

Predicting 9-Year Language Ability from Preschool Speech Recognition in Noise in Children Using Cochlear Implants

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Abstract

The presence of congenital permanent childhood hearing loss has a negative impact on children's development and lives. The current literature documents weaknesses in speech perception in noise and language development in many children with hearing loss. However, there is a lack of clear evidence for a longitudinal relationship between early speech perception abilities and later language skills. This study addressed the evidence gap by drawing on data collected as part of the Longitudinal Outcomes of Children with Hearing Impairment (LOCHI) study. Cross-lagged regression analyses were used to examine the influence of speech perception in noise at age 5 years on language ability at age 9 years and vice versa (i.e. the influence of language ability at age 5 years on speech perception in noise at age 9 years). Data from 56 children using cochlear implants were analysed. We found that preschool speech perception in noise was a significant predictor of language ability at school age, after controlling for the effect of early language. The findings lend support to early intervention that targets the improvement of language skills, but also highlight the need for intervention and technology to enhance young children's auditory capabilities for perceiving speech in noise in early childhood so that outcomes of children with hearing loss in school can be maximized.

Keywords

speech perception, language skills, children, cochlear implants, longitudinal relationship

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Introduction

Pinker (1994, p. 161) referred to speech perception as “one of the biological miracles making up the language instinct.” Infants' ability to perceive speech during the first year of life not only contributes to their development of phonological aspects of language, but also to later acquisition of syntactic and semantic knowledge (Gervain & Mehler, 2010; Kuhl et al., 2008; Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005). Given the importance of speech perception in early spoken language development, it is not surprising that young children with hearing loss generally perform below the level of their hearing peers on assessments of spoken language (e.g., Cupples et al., 2018; Lund, 2016; Tomblin et al., 2015; Wake, Poulakis, Hughes, Carey-Sargeant, & Rickards, 2005). What is missing from the current published research base, however, is clear evidence for a longitudinal relationship between early speech perception abilities and later language skills in children with hearing loss. The current study was aimed primarily at filling this gap in the literature, using data from children with congenital severe to profound

hearing loss who experienced a period of auditory deprivation early in life prior to receiving treatment with cochlear implants (CIs).

Increased understanding of the longitudinal relationship between speech perception and language development has important theoretical and practical implications, including for effective intervention for hearing loss in children. From a theoretical perspective, the effect of speech perception on language ability can be understood within the framework of Native Language Magnet theory (NLM; Kuhl et al., 2005) and Native Language Magnet theory – expanded (NLM-e; Kuhl et al., 2008). According to this theory,

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children's exposure to their native language during the first year of life is associated with enhanced sensitivity to native phonetic contrasts and decreased sensitivity to non-native phonetic contrasts. This developmental pattern is, in turn, associated with better language acquisition over the following two years of life. Although hearing loss is not a focus of the model, Kuhl et al. (2008) acknowledged that, for infants to learn native phonetic contrasts, they must possess the auditory ability to discriminate between phonetic units at birth. As such, the NLM-e model can be applied in an effort to understand how language development might be adversely affected by poor speech perception, especially in children who have experienced a period of auditory deprivation as a result of severe to profound congenital hearing loss before they receive treatment with CIs.

With regard to empirical studies examining the effect of speech perception on language development, it is important to acknowledge that the data they report are typically correlational in nature, rather than causal. Nevertheless, individual research studies can be distinguished according to their focus on a particular unidirectional relationship; namely, the effect of speech perception on language, or the effect of language on speech perception. Given the theoretical relevance of this distinction, the following review of empirical findings is organized according to whether the studies focused on the effect of speech perception on language, as per the current research, or the effect of language on speech perception, an alternative research focus. In addition, given the developmental focus of the current research, a further organizing principle relates to the use of concurrent or longitudinal data. Concurrent data, which are also referred to as cross-sectional data, are collected at a single point in time; whereas longitudinal data are collected on more than one occasion over time.

Relationship Between Speech Perception and Language Measured Concurrently

Effect of Language on Speech Perception. To date, the majority of published studies that investigate the relationship between speech perception and language use concurrent measurement of the two variables, and focus on the effect of language on speech perception. This approach is based on the premise that listeners with stronger language skills will be better able to fill any gaps in the auditory input. Along these lines, McCreery et al. (2017) investigated the effects of working memory and language ability on recognition of speech in noise (SIN), which is a commonly used measure that approximates speech perception in real-world settings. A sample of ninety-six 5- to 12-year-old children with typical hearing took part. Regression analyses showed that receptive vocabulary and working memory were both significant predictors of SIN for low and zero predictability sentences when measured concurrently. On the other hand, SIN for monosyllabic words was predicted by working

memory but not by vocabulary knowledge. McCreery et al. noted that the latter finding was not consistent with their expectations for a positive association between vocabulary knowledge and SIN across all stimulus types. They suggested that the absence of the predicted association may have been due to all words in the SIN task being within the lexicons of the child participants. This reasoning was based on other results showing a *selective effect of vocabulary knowledge on recognition of words acquired late in development* (Klein, Walker, Kirby, & McCreery, 2017).

In two subsequent studies, language skill was related to SIN in children with hearing loss. Ching et al. (2018) reported on a large sample of 5-year-old children, 168 using hearing aids (HAs) and 84 using CIs. Regression analyses were conducted separately for the HA and CI groups. In both groups, a standardized measure of language ability, the Pre-school Language Scale version 4 (PLS-4; Zimmerman et al., 2002), accounted for significant variance in SIN after controlling for demographic variables including: age at fitting of HAs or cochlear implantation, presence of additional disabilities, maternal education, communication mode, and non-verbal cognitive ability. Further evidence comes from a study by von Koss Torkildsen, Hitchins, Myhrum, and Wie (2019) who reported that language ability accounted for significant unique variance in SIN after controlling for speech perception in quiet in groups of children, ages 5.5 to 12.9 years, using HAs or CIs. Notably, however, a similar association was not found for children with typical hearing.

In brief, findings are mixed in regard to whether children's speech perception, as measured using SIN tasks, might be influenced by their language ability. Of greater direct relevance to the current study, however, is the possibility of a link in the opposite direction; that is, the role of speech perception in language development.

Effect of Speech Perception on Language. This issue was investigated in a recent study conducted by Davidson, Geers, Uchanski, and Firszt (2019). They reported on a group of 117 CI recipients, 5 to 9 years of age, whose speech perception was assessed using segmental tasks (in noise and in quiet) and suprasegmental tasks (e.g. emotion identification, talker discrimination, and stress discrimination). Regression analyses were used to examine the effect of speech perception on concurrently measured receptive language (assessed using the Clinical Evaluation of Language Fundamentals 4th edition [CELF-4]; Semel, Wiig, & Secord, 2003), and receptive vocabulary (assessed using the Peabody Picture Vocabulary test 4th edition [PPVT-4]; Dunn & Dunn, 2007). The results showed that, after controlling for nonverbal IQ, age at cochlear implantation, gender, and maternal education, segmental and suprasegmental speech perception skills each accounted for significant unique variance in receptive vocabulary scores; and suprasegmental skills accounted for significant unique variance in receptive language scores.

In an earlier study of younger children, ages 2.5 to 6 years, DesJardin, Ambrose, Martinez, and Eisenberg (2009) also reported findings consistent with the view that speech perception affects early language ability when measured concurrently. In their sample of 18 children with hearing loss, 11 used HAs and 7 used CIs. Regression analyses showed that children's scores for speech perception in quiet accounted for significant unique variance in mean length of utterance after controlling for child age. The authors concluded that their findings confirm how important it is for children to acquire speech perception skills and phonological knowledge in order to develop their language skills.

A third study to consider the effect of speech perception on language ability was reported by Chen, Wong, Zhu and Xi (2015). They used a Structural Equation Modeling (SEM) approach to examine the influence of concurrently measured demographic variables on speech perception (in noise and in quiet) and vocabulary abilities in a sample of 115 Mandarin-speaking children with CIs, ages 2.5 to 7.1 years. In the final model, 26% of the variance in speech perception scores was explained, compared to a much larger 74% of variance in vocabulary scores. Chronological age and age at cochlear implantation had a significant effect on both speech perception and vocabulary; whereas maternal education had a significant effect on vocabulary only. Of most relevance in the current context, however, is their finding that, of all variables included in the analysis, the strongest individual contributor to children's vocabulary ability was their speech perception (Chen et al., 2015).

Up to this point, we have considered research that investigates the association between speech perception and language using concurrently collected data. In light of the current research focus on development, however, studies that encompass a longitudinal aspect are of primary concern.

Relationship Between Speech Perception and Language Measured Longitudinally

Effect of Language on Speech Perception. In regard to the effect of language on speech perception, McCreery et al. (2015) reported on a group of 49 HA users who were assessed at 3- and 5-years-of-age. A linear regression model was used to investigate the association between children's receptive language ability at 3-years-of-age and their 5-year-old speech perception scores, measured using recognition of words presented in quiet. The results showed that 3-year-old receptive language accounted for significant unique variance in 5-year-old speech perception after controlling for variation in aided audibility (which was also significant), degree of hearing loss, and maternal education.

Walker, Sapp, Oleson, and McCreery (2019) also investigated the effect of language on speech perception using longitudinal data. They reported growth trajectories in SIN for a large group of 199 children with mild to severe hearing loss who were fitted with HAs and were approximately 7, 8, 9, or

10 years old (grade 1 to grade 4 respectively). The results showed that there was significant growth in SIN from 1st to 4th grade; that children with hearing loss showed a growth trajectory similar to that of children with typical hearing; and that vocabulary skill was a significant predictor of the rate of growth after controlling for grade, maternal education, age at confirmation of hearing loss, average working memory, and hearing aid dosage. They concluded that better vocabulary skills support better SIN, and that this pattern is stable across Grades 1 to 4. They also acknowledged, however, that their current analysis approach did not enable them to determine the direction of the relationship between vocabulary and SIN, because they did not investigate the reverse association, of SIN on language.

Finally, a longitudinal study by Hunter et al. (2017) also reported data relevant to the effect of early language on later speech perception. Participants in the study were 36 CI users, ages 17.8 years on average, who received their devices approximately 14 years earlier. Early measures of speech perception and language ability, which were collected one or two years post-implantation, were used to form a composite predictor variable. It encompassed scores on the Pediatric Speech Intelligibility Test (PSI; Jerger & Jerger, 1984), the Mr Potato Head Task (Robbins, 1994), and the Reynell Developmental Language Scales II (RDLS; Reynell & Gruber, 1990). However, the findings provided little support for an effect of early language on later speech perception in that the correlation between the composite measure of early speech perception and language was not significantly associated with later speech perception (measured in noise and in quiet) after controlling for age.

Effect of Speech Perception on Language. Importantly, data from the Hunter et al. (2017) study also reflect on the question of whether early speech perception might influence later language outcomes. In this regard, the results from correlation analyses, which controlled for age, provide evidence of a significant positive association between the early composite measure of speech perception and language ability and a measure of later language ability that included receptive language (CELF-4) and receptive vocabulary (PPVT-4). Moreover, a subsequent regression analysis shows that the early composite measure of speech perception and language ability was significantly associated with later language outcomes after controlling for age at implantation, pre-implant PTA, household income and non-verbal IQ.

While findings of the Hunter et al. (2017) study are relevant to the current research focus, it is worth noting that their study was not designed to reflect on the question of whether early speech perception *or* early language in particular influenced later outcomes, because the early predictor measure was a *composite* of speech perception and language.

Furthermore, the study participants differ from those in other related studies reviewed here. They received their CIs at a relatively late age (from 1.44 to 6.12 years) compared to current standards, and had considerably more experience with their CIs (from 8.19 to 22.44 years) at the long-term follow-up assessment. Most importantly, however, they were older at follow-up testing, with ages ranging from 11.59 to 27.39 years. In this regard, it seems likely, that the link between speech perception and language may well be especially relevant for younger participants, in particular those of early-school-age, because of the increased importance at that time of children's ability to recognise speech in noisy environments, especially classrooms. These considerations highlight the need for a study to collect longitudinal data on the reciprocal association between speech perception and language ability in children of primary school age whose audiological experiences with cochlear implantation are more in line with current practice.

Summary

Previous research studies investigating the association between speech perception and language ability have approached the issue from different perspectives. Using concurrent measures of speech perception and language, some researchers have obtained evidence for the effect of speech perception on language abilities (e.g., Chen et al., 2015; Davidson et al., 2019; Desjardin et al., 2009), whereas others have obtained evidence for the effect of language

ability on speech perception (e.g., Ching et al., 2018; Klein et al., 2017; McCreery et al., 2017; von Koss Torkildsen et al., 2019). At the same time, longitudinal studies have also started to appear in the literature (e.g., Hunter et al., 2017; McCreery, Walker, et al., 2015; Walker et al., 2019) to examine the role of early capabilities on later performance. There is an obvious need for additional longitudinal investigations that examine the reciprocal association between speech perception and language ability in children using CIs who were deprived of auditory stimulation early in life as a result of severe to profound congenital hearing loss. The current study was designed to address this gap in the literature.

The Current Study

The longitudinal study described here was aimed at examining the impact of early speech perception on later language ability, and vice versa. The participant sample was drawn from the cohort taking part in the Australian population-based study examining 'Longitudinal Outcomes of Children with Hearing Impairment' or the LOCHI study (Ching, Leigh, & Dillon, 2013). The current study drew on data collected at 5 years of age for predicting outcomes collected at 9 years of age in children using CIs.

The research questions addressed in the study were as follows:

1. Does early speech perception (at 5 years of age) predict later language outcomes (at 9 years of age) in a population-based sample of CI users after controlling for variation in age at cochlear implantation, maternal education, and 5-year-old language?
2. Does early language (at 5 years of age) predict later speech perception (at 9 years of age) in a population-based sample of CI users after controlling for variation in age at cochlear implantation, maternal education, and 5-year-old speech perception?

In regard to research question 1, we hypothesized that 5-year-old speech perception would predict 9-year-old language outcomes on the basis of previous empirical findings showing an effect of speech perception on language for variables measured concurrently (e.g., Chen et al., 2015; Davidson et al., 2019; Desjardin et al., 2009). In regard to research question 2, we offered no definitive hypothesis, in light of mixed results in past studies for variables measured longitudinally. Thus, although McCreery et al. (2015) reported an association between early language and later speech perception, Hunter et al. (2017) reported that a composite measure of early speech and language was not significantly associated with later speech perception outcomes for a group of teenagers and adolescents with CIs.

Table 1. Demographic Characteristics of Study Participants.

Characteristics	No. of participants (%)	
Sex		
Female	34 (60.7)	
Male	22 (39.3)	
Hearing device	Age: 5 years	Age: 9 years
Bilateral CI	42 (75.0)	48 (85.7)
CI + HA	13 (23.0)	8 (14.3)
*Unilateral CI	1 (2.0)	0 (0.0)
Age at first CI [#] (months)		
Mean (SD)	19.3 (11.0)	
Interquartile range	9.9–26.7	
Min-Max	5.3–46.8	
Maternal education		
1. University or Diploma	38 (68.0)	
2. 12 years or less of schooling	18 (32.0)	

* Bilateral profound hearing loss, with a cochlear implant in one ear only.

Cochlear implant activation.

Method

Participants

The Australian Hearing Human Research Ethics Committee approved the protocols used in the current study. Participants in the LOCHI study were included if they received a CI before 4 years of age; and completed direct assessments of speech perception in noise and language abilities at 5 and 9 years of age. Data on measures of 56 participants in the LOCHI study were included in this report. All participants use Nucleus cochlear implants manufactured by Cochlear Limited (Sydney, Australia) programmed by their case managers at cochlear implant centres. All participants use spoken English at home as the primary mode of communication, 21 of them also use a second language at home. Eight participants have additional disabilities, including vision impairment (3), auditory neuropathy spectrum disorder (2), dyspraxia (1) and Waardenburg Syndrome with Hirschsprung's disease (2). All have nonverbal IQ of >75, as assessed by professionals at 5 or 9 years of age using the Wechsler Nonverbal Scale of Ability (WNV, Wechsler & Naglieri, 2006). Table 1 provides descriptive statistics of the demographic characteristics of the current sample.

Procedure

Parents of participants provided written informed consent to the protocol approved by the local institutional human research review board. As part of the LOCHI study, each child was assessed directly by research audiologists on speech perception in noise at 5 and 9 years of age. The language ability of children was assessed at the same time points by speech pathologists on norm-referenced tests using standard protocols. All data were audited and checked for reliability by double scoring 10% of the evaluations.

Measures

Speech Perception in Noise

For measurement of speech perception in noise, the Northwestern University Children's Perception of Speech Test (NU-CHIPS, Elliott & Katz, 1980) or the Bamford-Kowal-Bench (BKB, Bench & Doyle, 1979) sentence material was used. The NU-CHIPS is a closed-set test requiring a picture-pointing response. Children were asked to respond to a speech stimulus by pointing at one of four pictures that best depicted the word they heard. Each list comprised 50 words. The BKB is an open-set test requiring children to repeat as much of the stimulus sentence as possible. Each list comprised 16 sentences with 50 score items. Each child completed either the NU-CHIPS or the BKB test, depending on test compliance, cognitive or language abilities, as judged by research speech pathologists who completed language assessments of the children.

For both types of speech material, digital recordings of native Australian English speakers were used as stimuli, and 8-talker speech babble was used as the competing sound to approximate listening in real-world situations. Testing was carried out in a sound-treated booth. The stimuli were presented in the free field, via an audiometer with the output channels connected to amplifiers and a loudspeaker located at 0° azimuth at a distance of 0.75m from the subject position. The speech stimuli were presented at 65 dB SPL in competing speech babble.

The children wore their cochlear implants at personal settings during assessment. Prior to testing, all children were given a practice run. During testing, the researcher monitored the child closely and provided verbal encouragement but did not provide feedback about the correctness of responses.

An adaptive procedure was used to measure the speech reception threshold (SRT) for 50% correct, in terms of signal-to-noise ratio (SNR; Mackie & Dermody, 1986). The level of the babble was varied according to whether a child identified a word correctly (in the NU-CHIPS) or repeated more than half of the keywords in a sentence correctly (2 out of 3 words in each BKB sentence). After practice, the test began with an SNR of 10 dB. The adaptive procedure began with a step size of 5 dB to achieve two reversals, followed by adjustments with a step size of 1 dB. The test stopped after 12 reversals with 1 dB step size were obtained (typically 2 lists) from each child. The SRT was the mean of the midpoints of the last 10 reversals, expressed as SNR. The standard error of the mean for each SRT was within 1 dB.

Language Assessments

The Peabody Picture Vocabulary Test 4th Edition (PPVT-4; Dunn & Dunn, 2007) was administered by research speech pathologists to the children at 5 years of age. This is a standardized test of receptive vocabulary, using a four-alternative-forced choice, picture-pointing format in administration. It gives an overall score on receptive vocabulary. The Clinical Evaluation of Language Fundamentals – 4th Edition (CELF-4; Semel et al., 2003) was administered to the children at 9 years of age. The CELF is a standardized test of spoken English. The test includes verbal tasks which enable children to demonstrate understanding of and ability to produce English language structures. It gives an overall core language score, and two subtest scores – receptive language and expressive language.

Parents completed a study questionnaire to provide demographic information, including their own level of education. Audiological information was retrieved from individual clinical files by chart review, with permission from parents.

Statistical Analyses

Descriptive statistics were used to report quantitative outcomes for each measure. To examine the relationship

Table 2. Descriptive Statistics for Language and Speech Perception Measures.

	Time 1 (T1): Age 5 years		Time 2 (T2): Age 9 years		Difference				Paired t-test for difference in means		
	Mean	SD	Mean	SD	T1-T2	SD	95% CI		t	df	p
RecLg	90.2	18.9	89.4	17.8	0.8	11.2	-3.9	2.4	0.5	50	0.629
SRT	7.0	5.0	2.5	2.4	4.5	4.5	-5.7	-3.3	7.4	50	<.0001

Note. RecLg = Receptive Language score: Peabody Picture Vocabulary Test standard score at 5 years of age; and CELF Receptive Language standard score at 9 years of age. SRT = Speech reception threshold for 50% correct, expressed as signal-to-noise ratio in decibel or dB SNR, measured in a speech perception in noise test.

between early measures of speech perception and later language ability, multiple linear regression analyses were conducted. The dependent variable was the CELF-4 receptive language standard score at age 9 years (Y9RecLg) in a first set of regression models. This set included 4 models, with the first model comprising two demographic characteristics - age at first cochlear implant activation (AgeCI) in months and maternal education (MEdn) as predictor variables. Maternal education was specified as a categorical variable with two levels, University or Diploma education versus formal schooling of ≤ 12 years. These factors were found to be significant predictors of children's speech perception in noise at age 5 years (Ching et al., 2018). The second model had additional predictor variables including the speech perception in noise score at age 5 years (Y5SRT), the speech test used for testing at 5 years (NUCHIPS or BKB), and an interaction term between maternal education and speech test. The third model had the two demographic characteristics and receptive vocabulary score at age 5 years (Y5PPVT) as predictor variables. The fourth model included all variables used in the first three models as predictor variables. To examine the relationship between speech perception at age 9 years and early language ability, a second set of regression models was fitted using speech perception in noise at 9 years (Y9SRT) as the dependent variable in a similar manner. The cross-lagged analyses were restricted to children who had language and speech perception measures at both 5 years and 9 years of age so that the analyses were directly comparable for the measures on the same group of children. Statistical analyses were performed using the Statistica software v.10 (Statsoft Inc, 2011). Statistical significance was set at the .05 level.

Results

Descriptive statistics for the scores of outcome measures are shown in Table 2. The mean scores on receptive vocabulary and language were within 1 SD (15) of the norm-referenced mean score of 100. The mean standard scores for receptive vocabulary and language showed little change with age. For speech perception in noise testing, 15 completed the BKB and 36 completed the NU-CHIPS at 5 years of age. All completed the BKB at 9 years of age. Speech perception performance was more than 2 SDs below the norm-

referenced mean score of -2.5 dB (SD 3.0) at age 5 years for NU-CHIPS, and -1.3 dB (SD 1.2) at age 5 years and -2.1 dB (SD 0.9) at age 9 years for BKB (Ching et al., 2011). There were improvements in speech perception in noise over time, and the difference in SRT was significant ($p < 0.001$; mean difference of 4.5 dB, 95% CI: [-5.7, -3.3]).

Relationship Between Measures of Language and Speech Perception in Noise

The correlations between language and speech perception scores at age 5 and 9 years are presented in Table 3. Concurrent measures of speech perception and receptive language were significantly correlated. At 5 years of age, children who perceived speech in noise better also had better receptive vocabulary. At 9 years of age, children who perceived speech in noise better also achieved better scores on receptive language. Across the two age intervals, early speech perception was significantly correlated with later speech perception. In a similar vein, early receptive vocabulary was significantly correlated with later receptive language. The speech perception score was negatively associated with concurrent and longitudinal receptive language scores, and these correlations were significant ($p < 0.001$). Better speech perception in noise, or lower SRT, was associated with higher language score.

To examine the longitudinal relations between speech perception and receptive language measures at both time points, cross-lagged regression analyses were performed with the same participants included in each set of models. Two separate sets of models were tested, first with receptive language at 9 years as a dependent variable, then with speech perception at 9 years as a dependent variable.

Table 4 shows regression models for predicting 9-year-old receptive language. The contribution of maternal education level was significant, but the age at activation of CI was not (model 1). Adding the 5-year speech perception score or the receptive vocabulary score resulted in a significant increase in the total proportion of variance accounted for by the models (models 2 and 3). The full model (model 4) shows that 5-year speech perception was a significant predictor of 9-year language, after controlling for the effect of 5-year receptive vocabulary. The effect of speech test

Table 3. Correlations (Pearson's *r*) between Speech Perception and Language Measures at age 5 Years and 9 Years.

	Y5PPVT	Y5SRT	Y9RecLg	Y9SRT
Y5PPVT	-			
Y5SRT	-0.46**	-		
Y9RecLg	0.83***	-0.52***	-	
Y9SRT	-0.40**	0.46**	-0.37*	-

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Note. Y5PPVT = Peabody Picture Vocabulary Test standard score at 5 years of age; Y5SRT = Speech reception threshold for 50% correct, expressed as signal-to-noise ratio in decibel or dB SNR, in a speech perception in noise test at 5 years of age; Y9RecLg = CELF Receptive Language standard score at 9 years of age; and Y9SRT = Speech reception threshold in dB SNR at 9 years of age.

material at 5 years of age was not significant ($p = 0.34$). This model accounted for 70.0% of the total variance in 9-year-old receptive language scores. Figure 1 shows that better speech perception at 5 years of age was associated with higher language scores at 9 years of age.

Table 5 shows regression models predicting 9-year-old speech perception. The contribution of maternal education level was significant, but the age at activation of CI was not significant (model 1). Adding either the 5-year receptive vocabulary score or the speech perception score accounted for a significant increase in the proportion of variance accounted for by the models (models 2 and 3). The full model (model 4) shows that 5-year-old receptive vocabulary was not a significant predictor of 9-year-old speech perception, after controlling for the significant effect of 5-year-old speech perception ability. The effect of speech test material at 5 years of age was not significant ($p = 0.09$). This model accounted for 34.0% of the total variance in 9-year-old speech perception ability (model 4).

Discussion

We report an investigation of the longitudinal relationship between speech perception abilities and language skills in children using CIs. Our first aim was to determine whether speech perception in noise at 5 years of age predicted 9-year-old language outcomes. We found a longitudinal relationship between speech perception in noise measured at 5 years of age and language ability measured at 9 years of age, after controlling for the effect of 5-year-old receptive vocabulary, maternal education and age at CI activation. The size of the regression coefficient between early speech perception and later language ability is modest (model 4, Table 4). However, it is noteworthy that the significant relationship should be identified in a prospective study with a four-year interval during which children transitioned from early intervention to formal schooling, a significant milestone in the lives of young children (Curle et al., 2017).

Our findings are broadly consistent with results reported by Davidson et al. (2019) in their study of the relationship between speech perception and language outcomes measured concurrently in children with CIs, but extends the evidence of relationship to longitudinal measures showing that 5-year-old speech perception in noise skills predicted 9-year-old language abilities, after controlling for the effect of early receptive vocabulary. The observed longitudinal relationship between pre-school and school age in children using CIs lends support to theoretical models of native language acquisition (NLM-e, Kuhl et al., 2008) that emphasizes the critical role of speech perception in early language acquisition.

Our second aim was to determine whether receptive vocabulary at 5 years of age predicts 9-year-old speech perception in noise outcomes, after controlling for variation in 5-year-old speech perception in noise. We found a longitudinal association between language ability measured at 5 years of age and speech perception in noise at 9 years of age, broadly consistent with previous reports on children using hearing aids (McCreery et al., 2015; Walker et al., 2019). McCreery et al. showed that pre-school children who had higher receptive language scores at 3 years of age also had higher word perception in quiet scores at 5 years of age. For school-age children between 7 and 10 years of age, Walker et al. (2019) showed that vocabulary level was a significant factor supporting growth for speech perception in noise. However, the two previous studies did not control for the effect of early speech perception ability on later performance. Our present results from the cross-lagged analyses show that the association between early vocabulary and later speech perception was no longer significant after controlling for the effect of early speech perception (see model 4, Table 5).

Although not a primary focus of this study, we note that on average, children's SRTs improved from 5 to 9 years of age by about 4.5 dB. The decrease in SRT with increase in age has been reported in previous literature (Byrne, 1983; Ching, van Wanrooy, Dillon, & Carter, 2011; Garadat & Litovsky, 2007; Litovsky, 2005), and has been attributed to efficiency of neural coding (Schneider, Trehub, Morrongiello, & Thorpe, 1986); maturation of central auditory processes and development of listening strategies (Allen & Wightman, 1994; Lutfi, Kistler, Oh, Wightman, & Callahan, 2003) as well as concomitant changes in speech and language abilities (Blamey et al., 2001; Byrne, 1983; Elliott, 1979). Despite the improvement, 9-year-old children using CIs need to learn in noisy classrooms or academic settings with an average deficit of about 5 dB SNR compared to their normal-hearing peers (Ching et al., 2011).

Why might children with better speech perception in noise skills at pre-school age achieve better language at school age? Children who have better speech perception skills at preschool age also develop better language, as shown by the correlations between concurrent measures of speech perception and language ability (Table 3). This may be explained by the ability

Table 4. Set of Models Using 9-Year-old Language as the Dependent variable. Multiple Regression Summary Table Showing Unstandardized Coefficient Estimates (Beta-Values), 95% Confidence Intervals (95%CI) and Significance Levels (p-Values) of Predictor Variables. Bolded Entries Indicate Significance at <.05 Level.

	Model 1			Model 2			Model 3			Model 4		
	Beta	95%CI	p-value	Beta	95%CI	p-value	Beta	95%CI	p-value	Beta	95%CI	p-value
AgeCI	-0.07	(-0.34, 0.20)	0.62	0.00	(-0.25, 0.25)	0.99	0.14	(-0.03, 0.31)	0.11	0.14	(-0.03, 0.31)	0.10
MatEdn	0.35	(0.08, 0.62)	0.01	0.26	(0.03, 0.54)	0.08	0.10	(-0.07, 0.27)	0.25	0.07	(-0.13, 0.27)	0.48
Y5SRT				-0.47	(-0.71, -0.23)	<0.001				-0.19	(-0.37, -0.01)	0.04
Y5PPVT							0.82	(0.64, 1.00)	<0.0001	0.71	(0.52, 0.90)	<0.001
Y5Sp Test				0.21	(-0.07, 0.45)	0.14				0.15	(-0.04, 0.34)	0.34
MatEdn*				-0.02	(-0.34, 0.30)	0.89				-0.04	(-0.25, 0.17)	0.70
Y5Sp Test												
AdjR ²	0.10		<0.001	0.33		<0.0001	0.67		<0.0001	0.70		<0.0001

Note. AgeCI = Age at first cochlear implant activation, in months; Y5SRT = Speech reception threshold for 50% correct, expressed as signal-to-noise ratio in decibel or dB SNR, in a speech perception in noise test at 5 years of age; Y5PPVT = Peabody Picture Vocabulary Test standard score at 5 years of age; MatEdn = Maternal education; Y5Sp Test = Speech test used at age 5 years; NUCHIPs or BKB; and MatEdn * Y5Sp Test = interaction term of the two categorical variables.

of listeners with stronger language skills to better fill in missing information when processing an incoming signal in conditions of limited sensory input or degraded speech (Nittrouer et al., 2013; Conway, Deocampo, Walk, Anaya, & Pisoni, 2014; Zekveld et al., 2011). Those who have better language at pre-school age continue to develop better language at school age. However, children who have hearing-in-noise deficits from a young age experience difficulties in language development (Chen et al., 2015) partly because they receive impoverished language input in everyday situations that are typically noisy (Barker & Newman, 2004), and partly because they are less proficient than their typically hearing peers in acquiring language through incidental hearing (Akhtar, Tolins, & Tree, 2019). This difficulty is exacerbated in classroom environments.

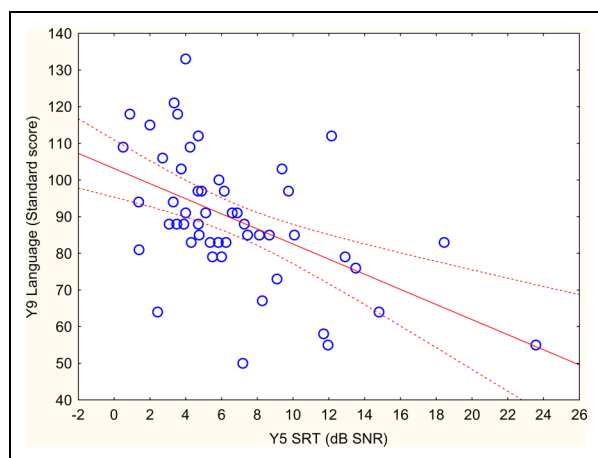


Figure 1. Receptive language at 9 years of age (in standard score) as a function of speech perception (speech reception threshold in decibels signal-to-noise ratio or SRT (dB SNR)) at 5 years of age.

Other possible mechanisms that could produce a link between speech perception and language ability in children might include the possible impact of speech perception difficulties on mediators such as executive function and working memory (Pierce, Genesee, Delcenserie, & Morgan, 2017). As posited by Kral et al. (2016), the reciprocal interplay of auditory experiences, language and cognitive outcomes during development contributes to functional and behavioral outcomes. Better sensory functioning with a CI supports the development of stronger language skills (e.g. Davidson, Geers, & Nicholas, 2014; Davidson, 2006) and better cognitive outcomes; and better cognitive functioning supports better speech perception and language (e.g. Kronenberger, Colson, Henning, & Pisoni, 2014). Speech perception may also be dependent on the quality of phonological representations of the spoken language. The phonological short-term store mediates language learning, especially vocabulary development (Baddeley et al., 1998; Baddeley & Hitch, 2019). For children who rely on CIs for auditory access to sounds, the distorted signal they receive is likely to have a negative impact on the quality of phonological representations. Nittrouer et al. (2013) found that phonological sensitivity explained a significant amount of variance in speech perception in noise between children with CIs and those with typical hearing. The possible influence of cognitive and phonological skills on the observed longitudinal relationship between early speech perception and later language ability requires further examination.

We note that the estimated effects reported in this study are specific to the time interval of measurements, viz, from pre-school-age to elementary-school-age performance. The transition from early intervention to formal primary school presents many challenges (Curle et al., 2017; Skouteris, Watson, & Lum, 2012), including changes in the physical environment of learning that drastically increases the demand on listening abilities of children with hearing loss.

Table 5. Set of Models Using 9-Year-old Speech Perception in Noise as the Dependent variable. Multiple Regression Summary Table Showing Unstandardized Coefficient Estimates (Beta-Values), 95% Confidence Intervals (95%CI) and Significance Levels (*p*-Values) of Predictor Variables. Bolded Entries Indicate Significance at <.05 Level.

	Model 1			Model 2			Model 3			Model 4		
	Beta	95%CI	<i>p</i> -value	Beta	95%CI	<i>p</i> -value	Beta	95%CI	<i>p</i> -value	Beta	95%CI	<i>p</i> -value
AgeCI	0.05	(-0.33, 0.22)	0.71	-0.18	(-0.44, 0.08)	0.17	-0.18	(-0.44, 0.08)	0.16	-0.25	(-0.51, 0.01)	0.06
MatEdn	-0.32	(-0.60, -0.05)	0.02	-0.08	(-0.39, 0.23)	0.60	-0.14	(-0.42, 0.13)	0.29	-0.13	(-0.38, 0.13)	0.32
Y5SRT				0.45	(0.20, 0.71)	<0.001				0.34	(0.07, 0.61)	0.01
Y5PPVT							-0.48	(-0.76, -0.20)	<0.001	-0.29	(-0.59, -0.01)	0.06
Y5SpTest				-0.27	(-0.55, 0.01)	0.06				-0.23	(-0.50, 0.04)	0.09
MatEdn* Y5SpTest				0.20	(-0.13, 0.53)	0.22				0.23	(-0.10, 0.55)	0.16
AdjR ²	0.07		0.07	0.30		<.001	0.24		<.01	0.34		<.001

Note. AgeCI = Age at first cochlear implant activation, in months; Y5SRT = Speech reception threshold for 50% correct, expressed as signal-to-noise ratio in decibel or dB SNR, in a speech perception in noise test at 5 years of age; Y5PPVT = Peabody Picture Vocabulary Test standard score at 5 years of age; MatEdn = Maternal education; Y5SpTest = Speech test used at age 5 years: NUCHIPs or BKB; and MatEdn * Y5SpTest = interaction term of the two categorical variables.

As such, the current findings have important implications for early intervention.

Clinical Implications

Our findings on the relationship between early speech perception in noise and later language abilities suggest that early intervention needs to go beyond developing good language skills (e.g. through providing listening and spoken language early intervention or auditory verbal therapy; see Percy-Smith et al., 2018; Binos, Nirgianaki, & Psillas, 2021) to also enhancing auditory abilities for listening to speech in noise. Children who demonstrate good structural language skills in quiet environments may experience difficulties when listening in noise, yet they need to learn in noisy classrooms in schools and function in noisy situations in everyday life. Formal speech perception training, including auditory and audio-visual training for young children would contribute to enhancing speech perception skills. There is some evidence from children with normal peripheral hearing who had problems with speech perception in noise that training to use spatial cues can improve performance (Cameron, Glyde, & Dillon, 2012; Lotfi, Moosavi, Abdollahi, Bakhshi, & Sadjedi, 2016). A recent study on 8–12-year-old children who used CIs and hearing aids has shown that auditory training in using spatial cues improved speech perception in noise (Lotfi, Hasanlifard, Moosavi, Bakhshi, & Ajalloueyan, 2021). Most recently, a study on children aged between 5 and 12 years who used CIs or hearing aids showed that audio-visual training improved children's listening and speechreading skills (Tye-Murray et al., 2022). However, there is a paucity of evaluation studies to identify optimal intervention strategies to enhance speech perception in noise in pre-school children with hearing loss.

The speech-perception-in-noise deficit observed in this study suggests that children require more favorable SNR than their normal-hearing peers to achieve similar performance in speech perception in noise, consistent with that reported by von Koss Torkildsen et al. (2019) for children aged between 5.5 and 12.9 years using CIs. These findings lend support to the use of noise-reduction technology and remote microphones not only at school age in formal schooling environments, but also at a young age in early childhood centres and at home (Thompson, Benítez-Barrera, Angley, Woynaroski, & Tharpe, 2020; Benítez-Barrera, Angley, & Tharpe, 2018; Schafer & Thibodeau, 2006). Combined with early intervention that targets the improvement of language skills and speech perception in noise abilities in young children, these strategies can contribute to optimizing the outcomes of children with hearing loss.

Limitations and Further Research

The current findings are based on children using CIs that communicate primarily using spoken language. Therefore,

the findings should not be generalized to children using hearing aids, or to children wearing CIs who use alternative modes of communication. This study used two speech test materials (words or sentences) for assessing speech perception at 5 years of age so that more children could contribute data at this young age (Dettman, Wall, Constantinescu, & Dowell, 2013) for exploration of a longitudinal relationship of speech perception and language between 5 and 9 years of age. Regression analyses revealed that the effect of speech test material at 5 years was not significant. Future studies would aim to replicate findings using the same speech test material at both measurement time-points. The estimated effects are specific to the time interval studied, viz, when children transitioned from early intervention (or preschool) to formal schooling. The longitudinal findings should be treated with caution, since cross-lagged analysis cannot definitively establish causality (Card & Little, 2007), and applying a cross-lagged model to just two time points provides only a weak test of putative direction of causality (Newsom, 2012). Future work would aim to replicate these findings using multiple assessment time points within a cohort of children with hearing loss. Finally, future investigations may examine the contributions of cognitive and phonological skills to the longitudinal relationship between speech perception and language skills in children with hearing loss.

Summary and Conclusions

This study investigated the longitudinal relationships between speech perception in noise and language development in young children using CIs. We found that preschool speech perception in noise was a significant predictor of language ability in school, after controlling for the effect of early language in the form of receptive vocabulary. On the other hand, preschool receptive vocabulary influenced speech perception in noise ability at school age, but this effect was no longer significant after controlling for the effect of early speech perception ability. The findings lend support to early interventions to go beyond targeting the improvement of language skills to also enhancing speech perception in noise abilities. Complemented by appropriate technology, these would contribute to optimizing the speech perception and language outcomes of children with hearing loss in school.

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Individual participant data will not be available. The study protocol is available following article publication.


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