who are deaf by 12 months of age (Boons et al., 2012; Dettman, Pinder, Briggs, Dowell, & Leigh, 2007). Children who receive implants according to these guidelines will have had years of experience with their implants by preschool. It follows that identification of risk for a poor outcome in the preschool period will not be early enough to target interventions for many children during their first years of exposure to sound. Gains in speech and language skills following cochlear implantation are measurable on a variety of assessments very early postimplantation, following CI use of less than 1 year (Nikolopoulos, Archbold, & Gregory, 2005; Niparko et al., 2010; Svirsky et al., 2004; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). To date, practically no studies have investigated whether speech and language skills after less than 1 year of CI use predict long-term outcomes. The major aim of the current study was to address this gap in our knowledge by examining the relations of pediatric CI users' SP-L skills, measured as soon as possible following cochlear implantation, to long-term outcomes in speech perception, language, and neurocognitive domains.

Both for children who use CIs and for children with NH, language development is closely linked to executive functioning (EF), an umbrella term for the neurocognitive skills that are involved in the self-regulation of thoughts and behaviors (Astington & Jenkins, 1999; de Rosnay & Hughes, 2006; Figueras, Edwards, & Langdon, 2008; C. C. Peterson, 2004). Pediatric CI users tend to score below their peers with NH on several domains of EF, and these group differences may be evident as early as preschool age (Beer et al., 2014; Kronenberger, Pisoni, Henning, & Colson, 2013). In addition, speech and language abilities are more strongly associated with EF processes related to verbal working memory and fluency-speed for CI users who received prelingual implantation than for their peers with NH (Cleary, Pisoni, & Kirk, 2000; Kronenberger, Colson, Henning, & Pisoni, 2014; Pisoni, Kronenberger, Roman, & Geers, 2011). Thus, examination of outcomes in domains such as neurocognitive functioning in addition to language is important for providing converging information about individual differences in benefit from cochlear implantation.

One recent study has provided evidence that long-term neurocognitive outcomes can be predicted from speech and language skills after an average of 1 year of CI experience. Castellanos et al. (2016) examined the relation between expressive language skills as measured by the MacArthur–Bates Communicative Development Inventories (Fenson et al., 2006) after an average of 1 year of CI use and long-term neurocognitive outcomes an average of 11 years later. The MacArthur–Bates Communicative Development Inventories are a parent-completed inventory of a child's earliest words and sentences. Castellanos et al. (2016) controlled for nonverbal intelligence and demographic factors, and found strong relations between early expressive language scores on the instrument and long-term neurocognitive outcomes. The neurocognitive outcomes that were related to early expressive language included verbal working memory, fluency and speed of information processing, and parent ratings of everyday EF and learning. These findings suggest that an inventory of a child's earliest expressive language taken after an average of 1 year of CI experience may be clinically useful for identifying pediatric CI users who may be at high risk of poor long-term neurocognitive outcomes.

The goal of the current study was to investigate whether SP-L abilities measured very early postimplantation would be useful for predicting long-term language and neurocognitive outcomes in CI users who received their implants in early childhood. We used SP-L measures taken as early as possible postimplant, at the first postimplant visit to our clinic during which assessments of SP-L were given; this occurred on average at approximately 6 months after implantation (range = 0.35–1.05 years; see Table 1). A second aim was to compare the prediction of long-term outcomes on the basis of this earliest postimplant measure with prediction on the basis of SP-L measures taken in the second year of implant use. We were particularly interested in creating a measure of growth in SP-L from the first to the second postimplant year. Prior studies have not evaluated relations of long-term outcome to early postimplant improvement in speech and language skills. We obtained measures of SP-L skills at approximately 6 and 18 months postimplantation, and used these two time points to create a measure of early growth. Both the earliest sampled SP-L skills and growth in the following year were used as predictors of long-term language and neurocognitive outcomes in regression models.

Further, we obtained a measure of open-set word recognition for a subset of participants in their third and fourth years postimplantation and used these scores to assess continuity between SP-L skills measured very early postimplantation, open-set word recognition, and long-term outcomes. Open-set word recognition, which refers to the ability to identify spoken words without being given a set of response alternatives, is an important indicator of the ability to understand speech in naturalistic settings (Kirk, Pisoni, & Osberger, 1995; Meyer & Pisoni, 1999). Although some degree of open-set word recognition is achieved by a majority of pediatric CI users, individual performance in a quiet environment after several years of CI use ranges from 0 to 100 percent correct (Barnard et al., 2015; Dowell,

Table 1. Year 1 participant demographics and hearing history ($N = 36$).

	Early postimplantation visit		**Long-term follow-up visit**	
Characteristic	***M* (*SD*)**	**Range**	***M* (*SD*)**	**Range**
Onset of deafness (years)	0.31 (0.73)	0.00–3.00		
Age at implantation (years)	3.44 (1.55)	1.44–6.12		
Duration of deafness (years)	3.13 (1.60)	0.49–6.12		
Age at testing (years)	3.98 (1.54)	1.96–6.64	17.82 (4.45)	11.59–27.39
Duration of CI use (years)	0.53 (0.25)	0.35–1.05	14.38 (3.56)	8.19–22.44
Preimplant PTA[a]	109.64 (9.87)	85.00–118.43		
Nonverbal IQ[b]	—		53.81 (7.50)	35.00–66.00
Household income[c]	—		6.86 (2.59)	2.00–10.00
		Count (% of sample)		
Age at testing (years)				
≤ 3.00	13 (36.1)			
3.10–5.00	12 (33.3)			
5.10–7.00	11 (30.6)			
11.10–15.00			11 (30.6)	
15.10–19.00			12 (33.3)	
19.10–28.00			13 (36.1)	
Onset of deafness (years)				
0.00	28 (77.8)			
0.10–1.00	2 (5.6)			
1.10–2.00	5 (13.9)			
2.10–3.00	1 (2.8)			
Hearing device				
Bilateral CIs	0 (0.0)		12 (33.3)	
Unilateral CI	36 (100.0)		24 (66.7)	
Etiology of hearing loss				
Meningitis	6 (16.7)			
Other/unknown	30 (83.3)			
Communication mode				
Signed/total	14 (38.9)		4 (11.1)	
Oral/cued	22 (61.1)		32 (88.9)	
Gender				
Female	15 (41.7)			
Male	21 (58.3)			

Note. Em dashes indicate data not obtained. CI = cochlear implant; PTA = pure-tone average.

[a] Unaided PTA (in dB HL) in the better ear for 500, 1000, and 2000 Hz. [b] Expressed as *t* scores ($M = 50$, $SD = 10$) from the Wechsler Abbreviated Scale of Intelligence Matrix Reasoning Subtest for Nonverbal Intelligence. On average, our sample of CI users had nonverbal IQ scores within the normal range, although individual scores ranged between more than 1 *SD* above and below the normed mean. [c] Coded on a scale from 1 (*under $5,000*) to 10 (*$95,000 and over*).

Blamey, & Clark, 1995; Geers, Brenner, & Davidson, 2003). Thus, an additional aim of the current study was to assess the relation between open-set word recognition, long-term outcomes, and early postimplant measures of SP-L skills.

Method

Participants

Study participants were 36 children who received CIs in our center, completed assessments of SP-L skills in the first 2 years following pediatric cochlear implantation, and were part of a larger study of long-term outcomes in CI users who received implantation in childhood (for descriptive statistics of the demographic, hearing-history, and speech and language variables for the full participant sample for long-term outcomes, see Castellanos et al., 2016; Kronenberger, Colson, et al., 2014; Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013). The 36 participants were adolescents and young adults at the time of the long-term-outcomes study. Table 1 provides descriptive statistics of the demographics and hearing history of the current sample. In order to be included in the long-term-outcomes study, participants were required to meet the following inclusionary criteria: have prelingual severe-to-profound sensorineural hearing loss (> 70 dB HL in the better-hearing ear prior to age 3 years); have received their CI prior to age 7 years; have used their CI for 7 years or more; use a currently available state-of-the-art multichannel CI system; live in a household with spoken English as the primary language; and pass a screening performed by licensed speech-language pathologists prior to testing, confirming that no additional developmental, neurological, or cognitive conditions were present other than hearing loss. Participants were also required to have completed one or more of the following assessments of SP-L skills at our clinic in the first year following cochlear implantation: Reynell Developmental Language Scales II (RDLS; Reynell & Gruber, 1990), Pediatric Speech Intelligibility Test (PSI; Jerger & Jerger, 1984), or the Mr. Potato Head™ task (Robbins, 1994). A subset of the current sample (*n* = 25) also completed these assessments in the second year following implantation. Some of the participants in the current sample were included in prior studies in which other assessments of early language were used to predict long-term outcomes; to be specific, 52.8% of the current sample (*n* = 19) was included in a prior study in which parent reports of expressive language after approximately 1 year of CI use were used to predict speech and language outcomes (Castellanos et al., 2016), and 52.8% of the current sample (*n* = 19) was included in a prior study in which speech intelligibility or vocabulary after approximately 2 years of CI use was used to predict speech, language, and neurocognitive outcomes (Castellanos et al., 2014). Demographic and hearing-history characteristics of the current sample are shown in Table 1.

At the time of testing in the first year postimplantation, participants ranged in age from 2.0 to 6.6 years (*M* = 4.0, *SD* = 1.5) and had used their implant for 4.2–12.6 months (*M* = 6.4, *SD* = 3.0). Participants tested again in the second year after implantation ranged in age from 3.0 to 7.7 years (*M* = 4.9, *SD* = 1.6) and had used their implant for 17.3–23.5 months (*M* = 18.9, *SD* = 1.2) at the second-year visit. At the long-term follow-up visit, participants ranged in age from 11.6 to 27.4 years (*M* = 17.8, *SD* = 4.5) and had used their implant for 8.2–22.4 years (*M* = 14.4, *SD* = 3.6).

Procedure

Participants or their parents gave written informed consent to the protocol approved by the local institutional review board. Participants in the larger long-term-outcomes study were included in the current study if data for the assessments of early speech and language were available in the longitudinal database. All tests were administered by licensed speech-language pathologists.

Measures

Early SP-L

We selected several conventional clinical tests that are routinely used to assess the SP-L skills of pediatric CI recipients to serve as measures of SP-L development within the first and second years postimplantation. Language development was assessed with the RDLS, and speech perception was assessed with the PSI and the Mr. Potato Head task. The RDLS is a standardized measure of language development for children ages 1.5–7 years that uses picture books and props to elicit responses. Raw scores on separate scales of receptive and expressive language were obtained from the RDLS. Raw scores were used rather than age-normed scores because most participants' raw scores were outside of the normed range—that is, below the lower bound of available normed scores for their age. The RDLS was administered in each child's preferred mode of communication at the time of testing (total communication: Year 1, *n* = 14; Year 2, *n* = 11).

The PSI is a nonstandardized closed-set assessment of speech perception in which the child points to one of several pictures in response to age-appropriate spoken words and sentences. The influence of language ability on performance on the PSI is minimized, given the picture-pointing response that is made to a limited number of response choices on each trial and the use of pictures that are drawn from a simple vocabulary, which the child is familiarized with prior to testing. The PSI was designed to measure speech perception in young children with hearing loss, and is commonly used in speech audiometry assessment of pediatric CI users from ages 2 or 3 to 7 years (Fink et al., 2007; Mendel, 2008; Robbins & Kirk, 1996). Two scores were obtained from the PSI: a word score for the percent correct responses to monosyllabic nouns and a separate percent correct score for responses to sentences.

The Mr. Potato Head task is a nonstandardized closed-set measure of speech perception that was developed in our center for use with young children with hearing loss from age 2 years (Robbins, 1994). In this task, the child follows spoken instructions to manipulate a Mr. Potato Head toy (e.g., “Put a hat on Mr. Potato Head” or “Make him wave good-bye”). There are 20 parts to choose from, and so correct responses have a low probability of being chosen by chance. The Mr. Potato Head task may be influenced by vocabulary knowledge as well as speech-perception ability, particularly for younger children (Robbins & Kirk, 1996). The percentage of sentences that were correctly responded to was obtained for the Mr. Potato Head task. Both of the speech-perception tasks were given in auditory–visual format—that is, children were able to see the face of the speech-language pathologist during testing.

Scores for these assessments were obtained for the first year after implantation (Year 1) and the second (Year 2). Participants were seen at our clinic at approximately 6-month intervals in the first few years after receiving an implant. If a participant had more than one score for a given test in either Year 1 or Year 2, the score from the earlier test was retained, so that the data analyzed reflect the earliest available assessment. Because most participants had two data points in each interval, the majority of data points in Year 1 were from approximately 6 months postimplantation and the majority of data points in Year 2 were from approximately 18 months postimplantation. However, not all participants had data for all assessments. Data were available for an average of four out of the five assessment scores at the Year 1 interval (M = 4.11, SD = 1.14, range = 2–5) and at the Year 2 interval (M = 4.08, SD = 1.26, range = 1–5). The number of available assessments was similar for children with congenital deafness (M = 4.01, SD = 1.20) and with acquired deafness (M = 4.38, SD = 1.12). Missing data generally occurred if a child became fatigued or did not appear to understand a task.

Scores on the five subtests of early SP-L were all strongly intercorrelated, indicating that these tests measure a common underlying source of variance. In Year 1, correlations ranged from .73 to .95 (median = .88), and partial correlations controlling for chronological age ranged from .46 to .91 (median = .75). The correlations were similar in Year 2 (see Supplemental Material S1–S4). Therefore, composite scores of early SP-L were generated and used for all subsequent analyses. Composite scores were created by first transforming raw scores of each of the five subtests of SP-L into z scores and then taking the mean of the z-transformed scores across subtests. Transformation to z scores was accomplished by subtracting the mean of each subtest from the individual raw scores of that subtest and dividing each resultant value by the standard deviation of raw scores for that subtest.

In order to measure change in participants' z scores across time points in a repeated measures design, it is necessary to use a common mean and standard deviation for z transformation at all time points. Therefore, so that the difference in children's z scores at Year 1 and Year 2 would reflect the growth in their SP-L skills from Year 1 to Year 2, a common mean and standard deviation were used to z transform the raw scores from Years 1 and 2 for each subtest. To be specific, the z scores for each subtest were computed using the mean and standard deviation of the pooled raw scores for that subtest from Years 1 and 2 (Cohen, Cohen, West, & Aiken, 2003; Edgington & Onghena, 2007). For example, the mean and standard deviation used to standardize scores for the RDLS-Receptive subtest were the mean and standard deviation across all raw RDLS-Receptive scores from both years. The resultant composite scores for Year 1 (M = −.33, SD = .91) were lower than those for Year 2 (M = .55, SD = .71), and every participant's composite score was higher in Year 2 than Year 1, indicating that children's performance on the SP-L assessments improved from Year 1 to Year 2.

The majority of composite scores included both speech-perception and language subtests; however, a substantial minority of composite scores included either one or the other but not both. For the full sample (N = 36), 83% of the sample had at least one measure of language at Year 1, 95% had at least one measure of speech perception, and 78% had at least one measure of language and at least one measure of speech perception. For the subsample with data from Year 2 (n = 25), 92% of the sample had at least one measure of language at Year 2, 88% had at least one measure of speech perception, and at both the Year 1 and Year 2 time points, 80% of children had at least one measure of language and at least one measure of speech perception. On average, if a child had one of the five subtests in Year 1, that child completed the same subtest in Year 2 75% of the time. Thus, improvement in SP-L scores from Year 1 to Year 2 does not necessarily mean that the child's performance improved on the same subtests, although this was often the case. However, for every participant, growth in SP-L scores from Year 1 to Year 2 indicates that performance on available subtests was better relative to other scores in the pooled distribution in Year 2 than in Year 1.

Open-Set Word Recognition

To obtain a measure of open-set word recognition, scores on the Phonetically Balanced Kindergarten Test (PBK) were accessed for the subset of participants who had completed a PBK in the third or fourth year postimplantation. The PBK is a nonstandardized test that is widely used for the clinical assessment of open-set word recognition in young children with hearing loss (Haskins, 1949; Meyer & Pisoni, 1999; Waltzman et al., 1994; Uziel et al., 2007). In the PBK, the examiner verbally presents spoken words from one of four lists, and the child is asked to repeat each word aloud. The PBK score is the percent words repeated correctly. For participants who completed more than one PBK list in their third and fourth years after implantation, the best score was used in order to represent the maximum open-set word recognition achieved during this time period.

Long-Term Speech and Language Outcomes

Speech-perception skills at long-term follow-up were assessed with the Hearing in Noise Test for Children (HINT-C; Nilsson, Soli, & Gelnett, 1996). The HINT-C is a nonstandardized test that requires participants to listen to a list of spoken sentences presented either in quiet or in speech-shaped noise and repeat back the sentence. The HINT-C is widely used in clinical and research settings and is appropriate for children age 6 years and older. Long-term language outcomes were assessed with standard scores on the Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4; Dunn & Dunn, 2007), and Core Language standard scores from the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003). The PPVT-4 is a receptive measure of vocabulary development that requires a child to point to one of four pictures matching a spoken word. The CELF-4 Core Language score provides a global index of receptive and expressive language derived from several subtests depending on the participant's age, such as understanding concepts and following directions, recalling sentences, formulating sentences, and vocabulary knowledge. The PPVT-4 and CELF-4 were administered in each child's preferred mode of communication at the time of testing (total communication: $n = 4$; see Table 1).

Long-Term Neurocognitive Outcomes

Participants also completed a battery of neurocognitive assessments at the long-term follow-up visit. Composite scores for verbal working memory, visual-spatial working memory, fluency-speed, and inhibition-concentration were created from the individual measures. Composite scores were created by summing z-transformed scores for the individual assessments detailed in the following (on the basis of the means and standard deviations in the current study sample), and were used for all subsequent analyses (Castellanos et al., 2016; Kronenberger, Colson, et al., 2014). The individual assessments that contributed to the composite scores have strong psychometrics, including excellent internal consistency, test–retest reliability, and construct validity. For evidence that these composite scores represent the principal components of the executive functions measured by the individual assessments in a larger sample of CI users and peers with NH, see Kronenberger, Colson, et al. (2014).

Verbal working memory. To assess verbal working-memory capacity, we used scaled scores on the Digit Span Forward and Digit Span Backward subtests of the Wechsler Intelligence Scale for Children–Third Edition (Wechsler, 1991) and scaled scores on the Visual Digit Span subtest of the Wechsler Intelligence Scale for Children–Fourth Edition Integrated (WISC-IV-I; Wechsler et al., 2004). These tasks require participants to repeat sequences of spoken digits in either forward order (Digit Span Forward) or backward order (Digit Span Backward) or to repeat sequences of digits presented visually in forward order (Visual Digit Span).

Visual-spatial working memory. Scaled scores on the Spatial Span Forward and Spatial Span Backward subtests of the WISC-IV-I were used to assess visual-spatial working-memory capacity. For these tasks the experimenter points to a series of blocks arranged on a board, and participants are required to reproduce the sequence by pointing to the same series of blocks in either forward or backward order.

Fluency-speed. Fluency-speed was assessed with measures of processing speed obtained from simple visual tasks that require sustained attention to be performed quickly (Prifitera, Saklofske, & Weiss, 2008). Fluency-speed was composed of standard scores on the Pair Cancellation subtest of the Woodcock–Johnson Tests of Cognitive Abilities, Third Edition (Woodcock, McGrew, & Mather, 2001) and scaled scores on the Coding and Coding Copy subtests of the WISC-IV-I. The Pair Cancellation subtest requires participants to view an array of visual items and rapidly circle pairs of items that occur in sequence. The Coding subtest requires participants to associate symbols with numerals and to rapidly reproduce a sequence of symbols when given the corresponding sequence of numerals. The Coding Copy subtest requires participants to rapidly draw a sequence of visual symbols.

Inhibition-concentration. Inhibition-concentration skills were assessed using the Test of Variables of Attention (Leark, Dupuy, Greenberg, Corman, & Kindschi, 1996). The Test of Variables of Attention requires participants to press a button when a visual target stimulus appears at the top of a computer screen, and not to respond when the same stimulus is presented at the bottom of a screen. Standard scores for omissions (failing to respond to the target), commissions (responding to the distractor), and response-time variability in the speed of responding to the target were included in the composite score.

Long-Term Neurocognitive Questionnaire-Based Outcomes

Parent reports of the child's neurocognitive functioning in daily life were obtained using the Learning, Executive, and Attention Functioning scale (LEAF). The LEAF is a questionnaire-based assessment consisting of 55 items that form eight cognitive and three academic subscales (Kronenberger & Pisoni, 2009; Kronenberger, Castellanos, & Pisoni, 2016). Although normative data are not available for the LEAF, its subscales have demonstrated strong internal consistency, test–retest reliability, and correlations with other assessments of EF (Kronenberger & Pisoni, 2009). Summed ratings across the five items of each LEAF subscale were analyzed. Items on the LEAF assess everyday neurocognitive functioning—for example, "Does not stay focused on learning material" or "Can't do more than one thing at a time." Parents rate each item on a 4-point scale: 0 (*never*), 1 (*sometimes*), 2 (*often*), 3 (*very often*). Higher scores on the LEAF indicate more parent-reported problems in EF or related learning (e.g., academic functioning, concept formation). Thus, lower LEAF scores indicate better everyday neurocognitive functioning. Given the age range of participants at long-term follow-up (see Table 1), in many cases parents were reporting on the EF of their adult children. Interestingly, many parent-report checklists are widely used for reporting on adult children and have been reported to be valid for this purpose (see Reynolds & Kamphaus, 2004).

Data Analysis

To examine the relations between SP-L skills in the first 2 years after implantation and long-term speech-perception, language, and neurocognitive outcomes, scores on the composite measures of early SP-L in Years 1 and 2 were correlated with the long-term follow-up measures. For variables that were composed of raw scores, partial correlations were used controlling for chronological age, which varied from 1.9 to 6.6 years at early test and from 11.6 to 27.4 years at long-term follow-up—to be specific, partial correlations with long-term language, verbal working-memory, visual-spatial working-memory, fluency-speed, and inhibition-concentration scores that were composed of age-scaled scores controlled for age at early testing. Partial correlations with the long-term speech-perception and questionnaire-based parent-reported LEAF scores that were composed of raw scores controlled for age at early testing and at long-term follow-up. To compare the predictive power of early SP-L in Years 1 and 2 in the same set of participants, correlations for Year 1 were computed both for the full sample and for the subset of participants that were retested in Year 2. To examine the relation of early open-set word recognition to long-term outcomes, participants' best PBK scores within the third and fourth year post-implantation were correlated with long-term speech-perception, language, and neurocognitive measures. The relations between open-set word recognition and early SP-L skills in Years 1 and 2 were also assessed using partial correlations controlling for age at early test. Correlations between Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) nonverbal IQ measured at long-term follow-up and the composite measures of long-term outcome were also examined.

For early SP-L measures that were significantly correlated with long-term outcomes in the subset of participants that were tested both in Year 1 and Year 2, hierarchical regression analyses were then used to determine whether any relations found between early SP-L measures and long-term outcomes remained after accounting for conventional demographic and hearing-history variables and nonverbal intelligence, and what the independent contributions were of early SP-L skills after approximately 6 months of implant use and improvement in the following year. Growth in the second year postimplantation was quantified by the difference between the early SP-L composite scores in Years 1 and 2. Entered in the first block were demographic and hearing-history variables that have shown consistent relationships with outcomes in prior research (i.e., age at implantation, duration of deafness, preimplant residual hearing, and communication mode), household income, and Wechsler Abbreviated Scale of Intelligence nonverbal IQ. Year 1 SP-L scores were entered in the second block, and growth scores were entered in the third block (note that Year 2 scores were not added to the model because they are redundant with Year 1 scores and growth). Block 1 variables that did not add significantly to the regression model were dropped in reverse order of coefficient magnitude, so that only predictors that were significant at the $p < .05$ level were retained in the final regression equation.

A similar regression analysis was not conducted for outcomes on LEAF, due to low sample size for the matched-*n* subgroup with data for both Year 1 and Year 2 ($n = 18$). Instead, partial correlations of LEAF outcomes with demographic and hearing-history variables and nonverbal intelligence were used to assess the potential relation of these factors to LEAF outcomes. For each demographic or hearing-history factor and for nonverbal intelligence, partial correlations (factoring out age at LEAF test) with those LEAF outcomes that were significantly correlated with early language in Year 1 were computed in the full sample of participants with LEAF data in Year 1 ($n = 28$).

Results

Descriptive statistics for the early SP-L measures are shown in Table 2. Performance on all early SP-L tasks showed a wide range of variability in both the first and second years after cochlear implantation. For example, performance on the PSI and Mr. Potato Head tasks ranged from less than 10% to 100% correct in Year 1, and from less than 20% to 100% correct in Year 2. The range of performance on these early measures clearly shows large individual differences in spoken language skills following cochlear implantation.

Descriptive statistics for the long-term outcome measures are shown in Table 3. A high degree of variability in the scores can be seen in several of the measures. Participants had a wide range of chronological ages at long-term follow-up; however, the extent to which chronological age can explain the variability in the data is limited because language and neurocognitive performance scores were scaled

Table 2. Descriptive statistics for early speech and language measures.

Early speech-language measure	Year 1			Year 2		
	N	*M* (*SD*)	Range	*N*	*M* (*SD*)	Range
PSI–Sentences	30	41 (35)	10–100	20	76 (22)	17–100
PSI–Words	30	45 (39)	5–100	18	79 (27)	17–100
RDLS–Expressive	31	24 (16)	5–56	21	32 (12)	13–55
RDLS–Receptive	31	23 (18)	0–54	23	36 (16)	9–67
Mr. Potato Head	31	20 (31)	0–100	20	48 (29)	0–100

Note. Scores for all measures are expressed as raw scores. Year 1 data are presented for the full sample ($N = 36$), and Year 2 data are presented for the subgroup with data in Year 2 ($n = 25$). PSI = Pediatric Speech Intelligibility Test; RDLS = Reynell Developmental Language Scales II.

Table 3. Descriptive statistics for long-term speech, language, and neurocognitive outcome measures.

Measure	N	M (SD)	Range
Speech and language outcomes			
Speech perception			
HINT-C in quiet[a]	35	80.5 (29.3)	4–100
HINT-C in noise, +5 dB[a]	31	69.0 (24.7)	15–98
Language			
PPVT-4[b]	36	86.0 (21.9)	42–123
CELF–Core[b]	34	84.5 (26.3)	40–124
Performance-based neurocognitive outcomes			
Verbal working memory			
WISC-III Digit Span Forward[c]	36	6.0 (2.2)	2–11
WISC-III Digit Span Backward[c]	36	8.9 (2.9)	1–14
WISC-IV-I Visual Digit Span[c]	36	7.8 (3.2)	1–15
Visual-spatial working memory			
WISC-IV-I Spatial Span Forward[c]	36	9.1 (2.4)	5–16
WISC-IV-I Spatial Span Backward[c]	35	10.9 (2.6)	5–17
Fluency-speed			
WJ-III Pair Cancellation[b]	36	96.4 (12.9)	68–127
WISC-IV-I Coding[c]	36	8.9 (3.3)	2–15
WISC-IV-I Coding Copy[c]	36	9.8 (3.5)	2–17
Inhibition-concentration			
TOVA Omissions[b]	36	79.3 (27.2)	40–113
TOVA Commissions[b]	36	84.1 (23.4)	40–120
TOVA Response Time Variability[b]	36	89.9 (22.5)	43–119
LEAF parent-report outcomes[a]			
Cognitive subscales			
Comprehension and Conceptual Learning	28	4.4 (3.4)	0–12
Factual Memory	28	2.7 (2.7)	0–9
Attention	28	3.6 (3.64)	0–10
Processing Speed	28	4.1 (3.8)	0–13
Visual-Spatial Organization	28	2.5 (2.4)	0–7
Sustained Sequential Processing	28	3.8 (3.0)	0–11
Working Memory	28	3.4 (2.9)	0–11
Novel Problem Solving	28	3.5 (3.2)	0–12
Academic subscales			
Mathematics Skills	28	4.0 (3.9)	0–12
Basic Reading Skills	28	5.0 (4.9)	0–15
Written Expression Skills	28	4.8 (4.7)	0–15

Note. HINT-C = Hearing in Noise Test for Children; PPVT-4 = Peabody Picture Vocabulary Test–Fourth Edition; CELF–Core = Clinical Evaluation of Language Fundamentals–Fourth Edition, Core Language; WISC-III = Wechsler Intelligence Scale for Children–Third Edition; WISC-IV-I = Wechsler Intelligence Scale for Children–Fourth Edition Integrated; WJ-III = Woodcock–Johnson Tests of Cognitive Abilities, Third Edition; TOVA = Test of Variables of Attention; LEAF = Learning, Executive, and Attention Functioning scale.

[a] Raw scores. [b] Standard scores ($M = 100$, $SD = 15$). [c] Scaled scores ($M = 10$, $SD = 3$).

to age norms. Mean scores on the CELF-4 and PPVT-4 measures of language were approximately 1 *SD* below the norm-referenced mean score of 100, and ranged from clinical deficits of more than 3 *SD*s below the norm-referenced mean score to above average relative to norms. Performance on the HINT-C measure of speech perception in quiet, which is not scaled to age norms but uses a vocabulary suitable for children, ranged from 4% to 100% correct. Scores on the WISC-III digit-span tasks in the current sample of long-term CI users were lower on average than the age-normed mean score of 10, and the mean score for Digit Span Forward was more than 1 *SD* below the normed mean. Scores on the digit-span tasks ranged from 1 to 14. Mean scores on the assessments of Visual-Spatial Working Memory were within the normal range, but individual scores ranged from more than 1 *SD* below to more than 2 *SD*s above the normed mean. Mean scores on Fluency-Speed were within the normal range, but individual scores ranged more than 2 *SD*s above and below the normed mean. Mean scores on the Test of Variables of Attention subtests for Inhibition-Concentration were approximately 1 *SD* below the normed mean, and ranged from more than 3 *SD*s below to 1 *SD* above the normed mean. At long-term follow-up, the participants from Table 1 who continued to use total communication had z-standardized composite scores of speech perception that were more than 2 *SD*s below the mean for the current sample ($M = -2.05$, range = -2.72 to -1.09), language scores less than 1 *SD* below the mean for the sample ($M = -.57$, range = -1.91 to 0.45), verbal working-memory and fluency-speed scores less than 0.5 *SD* below the mean for the sample, and visual-spatial working-memory and inhibition-concentration scores that were approximately average compared to those of the other long-term CI users in the current sample. Overall, the wide range in outcome scores attests to the high individual variability in outcomes that is present in the population of CI users who received prelingual implantation (Niparko et al., 2010).

Correlational Analyses

Partial correlations (controlling for age at first testing) of the early SP-L composite measures in Years 1 and 2 and of open-set word recognition in Years 3 and 4 with long-term performance outcomes are summarized in Table 4. Early SP-L skills measured on average 6 months after cochlear implantation were significantly correlated with long-term language, verbal working-memory, and fluency-speed outcomes measured approximately 15 years after implantation. In the subset of participants with available data in the second year after implantation, early SP-L skills measured approximately 18 months after cochlear implantation were also significantly correlated with long-term language and verbal working-memory outcomes. Open-set PBK word-recognition scores in Years 3 and 4 were also significantly correlated with long-term SP-L outcomes (see Table 4). Open-set word recognition was significantly related to early SP-L scores in Year 2, $r(15) = .62$, $p < .05$, but not in Year 1, $r(16) = .46$, $p = .09$. Nonverbal IQ measured at long-term follow-up was correlated with outcomes in language, $r(34) = .36$, $p < .05$, verbal working memory, $r(34) = .49$, $p < .01$, and inhibition-concentration, $r(34) = .35$, $p < .05$. However, the long-term outcome composite scores for the participants who scored more than 1 *SD* below the normed mean on nonverbal IQ were on average within 1 *SD* of the sample mean ($n = 2$), as were the mean scores for participants who scored more than 1 *SD* above the normed mean ($n = 3$).

Partial correlations of the early SP-L composite measures from Years 1 and 2 with long-term parent-reported LEAF Cognitive and Academic Functioning scores are summarized in Table 5. Early SP-L skills measured on average 6 months postimplantation were significantly correlated with seven out of the eight LEAF Cognitive subscales (Comprehension and Conceptual Learning, Factual Memory, Attention, Processing Speed, Sustained Sequential Processing, Working Memory, and Novel Problem-Solving) and with the Academic subscales of Basic Reading Skills and Written Expression Skills. Early SP-L scores obtained in the second year after implantation showed similar correlations with the LEAF subscales (see Table 5). Partial correlations of LEAF outcomes with demographic and hearing-history variables and nonverbal intelligence were all nonsignificant (ranging in absolute value from .03 to .26), indicating that these factors were not related to the LEAF outcomes that were predicted by early SP-L.

Regression Models Predicting Long-Term Outcomes

Table 6 shows the results of hierarchical regression analyses with demographic and hearing-history variables, early SP-L scores in Year 1, and growth in SP-L scores from Year 1 to Year 2 as predictors of long-term language and verbal working-memory outcomes. None of the demographic, hearing-history, or nonverbal-intelligence factors accounted for significant variance in long-term outcomes at Block 1. For long-term language outcome, adding early SP-L scores for Year 1 in the second block resulted in a significant 29% increase in the variance accounted for by the model. Age of implantation also became a significant predictor when SP-L at Year 1 was added to the model.

Table 4. Partial correlations between early speech and language predictors and long-term performance outcomes, controlling for age at early test.

Long-term performance outcome	Early speech and language composite[a]			Open-set SWR[b]
	Year 1 ($N = 36$)	Year 1[c] ($n = 25$)	Year 2 ($n = 25$)	Years 3–4 ($n = 16$)
Speech perception[d]	.24	.06	.27	.75***
Language[e]	.60***	.64**	.70***	.60**
Verbal working memory[f]	.41*	.42*	.64***	.26
Visual-spatial working memory[g]	−.11	−.24	−.17	−.41
Fluency-speed[h]	.34*	.20	.22	.04
Inhibition-concentration[i]	.21	.19	.11	−.09

Note. SWR = spoken-word recognition.

[a] Includes scores on the Reynell Developmental Language Scales II, the Pediatric Speech Intelligibility Test with sentence and word materials, and the Mr. Potato Head task (see text for details). [b] Phonetically Balanced Kindergarten Test. [c] Year 1 data including only the matched set of participants who had data for Year 2. [d] Hearing in Noise Test for Children performance in quiet and with white noise added at a signal-to-noise ratio of +5 dB. [e] Peabody Picture Vocabulary Test–Fourth Edition and Clinical Evaluation of Language Fundamentals–Fourth Edition, Core Language. [f] Wechsler Intelligence Scale for Children–Third Edition Digit Span Forward and Digit Span Backward subtests and Wechsler Intelligence Scale for Children–Fourth Edition Integrated Visual Digit Span subtest. [g] Wechsler Intelligence Scale for Children–Fourth Edition Integrated Spatial Span Forward and Spatial Span Backward subtests. [h] Wechsler Intelligence Scale for Children–Fourth Edition Integrated Coding and Coding Copy subtests and Woodcock–Johnson Tests of Cognitive Abilities, Third Edition Pair Cancellation subtest. [i] Test of Variables of Attention Omissions, Commissions, and Reaction Time Variability subtests.

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 5. Partial correlations between early speech and language predictors and long-term LEAF outcomes, controlling for age at early and long-term test.

Long-term parent-reported LEAF outcome	Early speech and language composite[a]		
	Year 1 (*n* = 28)	**Year 1[b] (*n* = 18)**	**Year 2 (*n* = 18)**
Cognitive subscales			
Comprehension and Conceptual Learning	–.54**	–.28	–.50*
Factual Memory	–.45*	–.29	–.37
Attention	–.51**	–.54*	–.53*
Processing Speed	–.47*	–.20	–.61**
Visual-Spatial Organization	–.28	–.28	–.42
Sustained Sequential Processing	–.46*	–.43	–.58*
Working Memory	–.44*	–.27	–.53*
Novel Problem Solving	–.43*	–.15	–.44
Academic subscales			
Mathematics Skills	–.28	.06	–.33
Basic Reading Skills	–.53**	–.46	–.56*
Written Expression Skills	–.44*	–.37	–.61**

Note. Higher scores on the Learning, Executive, and Attention Functioning scale (LEAF) indicate greater problems with executive functioning or related learning (see text for details).

[a] Includes scores on the Reynell Developmental Language Scales II, the Pediatric Speech Intelligibility Test with sentence and word materials, and the Mr. Potato Head task (see text for details). [b] Year 1 data including only the matched set of participants who had data for Year 2.

**p* < .05. ***p* < .01.

The amount of variance accounted for increased by 14% when growth from Year 1 to Year 2 was added in Block 3, with the full model accounting for 46% of the total variance in long-term language outcome. For long-term verbal working memory, adding early SP-L scores for Year 1 in the second block resulted in a significant 21% increase in the variance accounted for by the model. Residual hearing also became a significant predictor when SP-L at Year 1 was added to the model. The amount of variance in verbal working memory accounted for increased by 30% when SP-L growth from Year 1 to Year 2 was added in Block 3. Nonverbal IQ and household income at long-term follow-up also became significant predictors when language growth was added to the model in Block 3. The full model accounted for 71% of the total variance in long-term verbal working-memory outcome (see Table 6).

In summary, both long-term language and verbal working memory were predicted by SP-L skills measured an average of 6 months after implantation. Further, the addition to the model of growth in SP-L skills from Year 1 to Year 2 predicted an additional 13% to 28% of variance in long-term language and verbal working-memory outcomes, respectively. These predictive relationships could not be accounted for by conventional demographic or hearing-history factors.

Last, given that there are different expectations for early postimplant performance for children who receive an implant before and after the age of 4 years (Robbins, 2007), we examined whether our results were representative of the participants in our sample who were implanted younger than age 4 years. To this end, the regression analyses for language and verbal working-memory outcomes were rerun including only participants from this age subsample (*n* = 18) and excluding children implanted after age 4 years (*n* = 7). The pattern of significant results was the same as in the original analysis.

Discussion

The current study departs from earlier work on CI outcomes in three major respects. First, we focused on early postimplant performance measures of children's speech and language skills to predict outcomes rather than conventional demographic and hearing-history factors, and we obtained these predictors earlier postimplant than did any prior study of long-term outcomes. Second, we examined long-term neurocognitive outcomes in addition to language outcomes. Last, we compared SP-L skills measured very early postimplant as well as growth in the following year as predictors of long-term language and neurocognitive outcomes.

The first major finding was that SP-L skills measured as early as 6 months after cochlear implantation predicted long-term language and neurocognitive outcomes. Although the correlations between SP-L skills and long-term outcomes were stronger at 18 months than 6 months postimplantation when compared in the same set of participants, both the correlation and regression analyses indicated that SP-L skills after 6 months of implant use predicted substantial variance in long-term language and neurocognitive outcomes after a decade and a half of CI experience. Prior work has indicated stability between long-term language and neurocognitive outcomes and speech and language skills as early as 1 to 2 years after implantation (Castellanos et al., 2014, 2016). The current results extend these earlier findings by documenting that stability in SP-L skills is observable using conventional clinical assessments as early as 6 months

Table 6. Regression models predicting long-term language and neurocognitive performance outcomes.

	Long-term follow-up composite score			
	Language		Verbal working memory	
Block	**β**	***t***	**β**	***t***
Block 1: Demographic and hearing history				
Age at implantation	.17	.82		
Best PTA[a]			.29	1.49
Household income			.24	1.16
Nonverbal IQ[b]			.36	1.72
R^2	.03		.20	
Block 2: Early language Year 1				
Age at implantation	−1.04	−2.42*		
Best PTA[a]			.45	2.45*
Household income			.39	1.98
Nonverbal IQ[b]			.34	1.83
Speech-language Year 1[c]	1.32	3.09**	.44	2.64*
ΔR^2	.29**		.21*	
R^2	.32*		.41*	
Block 3: Language growth Year 2 – Year 1				
Age at implantation	−.87	−2.18*		
Best PTA[a]			.48	3.38**
Household income			.35	2.55*
Nonverbal IQ[b]			.34	2.50*
Speech-language Year 1[c]	1.47	3.70**	.86	5.58***
Speech-language growth Year 2 – Year 1[d]	.48	2.30*	.69	4.47***
ΔR^2	.14*		.30***	
R^2	.46***		.71***	

Note. Analysis includes participants with data for both Year 1 and Year 2 ($n = 25$ for all composite scores). The standardized coefficients (β) and t values are provided for each predictor. The overall R^2 is provided for each block. Only demographic and hearing-history variables significant at the $p < .05$ level are displayed. Composite outcome measures include language (Peabody Picture Vocabulary Test–Fourth Edition and Clinical Evaluation of Language Fundamentals–Fourth Edition, Core Language) and verbal working memory (Wechsler Intelligence Scale for Children–Third Edition Digit Span Forward and Digit Span Backward subtests and Wechsler Intelligence Scale for Children–Fourth Edition Integrated Visual Digit Span subtest).

[a] Best preimplant pure-tone average (PTA) hearing threshold. [b] Wechsler Abbreviated Scale of Intelligence Matrix Reasoning subtest at long-term follow up. [c] Year 1 composite measure of speech-language. [d] Difference between Year 2 and Year 1 composite speech-language measures.

*$p < .05$. **$p < .01$. ***$p < .001$.

postimplantation and that very early postimplant SP-L skills predict long-term neurocognitive outcomes as well as long-term language outcomes. Thus, SP-L skills measured after only 6 months of access to sound from a CI appear to be reliable markers of long-term language and neurocognitive outcomes, and may have important clinical utility in identifying children who may be at high risk for poor outcomes following cochlear implantation.

Assessment of at-risk status very early postimplant is in line with recommendations that speech-language pathologists should closely monitor speech and language progress within the first year after implantation for “red flags” of a poor outcome (Bradham & Houston, 2014; Nikolopoulos et al., 2005; Robbins, 2007; Osberger, Robbins, & Trautwein, 2006). Robbins (2007) provides different guidelines for assessing progress in the first year after implantation for children who receive an implant before and after the age of 4 years. We found that the pattern of significant results for regression analysis that included only the subset of children in our sample who were implanted before the age of 4 years was the same as in the main analysis, which suggests that the conventional clinical assessments of SP-L skills that we used in this study may have utility for the assessment of risk after 6 months of implant use in children who receive their implants younger than age 4 years.

The second major finding of the current study is that growth in SP-L skills from 6 to 18 months postimplantation predicted long-term language and verbal working-memory outcomes. It has been known that very early experiences with a CI promote language growth and development. For example, Svirsky et al. (2000) reported gains of approximately 6 months of language age for each 6-month period from 0 to 30 months following cochlear implantation. Although growth in the speech and language skills of CI users who received implantation prelingually has been documented over the long term (e.g., Dunn et al., 2014), no prior study has examined whether early growth in speech and language skills is a reliable predictor of long-term language and neurocognitive outcomes. The significant variance accounted for in the regression analyses by early growth in SP-L skills indicates that long-term language and verbal working-memory outcomes following cochlear implantation are not only a function of demographics, hearing history, and SP-L ability in the first year postimplantation, but are also related to the development of these skills that occurs within the first two years of implant use. Our finding is consistent with the suggestion that the identification of slow progress within the first year, followed by appropriate intervention, could make a substantial difference in long-term outcomes for pediatric CI recipients (Bradham & Houston, 2014; Osberger et al., 2006; Robbins, 2007).

In fact, the observed relation between early growth in SP-L skills and long-term language and verbal working-memory outcomes implies that waiting until the second postimplant year to adjust habilitation strategies fails to take advantage of an opportunity to intervene during a period of rapid development in which progress in the acquisition of SP-L skills is related to the language and verbal working-memory abilities that are ultimately achieved after more than a decade of CI use. The current findings differ from those of a study of long-term speech sound production outcomes, in which long-term speech-production skill was not predicted by growth in speech-production ability, and was also not predicted by speech-production skill until the fourth year of implant use (Tomblin, Peng, Spencer, & Lu, 2008). However, other research indicates that speech production measured after an average of 2 years of implant use predicts long-term receptive language and verbal working memory (Castellanos et al., 2014), and that concurrently measured speech intelligibility and receptive language skills are correlated in long-term CI users (Montag, AuBuchon, Pisoni, & Kronenberger, 2014). Future research will be needed to determine whether receptive language can be more readily predicted from early postimplant ability than speech sound production.

It is clear that SP-L skills were better predictors of long-term outcomes when measured after 18 months of implant use than after 6 months of use. Long-term outcomes were consistently more highly related to scores from Year 2 than Year 1 (see Tables 4 and 5). Further, the addition of growth as a predictor in the regression model for verbal working memory accounted for similar amounts of variance as the Year 1 scores, indicating that the predictive power of SP-L skills for verbal working-memory outcomes approximately doubled from Year 1 to Year 2 (see Table 6). Current clinical recommendations are to use the results of early postimplant assessments to identify potential areas of concern in order to facilitate the development of strategies that clinicians and families can use to support a child's progress, rather than to label a child as low-performing (Bradham & Houston, 2014; Robbins, 2007). The stronger relation between long-term outcomes and SP-L skills when assessed in Year 2 than in Year 1 in the present data indicates that this approach is especially important for postimplant assessments taken within the first year of implant experience.

Large individual differences in language and neurocognitive outcomes were observed, in line with the enormous variability that is typical of outcomes following cochlear implantation (Niparko et al., 2010; Pisoni et al., 2008; Svirsky et al., 2004). Neurocognitive outcomes are much less studied than speech and language outcomes but represent an important domain of individual differences in the benefit received from a CI. In comparison to peers with NH, pediatric CI users have an elevated risk of delays and deficits in several areas of EF including behavioral regulation, working memory, inhibition-concentration, and parent-reported everyday neurocognitive functioning (Beer et al., 2014; Beer, Kronenberger, & Pisoni, 2011; Figueras et al., 2008; Kronenberger et al., 2013; Kronenberger, Beer, Castellanos, Pisoni, & Miyamoto, 2014; Pisoni & Cleary, 2003). Language development is closely linked to EF, especially verbal working memory (Adams & Gathercole, 1995) and cognitive control over thoughts and behaviors when mediated by self-talk (Fuhs & Day, 2011; Vygotsky, 1978; Winsler, Fernyhough, & Montero, 2009). For pediatric CI users, speech and language abilities may be more strongly associated with verbal working memory than for their peers with NH (Kronenberger, Colson, et al., 2014). Thus, early auditory deprivation and consequent delay in language development evidently have consequences for neurocognitive development in addition to speech and spoken language development. In the current study, SP-L skills at 6 and 18 months after implantation predicted verbal working memory and parent-reported EF after a decade and a half of CI use, and these predictive relations were not explained by conventional demographic or hearing-history variables. Castellanos et al. (2016) reported similar predictive results on the basis of early expressive language skills measured after an average of 1 year of implant use. Taken together, these findings suggest that early postimplant measures of speech and language skills are markers of risk for delays and disturbances in EF after long-term CI use.

Speech and language and EF almost certainly have a bidirectional relationship in development (Singer & Bashir, 1999; Zelazo et al., 2003). For example, it is generally accepted that children who have high verbal working-memory capacity also have an advantage in vocabulary acquisition, because they are better able to encode and store unfamiliar sequences of speech sounds in memory and to link novel sound sequences with word meanings (Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1989). Verbal working-memory capacity of pediatric CI users has been shown to predict later language skills (Harris et al., 2013). Interdependence of language and EF development may be an important consideration in the design of interventions to improve the development of language and EF in children with CIs and who are lower-functioning. Although speech-language therapy is universally available to pediatric CI users, assistance for neurocognitive development is not routinely provided. In this context, it is notable that long-term language outcomes were more strongly predicted by Year 1 SP-L skills than verbal working-memory outcomes, and that the increase in predictive power from Year 1 to Year 2 was greater for the verbal working-memory and other neurocognitive outcomes than for the language outcomes (see Tables 4–6). This pattern in the current data may provide some indication that long-term neurocognitive outcomes could potentially be more plastic in the years immediately following cochlear implantation than long-term language outcomes. Given links between language and neurocognitive development, future intervention strategies that target both language and neurocognitive skills with a view toward their mutual development may hold promise for children who are lower-functioning, deaf, and use CIs (Singer & Bashir, 1999). For example, instruction in how to use self-talk to reason through problems could possibly help children with CIs practice EF and language skills in tandem (Figueras et al., 2008; Winsler et al., 2009).

In the present study, we also found that SP-L skills in the first 2 years after cochlear implantation were related to open-set word recognition in Years 3 and 4, which was in turn found to be related to long-term SP-L outcomes. This pattern suggests continuity between early SP-L skills measured within the first 18 months of implant use, open-set word recognition, and long-term speech and language outcomes. Open-set word recognition is considered one of the most important benchmarks of a good CI outcome because it is an indication of the ability to recognize spoken words in a naturalistic format—that is, without a closed set of response alternatives—and thus has face validity as a measure of the ability to recognize spoken language in everyday life. Close links with open-set word recognition have been observed for concurrently measured speech perception, production, and vocabulary (Blamey et al., 2001; Geers, Brenner, & Davidson, 2003). However, the field is still far from understanding why a significant minority of CI recipients do not achieve open-set word recognition in a timely fashion. A recent prospective study of children who failed to achieve open-set word recognition by the age of 5 years focused exclusively on conventional demographic and hearing-history factors, finding that older age at implantation, less preimplant residual hearing, lower maternal sensitivity, minority status, and complicated perinatal history predicted failure to achieve open-set word recognition (Barnard et al., 2015). Demographic and hearing-history factors are available to the medical team prior to implantation. However, early postimplant indicators of the risk of failing to achieve open-set word recognition are also of considerable interest.

The current findings suggest that speech-language skills measured early postimplant predict the ability in the next few years of recognizing spoken words in an open-set format, and that open-set word recognition predicts long-term SP-L outcomes. Nevertheless, it should be noted that we did not observe a reliable correlation between early postimplant SP-L skills and long-term speech-perception outcome, indicating that relatively little variance was shared between the predominantly closed-set early SP-L assessments and the open-set sentence-recognition assessments that composed the long-term outcome measure of speech perception. This null finding may be due to the differing nature of the tasks involved, to substantial development of speech-perception skills after the first 2 years of CI use, or both.

Limitations of the current study stem from the challenges of carrying out a retrospective study of a clinical sample across decades. Our analyses relied on a relatively small sample size with a wide range of chronological ages. The effects of chronological age on early SP-L scores were statistically controlled by using partial correlations and including age of implantation at the first step in the regression analyses. Therefore, the results reflect children's early SP-L performance relative to their chronological age. Although the results appear to be representative of the children in the sample who received CIs earlier than age 4 years (see earlier), it will be important to replicate the current findings in other samples from this clinical population.

A related limitation is that our participants received CIs at relatively late ages (M = 3.25, range = 1.4–6.1 years) in comparison to what is now standard clinical practice (Niparko et al., 2010). Children who receive implants earlier in life may be more likely to improve their speech and language skills after the first and second year postimplantation. Thus, the most direct application of the current results is to older children who present as candidates for implantation (Osberger et al., 2006). Further work, which should use a set of assessments suitable for very young children (see, e.g., Nikolopoulos et al., 2005; Osberger et al., 2006), will be needed to determine whether long-term outcomes for children who received CIs at younger ages than our sample can be predicted by early postimplant scores on speech and language assessments. However, such studies will not be available until a cohort of children who received CIs according to current clinical criteria and who have been assessed early postimplant have had long-term experience and activity with their implants. The cohort of children included in the current study is to our knowledge a unique clinical sample in terms of the time period of observation, ranging from the earliest years postimplant to after a decade or more of CI use, and in terms of the assessments that have been completed, which constitute a broad profile of SP-L as well as neurocognitive functioning.

A further limitation, again related to the retrospective nature of the study design, is that not all participants completed all of the early assessments that were used to create the composite measure of early SP-L. It is possible that missing data could have influenced the current results. This could occur if a child's performance on unavailable subtests would have been different, relative to available scores from the rest of the sample for that subtest, from his or her performance on the available subtests, again relative to available scores from other participants in the sample. However, participants' scores on the individual subtests were strongly correlated (see Supplemental Material S1–S4). In addition, given that our predictor in this study was a composite measure of SP-L skills, we cannot tease apart the relation of any single subtest of early postimplant SP-L to long-term outcomes. In particular, our composite measure of early SP-L included assessments of speech perception as well as receptive and expressive language. Translation of the speech-perception measures used in the current study into clinical practice for prediction of long-term outcomes may also be limited by the fact that these measures are nonstandardized.

Last, although the relations observed between early SP-L and long-term outcomes were not explained by conventional demographic factors alone—such as age of implantation, duration of deafness, hearing history, and others (see Table 1)—other potentially important demographic factors were not collected from this sample, including parent education, quality of the language environment in the home (Szagun & Stumper, 2012), and family support (Holt, Beer, Kronenberger, & Pisoni, 2013; Holt, Beer, Kronenberger, Pisoni, & Lalonde, 2012). It remains possible that if additional demographic factors had been included, early SP-L abilities would not have had a significant additional influence on long-term outcomes. However, it should be noted that household income, which was included as a demographic variable in the regression analyses, is typically correlated with parent education and may be considered, together with parent education, as a proxy for socioeconomic status (Geers, Nicholas, & Moog, 2007).

In summary, the current study investigated the relations between SP-L skills measured early postimplantation and long-term SP-L and neurocognitive outcomes in a sample of pediatric CI users after a decade and a half of CI experience. The primary findings were that SP-L skills measured as early as 6 months after cochlear implantation predicted long-term language, verbal working memory, and parent-reported EF, and that growth of SP-L skills from 6 to 18 months postimplantation predicted long-term language and verbal working-memory outcomes. These findings were obtained even after conventional demographic and hearing-history measures and nonverbal IQ were statistically removed from the analyses. The present results indicate that speech and language skills measured after as little as 6 months of experience and activity with a CI may have clinical utility in identifying children who may be at high risk for poor long-term language and neurocognitive outcomes and, further, that interventions within the first 18 months of implant use focus on a developmental period during which improvement in speech and language affects long-term outcomes.

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