

# Age-Related Performance on Vowel Identification and the Spectral-temporally Modulated Ripple Test in Children With Normal Hearing and With Cochlear Implants

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## Abstract

Children's performance on psychoacoustic tasks improves with age, but inadequate auditory input may delay this maturation. Cochlear implant (CI) users receive a degraded auditory signal with reduced frequency resolution compared with normal, acoustic hearing; thus, immature auditory abilities may contribute to the variation among pediatric CI users' speech recognition scores. This study investigated relationships between age-related variables, spectral resolution, and vowel identification scores in prelingually deafened, early-implanted children with CIs compared with normal hearing (NH) children. All participants performed vowel identification and the Spectral-temporally Modulated Ripple Test (SMRT). Vowel stimuli for NH children were vocoded to simulate the reduced spectral resolution of CI hearing. Age positively predicted NH children's vocoded vowel identification scores, but time with the CI was a stronger predictor of vowel recognition and SMRT performance of children with CIs. For both groups, SMRT thresholds were related to vowel identification performance, analogous to previous findings in adults. Sequential information analysis of vowel feature perception indicated greater transmission of duration-related information compared with formant features in both groups of children. In addition, the amount of F2 information transmitted predicted SMRT thresholds in children with NH and with CIs. Comparisons between the two CIs of bilaterally implanted children revealed disparate task performance levels and information transmission values within the same child. These findings indicate that adequate auditory experience contributes to auditory perceptual abilities of pediatric CI users. Further, factors related to individual CIs may be more relevant to psychoacoustic task performance than are the overall capabilities of the child.

## Keywords

children, cochlear implants, development, vowel identification, spectral resolution

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## Introduction

Cochlear implants (CIs) are highly successful in restoring auditory perception to individuals with severe to profound hearing loss. Still, some adults and children with CIs perform more poorly than others on tests of speech identification. This is a particularly significant problem for children with CIs because a child's ability to perceive speech sounds is critical for development of verbal speech and language skills (e.g., Eisenberg et al., 2016; Niparko et al., 2010). Early-implanted children who receive a CI prior to 5 years of age often exhibit the most favorable outcomes in verbal speech and language

development; nevertheless, speech perception performance remains highly variable even among these children (Horn et al., 2017; Jung et al., 2012; Tyler et al., 1997; N.-Y. Wang et al., 2008). Delayed or deficient spoken language abilities can affect a child's ability to learn

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effectively and to develop social skills (Wake, Hughes, Poulakis, Collins, & Rickards, 2004). Therefore, identifying and attempting to ameliorate factors that can decrease speech perception abilities is imperative for optimizing verbal language outcomes for children with CIs.

Older children with normal hearing (NH) perform better than younger children on many psychoacoustic tasks, including spectrally degraded speech identification (e.g., Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000), and the timeline of auditory cortical development corresponds well with these improvements in NH children's speech perception abilities (e.g., Eggermont & Ponton, 2003). Despite copious evidence of the relationship between development and auditory task performance in NH children, chronological age has not been found to predict pediatric CI users' speech recognition scores (e.g., Eisenberg, Martinez, Holowecky, & Pogorelsky, 2002) or performance on other psychoacoustic tests (e.g., Horn et al., 2017; Jung et al., 2012; Landsberger, Padilla, Martinez, & Eisenberg, 2017). These null findings may have resulted from the tremendous variability in outcomes of children with CIs. Still, auditory experience has been demonstrated to be critical for both the structural (e.g., J. K. Moore & Linthicum, 2007), and functional (Eggermont, Ponton, Don, Waring, & Kwong, 1997; Kral, Tillein, Heid, Hartmann, & Klinke, 2005) development of the central auditory system; therefore, this study investigated the role of auditory experience in children with CIs as a mediator of the improvements in psychoacoustic task performance that normally occurs with chronological age.

The central auditory system undergoes many physiological changes during the process of normal development, including changes in neuronal and axonal structure and density, which reach adult levels in adolescence (J. K. Moore & Guan, 2001). In addition, the morphology of auditory evoked potentials becomes adult-like around the age of 12 in NH children (e.g., Ponton, Eggermont, Kwong, & Don, 2000; Sharma, Kraus, McGee, & Nicol, 1997), corresponding to the structural maturation of the generators of these potentials. However, the development of central auditory structures depends on auditory experience (for review, see D. R. Moore, 2002). Auditory brainstem and cortex are stunted with a lack of auditory stimulation in the perinatal period and early childhood (e.g., J. K. Moore & Linthicum, 2007). Most prelingually deafened children do not receive a CI until they are at least 1 year old, and often later, while audition begins as early as 19 weeks gestation in humans (Hepper & Shahidullah, 1994). Auditory system development as discussed earlier is thus likely impeded in prelingually deafened CI users, even when implanted early. Both the auditory deprivation prior to implantation and the degraded auditory

signal (compared with normal, acoustic hearing) that the CI provides could impair development.

In NH children, developmental changes in the central auditory system coincide with the time course of improvements in psychoacoustic abilities (e.g., Eggermont & Ponton, 2003; J. K. Moore & Linthicum, 2007) such that older children achieve higher performance levels than younger children on a number of auditory tasks (e.g., Dawes & Bishop, 2008; Elliott, 1979; Hall, Buss, Grose, & Dev, 2004; Hartley, Wright, Hogan, & Moore, 2000; Maxon & Hochberg, 1982; Peter et al., 2014; Talarico et al., 2007). In particular, spectral resolution, or the ability to resolve the frequencies in a complex auditory signal, has been found to be poor at young ages and is enhanced with normal development (Dorman, Loizou, Kemp, & Kirk, 2000; Eisenberg et al., 2000, 2002; Vongpaisal, Trehub, Glenn Schellenberg, & Van Lieshout, 2012). Age-related effects have been observed in studies utilizing a nonlinguistic test of spectral resolution called spectral ripple discrimination (SRD), in which an individual discriminates between spectrally modulated rippled noise stimuli (Supin, Popov, Milekhina, & Tarakanov, 1994). For example, Kirby, Browning, Brennan, Spratford, & McCreery (2015) observed that young NH children's SRD performance improved with age. Several additional investigations have found poorer SRD performance in groups of younger NH children compared with groups of older NH children and adults (Allen & Wightman, 1992; Landsberger et al., 2017; Peter et al., 2014; Rayes, Sheft, & Shafiro, 2014). NH children (Allen & Wightman, 1992) as well as adults with NH, hearing loss, and CIs (e.g., Henry, Turner, & Behrens, 2005; Won, Drennan, & Rubinstein, 2007) who perform well on SRD tasks also tend to demonstrate high speech identification scores. Presumably, this relationship exists because spectral smearing or distortion will reduce an individual's speech recognition abilities (e.g., Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). The relation between spectral resolution and speech recognition scores in children with CIs, however, is not as well understood, as results have varied depending on the speech materials used (e.g., Jung et al., 2012). These mixed findings may be at least partly because of variance in the maturity of spectral discrimination abilities among children with CIs.

Behavioral findings support this hypothesis: For example, Kirby et al. (2015) tested NH children and children with hearing impairment on a recently developed SRD task, the Spectral-temporally Modulated Ripple Test (SMRT; Aronoff & Landsberger, 2013) and found that performance in both groups was better for older children. However, performance began to asymptote around the age of 9 for NH children but seemed to continue to improve beyond this age in the hearing-impaired

group. While the authors did not specifically discuss the age at which SMRT performance peaked in hearing-impaired children, a possible interpretation of this observation is that decreased access to auditory information, and the degraded auditory signal that the central auditory system receives because of hearing loss, prolongs the maturation of spectral resolving capabilities. Other prior studies with pediatric CI users have demonstrated immature temporal sensitivity (Jung et al., 2012) and intensity resolution (Park, Won, Horn, & Rubinstein, 2015) in school-age children and adolescents compared with adults with CIs.

While these findings, as well as those from previous studies in NH children, indicate that pediatric CI users' performance on psychoacoustic tasks should improve with age (but perhaps on a delayed time course), previous studies have found no relationship between chronological age and SRD performance (Horn et al., 2017; Jung et al., 2012) or speech identification scores (Eisenberg et al., 2002) in early-implanted, school-age children with CIs. Evidence from structural examinations of auditory system development with auditory deprivation (e.g., J. K. Moore & Linthicum, 2007) suggests that aided hearing age or amount of time with the CI may instead be better predictors of auditory capabilities in these children.

This study explored the link between chronologic and hearing age and auditory perception, as well as the relationship between spectral discrimination and speech identification performance, in school-age children. Both NH children and prelingually deafened, early-implanted children with CIs were tested with the goal of relating auditory perceptual development with acoustic hearing to that with a CI. Further, immature speech identification and spectral discrimination abilities were investigated as a potential contributor to the variance in speech identification outcomes among pediatric CI users. In addition, bilateral, sequentially implanted children were assessed with each CI individually, providing the ability to compare performance with CIs implanted at different time periods within the same child. This also allowed for the evaluation of age-related effects while minimizing potential confounding variables such as linguistic knowledge, cognitive abilities, and intelligence quotient (IQ).

## Materials and Methods

### Participants

In total, 12 children with CIs between the ages of 11 and 17 (mean age at first lab visit = 14.2 years) were recruited from the Seattle area to participate in this study. No pediatric CI users in this study were younger than 11 years old because of the limited number of children in

the Seattle area who met eligibility criteria for the study. Half of the participants with CIs failed a newborn hearing screening in both ears (P01, P02, P03, P10, P11, and P12). The remaining participants either passed their newborn hearing screening (P04, P08) or did not have one (P05, P06, P07, P09). However, all child CI users in this study were diagnosed with unilateral ( $n = 1$ ) or bilateral ( $n = 11$ ) severe to profound hearing loss prior to 4 years of age and were thus considered to be prelingually deafened. These children were either unilaterally implanted ( $n = 1$ ) or sequentially bilaterally implanted ( $n = 11$ ) and received their first implant before their fifth birthday (mean age at first implantation = 2.18, mean age at second implantation = 8.0; see Table 1 for demographic details).

All children with CIs had Advanced Bionics HiRes90K devices and used oral communication. Two participants were fraternal twins (P11 and P12). One bilateral CI user had been diagnosed with severe to profound hearing loss at the age of 4 in their second-implanted ear (P05L), so data from that perilingually deafened ear were not included in this study. The one unilaterally implanted participant (P08) wore a hearing aid in their contralateral ear that was turned off during testing. Bilaterally implanted participants completed the study tasks with each CI individually in separate testing sessions. A total of 22 CI ears were included in the analyses for this investigation.

In total, 37 NH children between the ages of 8 and 17 performed a test battery that was comparable with that performed by the group of children with CIs to obtain a metric of performance levels on the psychophysical tasks resulting from normal auditory system development. Three NH children could not fully complete the tasks and thus the final sample included 34 NH children (mean age = 12.97 years; 14 boys). The age distribution of NH child participants was approximately uniform, with at least three children falling within each 1-year age-group. One NH child (NHP09) was a fraternal twin of the CI participant P03 and another (NHP14) was a fraternal triplet of the CI participant P04. Several other NH participants were nontwin siblings. NH children were recruited from the Seattle community and the University of Washington Speech and Hearing Sciences Communication Studies Participant Pool (NIH P30 DC004661). These participants did not have any prior hearing problems or ear surgeries and completed a screening to verify hearing at 20 dB HL from 250 to 8000 Hz.

Children with NH and with CIs were all native speakers of American English and were born and raised in the Pacific Northwest. Most participants had no impairments in speech, language, vision, motor skills, or cognition. One pediatric CI user, P01, had a diagnosis of mild Asperger Syndrome but was able to perform the

**Table 1.** Cochlear Implant User Participant Demographics.

Subject	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12
Gender	M	M	M	F	M	F	F	M	F	M	F	M
Etiology	Unknown	EVA	Unknown	Unknown	DFNBI	Unknown	Unknown	EVA	Unknown	DFNBI	DFNBI	DFNBI
First-implanted ear												
Ear	R	R	R	R	R	R	R	L	L	L	R	R
Age at implantation	2.3	1.1	1.4	1.5	4.1	4.3	1.9	2.9	2.6	1.1	1.4	1.7
Chronological age	15.7	11.8	12.9	13.2	17.7	17.2	13.3	15.3	13.5	13.3	13.3	13.3
Aided hearing age	14.7	11.8	12.6	12.1	16.6	15.3	11.8	13.0	13.0	13.1	13.0	13.0
CI age	13.4	10.8	11.5	11.7	13.7	12.8	11.4	12.3	10.9	12.2	11.9	11.6
Preoperative unaided thresholds	>105	102.5	N/A	N/A	108.3	85	>115	90–105	103.3	90–>115	108	>108
Second-implanted ear												
Ear	L	L	L	L	L	L	L	R	R	L	L	L
Age at implantation	12.1	3.1	5.6	4.5	13.9	11.0	4.9	3.9	5.1	10.2	10.2	10.2
Chronological age	16.1	12.1	13.2	13.2	17.9	17.2	13.7	13.7	13.4	13.4	13.4	13.4
Aided hearing age	15.1	12.1	13.0	12.1	16.8	15.3	12.2	13.3	13.1	13.1	13.1	13.1
CI age	4.0	9.1	7.6	8.7	4.1	6.2	8.8	9.8	8.2	3.2	3.2	3.2
Preoperative unaided thresholds	101.7	80–110	96.6	N/A	100	98.3	>115	106.7	92	108	108	108

The reported preoperative unaided thresholds are the average or range of pure-tone hearing thresholds at 500, 1000, and 2000 Hz in decibels relative to hearing level (dB HL). The “>” symbol indicates no response to sound at equipment level limits. N/A indicates information not available. The CI in the gray-shaded column (P05L) was not included in the analysis for this study, as hearing loss in this ear was not diagnosed at a prelingual age. DFNBI = genetic nonsyndromic hearing loss; EVA = enlarged vestibular aqueduct.

tasks. Children gave written informed assent and a parent or guardian gave written informed consent. Families were compensated for their participation. Experimental procedures were approved by the University of Washington Human Subjects Division (IRB #28778).

### Assessments

Participants performed testing in a double-walled sound-treated booth (IAC RE-243). Stimuli were played through a Crown D75 amplifier and an external A/D device (SIIF USB SoundWave 7.1) and were presented through a Bose 161 speaker placed at 0° azimuth 1 meter from the subject. Children with CIs performed the tests using their clinical CI processor with the contralateral hearing aid or CI turned off. Bilaterally implanted children completed testing in this manner with each CI separately on different dates. NH children performed the tests with both ears simultaneously.

**Vowel Identification.** Speech stimuli consisted of 10 vowels (/i/, /ɪ/, /eɪ/, /ɛ/, /æ/, /a/, /u/, /ʊ/, /o/, /ʌ/) in /hVd context presented at 60 dB SPL. Vowels were naturally spoken by a female talker from the Pacific Northwest because regional dialect can influence speech identification performance (Wright & Souza, 2012). Vowels were chosen as the stimuli for this study for several reasons: (a) Vowel identification performance in quiet matures at a younger

age than for other speech stimuli (Johnson, 2000); (b) vowels are simple units of speech and thus minimize the effects of children’s linguistic knowledge on recognition scores; and (c) while nonspectral cues can be utilized for vowel identification, one’s ability to resolve the formants, or spectral peaks, in the vowel sound is important for accurate vowel recognition (e.g., Boothroyd, Mulhearn, Gong, & Ostroff, 1996; DiNino, Wright, Winn, & Bierer, 2016; Shannon et al., 2002). Accordingly, vowels are appropriate speech stimuli for an investigation of spectral resolution and speech identification in children.

Participants used a computer mouse to select the presented vowel from the closed set of possible responses listed on the computer screen. Custom software (ListPlayer, Version 2.2.11.52, Advanced Bionics, Valencia, CA) was used to present the stimuli and record subject responses.

Children with CIs first identified the vowels in quiet. Participants who received a score of 80% or higher in quiet with the CI being tested also performed the task in the presence of Auditech 4-talker babble at a +10 dB signal-to-noise ratio.

NH children identified vowel stimuli that were processed through a 15-channel noiseband vocoder with a 30 dB/octave filter slope to mimic the reduced spectral resolution of listening through a CI. This vocoder processing utilized the same frequency band allocations as the Fidelity F120 or Optima speech processing strategies

used in Advanced Bionics implants. These settings were chosen because a previous study demonstrated similarities between adult CI users' unprocessed vowel identification scores and NH adults' performance on vowel identification with these settings (DiNino et al., 2016). No floor or ceiling effects were observed for the NH children in this experiment.

Both groups of children completed two runs, each consisting of three repetitions of each vowel. Runs were scored in percentage correct. If the difference in performance between the two runs was greater than 10%, the child performed a third run. Scores from all test runs were averaged for each subject.

Prior to the test runs, subjects completed a practice run consisting of three presentations of each vowel in which they could repeat the sound as many times as desired. Feedback was also given after each response. The practice runs consisted of the stimuli (vowels in quiet, in noise, or vocoded) that the child was going to be tested on following the practice. In addition, NH children completed a practice run with one repetition of the unvocoded vowel stimuli in quiet at the beginning of the test. This familiarized the children with the vowel list and ensured that they could accurately identify the vowels prior to vocoder processing. Practice data were not included in the average performance scores.

*Spectral-temporally Modulated Ripple Test.* A potential issue with the conventional spectral ripple tasks used in many previous studies is that subjects may rely on local loudness cues to discriminate between stimuli (Aronoff & Landsberger, 2013). Intensity resolution continues to mature through adolescence in NH children (Horn et al., 2017; Maxon & Hochberg, 1982) and in children with CIs (Park et al., 2015) and therefore cues in the intensity domain may confound results on this test. The SMRT, which uses spectral ripples with drifting modulation phases to diminish potential within-channel loudness cues, may be more appropriate than traditional SRD tasks for use with pediatric populations.

The SMRT assesses the ability to discriminate between rippled noise stimuli at increasing densities of spectral peaks and valleys. The stimuli consisted of the sum of 202 amplitude-modulated pure tones from 100 to 6400 Hz with a modulation depth of 20 dB and a drifting phase rate of 5 Hz (Aronoff & Landsberger, 2013). Stimuli were presented at 65 dB SPL in a three-interval forced-choice 1-down/1-up adaptive procedure with 10 reversals. Each trial consisted of two reference stimuli and one target stimulus. The ripple density, or density of spectral peaks and valleys, of the reference stimuli were set at 20 ripples per octave (RPO), while the target stimulus was set initially at 0.5 RPO and was altered in step sizes of 0.2 RPO. The starting phase of each target and reference stimulus for each trial was

randomly selected between values of 0,  $\pi/2$ ,  $\pi$ , and  $3\pi/2$ . The SMRT becomes more difficult as the RPO value of the target stimulus, and thus the density of the ripples, increases. The threshold for each run was calculated based on the average of the last six reversals and indicated the highest RPO of the target stimulus at which 50% discrimination was achieved. Hence, larger threshold values indicate better spectral discrimination abilities.

Each participant completed one practice run and two test runs. The practice run was identical to the test run, but these data were not included in the calculation of participants' average SMRT thresholds. If a participant's thresholds from two test runs were greater than one RPO apart, they completed a third run. Results from all test runs were averaged to determine the mean SMRT threshold for each subject.

Despite the consistent finding of a strong association between performance on SRD tasks and speech identification scores in adults with CIs (e.g., Henry et al., 2005; Won et al., 2007), potential issues exist in the interpretation of such results at medium and high ripple density rates. In particular, the CI processor cannot accurately represent spectral ripple stimuli at high RPO values, which results in a nonmonotonic relationship between presented and perceived stimuli with increasing ripple density. However, SRD tasks have been a very popular method for assessing spectral discrimination abilities and have been utilized extensively in populations of adults with NH and hearing impairment; thus, goals of the current study were to examine performance on such assessments by children and compare those with results found consistently in adults with NH and with CIs. Precautions were taken in this study to interpret the results of the SMRT appropriately (see Discussion section).

Efforts were made to minimize the influences of decreased attention and practice effects on auditory task performance. All children were given several breaks and active participation was incentivized with snacks and small toys. The order in which a participant performed vowel identification, the SMRT, and one other task not reported here was randomized. Bilaterally implanted pediatric CI users completed the tasks over two sessions to reduce testing fatigue. These individuals performed vowel identification and the SMRT with one CI during the first visit and with their other CI during their second visit. However, previous research has found that psychophysical test scores, particularly those on the SMRT, improve between sessions (e.g., De Jong, Briaire, & Frijns, 2017); testing each ear separately over two sessions could thus result in a bias of better performance with the second-implanted ear if that CI was always tested last. Therefore, two of our participants performed the tasks with their second-implanted ear first. Full randomization of implant testing order was

not completed because of a concern that participants with CIs may not be interested in or available to return for a second visit, and data with the earlier-implanted ear were most valuable for this study.

### Demographic Information

Birthdates were obtained for each child participant in the study to determine the potential influence of age on vowel identification and SMRT performance. The dates that each child with a CI received a hearing aid in each ear and the date(s) of the first stimulation of their implant(s) were obtained via parent report and were corroborated by examination of medical records from Seattle Children's Hospital (see Table 1).

### Statistical Analyses

Age at testing was calculated for each participant. Aided hearing age (time between receiving a hearing aid and receiving a CI) and CI age (time between CI activation and the date of testing) were also calculated for participants with CIs. These variables were determined separately for each ear of bilaterally implanted children because they (a) had been sequentially implanted and (b) had completed testing with each of their CIs during separate sessions, which were typically months apart.

The vowel identification scores in quiet and in noise for children with CIs and vocoded vowel identification scores for NH children were converted to rationalized arcsine units to normalize error variance and transform the data into a more appropriate form for analysis (Studebaker, 1985).

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 19.0. For data obtained from NH children, a multiple linear regression analysis was conducted to determine whether SMRT thresholds or age predicted vocoded vowel identification performance. A second linear regression testing an additional hypothesis was performed to determine whether chronological age, representing maturity of auditory perception, significantly predicted spectrally degraded vowel identification.

A series of planned mixed-model, repeated-measures linear regressions testing separate hypotheses were conducted with data obtained from pediatric CI participants to identify the relationships between auditory perceptual development, SMRT thresholds, and vowel identification performance in quiet and noise. For all models, data from each CI of bilaterally implanted children were analyzed as separate data points while including "subject" as a random intercept and ear tested (first- or second-implanted ear) as the repeated measure to address the lack of independence in the data set. An unstructured covariance matrix was specified for each model. The

first set of analyses examined whether chronological age, aided hearing age, or CI age significantly predicted vowel identification in quiet (Model 1) or in noise (Model 2) or SMRT thresholds (Model 3). The next set of analyses determined whether SMRT performance was a significant predictor of vowel identification in quiet (Model 4) and in noise (Model 5). All predictor variables were set as fixed factors in each model.

To examine the effects of ear implanted (first- or second-implanted CI) on spectral discrimination and vowel identification of bilaterally implanted children, a multivariate analysis of variance (MANOVA) was performed with ear tested as the predictor variable for the independent variables of vowel identification in quiet, vowel identification in noise, and SMRT performance.

Vowel recognition scores and SMRT thresholds were not directly compared between children with CIs and with NH; vowel stimuli differed between groups, and device limitations of CI users restrict global performance on the SMRT. In addition, a positive relationship between SMRT performance and vowel identification scores would be interpreted differently for each group of children. Identifying vocoded vowel stimuli mimics CI listening, but NH children have an intact peripheral auditory system to process spectrally degraded speech. Accordingly, NH children would not utilize the same frequency-resolving mechanisms to perform both vocoded vowel identification and spectral discrimination; a positive relationship between performances on these tasks would more likely result from general development of the auditory system. In children with CIs, however, performance on both tests would be affected by the limited spectral resolution of the implant as well as potentially delayed auditory system maturation. The relationship between spectral discrimination abilities and vowel identification performance were examined separately for children with CIs and with NH, while the effects of presumed auditory perceptual development on psychophysical tasks were compared between the two groups of children.

### Sequential Information Analysis

Sequential information analysis (SINFA) was performed on each participant's pattern of vowel confusions to determine the degree of vowel phonetic feature perception of children with CIs and with NH. This feature analysis is based on that of Miller and Nicely (1955) and utilizes perceptual responses to a closed set of presented phonemes to calculate the percentage of information transmitted related to a specific phonetic feature. Yet, the contribution of phonetic features to their identification is not completely independent; SINFA was created to account for at least some of this redundancy. The SINFA performs iterations in which the feature with

the highest amount of information transmitted is first identified, its percentage information transmitted calculated, and then held constant while the next iteration is performed to determine the next most important feature (M. D. Wang & Bilger, 1976). While SINFA does not control for the entirety of vowel feature interdependence, and thus may be better suited for use with stimuli with less internal redundancy (e.g., DiNino et al., 2016), this analysis provides a means of at least approximating the amount of vowel feature information available to each group of children for perceiving these sounds.

Three features integral for accurate vowel discrimination were chosen for the SINFA: the first formant (F1; the lowest-frequency spectral peak), the second formant (F2; the next lowest-frequency spectral peak), and duration (as in DiNino et al., 2016; Xu, Thompson, & Pfingst, 2005). Vowels were classified as having low (<420 Hz), middle (420–520 Hz), or high (>520 Hz) F1 values, low (<1330 Hz), middle (1330–2000 Hz), or high (>2000 Hz) F2 values, and short (<250 ms) or long (>250 ms) duration.

The matrices of vowel responses to vowel stimuli presentations, or confusion matrices, from test runs within a vowel identification condition (vocoded, in quiet, or in noise) were averaged for each NH participant and for each ear tested of the children with CIs. SINFA was utilized to calculate the percentage, from 0% to 100%, of information transmitted for F1, F2, and duration from each averaged confusion matrix. Higher percentages signify a larger amount of transmitted information for that feature. Although different vowel stimuli were presented to each group, vocoder processing degrades spectral feature information in a manner which simulates CI listening. Thus, an independent *t* test was performed to compare vowel feature information transmission values resulting from vowel identification in quiet of children with CIs and spectrally degraded vowel identification of NH children. The ranking of F1, F2, and duration feature transmission (from most to least information transmitted) was also examined between the groups as well as between the quiet and noise conditions for pediatric CI users' vowel recognition.

In addition, as spectral resolving capabilities are important for accurate identification of speech sounds, this study sought to determine whether SMRT performance was related to perception of specific vowel features. The relationship between vowel feature information transmission values and SMRT thresholds was examined for each group to determine if one's ability to perceive a certain vowel feature may have contributed to SMRT performance. Multiple linear regression analyses were performed for NH children's data and mixed-models repeated-measures regression analyses were conducted for data from children with CIs, with SMRT threshold as the independent variable and F1, F2, and duration

information transmission values as predictors. Diagnostic tests of collinearity revealed that the information transmission values of all vowel features from children with CIs' vowel identification in quiet were highly correlated with each other (Variance Inflation Factor [VIF] values ranging from 9.3 to 16.0). High VIF values were not observed among these variables for vocoded vowel identification of children with NH (VIF values between 1.4 and 2.5), but follow-up correlation analyses revealed strong, statistically significant correlations between information transmission values of all vowel features (*R* values between 0.51 and 0.75). For these reasons, separate regression models with corrections for multiple comparisons were run to determine the relation between F1, F2, and duration information transmission values on SMRT thresholds. Neither multicollinearity (VIF values: 1.1, 1.2, and 1.1) nor significant correlations were observed among F1, F2, and duration-related information transmission for vowel identification in noise of children with CIs, and therefore all three independent variables were included in the same repeated-measures regression model for this condition.

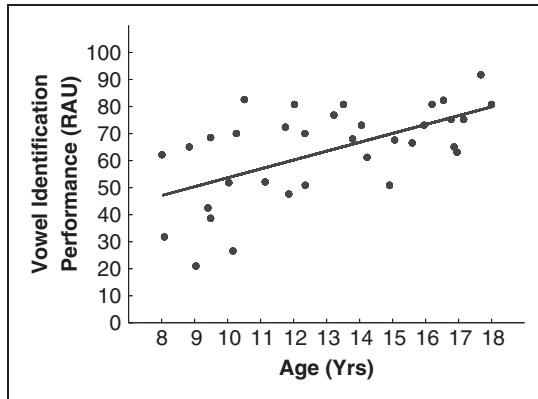
Means (*m*) and standard deviations (*SD*s) of all data are reported.

## Results

### Children With NH

Vocoded vowel identification performance varied greatly among NH children, ranging from 20.0 to 88.5 (*m* = 63.1, *SD* = 17.3) percentage correct. SMRT thresholds (with larger numbers indicating better performance) of NH children varied between 5.2 and 10.7 (*m* = 8.6, *SD* = 1.34) RPO. A multiple linear regression analysis to predict vocoded vowel identification performance based on chronological age and SMRT thresholds resulted in a significant regression equation:  $F(2,31) = 12.4$ ,  $p < .001$ ,  $R^2 = 0.44$ . Both age ( $p = .001$ ) and SMRT thresholds ( $p = .03$ ) in this analysis were significant predictors of vocoded vowel identification scores. Figure 1 shows the relationship between chronological age and vocoded vowel identification performance of NH children. On average, the regression model revealed that vocoded vowel recognition performance improved 2.9 percentage points for each 1-year increase in age, and 4.0 percentage points for each 1 RPO increase in SMRT thresholds.

While age was found to significantly predict vocoded vowel identification, a simple linear regression analysis revealed no significant relationship between age and SMRT thresholds of NH children:  $F(1,32) = 1.78$ ,  $p = .19$ ,  $R^2 = 0.05$ . However, the analysis revealed that, on average, SMRT thresholds did increase slightly (0.1 RPO) for each year increase in age (see Figure 4(a)).

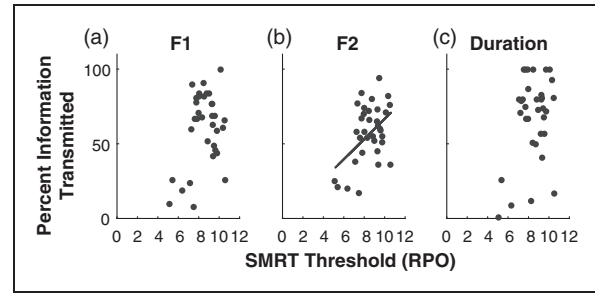


**Figure 1.** Vocoded vowel identification performance of normal hearing children as a function of age. Vowel identification scores are in rationalized arcsine units (RAU). Each circle represents data from one child. Solid line represents the line of best fit.

Results of the SINFA indicated a large amount of variation in the percent of vowel feature information transmitted among NH children. These values ranged between 8% and 100% for F1, 17% and 94% for F2, and 1% and 100% for duration. On average, duration exhibited the highest amount of information transmitted ( $m=68.0\%$ ,  $SD=27.8$ ), followed by F1 ( $m=61.1\%$ ,  $SD=24.3$ ) and F2 ( $m=57.4\%$ ,  $SD=19.4$ ). The analyses to determine the relationship between vowel feature information transmission and SMRT thresholds revealed a significant relation between F2 transmission on SMRT performance:  $F(1,32)=9.0$ ,  $p=.005$ ,  $B=3.3$ ,  $R^2=0.22$ . The relationships between SMRT thresholds and transmission of F1-related information,  $F(1,32)=4.2$ ,  $p=.05$ ,  $B=1.9$ ,  $R^2=0.12$ , and transmission of duration feature information,  $F(1,32)=4.4$ ,  $p=.045$ ,  $B=1.7$ ,  $R^2=0.12$ , did not survive correction for multiple comparisons ( $\alpha=0.016$ ). These analyses also revealed that F2 information transmission had larger effects on SMRT thresholds than did F1 and duration information transmission. These results therefore indicated that NH children's perception of the F2 feature was a predictor of SMRT performance (see Figure 2).

### Children With CIs

Analogous to speech testing results observed in previous studies, a large amount of variability was observed in vowel identification performance among children with CIs. This variance was found also between the bilateral CIs of a child. Vowel recognition scores in quiet ranged from 13.5 to 100 ( $m=79.0$ ,  $SD=25.5$ ) percentage correct. Only children who received 80% correct or higher on vowel identification in quiet performed the test in noise; among those individuals, scores varied between 40 and 86.5 ( $m=71.7$ ,  $SD=12.7$ ) percentage correct.



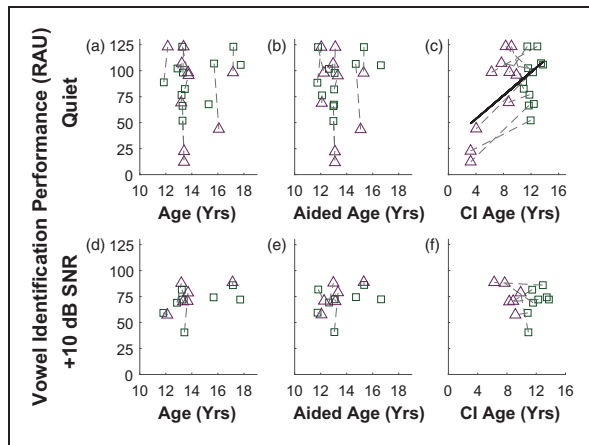
**Figure 2.** Relationships between vowel feature information transmission and SMRT thresholds in normal hearing children. Percentage of information transmitted for (a) F1, (b) F2, and (c) duration plotted against SMRT thresholds. Each circle represents data from one child. Solid line represents the line of best fit for the significant relationship.

In addition, as expected, on average pediatric CI user's SMRT thresholds were much lower (indicating poorer performance) than those observed in NH children, ranging between 0.6 and 7.7 ( $m=2.9$ ,  $SD=1.9$ ) RPO.

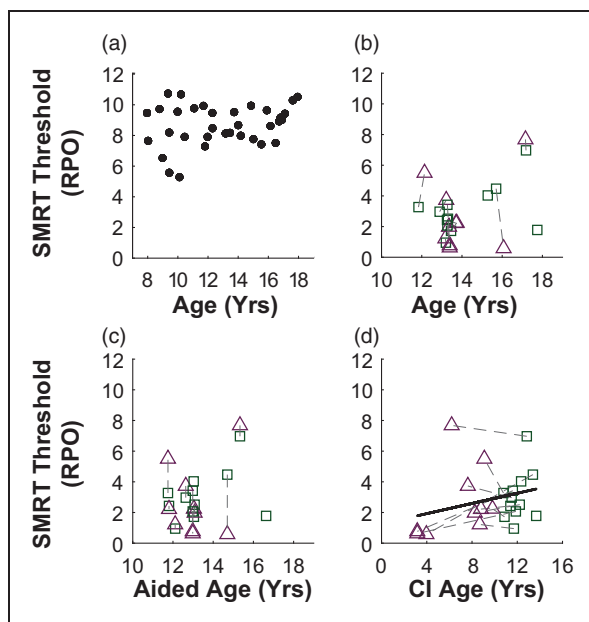
Unlike the observed results in NH children, mixed-model regression tests of fixed effects revealed that chronological age did not significantly predict vowel identification performance in quiet ( $p=.46$ ) or in noise ( $p=.26$ ), nor did aided hearing age (quiet:  $p=.70$ ; noise:  $p=.57$ ), likely because most children were fit with amplification soon after birth. Instead, CI age significantly predicted vowel identification performance in quiet,  $F(1, 9.4)=10.1$ ,  $p=.011$ , suggesting that the timeline of speech perception development may coincide with the amount of time a child has had their CI. Further examination of this relationship revealed that performance with the second-implanted CIs were driving these results: When the data were separated by first- or second-implanted ears, a significant result between vowel identification scores in quiet and CI age was found for second-implanted ears,  $F(1,6)=22.2$ ,  $p=.003$ , but not for first-implanted ears,  $F(1,8)=0.02$ ,  $p=.90$ . No significant relationship between CI age and vowel identification performance in noise was observed ( $p=.27$ ), although only the better-performing children (who most often had their implants for longer periods of time) were tested in noise (see Figure 3).

A mixed-model regression analysis to investigate the relationship between age variables and spectral discrimination abilities revealed that CI age also predicted SMRT performance,  $F(1,9.8)=9.4$ ,  $p=.012$ , while chronological age ( $p=.32$ ) and aided hearing age ( $p=.67$ ) did not (see Figure 4). However, unlike the relationship between CI age and vowel identification scores, separate-ear analyses revealed no significant relationship between CI age and SMRT thresholds for either first- or second-implanted ears alone.





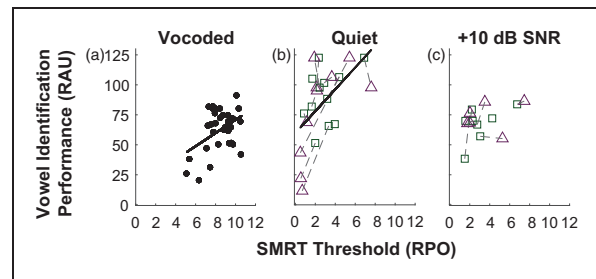
**Figure 3.** Vowel identification performance of children with CIs as a function of age-related variables. (a–c), vowel identification in quiet versus (a) chronological age, (b) aided hearing age, and (c) CI age. (d–f), vowel identification in noise versus (d) chronological age, (e) aided hearing age, and (f) CI age. Vowel identification scores are in rationalized arcsine units (RAU). Each symbol represents data from one CI. Squares indicate first-implanted CIs and triangles indicate second-implanted CIs. Dashed lines connect data from the two CIs of each bilaterally implanted child. Solid lines represent the lines of best fit for significant relationships.



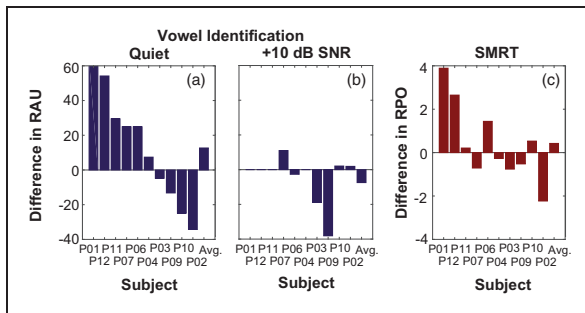
**Figure 4.** SMRT thresholds of children with NH and with CIs as a function of age-related variables. (a) SMRT thresholds of NH children by age. Each circle represents data from one child. (b–d) SMRT thresholds of children with CIs by (b) chronological age, (c) aided hearing age, and (d) CI age. Each symbol represents data from one CI. Squares indicate first-implanted CIs and triangles indicate second-implanted CIs. Dashed lines connect data from the two CIs of each bilaterally implanted child. Solid lines represent the lines of best fit for significant relationships.

Tests of multicollinearity revealed that the chronological and aided hearing age variables in models testing data from pediatric CI users were highly correlated with each other ( $r = 0.93, p < .001$ ). Both variables also exhibited high VIF values (between 7.52 and 12.2) in all models. This likely occurred because most of the children received their hearing aid(s) shortly after birth, and thus aided hearing age values were very similar to those of chronological age. As chronological age was more relevant to the goals of the study than was aided hearing age, the repeated-measures models were run again after removing aided hearing age as a factor. Multicollinearity was no longer present (VIF values between 1.01 and 1.07), and the pattern of results was the same as those found in the prior repeated-measures analyses: Chronological age was not a significant predictor of any independent variable, and CI age was significantly related to vowel identification in quiet,  $F(1, 9.3) = 10.0, p = .011$ , and SMRT performance,  $F(1, 10.2) = 10.8, p = .008$ .

Consistent with previous studies in adults (e.g., Henry et al., 2005) and one study in NH children (Allen & Wightman, 1992), the next set of analyses revealed that SRD performance was a significant predictor of vowel identification scores in quiet,  $F(1, 15.4) = 20.0, p < .001$ , of children with CIs. The relationship between SMRT threshold and vowel identification in noise was not significant ( $p = .16$ ; see Figure 5). However, again, only the better-performing children performed vowel identification in noise, which reduced the sample size for analysis.



**Figure 5.** Vowel identification performance of children with NH and with CIs compared with SMRT thresholds. (a) Vocoded vowel identification performance in rationalized arcsine units (RAU) of NH children plotted against SMRT thresholds. Each symbol represents data from one child. (b) Vowel identification in quiet scores in RAU of pediatric CI users plotted against SMRT thresholds. (c) Vowel identification in noise scores in RAU of pediatric CI users plotted against SMRT thresholds. Each symbol represents data from one CI. Squares indicate first-implanted CIs and triangles indicate second-implanted CIs. Dashed lines connect data from the two CIs of each bilaterally implanted child. Solid lines represent the lines of best fit for significant relationships.



**Figure 6.** Comparison of task performance between first- and second-implanted ears of bilateral CI users. Bars indicate differences in performance (first implant – second implant) on (a) vowel identification in quiet, (b) vowel identification in noise, and (c) the SMRT. Scores above 0 indicate better performance when tested with the first implanted ear. Subjects are ordered by amount of enhancement in vowel identification in quiet scores with their first-implanted ear compared with their second. Only subjects who scored >80% on vowel recognition in quiet were tested in noise (P02, P03, P06, P07, P09, and P10).

No significant differences in performance were observed between first and second CIs of bilaterally implanted children for vowel identification in quiet ( $p = .62$ ) or in noise ( $p = .51$ ) or on the SMRT ( $p = .57$ ). Some children performed better on these assessments with their first-implanted ear, while others exhibited better performance with their second (see Figure 6).

Similar to the SINFA results observed in NH children, vowel feature information transmission values varied greatly among children with CIs. These values also differed between the two CIs of the same child (see Table 2). For vowel identification in quiet, information transmission ranged between 9% and 100% for F1, 7% and 100% for F2, and 4% and 100% for duration. For vowel identification in noise, they ranged between 21% and 94% for F1, 27% and 86% for F2, and 35% and 100% for duration. Results of the SINFA for individual ears of children with CIs are shown in Table 2.

Pediatric CI users demonstrated the same pattern of vowel feature ranking as children with NH: On average, the feature with the largest amount of information transmitted for vowel identification in quiet and in noise was duration (quiet:  $m = 81.6\%$ ,  $SD = 31.6$ ; noise:  $m = 76.2\%$ ,  $SD = 18.0$ ). The second highest amount of information transmitted was found for F1 (quiet:  $m = 77.9\%$ ,  $SD = 30.9$ ; noise:  $m = 63.8\%$ ,  $SD = 23.0$ ), and the least amount for F2 (quiet:  $m = 73.2\%$ ,  $SD = 27.4$ ; noise:  $m = 62.1\%$ ,  $SD = 18.3$ ). The amount of information transmitted for each feature was lower for vowel identification in noise compared with identification in quiet.

Examinations of the relationship between the amount of vowel feature information transmitted and SMRT thresholds revealed significant results for F1,

**Table 2.** Cochlear Implant User Sequential Information Analysis Results.

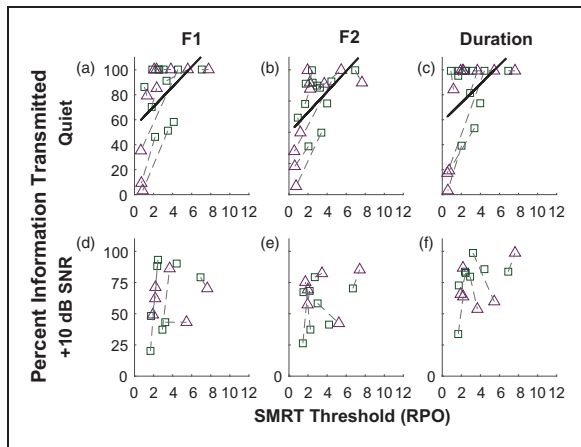
Participant	Ear	Percentage information transmitted					
		Quiet			Noise		
		F1	F2	Duration	F1	F2	Duration
P01	R	100	91	100	91	42	87
	L	35	35	18	N/A	N/A	N/A
P02	R	91	86	100	44	59	100
	L	100	100	100	44	43	61
P03	R	100	87.7	82.2	38	80	81
	L	100	89	100	87	83	55
P04	R	86	62	100	N/A	N/A	N/A
	L	79	50	85	N/A	N/A	N/A
P05	R	100	89.2	100	49	68	74
P06	R	100	100	100	80	71	85
	L	100	90	100	71	86	100
P07	R	100	100	100	89	69	85
	L	100	90	100	63	58	88
P08	L	58	73.4	74	N/A	N/A	N/A
P09	L	70	73	96	21	27	35
	R	85	85	100	72	70	65
P10	L	100	90	100	94	38	84
	R	100	100	100	50	76	67
P11	R	46	39	40	N/A	N/A	N/A
	L	9	23	4	N/A	N/A	N/A
P12	R	51	50	54	N/A	N/A	N/A
	L	3	7	20	N/A	N/A	N/A

N/A = information not available, as these children were not tested on vowel identification in noise.

$F(1,10.7) = 40.5$ ,  $p < .001$ , F2,  $F(1,12.8) = 32.0$ ,  $p < .001$ , and duration,  $F(1,11.1) = 23.4$ ,  $p = .001$ , of vowel identification in quiet. All results were significant after correcting for multiple comparisons ( $\alpha = 0.016$ ), indicating that high transmission of any of the three vowel features when identifying vowels in quiet predicted better SMRT performance. As expected, no significant relationships were observed between SMRT thresholds and information transmission values of any feature from vowel identification in noise (F1:  $p = .16$ , F2:  $p = .71$ , duration:  $p = .29$ ), as performance on this test had not been found to relate to performance on the SMRT (see Figure 7).

### Comparison of SINFA Results Between Children With NH and With CIs

Statistical comparisons of the mean vowel feature information transmission values between groups indicated that NH children had significantly lower transmission



**Figure 7.** Relationships between vowel feature information transmission and SMRT thresholds in children with CIs. Percentage of information transmitted for F1 (a, d), F2 (b, e), and duration (c, f) from vowel identification in quiet (a–c) and vowel identification in noise (d–e) plotted against SMRT thresholds. Each symbol represents data from one CI. Squares indicate first-implanted CIs and triangles indicate second-implanted CIs. Dashed lines connect data from the two CIs of each bilaterally implanted child. Solid lines represent the lines of best fit for significant relationships.

of F1-related information,  $t(54) = 2.3$ ,  $p = .027$ , and F2-related information,  $t(54.4) = 2.4$ ,  $p = .025$ , for vocoded vowel recognition compared with that from pediatric CI users' identification of vowels in quiet. No significant differences were found between groups for transmission of the duration feature:  $t(54) = 1.6$ ,  $p = .12$ .

## Discussion

This study examined the influence of age-related variables on pediatric CI users' vowel recognition scores as well as the relationship between spectral discrimination abilities and vowel identification performance. NH children completed tasks analogous to those performed by children with CIs to compare the differences in psychoacoustic abilities with acoustic hearing across ages to that with a CI. Each CI of bilaterally implanted children was tested separately to assess age-related factors while limiting other potential sources of variability. In addition, a SINFA was performed to investigate whether the pattern of vowel feature perception differed between children with CIs and with NH. Information transmission values were also compared with SMRT thresholds to determine the relationship between conveyance of specific vowel features and spectral discrimination abilities.

### Age-Related Factors

**Vowel Identification Performance.** Vocoded vowel identification scores were found to increase with age of NH

children. These results are consistent with those from previous studies that have observed age effects in children's recognition of spectrally degraded stimuli. For example, Dorman et al. (2000) found that very young children required more channels of spectral information than adults did to correctly identify words processed through a sine-wave vocoder. Similarly, several prior studies have observed better performance on noise-vocoded word and sentence recognition in older compared with younger school-age children (Eisenberg et al., 2000, 2002; Roman, Pisoni, Kronenberger, & Faulkner, 2016). This study extended these findings to vowel stimuli, whose identification is more dependent on spectral cue resolution than are words or sentences. Data from this study demonstrate that vocoded vowel recognition performance may begin to plateau around the age of 14, the age of the oldest children tested in Eisenberg et al. (2000, 2002) and Roman et al. (2016). However, several 16- and 17-year-olds performed at higher levels than children 14 years old and younger (see Figure 1). These results suggest that spectrally degraded vowel identification performance might continue to improve through the late teenage years, but other 16- and 17-year-olds performed more poorly on vocoded vowel identification than did younger children. Thus, the number of children tested from each 1-year age bin was too small, and the variability among these children's scores too large, to conclusively determine the age at which vocoded vowel recognition abilities are fully mature.

A number of factors may underlie the large amount of variance in vocoded vowel identification scores observed among the NH children. As unprocessed vowel identification matures at an age earlier than the youngest NH children tested (e.g., Allen & Wightman, 1992; Johnson, 2000), and because phonemes are the simplest speech stimuli, linguistic or vocabulary knowledge should not have significantly contributed to this variability. However, Roman et al. (2016) found correlations between children's performance on vocoded word and sentence identification and both auditory attention and short-term memory capacity. Further, because the vowel identification task required children to read and select the vowel sound they perceived from a visual display, differences in children's reading skills could have affected the difficulty of this test. These variables may explain the range of vocoded vowel identification scores that were observed even in NH children of the same age, although cognitive factors or reading skills were not tested in this study.

In children with CIs, vowel identification performance was significantly related to time with the implant, demonstrating the importance of auditory experience for development of speech recognition abilities. Previous research has shown that the speech perception

performance of children with CIs indeed improves between implantation and 2 to 3 years later. Parkinson, El-Kholy, and Tyler (1998) tested prelingually deafened children (who received a CI between the ages of 4 and 14) on vowel identification at 12, 24, and 36 months after receiving their implant. They found that most children's vowel recognition scores improved significantly between 12 and 24 months postimplantation and continued to improve between the 24- and 36-month time points. Similarly, N-Y. Wang et al. (2008) tested prelingually deafened, early-implanted children with CIs on a hierarchy of speech identification tests at 6, 12, 18, and 24 months after implantation. Children were required to obtain a criterion score on each test before moving on to a progressively more difficult test. They found that at 6 months postimplantation, most children did not perform well enough to move past the first test. However, by 24 months after receiving their CI, many children were able to advance to the most difficult assessment. Results from the current study demonstrate that children may continue to improve on speech identification longer than 3 years postimplantation.

Separate analyses of first- and second-implanted CIs showed that the relationship between vowel identification scores in quiet and CI age was significant for the second- but not first-implanted ears. A *t* test revealed that the average CI age of first implants ( $m = 12.02$ ,  $SD = 0.92$  years) was significantly greater than that of second implants:  $m = 6.87$ ,  $SD = 2.86$ ;  $t(10.9) = 6.02$ ,  $p < .001$ . The findings from the separate-ear analyses may be indicative of an upper limit on vowel identification improvement with time. However, a much broader range of CI ages as well as vowel identification scores existed for second- compared with first-implanted ears, potentially explaining why such a relationship was detected for second- but not first-implanted ears.

**SMRT Thresholds.** In this study, no relationship was found between age and spectral discrimination performance of NH children aged 8 years and older. However, previous studies which have found improvements in SRD abilities beyond the age of 9 utilized traditional SRD tasks (e.g., Peter et al., 2014; Rayes et al., 2014). The test used in this study, the SMRT, attempts to control for the potential confound of within-channel intensity cues that may exist in traditional SRD tests (Aronoff & Landsberger, 2013). Intensity resolution continues to develop through at least early adolescence in NH children (e.g., Maxon & Hochberg, 1982), and this maturation is likely further delayed in children with CIs (Park et al., 2015). Older children may perform better than younger children on traditional SRD tests because they are better able to discriminate within-channel intensity differences in the stimuli. It is therefore possible that performance on the SMRT, which may reduce these developmental effects

of intensity resolution, could mature at a younger age than performance on a traditional SRD task. Results from studies conducted by Kirby et al. (2015) and Landsberger et al. (2017) provide evidence for this theory: Both investigations found an effect of age on SMRT thresholds in children aged 6 to 12 years old, but observed that SMRT performance began to peak at the age of 8 or 9. These findings, in combination with those from this study, suggest that NH children's performance on the SMRT (which diminishes the potential confound of immature intensity resolution within a single channel) may mature at 8 or 9 years old. Comparison of SMRT and traditional SRD test performance within the same group of children is thus necessary to determine whether age-related performance differences indeed exist between traditional SRD tasks and the SMRT.

While no significant relationship was found between SMRT performance and age in the group of NH children tested in this study, an age-related factor, CI age, was found to predict SMRT thresholds of pediatric CI users in the repeated-measures statistical model. Maturation of SMRT performance with a CI may be prolonged compared with NH children; in this study, NH children's spectral discrimination abilities seem to have matured by the age of 8 but pediatric CI users' performance seems to improve up to a "CI age" of 13.7. As delayed maturation of performance on other psychoacoustic tasks has been observed in children with CIs (e.g., Park et al., 2015), the period of auditory deprivation prior to receiving a CI as well as the degraded auditory signal through a CI compared with acoustic hearing may indeed impede maturation of spectral discrimination abilities.

Although the results from this study suggest that CI age may play a role in SMRT performance of pediatric CI users, a recent study conducted by Landsberger et al. (2017) did not find an effect of time with the CI on SMRT thresholds of early-implanted children. However, these studies assessed participant populations that differed in two key ways. While both groups of participants received their first implant very early in life, the children tested in the current study were older (aged 11.94–17.92 years) than those tested in Landsberger et al. (aged 6.0–13.1 years), resulting in older "CI ages" as well. Perhaps the effect of time with the CI on spectral resolving capabilities does not appear until the child has had their CI for longer periods of time. In addition, the interaction between development of the auditory system and auditory experience may be more discernable at later chronological ages.

Another possible explanation for the dissimilar findings between the two studies could be the difference in statistical methods utilized. Landsberger et al. (2017) performed separate correlation analyses between time with the implant and SMRT thresholds for first- and second-implanted CIs of bilaterally implanted children;

the current study combined data from both CIs of bilaterally implanted children into a mixed-model repeated-measures design. This model inherently possessed greater power for detecting statistical effects because repeated-measures analyses control for between-subject error. Indeed, when the authors of this study separated the data set by ear implanted, and also performed correlation analysis akin to those performed by Landsberger et al., the results were not significant ( $r = 0.35$ ,  $p = .27$  for first-implanted CIs and  $r = 0.35$ ,  $p = .33$  for second-implanted CIs). Still, because these children do have two CIs, not one, a repeated measures design is a more appropriate statistical analysis to determine the influence of CI age for bilaterally implanted children: Such an analysis simultaneously considers the effects of auditory experience on SRD performance of each individual CI. Despite these differences in methods and subject populations, the discrepancy in results between the two studies could potentially be explained by the large degree of variability among pediatric CI users. Additional studies utilizing the SMRT in children with CIs are necessary to fully elucidate the relationship between time with the CI and spectral discrimination performance with this test.

### *Relation Between Spectral Discrimination and Vowel Identification Performance*

This is the first study to our knowledge to examine the relationship between performance on a modified version of traditional SRD tests, the SMRT, and speech identification performance of children. SMRT thresholds were found to positively relate to vocoded vowel identification scores of NH children and vowel identification performance in quiet of children with CIs. These relationships are consistent with those found previously between performance on traditional SRD tasks and scores on speech identification tasks in adults with NH (Henry & Turner, 2003) and with CIs (e.g., Henry et al., 2005; Won, Drennan, & Rubinstein, 2007; Won et al., 2011) as well as those previously observed between SMRT and speech identification performance of adult CI users (Holden et al., 2016; Lawler, Yu, & Aronoff, 2017; Zhou, 2017). Data from this study demonstrate that the SMRT, while distinct from traditional SRD tasks, could be used to predict vowel identification performance of children.

Previous studies with pediatric CI users have observed varying relationships between SRD thresholds and speech identification scores. Specifically, Jung et al. (2012) found a strong correlation between SRD performance and identification of spondees in noise in prelingually deafened, early-implanted children, but did not observe this result when correlating SRD thresholds and monosyllabic word recognition scores. Similarly, Horn et al. (2017) found significant positive relationships between SRD performance and spondee identification in

noise in early-implanted, school-age children, but only in two of five SRD ripple depths tested. In both studies, the correlations observed in children with CIs were weaker than those observed in adults.

The differences between these findings and those from this study may be because of speech stimuli: Formant frequencies are an important cue for accurate vowel identification (e.g., DiNino et al., 2016; Shannon, Galvin, & Baskent, 2002), so vowels may be more related to spectral discrimination than are monosyllabic words. The vowels within spondees are indeed the main cue for their recognition, and this may explain why these prior investigations have found some positive relationships (although weaker than the relation observed between SMRT performance and vowel identification scores in this study) between SRD thresholds and spondee identification in noise. In addition, the speech stimuli for NH listeners in Jung et al. (2012) and Horn et al. (2017) were unprocessed and presented in quiet or in noise, whereas the vowel stimuli in this study were vocoded. Perhaps SRD requires cognitive or developmental mechanisms that are more related to identifying spectrally degraded speech than they are to recognizing speech in quiet or in noise. Further, the SMRT attempts to control for potential local loudness cues in traditional SRD stimuli (e.g., Aronoff & Landsberger, 2013). This test may thus eliminate the developmental confound of immature single-channel intensity resolution which would delay maturation of children's performance on traditional SRD tasks compared to performance on the SMRT. If so, based on results from prior studies in children that utilized traditional SRD tests, frequency resolution as measured by the SMRT may be a better predictor of speech identification abilities of children than are other SRD tasks.

While this study found a strong, positive relationship between SMRT thresholds and vowel identification performance in children with CIs, an issue with presenting SRD stimuli to CI users warrants caution when interpreting such results. The CI speech processor contains a small number of frequency analysis channels (15 for those tested in this study), which limits the number of spectral peaks and valleys that can be transmitted. Recent evidence demonstrated that CI speech processor output is unpredictable for stimuli above about 2 RPO (O'Brien & Winn, 2017), and therefore, there is no monotonic relationship between ripple input and processor output that can be interpreted as a single spectral dimension. Above a critical ripple density, the spectral envelope is aliased (akin to aliasing of frequencies when a sound is undersampled), so the moderate- and high-density ripple stimuli contain spectral cues not intended by the experimenter. It is likely that CI users who achieve high SRD thresholds may be able to utilize different perceptual strategies that enable them to discern

these non-linear and non-monotonic spectral distortions, which consequently improves their performance on the test.

The SMRT differs from traditional SRD tasks in that the stimuli contain a temporal cue in addition to the spectral signal; however, when the SMRT is presented through a CI processor, the amplitude modulation of this temporal component has also been found to distort at high RPO values. Lawler et al. (2017) recorded electrograms from Advanced Bionics processors (the device used by all children with CIs in this study) and observed temporal smearing of the signal as ripple density increased from one to three RPO. The amplitude modulation depth of the temporal signal became shallower with increasing RPO values. The temporal component of SMRT stimuli may be thought of as an additional cue for SMRT discrimination, and substantial distortion of this cue through a CI processor may not occur until a larger RPO value than that at which spectral aliasing occurs; yet, if the spectral signal is smeared, both cues are no longer monotonically changing with increasing RPO. The stimulus parameter is thus unpredictable beyond the RPO value at which spectral distortion occurs.

As many children in this study achieved high SMRT thresholds, the relationship between SMRT performance and vowel identification was examined again after setting an SMRT threshold upper limit. A similar analysis was conducted by O'Brien and Winn (2017), in which they set a cutoff value of 2.56 RPO and recalculated the average thresholds for each participant. This cap on SRD thresholds resulted in stronger relationships between SRD and scores on speech-based outcome measures than in the analyses which had included higher threshold values. The cutoff value of 2.56 RPO was based on the frequency allocation table of Cochlear devices and was determined to be the critical limit after which ripple stimulus aliasing occurs in the spectral domain. However, CI participants in this study used Advanced Bionics devices, which contain a smaller number of frequency analysis bands than Cochlear devices. An approximation of the critical RPO limit for Advanced Bionics CIs was conducted and yielded a value of 1.46 RPO. All individual SMRT runs with thresholds greater than 1.46 RPO were changed to this value and the model relating vowel identification scores to SMRT performance was run again. The result was statistically significant with a higher certainty,  $F(1,11.4) = 35.4$ ,  $p < .001$ , than the original model that had included SMRT runs with higher thresholds.

The nonmonotonic relationship between rippled stimuli input and CI processor output may also explain why the ability to “discriminate” stimuli with high spectral ripple rates, as indicated by high SRD thresholds, has been found to consistently relate to identification of speech, which contain low densities of spectral peaks and

valleys. The spectral modulation rates of vowels are less than 1 to 2 peaks per octave; this explains why setting a critical limit on SMRT thresholds from this study resulted in a significant relation to vowel recognition performance with a larger  $F$  value than in the model that included RPO thresholds above 1.46 RPO. Discriminating between medium- to high-density ripple stimuli does not assess aspects of spectral resolution that relate to important features of speech (e.g., Saoji, Litvak, Spahr, & Eddins, 2009). An individual who demonstrates high SRD thresholds is likely instead using some beneficial perceptual process that they may also access to accurately identify speech sounds.

### SINFA Results

Statistical comparisons of SINFA results between groups indicated that children with CIs had significantly higher F1- and F2-related information transmission compared with NH children. The spectral information of vocoded vowel stimuli is degraded, but in a similar method as through a CI. This difference in results may be because of acclimatization (or, lack thereof). Perhaps, over time and with CI experience, children with CIs are able to resolve the frequency components of an auditory signal more effectively. NH children performed vocoded vowel identification without prior exposure to the stimuli. It is possible that allowing NH children more practice with the vocoded stimuli would result in better F1 and F2 feature perception of the spectrally degraded vowels.

Interestingly, despite significantly higher transmission of F1- and F2-related information in the children with CIs compared with NH listeners, both groups demonstrated similar values for transmission of the duration cue. The SINFA also revealed greater amounts of duration-related feature transmission compared with F1 or F2 cue transmission in both groups of children. These results are consistent with findings from previous studies in adults: Duration is an important cue for vowel recognition, especially when the contrasts between spectral cues are diminished (e.g., Ainsworth, 1972; Hillenbrand, Getty, Clark, & Wheeler, 1995). Because of the reduced spectral resolution of the implant, adults (e.g., Winn, Chatterjee, & Idsardi, 2012) and children (e.g., Nittrouer, Caldwell-Tarr, Moberley, & Lowenstein, 2014) with CIs have been found to rely less on spectral information and more on duration cues for speech identification compared with NH individuals. In addition, vocoder studies of NH adults have found greater transmission of duration-related information than F1- or F2-related information in vowel identification conditions with considerable spectral degradation (e.g., Xu, Thompson, & Pfingst, 2005). A previous study in NH adults with the same vocoder processing and vowel stimuli as this study also demonstrated

this pattern of SINFA results (DiNino et al., 2016); the current investigation extends these findings to NH children. This study provides further evidence that under conditions of spectral degradation, children and adults rely on temporal information to a greater extent than spectral cues to discriminate between vowel sounds because the spectral information is reduced.

The amount of F2 information transmitted in NH children's vocoded vowel recognition was significantly related to their SMRT performance. These results may pertain to the redundancy of vowel features, as F1 and duration covary—the F1 of vowels corresponds to vowel height, and high vowels (those with low F1 frequencies) are generally shorter in duration than low vowels (those with high F1 frequencies; Heffner, 1937). The F2 feature may simply be more salient in the SINFA, which assumes independence of phoneme features. Still, F2 corresponds to vowel advancement; this feature is akin to place of articulation, the primary spectral cue for consonant recognition, and perception of place of articulation is greatly affected by spectral smearing (e.g., Boothroyd et al., 1996). NH children's perception of the advancement feature of vocoded vowels may be positively related to SMRT performance because the ability to utilize F2 cues in the presence of spectral degradation is analogous to spectral discrimination abilities.

As in NH children, F2 information transmission values were found to significantly predict SMRT thresholds of children with CIs; however, transmission levels of the F1 and duration features were also positively related to SMRT performance of children in this group. It seems that high transmission rates of any vowel feature, even the nonspectral feature of duration, predicted spectral discrimination abilities of pediatric CI users. Greater perception of the vowel duration feature may relate to better SMRT performance because SMRT stimuli include a temporal signal in addition to a spectral signal. It is possible that individuals with CIs utilize similar temporal mechanisms to identify vowels and perform the SMRT. Nevertheless, the relationship between duration transmission values and SMRT thresholds was weaker than those observed between the transmission of formant features and SMRT thresholds (see Figure 7).

The finding that spectral cue perception of speech sounds is related to spectral discrimination abilities of child CI users is similar to that observed by Winn, Won, & Moon (2016) in a study with adults with CIs: They found that usage of a formant cue for categorizing speech sounds was significantly related to SRD thresholds of adult CI listeners. Evidence from that study also suggested that formant cue categorization relates more strongly to speech identification abilities than does SRD performance. Evaluation of the phonetic cues that children with CIs rely on to categorize speech sounds may further elucidate the relationship between utilization of

spectral and nonspectral speech-based cues, spectral discrimination performance, and speech recognition scores.

### *Comparisons Between CIs of Bilaterally Implanted Children*

Examination of vowel identification scores, SMRT thresholds, and SINFA results from individual CIs of bilaterally implanted children consistently revealed differences in performance and in information transmission values between the two ears of the same child. These results suggest that factors related to the individual CIs of bilaterally implanted children can influence both spectral discrimination and perception of speech sounds. Peripheral variables (such as differences in individual device program processing and in the electrode–neuron interface) as well as variables that could affect function of the central auditory system (such as age at implantation and amount of time with each CI) likely underlie the discrepancies in performance between the two ears of bilaterally implanted pediatric CI users. The current study provided evidence for the contribution of age-related variables on psychoacoustic task performance. Future investigations could examine the relationship between peripheral factors and bilaterally implanted children's auditory abilities with each CI.

Previous studies of bilateral, sequentially implanted individuals with CIs have observed better performance on speech identification in quiet and noise with the first-implanted CI compared with the second in adults (Ramsden et al., 2005) and in children (Reeder, Firszt, Cadieux, & Strube, 2017). However, in the current study, no significant differences in average vowel identification performance in quiet or in noise were observed between first- and second-implanted CIs. Further, not all bilaterally implanted children performed better with their first-implanted ear. Four of the 10 children (P02, P03, P09, and P10) obtained higher scores on vowel identification with their second-implanted CI. Two of the children who exhibited large gains in performance with their second-implanted compared with their first-implanted ear also had the shortest time periods between first and second implantations: 1.34 (P09) and 1.99 (P02) years. Previous studies have observed poorer speech recognition scores with the second-implanted ear if the duration between implantation is long (e.g., Reeder, Firszt, Holden, & Strube, 2014); these results provide additional evidence that simultaneous or quick successive bilateral implantation can result in good or equivalent speech identification outcomes for the second-implanted ear.

In addition, no significant differences in SMRT thresholds were found between first- and second-implanted CIs of the participants. These differences are in contrast with results found by Landsberger et al. (2017) who observed that SMRT thresholds were significantly

better for first-implanted ears compared with second-implanted ears of children with CIs. Half of the bilaterally implanted children tested (5 of 10) in the current study performed better on the SMRT with their second-implanted ear compared with their first. While testing conditions in Landsberger et al.'s study were completely randomized and those in this study were not, this difference in results is unlikely to be explained by practice effects: Two children in the current study (P04 and P06) completed the assessments with their second-implanted CI prior to testing with their first-implanted ear, and these were two of the five children who demonstrated higher SMRT thresholds with their second-implanted ear.

The finding that some children performed better on auditory tasks with their second-implanted ear compared with their first indicates that the relationship observed between CI age and these assessments was not simply because of the children performing better with their earlier-implanted CI; rather, the distribution of CI ages in this study engendered significant effects of this variable on auditory task performance. Still, numerous prior studies have demonstrated that earlier age at implantation is associated with higher scores on assessments of speech perception and language comprehension (e.g., Geers, Moog, Biedenstein, Brenner, & Hayes, 2009; Niparko et al., 2010; Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013; Svirsky, Teoh, & Neuburger, 2004; Tobey et al., 2013). In these studies, children who were implanted before the age of 5 (and often earlier) demonstrated the best outcomes. All children in this study received their first CI before the age of 5, but most bilaterally implanted children did not obtain their second implant until years later. Because most of the children in this study were around the same age, early receipt of a CI tended to be associated with a greater CI age in that ear; therefore, we performed follow-up analyses to disentangle the effects of time with the CI and age at implantation on the task performance observed in this study.

Repeated-measures mixed-model regression analyses were conducted with both age at implantation and CI age as predictor variables, as multicollinearity was low. Vowel identification scores in quiet (Model 1) and SMRT thresholds (Model 2) were the dependent variables. Results indicated that age at implantation did not significantly predict vowel identification performance in quiet,  $F(1,10.8)=1.1$ ,  $p=.324$ , or SMRT performance,  $F(1,9.0)=4.1$ ,  $p=.072$ , of the pediatric CI users in this study. Further, these analyses revealed that CI age had larger effects on auditory task performance compared with those of age at implantation, as well as a significant relation to SMRT thresholds,  $F(1,7.8)=9.7$ ,  $p=.015$ , and a nearly significant relationship to vowel identification in quiet,  $F(1,11.0)=4.5$ ,  $p=.057$ . This

suggests that the diminished spectral resolution of a CI could play a larger role in hindering maturation of vowel identification scores and SMRT thresholds than does the amount of time prior to receiving an implant. Further, these results indicate that age at implantation is not driving the relationships between CI age and auditory task performance observed in the population of CI users tested in this study.

At least some of the improvement over time with the CI is likely because of acclimatization, or adjusting to hearing with the implant. Adult CI users who lost their hearing later in life, and thus possess fully developed auditory systems, also tend to improve on tests of speech identification over time after implantation. This increase in performance presumably occurs as they adapt to perceiving sound through the implant, which is very different than the acoustic hearing they had previously. However, such improvement in adults appears to plateau after only about 1 year (Ruffin, Tyler, Witt, Dunn, Gantz, & Rubinstein, 2007; Zhang et al., 2015). A longitudinal investigation of speech identification performance of both adults and children with CIs demonstrated that adults' speech recognition scores peaked prior to 2 years postimplantation, while pediatric CI users' scores continued to improve throughout the 4 years of the study (Oh et al., 2003). In addition, performance on SRD tasks has been observed to be stable between 1 month and 12 months after implantation in adults with CIs (Drennan, Won, Timme, & Rubinstein, 2016). Because this study found that CI age was positively related to SMRT and vowel identification performance, and the difference in CI ages between the children tested was generally greater than 1 year, these results provide further evidence that children with CIs improve on auditory tasks for a longer duration than do adults with CIs. Further, the children tested in this study had little to no acoustic hearing at any time prior to receiving the implant. As a result, while acclimatization may have driven these children's improvement in psychoacoustic task performance for a short period of time, development of the auditory system is likely contributing to the improvements that occur over a longer duration.

The findings from this study suggest that immature auditory perceptual abilities may contribute to the variability among pediatric CI users' psychoacoustic task performance. However, children's improvements in auditory task performance over time with the CI are not expected to continue indefinitely; rather, some upper limit likely exists on the development of auditory abilities. Based on the coincident developmental timelines of psychoacoustic task performance and central auditory system function (e.g., Eggermont & Ponton, 2003), this limit is presumably set by the development of the auditory cortex. The current study was not a longitudinal study and thus the age of vowel identification and



SMRT maturation in children with CIs was not identified. Future research with a longitudinal design, larger sample size, and broader age range of child CI participants is warranted to form definitive conclusions about auditory development with a CI.

This investigation had several limitations. “Aided hearing age” and “CI age” represented auditory experience in this study, but the progression of hearing loss and effectiveness of aided hearing, which also define auditory experience, could not be quantified over time for the pediatric CI users who participated in this research. This study also did not assess cognitive or intellectual variables such as auditory attention, short-term memory capacity, and reading abilities. These factors could have contributed to the auditory task performance of children in this study. For example, the CI participant P06 performed very well with their second-implanted CI despite the moderate CI age of this ear; as P06 also performed well with their first-implanted ear, cognitive or intellectual factors could have played a role in this subject’s vowel identification scores and SMRT thresholds. An additional limitation to this study was the small sample size of pediatric CI users, which may have reduced the statistical power to find a significant relationship between predictor variables and vowel identification in noise, as well as between CI age and SMRT thresholds for the analyses conducted with first- or second-implanted CIs alone. Finally, this investigation was limited by the age range of children with CIs who met study eligibility criteria. Future studies could examine younger pediatric CI users.

In conclusion, this study demonstrated that chronological age predicted spectrally degraded vowel identification performance of NH children, but was not related to performance on any assessment in children with CIs. The amount of time with the implant was a better predictor of vowel recognition performance, as well as spectral discrimination abilities, than was chronological age. Further, spectral resolving capabilities significantly predicted vowel identification performance in both NH children and children with CIs. SINFA results revealed that transmission of F2-related information in vowel perception was positively related to SMRT thresholds of children with NH. However, transmission of F1, F2, and duration were all significantly related to SMRT thresholds of children with CIs, indicating that perception of any vowel feature may predict spectral discrimination abilities of these children. Further, differences in performance and vowel feature information transmission were observed between individual CIs of the same child, indicating a need for additional investigation of device-specific factors related to the electrode–neuron interface that could contribute to auditory task performance of these children.

The findings from this study have implications for assessment of verbal language abilities of pediatric CI

users at particular time periods after implantation; performance on such tests may continue to improve throughout childhood or adolescence. Results from this study suggest that normal auditory system development could interact with auditory experience to enhance speech perception and spectral resolution abilities of children.

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