Effects of age and hearing mechanism on spectral resolution in normal hearing and cochlear-implanted listeners

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Spectral resolution limits speech perception with a cochlear implant (CI) in post-lingually deaf adults. However, the development of spectral resolution in pre-lingually deaf implanted children is not well understood. Acoustic spectral resolution was measured as a function of age (school-age versus adult) in CI and normal-hearing (NH) participants using spectral ripple discrimination (SRD). A 3-alternative forced-choice task was used to obtain SRD thresholds at five ripple depths. Effects of age and hearing method on SRD and spectral modulation transfer function (SMTF) slope (reflecting frequency resolution) and *x*-intercept (reflecting across-channel intensity resolution) were examined. Correlations between SRD, SMTF parameters, age, and speech perception in noise were studied. Better SRD in NH than CI participants was observed at all depths. SRD thresholds and SMTF slope correlated with speech perception in CI users. When adjusted for floor performance, *x*-intercept did not correlate with SMTF slope or speech perception. Age and *x*-intercept correlations were positive and significant in NH but not CI children suggesting that across-channel intensity resolution matures during school-age in NH children. No evidence for maturation of spectral resolution beyond early school-age in pre-lingually deaf implanted CI users was found in the present study. © *2017 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4974203]

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I. INTRODUCTION

Despite reduced spectral and temporal cues, pre-lingually deaf infants with cochlear-implants (CIs) can discriminate speech and acquire spoken language through the auditory modality (Niparko *et al.*, 2010). However, efficacy of a CI for individual patients is highly variable and difficult to predict (Geers, 2004). Measures of open-set speech perception are typically used to assess device efficacy in older children and adults with CIs. They are not feasible for testing most early-implanted children during the first years of device use when optimization of intervention likely has the greatest impact. Therefore, non-linguistic measures of device efficacy for young CI patients would be of great clinical value (Drennan *et al.*, 2014).

Spectral ripple discrimination (SRD), a measure of spectral resolution, is one potential non-linguistic measure of efficacy that has been investigated extensively. Like any measure of spectral resolution, SRD measures the ability to perceive changes in the amplitude spectrum of a complex sound. Measures of spectral resolution have been shown to strongly correlate with open-set speech understanding in both post-lingually deaf adult CI users (Henry and Turner, 2003; Henry *et al.*, 2005; Won *et al.*, 2007; Saoji *et al.*, 2009; Green *et al.*, 2014; Winn and Litovsky, 2015) as well as in pre-lingually deaf school-age children with CIs (Jung *et al.*, 2012). Although various approaches have their merits, SRD is an efficient method to test spectral resolution that does not require any knowledge of phonemic or linguistic structure (Drennan *et al.*, 2014, 2016). In SRD, listeners discriminate between two spectrally-modulated noise stimuli with shifted spectral envelope phases (Supin *et al.*, 1994a, 1994b, 1999). Supin and colleagues developed a model for SRD involving two psychoacoustic dimensions which, in this paper, we will refer to as frequency resolution and across-channel intensity resolution (Supin *et al.*, 1999). Frequency resolution is related to the bandwidth or frequency tuning of the relevant auditory filters and, hence, to resolution of peak *location* across the spectrum. Across-channel intensity resolution is related to the resolution of *simultaneous*, peak, and trough intensity differences across the spectral envelope. The latter is analogous to "spectral profile analysis" (Green *et al.*, 1984; Green and Mason, 1985) with an observed limit of about 1.2 dB in normal hearing (NH) adults (Jesteadt *et al.*, 1977; Supin *et al.*, 1999).

Supin *et al.* (1999) measured listeners' sensitivity to spectral envelope shifts at various ripple densities. Listeners were less sensitive to envelope shifts as ripple density increased. The spectral modulation transfer function (SMTF) is typically used to describe the relationship between modulation depth threshold and modulation frequency and approximates an exponential function. As shown by Supin *et al.* (1999), frequency resolution determines the slope of the

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function whereas across-channel intensity resolution determines the y-intercept of the function.

The independence of frequency resolution and across-channel intensity resolution has been examined in adult, post-lingually deaf CI users. In a task similar to SRD, CI listeners' ability to detect spectral modulation relative to spectrally "flat" noise was measured at various modulation frequencies and fit to an exponential SMTF function (Saoji *et al.*, 2009). A non-significant correlation was observed between slope and y-intercept supporting the hypothesis that frequency and across-channel intensity resolution were independent factors in the task. Furthermore, speech identification in quiet was significantly correlated with y-intercept; in other words, better across-channel intensity resolution was related to better speech identification. However, speech identification was not correlated with slope, the measure of frequency resolution. Finally, spectral ripple detection thresholds at low ripple densities were more strongly correlated with speech identification than thresholds at high ripple densities. The authors concluded that it was across-channel intensity resolution, rather than frequency resolution, that was the important factor relating spectral ripple detection and speech understanding in quiet.

In a subsequent study, Anderson *et al.* (2012) reasoned that lower correlations between speech identification and spectral ripple detection thresholds at high ripple densities (relative to lower densities) were due to confounding by non-spectral, within-channel temporal cues. They demonstrated non-monotonicities in SMTFs at ripple densities above 2–4 ripples per octave lending support to this view. Furthermore, they found that performance on a broadband Gaussian noise intensity discrimination task did not correlate significantly with spectral ripple detection at any ripple density, refuting the hypothesis that across-channel intensity resolution was an important factor for spectral ripple detection.

To date, the relative importance of frequency resolution and across-channel intensity resolution for SRD in CI listeners has not been determined. While evidence that CI listeners with better frequency resolution show better SRD scores has been reported (Won *et al.*, 2011; Jones *et al.*, 2013; Won *et al.*, 2015), it is not clear whether across-channel intensity resolution is an important underlying factor. Before SRD can be adapted as a measure of device efficacy for young CI listeners, it is important to understand the relative importance, and the rates of development, of these underlying factors.

Spectral resolution matures gradually in NH listeners (Blagosklonova *et al.*, 1989; Peter *et al.*, 2014; Rayes *et al.*, 2014; Kirby *et al.*, 2015). Previous research has shown that NH human infants can perceive changes in spectral patterns and shape (Trehub, 1973; Tsang and Trainor, 2002). As noted, development of spectral resolution depends on two potentially independent mechanisms: frequency resolution and across-channel intensity resolution. Measures of frequency resolution, such as frequency tuning curves and critical bandwidths, are adult-like by 6 months of age in human infants suggesting that frequency resolution is mature by this age (Olsho *et al.*, 1987; Schneider *et al.*, 1990; Spetner and Olsho, 1990). The development of across-channel intensity resolution however, is poorly understood. The relatively slow maturation of intensity representation and sensitivity (Olsho *et al.*, 1987; Trehub, 1988; Werner and Gillenwater, 1990; Schneider *et al.*, 1991; Tharpe and Ashmead, 2001) might, therefore, constrain the representation of the power spectrum in the developing auditory system.

Studies in NH children suggest that SRD might mature at least as gradually as intensity resolution (Blagosklonova *et al.*, 1989; Allen and Wightman, 1994; Peter *et al.*, 2014). In a brief, early, report, Blagosklonova *et al.* (1989) found adult-like SRD thresholds in children aged 7–15. Allen and Wightman (1994) tested school-age children and adults on several measures of spectral resolution (including SRD), finding that children demonstrated poorer and more variable performance than adults at 4–5 yrs of age, but reached adult-like performance at older ages. More recently, Peter *et al.* (2014) found that SRD was adult-like in 12–18 yr old NH children, but not in 8–11 yr old children. Consistent with a similar rate of maturation in young CI listeners, Jung *et al.* (2012) found similar SRD thresholds in 8–16 yr old pre-lingually deaf, and adult post-lingually deaf CI users with similar peripheral (device, signal processing strategy) constraints. Taken together, these studies suggest that SRD performance and intensity resolution mature over a similar timeframe of 5–8 yrs of age (Maxon and Hochberg, 1982).

In the present study, it was hypothesized that SRD threshold is affected by two factors: hearing method and auditory development. To test this hypothesis, SRD was measured in four groups of listeners: school-age NH children, school-age pre-lingually deaf CI users, NH adults, and post-lingually deaf adult CI users. SRD thresholds were measured using the density method: ripple density was varied to find the highest density at which a listener could reliably detect an inversion of the ripple envelope. SRD threshold was measured for each listener at various ripple depths so that a SMTF could be determined. It is important to note that, in contrast to the SMTFs of Supin and others (Supin *et al.*, 1999; Saoji *et al.*, 2009; Anderson *et al.*, 2012), the axes of the SMTFs from the present study were inverted to reflect spectral modulation depth (the independent variable) on the x axis and spectral modulation density (the dependent variable) on the y-axis. Thus, SMTFs approximated a logarithmic function rather than an exponential function. Two SMTF parameters were determined based on the model of Supin *et al.* (1999). In this model, the parameter corresponding to slope of the SMTF is taken to reflect frequency resolution whereas the parameter corresponding to x-intercept is taken to reflect across-channel intensity resolution. These derived parameters were then used to compare frequency resolution and across-channel intensity resolution across the four participant groups.

There were three hypotheses tested in the present study. First, it was expected that frequency resolution would vary by hearing method (better for NH than CI users) but not by age group, given previous research suggesting early maturation of frequency resolution in NH children. Second, we predicted that across-channel intensity resolution would be affected by age in the CI group but not in the NH group. Immature across-channel intensity resolution was predicted based on a previous study that demonstrated slower development of intensity modulation detection in pre-lingually deaf CI users compared to NH listeners (Park *et al.*, 2015). Third, we predicted that frequency resolution would correlate more strongly than across-channel intensity resolution with speech perception in CI users. The last hypothesis was based on the lack of correlation between intensity resolution and speech identification reported by Anderson *et al.* (2012).

II. METHODS

The study was approved by the institutional review board at Seattle Children's Hospital.

A. Participants

Four groups of participants were recruited: Ten NH school-aged children, ten pre-lingually deaf school-aged children with CIs, ten NH adults, and ten post-lingually deaf adults with CIs. Inclusion criteria for NH listeners were: native speaker of American English, no history of ear disease or hearing loss, and passed audiometric screening on day of experiment. Both groups of NH listeners were recruited from a University of Washington subject pool for communication and hearing related studies. Inclusion criteria for CI subjects were: no neurocognitive impairments, subject and/or parent reports that implant is "working well," and native speakers of American English. Additional inclusion criteria for the CI children were: CI activation prior to age 2 yrs and habilitation method that incorporates auditory/oral communication. All CI adults were primary auditory/oral communicators. Mean age of the NH children, 12.65 [standard deviation (SD) = 1.33] and the CI children, 12.80 (SD = 1.68), did not differ significantly [independent samples $t(18) = 0.221$, $p = 0.827$]. An additional 5 CI children (7.3 to 9.5 yrs old) were recruited in order to increase sample size and obtain a wider age range for correlation analyses of SRD and speech perception. There was a significant difference between the mean age of the NH adults, 52.8 (SD = 9.60), and CI adults, 64.9 (SD = 9.05) [independent samples $t(18) = -2.90$, $p = 0.01$]. Demographic and audiometric data for the CI subjects are shown in Table I. All participants were paid $15 per hour for their participation.

TABLE I. Demographic characteristics of cochlear implanted participants. Note: *P* = participant. Chronological age in years, age at CI in months (for participants 1–9) or years (for participants 10–19). Participants 1–4, 6–9, and 13 were bilaterally implanted. * Age at CI in months for children and in years for adults. Ear tested was always better hearing ear or right ear if symmetrical. CM = communication mode. TC = total communication (Signed Exact English plus oral). Bil = oral plus American sign language. NS = genetic identified nonsyndromic. VS = post vestibular schwannoma resection. Genetic = hereditary, not specified.

P#	Age (y)	Gender	Age at CI* (*y*)	Ear tested	Device	CM	Etiology
1	15.2	M	1.1	Right	Cochlear	Bil	Unknown
2	14.4	M	1.1	Right	Cochlear	TC	Unknown
3	14.3	F	1.3	Left	Cochlear	Oral	Pendred
4	12.4	F	1.5	Right	Cochlear	Oral	Unknown
6	12.3	F	1.2	Right	AB	TC	NS
7	12.3	M	1.5	Right	AB	TC	NS
8	12.3	M	1.3	Right	AB	Oral	Unknown
4	11.5	M	1.0	Right	AB	Oral	Pendred
5	11.2	F	1.2	Right*	AB	Oral	Unknown
10	10.2	F	1.2	Right	Cochlear	Oral	Unknown
11	9.6	M	0.75	Right	AB	Oral	Genetic
12	9	F	1	Right	Cochlear	Oral	Unknown
13	7.9	M	0.92	Left	Cochlear	Oral	Unknown
14	7.6	M	2	Left	Cochlear	Oral	Unknown
15	7.3	F	0.67	Right	Cochlear	Oral	Unknown
10	64	F	50	Left	Cochlear	Oral	Unknown
11	54	F	50	Left	Cochlear	Oral	Genetic
12	79	F	73	Left	Cochlear	Oral	Measles
13	67	M	61	Right	AB	Oral	Unknown
14	71	M	59	Left	Cochlear	Bil	Unknown
15	76	M	60	Right	CI24	Oral	VS
16	62	F	59	Right	Med El	Oral	Genetic
17	67	M	52	Left	Med El	Oral	Genetic
18	58	M	47	Right	Med El	Oral	NS
19	51	F	30	Right	AB	Bil	Genetic

B. Procedure

Listeners were first oriented to the double-walled sound proof booth fitted with a B&W DM™ 303 loudspeaker (Worthing, England), a Dell (Round Rock, TX) 17 in. LCD monitor and computer mouse. They sat facing the loudspeaker at a distance of approximately 1 m, within view of the LCD monitor, and within comfortable reach of the mouse to make selections after each trial. They were told that they would be completing two types of listening tasks: one identifies which of three noises was different and another identifying a spoken word. Listeners, particularly the children, were encouraged throughout testing to take frequent breaks. For the SRD task, listeners were tested at 5 ripple depths (5, 10, 13, 20, and 30 dB) in a randomized order, for two runs each. This was followed by the speech perception in steady state noise task (3 runs), and subsequently an additional 2 runs of the SRD task at each ripple depth for a total of 27 runs per subject. Testing sessions lasted between 2 and 6 h including break periods. If listeners reached the 3 h point and had not completed testing, they were asked to return to complete testing on a future date.

NH listeners were tested binaurally. All CI listeners were tested in the unilateral condition using, for bilaterally implanted participants, their best ear with their preferred processor settings and clinical maps. If the ears were symmetrical, then the right ear was used. No participant wore a contralateral hearing aid during testing. None of the CI listeners had residual acoustic hearing in either ear better than 70 dB hearing level at any frequency.

1. SRD

Stimuli were constructed from summing 2555 pure-tone frequency components (bandwidth 100–5000 Hz) with a duration of 500 ms including rise/fall ramps of 15 ms. The component amplitudes followed a full-wave rectified sinusoidal envelope on a logarithmic amplitude scale with peaks spaced equally on a logarithmic frequency scale. Stimuli were either "standard" (reference stimuli) or "inverted" based on the starting phase of the spectral envelopes. Standard stimuli were created with random spectral envelope starting phases from 0 to 2π. For each standard stimulus, a corresponding inverted stimulus was created with a starting phase shifted by $+\pi/2$. Ripple densities of the stimuli varied by ratios of 1.414 from 0.125 to 11.317 ripples per octave. Five peak-to-valley ratios (or "ripple depths") were used: 5, 10, 13, 20, and 30 dB. Examples of acoustic spectra, cochlear filter excitation patterns, and sound processor output for similar stimuli can be found in Fig. 1 of Won *et al.* (2011). Stimuli were presented at 61 dBA in the sound field with ± 4 dB level rove in 1 dB steps.

The SRD task utilized a 3-interval, 3-alternative forced choice procedure with the same threshold estimation method described by Won *et al.* (2007). On each trial, 3 stimuli were presented with 200 ms interstimulus intervals, each with the same ripple density and depth. Two of the stimuli were standard and one of the three stimuli was an inverted stimulus (phase-shifted by $\pi/2$ radians). The listeners were asked to indicate which of the three stimuli sounded different by a mouse-click over the corresponding numbered square on the LCD screen. No feedback was given. Ripple density was then varied adaptively in a 2-up (higher ripples per octave) and 1-down (lower ripples per octave) procedure to determine SRD thresholds converging on 70.7% correct (Levitt, 1971) by averaging the ripple densities for the final 8 of 13 reversals. Minimum step sizes were in ratios of 1.414 ripples per octave (including 0.125, 0.176, 0.250, 0.354, 0.500, 0.707, 1.000, 1.414, 2.000, 2.828, 4.000, 5.657, 8.000, 11.314, etc.). For each adaptive track, ripple depths were constant. At each ripple depth, two adaptive tracks were completed prior to moving to the next ripple depth, for a total of ten initial tracks. This procedure was completed a second time, for a total of 20 adaptive tracks (4 at each ripple depth) with the order of ripple depths randomized each time. In between the first and second set of ten tracks, the participants completed the speech perception task described below. The final SRD threshold at each ripple depth was determined by the mean of the thresholds across the four tracks with the exception of four of the five youngest CI children who did not complete all four tracks at each ripple depth. Three of these children (participants 41, 42, and 44) completed two tracks at each ripple depth and an additional child (participant 43) completed four tracks at 20 dB depth and two tracks at the remaining ripple depths. Thresholds were determined, for these children, by averaging the completed tracks at each ripple depth. Mean thresholds were used without eliminating any of the more deviant thresholds after determining that threshold variance was similar across age groups (see Sec. III). For each participant, several practice trials were given, with feedback, to ensure that they understood the task.

2. Speech perception in steady state noise

This test measured the speech reception threshold as described by Won *et al.* (2007). Listeners were asked to identify a two-syllable spondee word (Harris, 1991) spoken by a single recorded female talker in the presence of steady-state, low-pass filtered, white noise (Turner *et al.*, 2004). The fundamental frequency of the spondee stimuli ranged from 212–250 Hz, and duration ranged from 112–163 ms. On each trial, one of 12 words was presented randomly and listeners were instructed to identify the corresponding picture from a set of 12 on the LCD monitor. No feedback was provided. In this single interval, 12-alternative forced-choice procedure, the level of the speech target was fixed at 65 dBA and the noise level varied in 2 dB steps. A one-up, one-down adaptive procedure was used (Levitt, 1971). The initial signal-to-noise ratio (SNR) was +10 dBA. The threshold for each adaptive track was estimated by averaging the SNR for the final 10 of 14 reversals to converge on the SNR at which 50% correct performance is achieved (SNR-50). Three tracks were run for each listener and the overall SNR-50 was computed as the average of the three thresholds. As for the SRD task, several practice trials were given, with feedback, to ensure that the participant understood the task.

III. RESULTS

Data from two NH children were excluded due to their inability to understand the task and complete training trials correctly. All other subjects were able to complete the training trials, including the youngest CI children. All statistical analyses described below were conducted using SPSS Version 24 (IBM Corp., 2016).

A. Variance in SRD thresholds across subject groups

Performance across tracks was variable both within and across participants. In order to determine if there were systematic differences in variance in SRD thresholds across participant groups, the SDs of threshold at each ripple depth were determined for each participant. A 3-way repeated measures analysis of variance (ANOVA) was conducted to examine the effects of depth (5 levels), age (2 levels), and hearing method (2 levels). SDs were significantly higher for NH than CI listeners [$F(1,41) = 58.612$, $p < 0.0001$] and at increasing ripple depths [$F(4,164) = 4.591$, $p = 0.002$] but no significant effect of age [$F(1,41) = 1.404$, $p = 0.243$] was found. None of the interactions were significant.

Thirty-three percent of subjects had at least 1 SD for a given ripple depth that was more than twice the average SD within their participant group, representing 4% to 16% of the derived thresholds for each group. When these thresholds were calculated by averaging all but the track farthest from the mean (representing an exclusion of 1%–4% of all tracks) the mean thresholds obtained were nearly identical to those obtained using all of the tracks. Furthermore, the statistical significance of the analyses reported below was identical regardless of whether the deviant tracks were included. Thus, the data reported here include those deviant tracks.

B. Effect of ripple depth on SRD threshold across subject groups

Figure 1 illustrates the mean SRD threshold plotted as a function of ripple depth for NH [Figs. 1(a) and 1(b)] and CI [Figs. 1(c) and 1(d)] listeners. These mean data reflect scores from 10 NH adults, 10 CI adults, 8 NH children, and 15 CI children. Given unequal variance across subject groups and unbalanced subject numbers, Levene's tests were performed

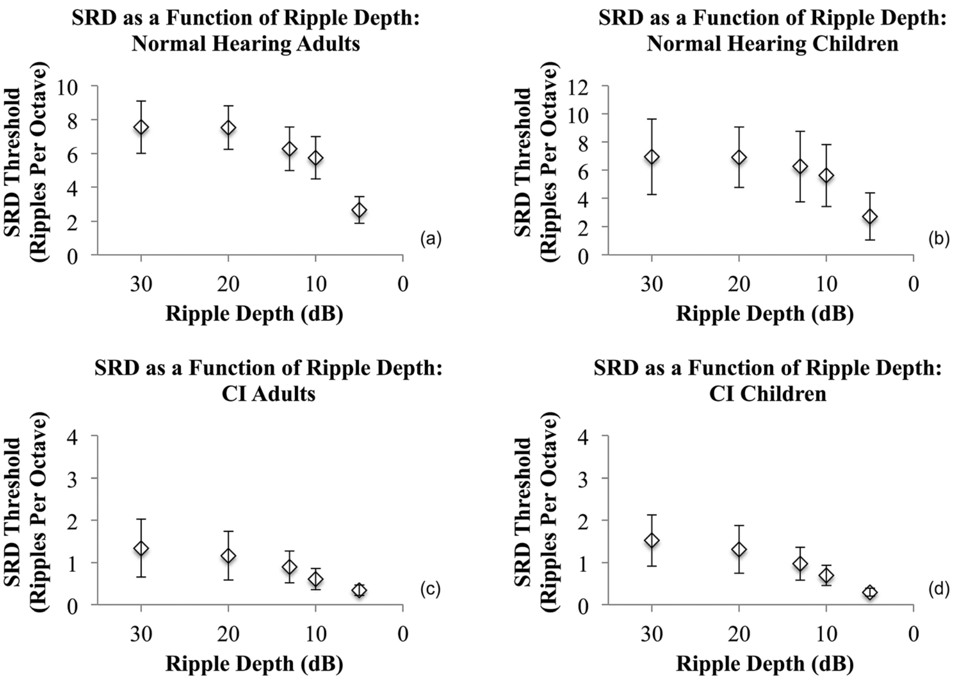

FIG. 1. Mean spectral ripple threshold as a function of ripple depth for NH adults (a), NH children (b), CI adults (c), and CI children (d). Error bars signify 95% confidence intervals.

to determine if homogeneity assumptions were violated for each between subjects variable. Levene's tests were significant at each ripple depth for Hearing Method [from $F(1{,}41) = 51.43$, $p < 0.0001$ to $F(1{,}41) = 9.54$, $p = 0.004$] indicating that the assumption of homogeneity of variance was violated. In contrast, Levene's tests were not significant at any ripple depth for Age Group [from $F(1{,}41) = 2.32$, $p = 0.135$ to $F(1{,}41) = 0.000$, $p = 0.983$].

In all four participant groups, SRD became more difficult as ripple depth decreased. SRD thresholds were much poorer in CI than in NH listeners, but no age effects were apparent. The effect of participant group (four levels) on SRD threshold was first examined using a series of 1-way ANOVAs, with one analysis for each ripple depth. Tests which do not require equality of variance (Welch tests for main effect of group and Games-Howell tests for *post hoc* comparisons) were used. Significant effects of group were found at each ripple depth [from $F(3{,}16.52) = 17.86$, $p < 0.0001$ to $F(3{,}17.73) = 43.662$, $p < 0.0001$]. Table II shows the difference in mean SRD threshold for all group comparisons at each ripple depth. SRD thresholds were similar between age groups within each hearing condition but lower (poorer) for CI listeners than for NH listeners. The significance of each comparison was measured using a *post hoc* Games-Howell test with results, including mean group differences, standard errors, and significance levels, are summarized in Table II. At all ripple depths, CI adults and CI children each showed significantly lower mean SRD scores than both groups of NH listeners. In contrast, mean SRD did not differ significantly between age groups for either CI or NH listeners.

A linear full-factorial mixed-model with diagonal covariance matrix was constructed with three fixed effects (Age Group, Hearing Method, and Depth) and one random effect (participant). Age Group and Hearing Method were between subjects variables and Depth was the repeated measures variable. Significant main effects of Hearing Method [$F(1{,}172.73) = 523.63$, $p < 0.0001$] and Depth [$F(4{,}73.71) = 35.45$, $p < 0.0001$] were found but the effect of Age was not significant [$F(1{,}172.73) = 0.137$, $p = 0.712$. Of the 2-way interactions, only Depth × Hearing Method reached significance, $F(4{,}73.71) = 15.88$, $p < 0.0001$. In order to determine if this interaction was due to a lack of effect of Depth for one Hearing Method, two additional linear mixed-models were constructed to investigate the effect of Depth for both Hearing Method groups. Depth had a significant effect on SRD for both NH [$F(4{,}30.16$, $p < 0.0001$] and CI [$F(4{,}37.85) = 19.87$, $p < 0.0001$], respectively. Thus, the Depth × Hearing Method interaction is explained by a greater effect of Depth on SRD threshold in NH than in CI

TABLE II. *Post hoc* group comparisons. Note: SRD = spectral ripple depth in dB. NHa = normal hearing adults. NHc = normal hearing children. CIa = CI adults. Mean Δ = mean group difference. Sig. = p value of Games-Howell test. NS = non-significant $p > 0.90$. ** = $p < 0.0001$. Redundant comparisons omitted.

		NH Children		CI Adults		CI Children	
	SRD	Mean Δ	Sig.	Mean Δ	Sig.	Mean Δ	Sig.
NHa	5	−0.08	NS	2.30	**	2.35	**
	10	0.11	NS	5.13	**	5.04	**
	13	0.00	NS	5.37	**	5.29	**
	20	0.60	NS	6.37	**	6.22	**
	30	0.60	NS	6.22	**	6.03	**
NHc	5			2.38	0.05	2.43	0.04
	10			5.02	**	4.93	0.01
	13			5.37	0.01	5.27	0.01
	20			5.77	**	5.62	**
	30			5.62	0.01	5.43	0.01
CIa	5					0.05	NS
	10					−0.08	NS
	13					−0.08	NS
	20					−0.15	NS
	30					−0.18	NS

listeners. The 3-way interaction did not reach significance [$F(4,73.71) = 0.21$, $p = 0.932$].

Finally, effects of age were examined within each group of children using bivariate correlations between chronological age and SRD. For NH children, r ranged from 0.049 to −0.370 across ripple depths with all $p > 0.366$. For CI children, r ranged from −0.035 to −0.201 across ripple depths with all $p > 0.470$. Thus, no significant relationship between chronological age and SRD was found for children within hearing group.

C. SMTFs across subject groups

As described in Sec. I, SMTFs are typically approximated by exponential functions when the independent variable (and x axis) is modulation density and the dependent variable (y axis) is modulation depth (Supin *et al.*, 1999; Saoji *et al.*, 2009; Anderson *et al.*, 2012). In the present study, the SMTF axes were inverted: modulation depth was the independent variable and modulation density was the dependent variable. Therefore, SMTFs for the four groups of listeners in the present study were analyzed by fitting logarithmic functions. The function

$$f(\mathrm{x}) = \mathrm{B} \times \ln(x/\mathrm{A}),$$

where f(x) represents modulation density threshold at modulation depth x, and parameters A and B define SMTF shape. Parameter A, the x-intercept, corresponds to across-channel intensity resolution in dB as ripple density approaches zero, whereas parameter B defines the slope of the SMTF corresponding to frequency resolution (Supin *et al.*, 1999). A higher value of constant A implies poorer across-channel frequency intensity resolution whereas a higher value of B implies better frequency resolution (Supin *et al.*, 1999; Saoji *et al.*, 2009; Anderson *et al.*, 2012).

The best-fit functions to the mean SRD thresholds for each participant group are shown in Fig. 2. SMTF fits were excellent with r^2 values ≥0.92 across groups. Across groups, coefficient A (x-intercept) varied from 0.95 to 3.47 and was somewhat higher for CI listeners than NH listeners. Coefficient B (slope) varied from 0.51 to 2.43 and was lower for CI listeners than NH listeners. The effects of Age Group and Hearing Method on both SMTF coefficients were then

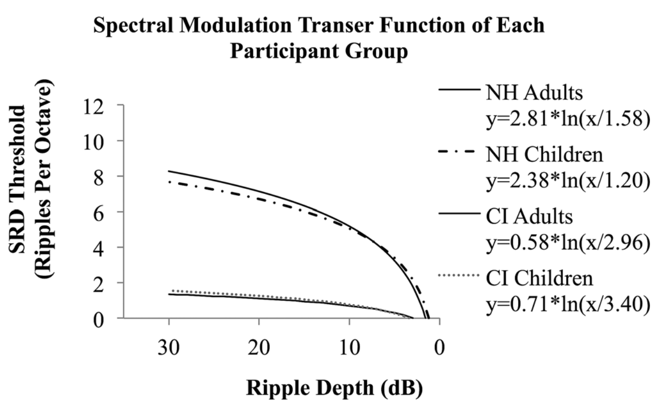

FIG. 2. SMTFs of each participant group. Each curve was fit to the mean participant group data. Fit equations shown in legend.

examined by first deriving an SMTF for each individual participant by fitting the logarithmic function to each listener's mean SRD thresholds. SRD threshold was a monotonic function for all but 7 participants (1 NH child, 1 NH adult, and 5 CI children). Data from one CI participant could not be fit due to floor performance at all ripple depths and, for this child the "B" parameter was set to 0.01 and no "A" parameter was assigned. Resulting fits were mostly good to excellent ($r^2 > 0.615$) with two in the modest range (one NH child with r^2 of 0.25 and one CI child with r^2 of 0.32).

In order to determine if observed differences in SMTF slope and x-intercept between hearing method groups were significant, two-way between subjects ANOVAs were conducted. Main effects of Age and Hearing Method, and the interaction, for each SMTF parameter were examined [Figs. 3(a) and 3(b)]. Levene's tests did not reach significance in either analysis. For dependent variable B [Fig. 3(a)], there was a significant main effect of hearing method [$F(1,42) = 78.11$, $p < 0.0001$]. For dependent variable A [Fig. 4(b)] there was also a significant main effect of Hearing Method [$F(1,42) = 8.23$, $p = 0.007$]. The main effects of age and interactions between Age and Hearing Method did not reach significance for either SMTF coefficient [all $p \geq 0.338$].

Bivariate correlations were used to investigate the relationship between chronological age and SMTF coefficients in NH and CI children. For CI children, no relationship between age and B [Pearson $r = -0.01$, one-tailed $p = 0.486$] or A [$r = 0.015$, $p = 0.480$] was found. Similarly, the correlation between B and age was weak and not significant for NH children [$r = -0.169$, $p = 0.344$]. In contrast, there was a moderate negative correlation between age and A [$r = -0.650$, $p = 0.0.041$] for NH children.

D. Relationship between SRD and speech perception in steady state noise

The relationships between SRD thresholds and SNR-50 score were investigated in CI participants using bivariate correlations as shown in Table III. As the correlations had predicted magnitude directions (negative), one-tailed tests were used. To correct for multiple comparisons, a Bonferroni-Holm correction was applied for each listener condition (Holm, 1979). Strong, significant negative correlations between SRD threshold at each depth and SNR-50 [$r \geq -0.787$, corrected p's < 0.018], were found for adult CI listeners indicating that better SRD thresholds at all ripple depths were associated with better speech perception in noise in this listener group. For CI children, correlations between SNR-50 and SRD at 20 dB depth [$r = -0.641$, corrected $p = 0.005$] and at 10 dB depth [$r = -0.539$, corrected $p = 0.038$] were significant. The remaining correlations between SRD thresholds and SNR-50 in CI children were significant using uncorrected p values. Although the magnitudes of the correlations between SMTF slope, SRD, and SNR-50 were invariably stronger for CI adults than for CI children, *post hoc* tests revealed no significant difference across CI age groups for any correlation [Fisher r to z's 0.69 to 1.71, 2-tailed p range 0.09 to 0.49].

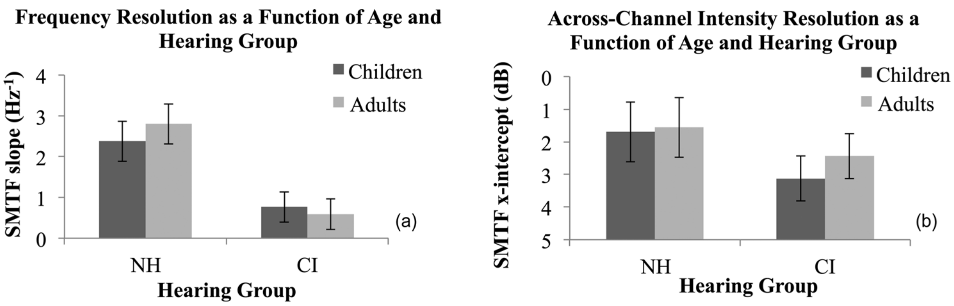

FIG. 3. Mean SMTF coefficient as a function of age and hearing group. Higher values of SMTF slope (coefficient B) indicate better frequency resolution (a). Higher values of SMTF *x*-intercept (coefficient A) indicate poorer across-channel intensity resolution (b). Error bars indicate 95% confidence intervals.

E. Relationship between SMTF and speech perception in steady state noise

The relationships between SMTF coefficients and SNR-50 score were investigated in adult and child CI participants using bivariate correlations as shown in Table IV. Again, correlations had predicted magnitude directions (negative for SMTF slope and positive for *x*-intercept) and one-tailed tests were used. Log_{10} transform of coefficient B was used in these correlations so that both SNR-50 and B were on a logarithmic scale. Significant negative correlations between B and SNR-50 were found for both CI adults [$r = -0.950$, corrected $p < 0.0001$] and CI children [$r = -0.479$, $p = 0.036$] indicating that a steeper SMTF slope was associated with better speech perception in noise in both groups of CI listeners. The magnitude of the correlation between B and SNR-50 was significantly greater for CI adults than for CI children [Fisher r to $z = -2.75$, 2-tailed $p = 0.007$].

Surprisingly, the correlation between A and SNR-50 was significantly negative for CI adults [$r = -0.761$, $p = 0.005$]. This correlation was in the opposite direction than predicted: adults with poorer across-channel intensity resolution (higher A) showed better speech perception in noise. The correlation between A and B was then examined for both CI groups revealing significant positive relationships as shown in Table V. This result implied that, for CI listeners, better frequency resolution was associated with poorer across-channel intensity resolution. Re-investigation of the raw data revealed that participants with thresholds close to the floor of 0.125 ripples per octave (only the CI participants) tended to have fit functions with very low *x*-intercepts. This likely stemmed from imprecision of the maximum-likelihood method for estimating the *x*-intercept when more than one data point in the SMTF was near baseline. To deal with this, the lowest depth SRD threshold was adjusted to zero for listeners with more than one SRD threshold within 1 SD of 0.125 ($n = 2$ CI adults and 4 CI children). In each case the adjusted threshold was at 5 dB depth. Resulting fits for these six participants were similar or higher than the unadjusted SMTF fits. As shown in Table V, the adjusted SMTF parameters were not significantly correlated for either CI adults or children.

Adjustment of SMTF coefficients did not alter the significance of the correlations between B and SNR-50 (Table IV). Moreover, the strength of the correlation remained greater for CI adults than for CI children [Fisher r to $z = 1.98$, $p = 0.048$]. In contrast, adjusted SMTF coefficient A showed no significant correlation with SNR-50 for either CI children [$r = -0.162$, $p = 0.283$] or adults [$r = 0.156$, $p = 0.333$]. The correlations between SNR-50 and each adjusted SMTF coefficient were significantly different for CI adults [Fisher r to $z = 2.83$, $p = 0.0124$] but not for CI children [Fisher r to $z = 0.88$, $p = 0.38$]. Scatterplots showing

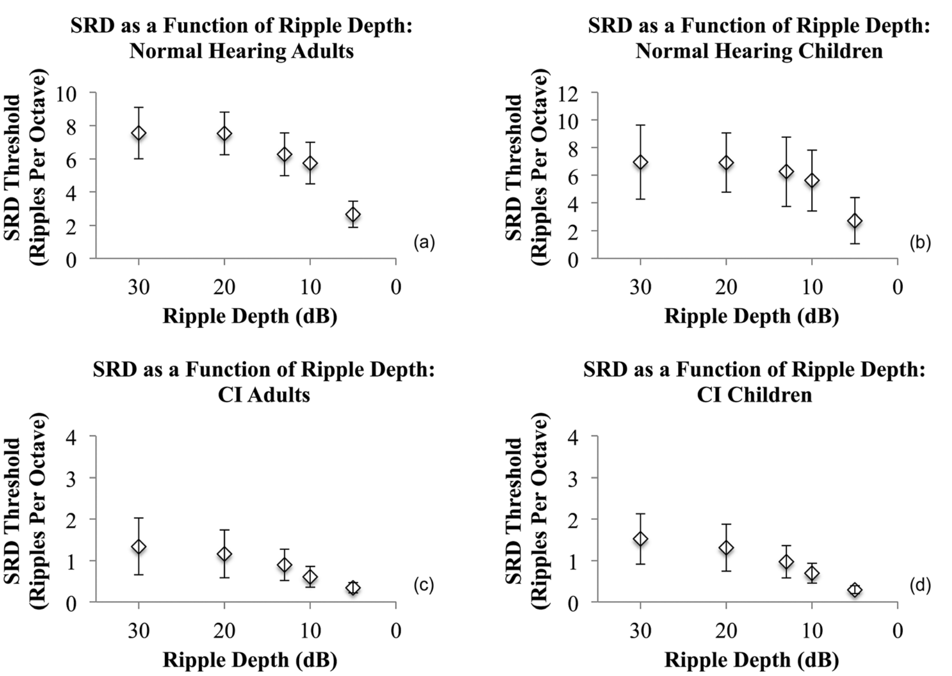

FIG. 4. Scatterplots illustrating individual speech reception in steady state noise (SNR-50) as a function of SRD threshold at 20 dB (a), SMTF slope (b), and SMTF *x*-intercept (c) in CI listeners stratified by age group. Line of best fit to data for each age group is shown with corresponding R^2 values for significant correlations. More negative SNR-50 indicates better speech reception in noise. Higher values of coefficient "B" indicate better frequency resolution. Higher values of coefficient "A" indicate poorer across-frequency intensity resolution.

TABLE III. Correlations between SNR-50 and SRD. Note: SRD = mean SRD thresholds at 5–30 dB. SNR-50 = SNR (dB) at 50% identification of spondees in steady state noise. Bivariate Pearson correlation r with p-values shown for 1-tailed tests. Bonferroni-Holm corrected p values shown. * = $p < 0.05$ (uncorrected). Group sample sizes in parentheses.

	5 dB	10 dB	13 dB	20 dB	30 dB
CI Adults	$r = -0.787$	$r = -0.815$	$r = -0.828$	$r = -0.796$	$r = -0.815$
($n = 10$)	$p = 0.017$	$p = 0.004$	$p = 0.002$	$p = 0.013$	$p = 0.007$
CI Children	$r = -0.528$*	$r = -0.539$	$r = -0.454$*	$r = -0.641$	$r = -0.497$*
($n = 15$)	$p = 0.065$	$p = 0.038$	$p = 0.223$	$p = 0.005$	$p = 0.118$

SNR-50 as a function of SMTF slope and SRD threshold at 20 dB depth in CI participants are shown in Figs. 4(a)–4(d).

IV. DISCUSSION

In the present study, the maturity of spectral resolution was examined in school-age children developing with different hearing methods relative to adults with similar peripheral hearing constraints. Three hypotheses were tested. First, it was predicted that frequency resolution would be worse in CI users than NH users but adult-like in both groups of school-age children. Second, across-channel intensity resolution was predicted to be immature in school-age children with CI but not in NH school-age children. Third, it was hypothesized that CI participants' frequency resolution would correlate more strongly than across-channel intensity resolution with their speech perception in noise.

A. Frequency resolution and SRD

Mature SRD thresholds were observed in school-age children regardless of hearing method. These results are consistent with previous work demonstrating adult-like SRD in both NH and CI children at the age ranges tested (Jung *et al.*, 2012; Peter *et al.*, 2014; Kirby *et al.*, 2015). The finding that SMTF slopes were flatter in CI listeners than in NH listeners but mature in both groups of children supports the hypothesis that frequency resolution is limited by hearing method but mature at least by school-age. This finding further strengthens the idea that SRD reflects frequency resolution in CI users (Won *et al.*, 2007, 2011; Jones *et al.*, 2013).

In the present study, binaural vs monaural testing confounded the effect of hearing method. Therefore, it is possible that some of the strong effect of the hearing method on SRD was due to a binaural benefit in the NH listeners. Comparing NH listeners' average SRD at 30 dB from the present study with earlier studies using monaural presentation (Henry and Turner, 2003; Henry *et al.*, 2005) suggests a possible 2 ripple per octave benefit to binaural presentation. However, Drennan *et al.* (2015) reported a statistically insignificant binaural benefit for SRD in adult CI listeners'. The degree of binaural benefit for speech perception appears to rely on symmetrical spectral resolution between ears (Chen *et al.*, 2012; Drennan *et al.*, 2015). Thus, the degree of binaural benefit for SRD is expected to be highly variable and relatively small compared to the large effect of hearing method observed in the present study. Importantly, presentation modality was constant within groups and, therefore, would not have confounded the results within each listening method.

TABLE IV. Pearson correlations between SNR-50 and SMTF coefficients. Note: Unadjusted = fit parameters to raw data. Adjusted = fit parameters to adjusted lower-depth data. A = SMTF x-intercept (dB). B = log10 of SMTF slope (Hz^{-1}). SNR-50 = SNR (dB) at 50% identification of spondees in steady state noise. p-values shown for 1-tailed tests. Group sample sizes in parentheses.

	Unadjusted		Adjusted	
	A	B	A	B
CI adults	$r = -0.761$	$r = -0.950$	$r = -0.156$	$r = -0.904$
($n = 10$)	$p = 0.005$	$p = < 0.0001$	$p = 0.333$	$p = 0.0001$
CI Children	$r = -0.132$	$r = -0.479$	$r = -0.162$	$r = -0.492$
($n = 14$)	$p = 0.320$	$p = 0.036$	$p = 0.283$	$p = 0.037$

TABLE V. Correlation between SMTF slope and x-intercept. Note: Unadjusted = fit parameters to raw data. Adjusted = fit parameters to adjusted lower-depth data. A = SMTF x-intercept (dB). B = log10 of SMTF slope (Hz^{-1}). SNR-50 = SNR (dB) at 50% identification of spondees in steady state noise. p-values shown for 2-tailed tests. Group sample sizes in parentheses.

	Unadjusted	Adjusted
CI Adults	$r = 0.834$	$r = 0.459$
($n = 10$)	$p = 0.001$	$p = 0.182$
CI Children	$r = 0.605$	$r = 0.394$
($n = 14$)	$p = 0.017$	$p = 0.146$

Consistent with previous research, NH children demonstrated adult-like frequency resolution (Olsho *et al.*, 1987; Schneider *et al.*, 1990; Spetner and Olsho, 1990). This finding suggests that previously reported age effects for SRD (Blagosklonova *et al.*, 1989; Peter *et al.*, 2014) are not due to maturation of frequency resolution. Similarly, frequency resolution in CI children appears to be mature at least by 7 yrs of age. Thus, despite atypical, spectrally impoverished auditory input during development, school-age CI listeners demonstrate frequency resolution similar to post-lingually deaf adult CI users. Taken together, these data suggest that the device and electro-neural interface are the primary constraints on frequency resolution in pre-lingually deaf children implanted prior to age 2 yrs. These findings are consistent with Leake and colleagues' work on the effects of chronic intracochlear stimulation in neonatally deafened cats (Leake *et al.*, 2000; Moore *et al.*, 2002; Vollmer *et al.*, 2007) where similarly-broad spatial selectivity at the level of the inferior colliculus is seen regardless of age of deafness onset.

B. Across-channel intensity resolution and SRD

Mature SRD thresholds were observed for both groups even at the lowest ripple depths tested, suggesting that across-channel intensity resolution is mature by early school-age (7 yrs old) in CI users. Moreover, SMTF x-intercepts were mature in CI children and the correlation with age was not significant. Immature across-channel intensity resolution was predicted based on previous findings that sensitivity to broadband intensity modulation develops more slowly in pre-lingually deaf CI users than in NH listeners (Park *et al.*, 2015). The inconsistency between the present findings and the work of Park *et al.* has several possible explanations. First, although the studies tested CI children with similar chronological age range and range of duration of CI use, the age at implantation criteria for the present study was lower (2 yrs old) than in the Park *et al.* study (3 yrs old). Thus, it is possible that age at implantation beyond age 2 yrs limits development of intensity resolution in pre-lingually deaf CI children. Second, in the previous study, intensity varied across-time rather than across-channel. As has been shown by Anderson *et al.* (2012), these two measures of intensity resolution are not strongly correlated suggesting that they involve different mechanisms. Finally, as described earlier, the SMTF x-intercepts derived from the raw data are, for CI users, confounded SMTF slope due to floor effects and, therefore may not reflect across-channel intensity resolution independently from frequency resolution.

In addition to poor frequency resolution, CI listeners also demonstrated poorer across-channel intensity resolution than NH listeners. These results were not expected, but in retrospect, are consistent with the reduced dynamic range of electric versus acoustic hearing. However, Park *et al.* (2015) found no significant relationship between electrical dynamic range of their participants' clinical maps and amplitude modulation sensitivity. Given that patients were using their clinical processors and preferred settings, the relative influence of neural intensity coding and signal processing/compression on this effect cannot be determined in the present study. Regardless, the present study found no evidence that across-channel intensity resolution is related to speech perception in noise in CI listeners with mature spectral resolution.

It was hypothesized that across-channel intensity resolution would be mature in NH children. The present data are somewhat inconsistent in that respect: Although no significant effect of age was found for x-intercept, the correlation with age was significant. In other words, although across-channel intensity resolution was mature in NH children on average, there is some evidence that development continues through 10–14 yrs of age. It is important to note that, for NH listeners, x-intercept was not related to SMTF slope and no floor effects were seen. Thus, the concerns about interpretation of x-intercept derived from the raw data are not present for the NH listeners.

Development of across-channel intensity resolution beyond 10 yrs old in NH children is consistent with earlier findings of immature SRD in 8–11 yr old children (Peter *et al.*, 2014). The present study was not powered to determine the cutoff age for development in NH children but future investigations might focus on the 10–11 yr range. The prediction that across-channel intensity resolution would be mature by this age range in NH children was inferred from earlier work showing maturation of temporal intensity resolution by 5–8 yrs old (Maxon and Hochberg, 1982). Future studies might compare development of temporal intensity resolution to that of spectral profile analysis (Jesteadt *et al.*, 1977; Green and Mason, 1985).

C. Relationship of SRD and SMTF shape to speech perception

Consistent with previous research, SRD thresholds across ripple depths were strongly correlated with speech perception scores in post-lingually deaf adult CI users (Won *et al.*, 2011; Shim *et al.*, 2014). This relationship was not as robust in CI children, reaching corrected significance at 10 and 20 dB depth only. Nevertheless, across all ripple depths, the correlations were in the predicted direction and were most were significant using uncorrected p values. Comparing the scatterplots for children and adults [e.g., see Fig. 4(a)], it would appear that CI children showed the same range of variability in SRD threshold but were less variable than adults in their speech perception in noise. In fact, the most striking difference between the two age groups is that the CI children with poor SRD thresholds still had SNR-50 scores in the upper range of performance for CI adults. This would suggest that, while spectral resolution is similarly limited in pre- and post-lingually deaf CI users, early-implanted children are able to overcome this limitation more than adults. However this remains speculative given that the present study was underpowered to detect a significant difference between SRD and SNR-50 correlations between age groups (given the correlation strengths, this would require $n > 35$ in each age group). Further work comparing speech perception in noise of pre-lingually and post-lingually deaf CI users with poor spectral resolution is needed to confirm this observation.

The hypothesis that frequency resolution would correlate more strongly than across-channel intensity resolution with speech perception in steady-state noise in CI participants, was supported by the present study. In CI adults, SMTF slope was strongly correlated with better speech perception in noise whereas adjusted x-intercept was not and the magnitudes of these correlations were significantly different. Thus, these findings strongly suggest that frequency resolution but not across-channel intensity resolution is the important common underlying both SRD and speech perceptual tasks in post-lingually deaf adult CI users. This finding further strengthens the prospect of using SRD as a measure of frequency resolving capacity of adult CI listeners (Won *et al.*, 2011; Jones *et al.*, 2013).

The relationship between SNR-50 and SMTF slope, although significant, was weaker for CI children than adults. This difference in correlation strength was statistically significant, suggesting that frequency resolution is less important for speech perception in noise for pre-lingually deaf school age children than for post-lingually deaf adults. Figure 4(b) illustrates that children with particularly poor frequency resolution are still able to perceive speech in noise as well as better-performing adult CI users. If this observation is confirmed in a larger sample size, it would be particularly interesting given the fact that NH children are more dependent than adults on spectral cues (particularly dynamic spectral cues) for speech perception and spoken-language development (Lowenstein *et al.*, 2012; Nittrouer and Lowenstein, 2014; Moberly *et al.*, 2016a). It is possible that pre-lingually deaf CI users' experience with reduced spectral resolution during development leads to modified listening strategies or enhanced attentional capacities for speech perception in noise.

The idea that perceptual cue weighting and auditory resolution can interact in CI listeners has been explored (Moberly *et al.*, 2016b). For instance, on a consonant contrast for which NH listeners strongly attend to spectral cues, post-lingually deaf adult CI users are more variable in their relative attention to spectral and amplitude cues (Moberly *et al.*, 2014). CI users with better spectral resolution weighted spectral cues more strongly than listeners with poorer spectral resolution. Similar findings were reported for pre-lingually deaf 8-yr old CI users (Nittrouer *et al.*, 2014), On a consonant contrast for which amplitude cues are most robust, NH and children with CIs showed similar cue weighting strategies. However, CI children showed more variable cue weighting on a contrast for which NH children strongly weighted spectral cues. Taken together, these findings suggest that limitations to auditory resolution may lead CI listeners to shift attention to cues that are more robustly encoded by the CI, such as amplitude structure (Nittrouer *et al.*, 2014). Further studies comparing perceptual strategies of pre- and post-lingually deaf CI users with poorer spectral resolution are needed to understand what speech perception cues children with poor SRD thresholds are using to achieve good (for CI users) speech perception in noise scores.

While independence of frequency resolution and across-channel intensity resolution is consistent with Supin's model of SRD (Supin *et al.*, 1999), this has not been verified for CI listeners. Due to the apparent influence of floor effects on x-intercepts derived from raw data, further research is required to verify independence of these factors with a CI. Given that the logarithmic function approaches an infinite slope at the x-intercept, this value might be estimated more precisely by varying the dimension parallel to the x axis (ripple depth) rather than ripple density. For instance, measuring the modulation depth required to discriminate spectral ripple stimuli at a low ripple density could provide the measure of across-channel intensity resolution. This would not be unlike the approach used to measure spectral ripple detection in CI users (Saoji *et al.*, 2009; Anderson *et al.*, 2012). Saoji and colleagues (2009) found that intercept, rather than slope, was significantly related to speech identification leading them to conclude that across-channel intensity resolution, rather than frequency resolution, was the important factor relating spectral ripple detection and speech understanding in quiet.

Although the present study appears to contradict this conclusion, Anderson *et al.* (2012) have shown that spectral ripple detection thresholds at high ripple densities beyond 4 ripples per octave are confounded by non-spectral, within-channel temporal cues. Moreover, they found no relationship between broadband Gaussian noise intensity resolution and SRD. In the present study, SRD was never above 4 ripples per octave in any of the CI users, thus the slope of the SMTF in this experiment was unlikely influenced by within-channel temporal cues.

V. CONCLUSION

The present study demonstrates that, by 7–14 yrs of age, pre-lingually deaf children with CIs have mature SRD relative to post-lingually deaf adult CI users. Similarly, SRD is mature by 10–14 yrs of age in NH children. Frequency resolution as well as across-channel intensity resolution is both reduced in CI users. Frequency resolution appears to be mature by the age-ranges tested regardless of hearing method. While across-channel intensity resolution is mature by 7 yrs of age in children with implants, some development may continue to occur in NH children beyond 10 yrs of age. The relationship between speech perception in steady-state noise and SRD appears to be driven by frequency resolution rather than across-channel intensity resolution. However, this finding should be verified with alternative methods to measure across-channel intensity resolution. Finally, poor frequency resolution does not appear to limit speech perception in noise for pre-lingually deaf, early implanted, children with CIs as much as it does for post-lingually deaf adults. Future research should examine development of SRD and the SMTF in younger pre-lingually deaf children to determine rates of maturation of frequency and across-channel intensity resolution in this population. Furthermore, the perceptual mechanisms that explain how pre-lingually deaf CI users with poor frequency resolution are able to achieve relatively good speech perception benefit in noise require further investigation.

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