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Nonword Repetition as a Predictor of Long-Term Speech and Language Skills in Children with Cochlear Implants

Elizabeth D. Casserly, MA^a and David B. Pisoni, PhD^{a,b}

^aSpeech Research Laboratory, Dept. of Psychological & Brain Sciences, Indiana University, Bloomington, Indiana

^bDeVault Otologic Research Laboratory, Indiana University School of Medicine, Indianapolis, Indiana

Abstract

Hypothesis—The rapid phonological processing skills of children with cochlear implants early in life (ages 8–10), as measured by nonword repetition performance, will predict their language development eight years later (ages 16–18). This core processing ability will also correlate with concurrent measures of language at both ages of testing.

Background—Understanding the causes of the wide range of performance in pediatric cochlear implant users currently constitutes a major barrier to clinical and research progress in the field. Research into children's neurocognitive abilities such as working memory capacity and verbal rehearsal speed, in addition to conventional demographic variables, has shown that these foundational skills play a key role in determining outcomes. Here we investigate the impact of rapid phonological processing, an ability which is critical in spoken language use, for children with cochlear implants.

Methods—52 deaf children with cochlear implants completed a battery of 14 clinical and research measures of language, neurocognitive, and nonword repetition skills in two testing sessions 8 years apart.

Results—Performance on the nonword repetition task at both testing sessions correlated significantly with concurrent language abilities. Importantly, nonword repetition accuracy at age 8–10 also significantly predicted performance on measures of language ability at age 16–18 in a wide range of domains, from speech intelligibility to sentence recognition in noise. These relations were significant even when other neurocognitive measures were controlled.

Conclusion—Early nonword repetition performance in children with cochlear implants predicts later language development, and therefore may identify those children at high risk for poor outcomes.

INTRODUCTION

One of the major goals of our current research program is to understand the substantial individual differences in the language development of profoundly deaf children with cochlear implants (CIs). Even among those children who receive their CI at a very young age, there are some individuals who do extremely well in terms of spoken language use and others who face enormous struggles to use even basic oral-only communication^{1,2}. We believe that understanding the elementary neurocognitive factors that cause these very

different outcomes, and using that knowledge to better identify children at risk for difficulties with their implant, is a crucial next step in the field of cochlear implant research.

Past research on speech-language outcomes in children with CIs has been focused almost exclusively on “product measures” of performance, such as the child’s ability to perceive speech, their vocabulary knowledge, or their score on standardized measures of global language skills². While these are the abilities which seem most relevant to successful spoken language use, a disturbance observed in any of these measures does not necessarily reveal anything useful about why a child is struggling. The reason that one child fails to accurately perceive novel sentences while another succeeds, for example, is not clear. As a result, there is little if any consensus in the field about to treat difficulties and delays in these children.

“Process measures” of speech and language performance, conversely, target fundamental cognitive abilities that underlie the linguistic skills of traditional assessments. These basic information processing capabilities, such as short-term and working memory capacity and verbal rehearsal speed, are not direct linguistic or auditory skills per se, but they are strongly affected by the basic hearing abilities of children, and robust speech communication cannot occur without their support. Indeed, cross-sectional and longitudinal work in our laboratory has shown that short-term memory capacity, working memory capacity and verbal rehearsal speed are not only strongly tied to co-occurring language processing, but these core abilities are also excellent predictors of later language development in children with CIs^{3,4}. Identification of these underlying sources of variation has led to the development of novel behavioral interventions, which provide new avenues for clinicians to use in aiding children experiencing disturbances or delays in speech and language processing⁵.

In this study, we investigated the impact and predictive strength of an additional process measure in the development of children with CIs: nonword repetition. This simple task (described in greater detail below) provides an assessment of rapid phonological processing, a fundamental skill underlying spoken language use. In order for a child to successfully recognize a novel word and repeat it back to an examiner, the following processing steps must occur in rapid succession: the acoustic signal of the word must first be detected, then the word must be encoded and analyzed in terms of its phonological constituents, this linguistic representation must be maintained in memory, the representation must be transferred to the speech production system, and finally, the phonological components must be reassembled into a novel articulatory pattern and executed accurately. Such high-speed encoding, decomposition, and manipulation of linguistic units, called phonological processing, underlies every spoken language skill, from sentence perception to word learning to speech production.

Pisoni, Cleary, Dillon and colleagues have studied pediatric CI users’ ability to perform this critical processing task, and found that children with CIs were able to successfully repeat novel nonwords, but they displayed a wide range of accuracies and intelligibility^{6–8}. The performance of individual children, however, was also found to be significantly correlated with a host of language outcome measures, including open-set spoken word recognition, sentence comprehension, and speech intelligibility⁶. These relations were significant even when conventional demographic variables such as age at onset of deafness and duration of deafness were controlled for in the analyses. The rapid phonological processing at the core of the nonword repetition task, therefore, seems to be a foundational skill which impacts diverse language-related abilities, and makes a promising target for further research and possible intervention.

In this report, we extend previous findings regarding nonword repetition and language abilities with longitudinal data detailing long-term development of language and nonword

repetition skills in a group of deaf children with CIs. Research and clinical assessments of speech and language, vocabulary, and nonword repetition were collected after 8 years of CI use in 52 deaf children in order to answer the following questions. First, how do language processing skills improve over the course of adolescence in children with CIs? Second, what is the relationship between rapid phonological processing skills (nonword repetition) and measures of language performance at different points in development? And third, do early phonological processing skills predict language abilities later in life, thereby identifying those children who may be at high risk for poor outcomes?

MATERIALS AND METHODS

Participants

The 52 children who participated in this research were recruited as part of a larger longitudinal study conducted at the Central Institute for the Deaf in St. Louis, Missouri^{9,10}. Although the total number of children participating in this larger project was much greater, only 53 children – those in the last four years of Session 1 testing – completed the critical nonword repetition task during the initial test session. Of these, all but one child returned for a second test session eight years later, when they repeated the nonword repetition task along with others detailed below.

The demographics of the study participants are summarized in Table 1. All of the children were diagnosed with profound hearing loss at or before 3 years of age, and had received their CI before age 5. All participants, therefore, had used their CIs for at least 3 years before the first testing session, with a mean duration of deafness of 3.2 years (9.2 months minimum, 5.4 years maximum). The participants used a mixture of primary communication modes, with 29 children in oral-only communication environments (spoken language only) and 23 in total communication (signed exact English plus spoken language). None of the children used American Sign Language, and none reported any other concomitant diagnoses.

Longitudinal Design

Participants were tested in two sessions, 8 years apart. Measures obtained at each testing session are summarized in Table 2. The first session took place when the children were between 8 and 10 years old, in elementary school¹⁰. During Session 1, they completed a battery of tests of spoken language skills, assessments of neurocognitive abilities such as working and short-term memory, and a nonword repetition task. Eight years after the first testing session, when the participants were between 16 and 18 years of age and in high school, they returned for a second session of testing⁹. During Session 2, they completed the same neurocognitive assessments and nonword repetition task given in Session 1. The children also completed a subset of the language tests from Session 1, and a number of new assessments. Those tests completed in either Session 2 alone or Sessions 1 and 2 are reported below.

Materials and Procedure

The tests given to participants fall into three groups: nonword repetition, neurocognitive measures, and speech-language measures. In Session 2, children completed 10 speech-language measures, 3 neurocognitive measures, and 1 nonword repetition task. All but 7 of the speech-language measures were obtained in both testing sessions (see Table 2). Each of the tasks is described below, with emphasis on nonword repetition.

Speech-Language Measures—The 10 speech-language measures consisted of a battery of clinical and research tools designed to quantify various facets of speech communication, from the perception of others' speech to linguistic expression and comprehension. To

differentiate these more traditional “product” outcome measures from the “process” measures of interest here, we will group all of these end-point assessments under the label of “speech-language” tests.

In this category, participants completed the following tests. The Clinical Evaluation of Language Fundamentals 4th Ed. assessment (CELF-IV)¹¹ was used to evaluate global language skills, from comprehension of syntactic dependencies to expressive facility. The Peabody Individual Achievement Test – Revised (PIAT) assessed reading abilities¹², along with the Test of Reading Comprehension (TORC)¹³. The Peabody Picture Vocabulary Test 3rd Ed. (PPVT-III)¹⁴ was used to assess receptive vocabulary, asking participants to indicate one of four pictures when it was named by an experimenter. Clinicians in this study completed the PPVT twice, once naming images orally and once using signed exact English; only the results of the oral presentation mode are reported below. Participants were also asked to recognize (i.e. verbally repeat) isolated, open-set, spoken words in the quiet using the Lexical Neighborhood Test¹⁵. Words were presented via loudspeaker at either comfortable listening levels (70 dB) or more quietly (50 dB). Sentence recognition tests were also administered, where children were asked to repeat meaningful English sentences (BKB materials)¹⁶ heard either in the quiet (70 dB) or in the presence of multi-talker babble, a “cocktail party” noise at 10 dB below the target sentences. Finally, the participants read short sentences aloud (McGarr sentences)¹⁷ so that recordings of their speech production could be analyzed later for intelligibility^{18,19} and verbal rehearsal speed^{3,4}.

Measurements from several standardized tests, the CELF, PIAT, TORC, and PPVT, were calculated in terms of age-based standard scores centered around means of 100. The word and sentence recognition tests were scored in terms of the percentage of words or sentence keywords correctly reproduced by a child. Speech intelligibility recordings were scored in two ways: first, they were transcribed by 3 trained, normal-hearing (NH) clinicians, and intelligibility was quantified using the number of keywords accurately understood by the transcribers^{18,19}. Second, a phonemic transcription of the McGarr sentence productions was conducted, and intelligibility was assessed in terms of segmental accuracy, or the percentage of consonants and vowels correctly produced^{18,19}. This first keyword-accuracy measure will also be reported from the data collected during testing in Session 1 (see Table 2).

Neurocognitive Tests—In addition to these speech-language measures, all of the children also completed three tests assessing their neurocognitive abilities. Verbal short-term and working memory capacity were evaluated, respectively, using forward and backward digit span subtests of the Wechsler Intelligence Scale for Children, 3rd Ed. (WISC-III)²⁰. In these digit span tests, a researcher reads a list of one-digit numbers aloud, and the children must either repeat the list exactly as given (forward span), or in reverse order (backward span). The longest list of digits to which a child can correctly respond in these tasks provides a measure of their immediate memory capacity. Estimates of the children’s verbal rehearsal speed were also obtained at both testing sessions by measuring the durations of their recorded McGarr sentence productions^{3,4}. Speaking rate has been shown to be highly correlated with verbal rehearsal speed²¹, allowing us to use a simple measure of utterance duration in our analyses. Such a measure of verbal rehearsal has previously been shown to be strongly related to concurrent language abilities in children with CIs^{3,4}.

Nonword Repetition—Of special interest for the current investigation were the scores obtained in the nonword repetition task. This task was completed by all 52 children at both testing Sessions 1 and 2. Stimulus materials were taken from the Children’s Test of Nonword Repetition²²; a subset of 20 nonwords was selected which had been used in previous testing with both NH children and deaf children with cochlear implants^{6,23}. The nonwords were all phoneme strings that are phonotactically legal, but unattested, in English,

and were between 2–5 syllables in length. Nonword targets were recorded by an adult female speaker of American English and played for participants in sound field from a loudspeaker at 70 dB.

Participants were told that they would hear a “silly, made-up word” and that they should repeat it aloud to the examiner. Their vocal responses were audio-recorded and later phonemically transcribed and analyzed in the following ways. All of the children’s productions from both sessions were scored for the percentage of consonants and the percentage of vowels correctly reproduced from the target stimulus. The nonword productions from Session 1 were also given a global repetition accuracy rating. The rating for each response was generated by sets of 10 NH, naïve listeners who heard both the target nonword and the child’s repetition of it. They then rated each production on a scale from 0 (“totally fails to resemble the target utterance”) to 6 (“perfectly accurate rendering of the ‘target’ utterance, ignoring differences in pitch”). These accuracy ratings do not pre-suppose dependence on particular segmental/phonemic content, and can therefore be taken to be a general measure of task success. Not every child produced a response for every item in the nonword repetition task; accuracy scores below reflect their average performance in a session.

RESULTS

Average scores for the speech-language measures (including standardized tests of reading, expressive language and comprehension, speech perception tests, and tests of speech intelligibility) obtained in the two testing sessions are given in Table 3. Performance on the nonword repetition and neurocognitive tests in Sessions 1 and 2 is summarized in Table 4. Analyses investigating improvement between sessions, correlations between process and product measures within sessions, and predictive relationships across sessions will be presented one at a time in the sections below.

Improvement Across Testing Sessions

Speech-Language Measures—The subset of 4 speech-language measures which were obtained in both testing sessions – open-set word recognition at 70 db presentation SPL, sentence recognition in the quiet, speech intelligibility, and the PIAT reading assessment – were examined first. These results are summarized in Table 3 for Session 1 and Session 2.

Word recognition, sentence perception, and speech intelligibility showed improvement in participants’ accuracy over time, but reading ability was delayed compared to NH peers (PIAT standard scores). That is, children’s open-set word recognition increased from 55.5% to 65.3% accuracy, perception of sentence keywords increased from 71.0% to 85.0%, and the intelligibility of keywords in their sentence productions increased from 72.5% to 85.6%. In contrast, average PIAT standard scores fell from 90.0 to 83.8. Because the PIAT scores are age-standardized, however, this drop reflects a delay relative to the scores of age-matched NH children, not a lack of progress in reading ability from elementary to high school. A repeated-measures ANOVA on performance in all four measures shows a significant effect of testing Session ($F = 13.537$, $p < .001$), with significant differences in all four univariate sub-comparisons: word recognition, sentence recognition, speech intelligibility and reading (all p ’s $< .001$).

The correlation between performance on a given test in Session 1 and performance in Session 2 was extremely high; those children who did well in early testing continued to perform well and improve after 8 years of CI use. Figure 1 shows this relationship in LNT open-set word recognition, plotting the percentage of words a child recognized in Session 1 against their Session 2 scores. Time-lagged Pearson correlations of Session 1 by Session 2

data were significant for all four repeated tests: word recognition at 70 dB ($r = .774$, $p < .01$), sentence recognition in the quiet ($r = .767$, $p < .01$), speech intelligibility by keywords ($r = .769$, $p < .001$) and PIAT reading scores ($r = .760$, $p < .01$).

Analysis of improvement, therefore, showed that all children improved their speech-language skills over the course of 8 years of cochlear implant use. It should also be noted here, however, that in the domain of reading, as measured by the PIAT, the improvement was not sufficient to keep up with the changes observed in normative data on NH peers.

Nonword Repetition—Children's nonword repetitions in Session 1 were assessed in several ways. Traditional scoring of the nonword repetition task is binary: either the child's repetition attempt is correct in all respects or it is incorrect^{22,24}. With such strict scoring criteria, the performance of many children with cochlear implants would be at floor; they appear to be unable to do the task. This is not the case, as the segmental accuracy data summarized in Table 4 demonstrate, but rather it is a by-product of the fact that a binary scoring method ignores any differences among incorrect responses. Prior detailed analysis by Pisoni and colleagues of the Session 1 nonword repetitions^{6–8} demonstrated that performance can be assessed more sensitively through phonological analysis and segmental transcriptions of children's responses – specifically, analysis of the consonants, vowels, or number of syllables repeated, the accuracy of stress placement, and the global repetition quality. The global measure was obtained via quality ratings obtained from a playback experiment using naïve listeners⁸. These listeners heard the model nonword, then a child's repetition, and were asked to rate the repetition on a scale from 0 (no resemblance to the model) to 10 (a perfect reproduction).

These more sophisticated, detailed scoring metrics were highly informative, but also very strongly correlated with one another (Pearson correlation, weakest measure-by-measure $r = .883$, all p 's $< .01$). That is, relative accuracy as reflected by one metric was virtually identical to relative accuracy obtained in the others. Given the resources needed to carry out these analyses, therefore, only two were conducted on the repetition data from Session 2: consonant repetition accuracy and vowel repetition accuracy. These Session 2 measures were also highly correlated with one another (weakest Pearson $r = .882$, all p 's $< .01$).

The data presented in Table 4 show that, in those measures common to both Session 1 and Session 2, participants' nonword repetition accuracy improved after eight years of CI use. Improvement for consonant repetition, as an example, is shown in Figure 2. The accuracy of consonant repetition improved from 31.5% to 43.5% across sessions, while vowel repetition accuracy increased from 42.9% to 48.8%. Repeated measures ANOVA confirmed that these increases were statistically significant (main effect of Session, $F = 19.950$, $p < 0.001$), and time-lagged Pearson correlations showed that nonword repetition performance was strongly associated across the two testing sessions ($r = .721$ (consonants), $r = .740$ (vowels), p 's $< .01$).

Neurocognitive Measures—Finally, the three neurocognitive measures obtained in both testing sessions (forward digit span, backward digit span, and speaking rate) also showed improvement after eight years of CI use, as seen in Table 4. Average longest forward digit span increased from 4.08 at Session 1 to 5.43 at Session 2, while longest backward digit span increased from a mean of 2.96 to 3.92. Speaking rate also increased between sessions, with the mean time needed for a participant to say a 7-syllable sentence decreasing from 3.09 s at Session 1 to 1.94 s at Session 2. Repeated-measures ANOVA confirmed that these changes were significant (main effect of Session, $F = 74.281$, $p < .001$).

Longitudinal Gains Summary—In all measures available for both Sessions 1 and 2, therefore, children with CIs showed significant improvements after eight years of CI use (although reading improvement as measured by the PIAT was not sufficient to maintain participants' standing relative to their NH peers' abilities). The data displayed in Figures 1 and 2 also demonstrate, however, a wide range of variability in performance that is present in all dependent study measures, with some children performing at very high levels and others struggling to even complete the tasks. Understanding the underlying sources of variation in performance and identifying those children at high risk for poor outcomes at early stages is therefore critical. The next two analyses address these issues.

Nonword Repetition and Language

If the rapid phonological processing tapped by nonword repetition plays a foundational role in the development of speech and language ability, then we would expect nonword repetition accuracy and speech-language measures to be strongly related. Pearson correlations were therefore conducted between these two sets of data obtained within Session 1 and within Session 2.

Although accuracy in the nonword repetition task was measured in a variety of ways, the relations with speech-language performance below will only be reported for one accuracy metric per session. Data from Session 1 will reference global quality ratings; these rating scores constitute a composite measure of accuracy across the entire spectrum of possible results, including syllable structure, stress placement, consonant articulation, and vowel quality. They are also the most objective measure of accuracy available, given that ratings originate from naïve listeners rather than transcription and subjective analysis, as is done to obtain segmental accuracies. As a result of these benefits, this measure is preferable as the benchmark of nonword repetition success, both for the data within Session 1 and for the critical predictive analysis of Session 1 with later linguistic and perceptual outcomes. There is no comparable metric for the data in Session 2, however, so vowel repetition accuracy will be used in lieu of the perceptual ratings. The two measures were highly correlated in Session 1, indicating that vowel accuracy is a comparable scoring metric. Correlations were conducted using all of the available accuracy measures for both sessions, regardless, and the results did not qualitatively depend on which measure was being used.

Early Nonword Repetition & Language Links—At Session 1, nonword repetition accuracy (as measured by global quality rating) correlated significantly with all four speech-language measures: open-set word recognition at 70 dB presentation ($r = .792, p < .01$), sentence perception in the quiet ($r = .833, p < .01$), sentence keyword speech intelligibility ($r = .708, p < .01$), and the PIAT standard scores of reading ($r = .437, p < .01$). The correlations with speech perception and production accuracy remained robust and significant even when variance from forward and backward digit spans (assessing short-term and working memory capacity) and verbal rehearsal speed were partialled out of the analyses (partial Pearson r -values for sentence recognition, $r = .700$, word recognition, $r = .687$, and speech intelligibility, $r = .512$; all p 's < 0.01). Partial correlation between nonword repetition and reading (PIAT), however, was not significant when these process measures were controlled for ($r = .025, p > .05$).

Late Nonword Repetition & Language Links—Nonword repetition accuracy at Session 2 (% vowels correctly reproduced) was also examined to identify relationships with the 10 speech-language measures obtained at that time. Pearson correlations between these product measures and nonword repetition are summarized in Table 5. Process-to-product correlations of within-session scores were significant for each assessment except the TORC reading quotient, which was marginally significant ($r = .268, p = .055$).

Partial Pearson correlations on the nonword/speech-language relationships were also conducted, controlling for short-term memory, working memory and verbal rehearsal speed. Table 5 also shows the results of these partial correlations, most of which still remained significant. Controlling for neurocognitive abilities did have the following effects, however: the TORC assessment was no longer marginally significant; the PIAT reading, CELF global language, and segmental intelligibility measures dropped below statistical significance; and the PPVT correlation was only marginal ($r = .245$, $p = .09$).

Within-Session Correlations Summary—The speech-language measures shown in Table 5 cover a wide variety of linguistic skills, including receptive vocabulary (PPVT), expressive language production (speech intelligibility), speech perception in isolation and in context (word and sentence recognition), reading comprehension (PIAT and TORC) and speech perception in adverse or noisy conditions (word recognition at 50 dB presentation, sentence recognition in noise). Yet despite this variety, nonword repetition accuracy was found to be significantly related to concurrent performance in nearly every speech and language outcome measure, even when the variance from other predictive process measures was taken into account.

Predicting Future Language Development

Our third and most important research question concerns the predictive relationship between nonword repetition and language development. If rapid phonological processing as assessed by the nonword repetition task can identify those children who are at high risk for language delays even after eight additional years of cochlear implant use, it could be used as a powerful tool in the application of targeted behavioral interventions and therapy tailored to the needs of individual children. In order to assess nonword repetition's predictive value for later language development, time-lagged correlations were conducted between nonword repetition scores at Session 1 (children aged 8–10) and speech-language measures at Session 2 (age 16–18).

Nonword Repetition as a Predictor—Taken by itself, early nonword repetition accuracy (global rating) was found to be strongly correlated with a wide range of later speech-language skills. Time-lagged Pearson correlations were significant for all 10 tests in Session 2 except the CELF, which was marginally significant ($p = .059$). These predictive, time-lagged relationships are summarized in Table 6. In fact, the correlations observed between Sessions 1 and 2 are in many cases even stronger than the within-session nonword repetition/language skill correlations (see Table 5). The Session 2 within-session correlation between nonword repetition and PIAT reading scores, for example, was $r = .331$. The same PIAT scores correlate with Session 1 nonword repetition scores at $r = .457$. Further examples of these strong predictive relationships between nonword repetition scores at Session 1 and speech-language ability at Session 2 are shown graphically in Figures 3, 4 and 5 for sentence perception in noise, receptive vocabulary, and open-set spoken word recognition at 50 dB SPL, respectively. Each of these diverse measures of perceptual and linguistic skill are predicted quite reliably by simple nonword repetition accuracy ratings from eight years prior to their collection.

Nonword Repetition vs. Other Process Measures—While this overall pattern is evidence of a powerful predictive relationship, it should also be interpreted in light of the predictive strength of the other process measures: short-term and working memory capacity and verbal rehearsal speed. Partial Pearson correlations controlling for these measures and their combined influence are summarized in Table 7. Almost all of the relationships that were significant in the simple bivariate correlations between nonword repetition and speech-language measures were also significant when forward and backward digit span were

partialled out. Little variance seems to overlap, therefore, between these measures of short-term and working memory and the nonword repetition scores.

Partialling out variance from verbal rehearsal speed had more impact, however, with high-school-age abilities in reading (PIAT, TORC) and vocabulary (PPVT) no longer being significantly predicted by early nonword repetition scores. Even after controlling for this powerful predictor, however, nonword repetition still significantly predicts unique variance in open-set word recognition at 70 dB and 50 dB presentation levels, sentence recognition in quiet and noise, and speech intelligibility. Moreover, these relationships all remain robust and significant in the partial correlations controlling for the combined effects of all three neurocognitive process variables together.

Longitudinal Predictive Power—Such pervasive predictive relations between nonword repetition and later speech-language skills, independent of the contributions of other process measures, suggest that rapid phonological processing is a core, foundational mechanism of action underlying the development of spoken language skills in children with CIs.

DISCUSSION

Children's ability to hear, perceive, and accurately reproduce a novel nonword requires performance of a number cognitive and linguistic processing operations, including detection, speech encoding, retention in immediate short-term memory, translation of perceptual objects into articulatory plans, and production of a novel sequence of phones. These processes form the foundation of everyday spoken language use; disturbances in any one component, therefore, may have cascading effects across language and cognitive development. To test this hypothesis and determine the relation between the rapid phonological processing required for accurate nonword repetition and language development, we studied the initial linguistic and neurocognitive abilities of 52 deaf children with CIs and how these abilities developed after eight additional years of CI use.

As Dillon, Pisoni and colleagues showed previously^{6–8}, the children in this study were capable of repeating novel phonetic sequences. Performance on the nonword repetition task improved significantly in our subjects after eight years of experience with their CIs, demonstrating comparable improvements in rapid phonological processing. Language skills, as measured by sentence and word recognition in quiet, speech intelligibility, and reading ability, also improved during this period of development. Importantly, the relationship between nonword repetition accuracy and language skill was found to be strongly correlated at both testing sessions, at ages 8–10 and then 8 years later at 16–18. At the least, therefore, rapid phonological processing was shown to be correlated with concurrent information processing skills in speech perception and reading throughout adolescence.

One of the barriers to providing effective clinical support to deaf children with CIs, however, is being able to *predict* which children may be at high risk for poor speech and language outcomes at an early age. Such predictive power would allow efficacious interventions to be made earlier, before a child falls too far behind NH peers to be able to catch up. It is this predictive relationship, therefore, that is of primary interest in the current study, rather than concurrent correlations between phonological processing and language.

Critically, this predictive relationship was observed: measures of nonword repetition obtained in childhood correlated significantly with speech and language abilities in adolescence, eight years later. Nonword repetition accuracy predicted linguistic performance in a wide range of domains, including expressive and receptive language measures, assessments of reading and vocabulary knowledge, and speech perception accuracy in both

quiet and adverse listening conditions. Moreover, many of these predictive relationships were quite strong, accounting for as much as 51.1% of the variance in accuracy at a speech perception in noise task, for example, and 56.0% of the variance in speech perception abilities at quiet presentation levels (50 dB). These time-lagged predictive correlations were stronger even than correlations obtained between concurrent nonword repetition and speech-language measures, for nearly every language-related area assessed in this study.

We believe that measures of nonword repetition skills have the potential, therefore, to serve as a powerful early behavioral marker of children who are at risk of poor language outcomes with their CIs. Several attributes of nonword repetition make it additionally attractive for use in this manner. First, nonword repetition takes very little time, training, or technology to administer; a researcher merely says or plays a recording of one of the target nonwords and records the child's response. Second, the links between nonword repetition and language development have been studied extensively in other pediatric populations, particularly typically developing children and children with specific language disorder (SLI)^{24,25}, and this literature provides a strong conceptual and theoretical foundation upon which to interpret findings in the CI population. Lastly, nonword repetition is a "process," rather than "product" measure; it reflects the operation of core neurocognitive skills underlying spoken language use, and can therefore inform clinicians and researchers about the causes of disturbances in linguistic and cognitive development and provide directions for possible areas of intervention.

Our results speak to this final point directly. We measured not only nonword repetition accuracy during childhood, but also several additional neurocognitive skills such as short-term memory, working memory and verbal rehearsal speed. Despite the fact that these informational processing abilities have previously been shown to predict language outcomes^{3,4}, we found that nonword repetition predicts unique variance, above and beyond the contributions of these other neurocognitive measures, in the linguistic and perceptual outcomes of children with CIs. Unique predictive strength was particularly strong in the domain of speech perception in quiet and in adverse listening conditions, but was also found in an expressive language measure: speech intelligibility. Rapid phonological processing skills therefore appear to play a pivotal role in the development of spoken language skills in these areas; short-term and working memory capacity and verbal rehearsal speed may also impact linguistic development, but their contributions appear to be independent.

Such knowledge of the cognition underlying atypical language and perceptual performance points to areas where intervention may be maximally beneficial. Pisoni and colleagues' earlier discovery of the impact of working memory in language outcomes of children with CIs, for example, has led to the application of neurocognitive training protocols targeting memory skills for these children. Results of the working memory training are preliminary, but promising⁵. Our results suggest that rapid phonological processing operations – the encoding, manipulation, and storage of phonological representations in verbal working memory – is another domain which might be addressed via novel interventions, potentially providing alternative options for children who are struggling with traditional clinical programs.

CONCLUSIONS

The breadth and strength of the relations observed between nonword repetition and measures of speech and language provide strong evidence for the critical role of rapid phonological encoding and manipulation as a core, underlying process in spoken language processing. We suggest that disturbances in these processing operations, such as the degree of uncertainty introduced by coarse perceptual outputs from cochlear implants, result in

effects that cascade across linguistic and non-linguistic domains. By better understanding the underlying neurocognitive processes used in spoken language processing, such as rapid phonological encoding and manipulation, verbal working memory capacity, and verbal rehearsal speed, and their impact on language development in this clinical population, we place ourselves in a better position to identify those children who may be at high risk for poor speech and language outcomes and to motivate the design of novel evidence-based behavioral interventions that specifically target these underlying areas of concern in individual children.

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FIG. 1.

Performance in the open-set Lexical Neighborhood Test word recognition task at a 70 dB presentation level at ages 8–10 in Session 1 (x-axis), and at ages 16–18 in Session 2 (y-axis). Dashed line indicates equal performance; data points above the line indicate improvement between sessions.

FIG. 2.

Performance in the nonword repetition task in terms of the percentage of consonants correctly reproduced at Session 1 (x-axis) and Session 2 (y-axis). Dashed line indicates equal performance across sessions; points above the line indicate improvement.

FIG. 3.

Predictive relationship between nonword repetition (global accuracy score, 0–6) at Session 1 and sentence recognition in noise performance at Session 2, eight years later. Time-lagged correlation was significant ($r = .715$, $p < .01$); solid line represents best-fit regression.

FIG. 4. Predictive relation between Session 1 nonword repetition performance and participants' receptive vocabulary standardized score at Session 2. Time-lagged correlation was significant ($r = .444$, $p < .01$); solid line represents best-fit regression.

FIG. 5. Predictive relation between Session 1 nonword repetition performance and Session 2 open-set LNT word recognition accuracy at a 50 dB presentation level. Time-lagged correlation was significant ($r = .748$, $p < .01$); solid line represents best-fit regression.

Demographic information for the children who completed both testing sessions and whose performance is reported in this study (N = 52)

Table 1

Participant gender	
Male	n = 24
Female	n = 28
Primary communication mode at Session 1	
Oral-only	n = 29
Total communication (Signed Exact English + speech)	n = 23
Age at onset of deafness	0.18 ±0.55 years
Age at cochlear implantation	3.35 ±0.94 years
Age at testing Session 1	8.86 ±0.55 years
Age at testing Session 2	16.58 ±0.51 years
Duration of deafness prior to Session 1 participation (years)	3.17 ±0.77 years
Duration of CI use prior to Session 1 participation (years)	5.51 ±0.84 years

Assessments conducted at the first testing session (Sessions 1: ages 8–10) and the second (Session 2: ages 16–18) of speech– language abilities, rapid phonological processing, and neurocognitive skills. See text for administration details.

Table 2

	Session 1	Session 2
Speech-Language Tests	LNT words at 70 dB	LNT words at 70 dB
		LNT words at 50 dB
	BKB sentences in quiet	BKB sentences in quiet
		BKB sentences in noise
	PIAT reading	PIAT reading
Speech intelligibility		TORC
		PPVT
		CELF
	Speech intelligibility	Speech intelligibility
		Phoneme production accuracy
Rapid Phonological Encoding	Nonword repetition	Nonword repetition
Other Neurocognitive Assessments	Forward digit span	Forward digit span
	Backward digit span	Backward digit span
	Verbal rehearsal speed	Verbal rehearsal speed

Table 3

Means and standard deviations of children's performance on speech-language measures given at Session 1 (ages 8–10) and Session 2 (ages 16–18) (N = 52)

	Mean Score (SD)	
	Session 1	Session 2
Open-set word recognition (Lexical Neighborhood Test, spoken response)		
70 dB presentation level	55.50% (22.98)	65.35% (20.78)
50 dB presentation level	n/a	55.46% (20.69)
Sentence recognition (BKB sentences, spoken response, % keyword correct scoring)		
Presentation in the quiet	71.00% (31.35)	85.04% (21.91)
Presentation in noise	n/a	58.77% (25.06)
Speech intelligibility (Analysis of children's productions of McGarr sentences)		
Percentage of keywords understood by 3 clinician transcribers	72.45% (24.32)	85.58% (15.70)
Percentage of consonants and vowels correctly produced	n/a	96.55% (8.38)
Receptive vocabulary (PPVT-IV standard score, oral-only administration)	n/a	93.17 (19.15)
Reading recognition and comprehension (PIAT, reading standard score)	90.02 (13.21)	83.77 (15.57)
Intensive reading comprehension (TORC-IV, reading quotient)	n/a	91.77 (14.54)
Global language skills (CELF-IV, language content index standard score)	n/a	95.67 (17.53)

Table 4

Means and standard deviations of scores on nonword repetition and neurocognitive assessments at Sessions 1 and 2 (N = 52)

	Mean Score (SD)	
	Session 1	Session 2
Nonword repetition (20 items from the Children's Test of Nonword Repetition)		
Vowel accuracy (% correct)	42.99% (16.37)	48.83% (17.35)
Consonant accuracy (% correct)	31.51% (16.40)	43.50% (19.08)
Global accuracy rating, naïve listeners (0-low to 6-high scale)	2.14 (1.14)	n/a
Verbal short-term memory		
Forward digit span (WISC III; longest span)	4.08 (0.81)	5.44 (0.95)
Verbal working memory		
Backward digit span (WISC III; longest span)	2.96 (1.01)	3.92 (0.85)
Verbal rehearsal speed		
7-syllable McGarr sentence repetitions (Utterance duration, seconds)	3.10 (1.09)	1.94 (0.35)

Table 5

Within-session correlations between nonword repetition and speech-language measures (Session 2, ages 16–18, N = 52)

	Nonword Repetition Accuracy (% vowels reproduced)	
	Simple Bivariate <i>r</i>	Partial <i>r</i>
Open-set word recognition (Lexical Neighborhood Test, spoken response)		
70 dB presentation level	.728 **	.644 **
50 dB presentation level	.581 **	.422 **
Sentence recognition (BKB sentences, spoken response, % keyword correct scoring)		
Presentation in the quiet	.624 **	.541 **
Presentation in noise	.701 **	.575 **
Speech intelligibility (Analysis of children's productions of McGarr sentences)		
Keywords understood by 3 clinician transcribers	.419 **	.312 *
Percentage of consonants and vowels correctly produced	.341 *	.203
Receptive vocabulary (Peabody Picture Vocabulary Test, 4 th Ed., oral-only administration)	.406 **	.245 %
Reading recognition and comprehension (Peabody Individual Achievement – Test Revised, reading standard score)	.331 *	.139
Intensive reading comprehension (Test of Reading Comprehension, 4 th Ed.)	.268 %	.112
Global language skills (Clinical Evaluation of Language Fundamentals, 4 th Ed.)	.309 *	.224

p < .01,

*
p < .05,

%
p < .10

"Partial *r*" correlations were performed with longest forward and backward digit span scores and verbal rehearsal speed partialled out.

Table 6

Time-lagged, predictive correlations between nonword repetition performance at Session 1 (ages 8–10) and speech-language measures at Session 2 (ages 16–18) (N = 52)

	<u>Nonword Repetition Accuracy at Session 1 (global score)</u>
	Simple Bivariate <i>r</i>
Open-set word recognition (Lexical Neighborhood Test, spoken response)	
70 dB presentation level	.725**
50 dB presentation level	.748**
Sentence recognition (BKB sentences, spoken response, % keyword correct scoring)	
Presentation in the quiet	.640**
Presentation in noise	.715**
Speech intelligibility (Analysis of children's productions of McGarr sentences)	
Keywords understood by 3 clinician transcribers	.516**
Percentage of consonants and vowels correctly produced	.373**
Receptive vocabulary (Peabody Picture Vocabulary Test, 4 th Ed., oral-only administration)	.444**
Reading recognition and comprehension (Peabody Individual Achievement – Test Revised, reading standard score)	.457**
Intensive reading comprehension (Test of Reading Comprehension, 4 th Ed.)	.336*
Global language skills (Clinical Evaluation of Language Fundamentals, 4 th Ed.)	.264%

p < .01,

*
p < .05,

%
p < .10

Table 7

Time-lagged partial correlations between nonword repetition at Session 1 and speech-language measures at Session 2, taking variance from other neurocognitive assessments into account (N = 52)

	Partial correlation <i>r</i> -values controlling for the following neurocognitive assessments (Nonword Repetition Accuracy at Session 1, global score)			
	Forward digit span	Backward digit span	Verbal rehearsal speed	All 3 tests
Open-set word recognition (Lexical Neighborhood Test, spoken response)				
70 dB presentation level	.710**	.746**	.678**	.674**
50 dB presentation level	.729**	.748**	.649**	.642**
Sentence recognition (BKB sentences, spoken response, % keyword correct scoring)				
Presentation in the quiet	.635**	.653**	.548**	.519**
Presentation in noise	.668**	.708**	.532**	.492**
Speech intelligibility (Analysis of children's productions of McGarr sentences)				
Keywords understood by 3 clinician transcribers	.517**	.514*	.357*	.352*
Percentage of consonants and vowels correctly produced	.271%	.329*	.125	.124
Receptive vocabulary (Peabody Picture Vocabulary Test, 4 th Ed., oral-only administration)	.405**	.418**	-.001	.028
Reading recognition and comprehension (Peabody Individual Achievement Test Revised, reading standard score)	.394**	.430**	.093	.196
Intensive reading comprehension (Test of Reading Comprehension, 4 th Ed.)	.289*	.300*	-.149	-.016
Global language skills (Clinical Evaluation of Language Fundamentals, 4 th Ed.)	.236%	.226	-.201	-.183

**
p < .01,

*
p < .05,

%
p < .10