

Single-Channel Focused Thresholds Relate to Vowel Identification in Pediatric and Adult Cochlear Implant Listeners

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Abstract

Speech recognition outcomes are highly variable among pediatric and adult cochlear implant (CI) listeners. Although there is some evidence that the quality of the electrode-neuron interface (ENI) contributes to this large variability in auditory perception, its relationship with speech outcomes is not well understood. Single-channel auditory detection thresholds measured in response to focused electrical fields (i.e., focused thresholds) are sensitive to properties of ENI quality, including electrode-neuron distance, intracochlear resistance, and neural health. In the present study, focused thresholds and speech perception abilities were assessed in 15 children and 21 adult CI listeners. Focused thresholds were measured for all active electrodes using a fast sweep procedure. Speech perception performance was evaluated by assessing listeners' ability to identify vowels presented in /h-vowel-d/ context. Consistent with prior literature, focused thresholds were lower for children than for adults, but vowel identification did not differ significantly across age groups. Higher across-array average focused thresholds, which may indicate a relatively poor ENI quality, were associated with poorer vowel identification scores in both children and adults. Adult CI listeners with longer durations of deafness had higher focused thresholds. Findings from this study demonstrate that poor-quality ENIs may contribute to reduced speech outcomes for pediatric and adult CI listeners. Estimates of ENI quality (e.g., focused thresholds) may assist in developing customized programming interventions that serve to improve the transmission of spectral cues that are important in vowel identification.

Keywords

Cochlear implant, Electrode-neuron interface, Focused thresholds, Vowel identification, Pediatric

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Introduction

Cochlear implants (CIs) allow listeners with severe to profound hearing loss or those who do not benefit from hearing aids to understand speech. Despite remarkable advances in CI technology, speech recognition scores remain highly variable among children and adults, and it is difficult to predict who will have poor outcomes (e.g., Arjmandi et al., 2021; Dilley et al., 2020; Holden et al., 2013; Niparko et al., 2010). It has been hypothesized that the quality of the electrode-neuron interface (ENI), or the efficacy with which CI electrodes activate their target auditory neurons, contributes to some of the variability in speech perception scores (e.g., DeVries et al., 2016; Pfingst et al., 2004). In particular, vowel identification relies heavily on the precise transmission of spectral information (e.g., first and second formant frequencies), which is prone

to degradation or/and distortion when the ENI quality is poor (e.g., DiNino et al., 2016; Jahn et al., 2019). This study aims to investigate how estimated ENI quality may

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relate to vowel identification in pediatric and adult CI listeners.

Estimating ENI Quality Using Focused Threshold

Single-channel auditory detection thresholds measured in response to spatially focused electrical fields (i.e., focused thresholds) have been shown to be sensitive to several aspects of ENI quality such as the electrode-to-modiolus distance (DeVries & Arenberg, 2018; Jahn & Arenberg, 2019; Long et al., 2014), intracochlear resistance (Jahn & Arenberg, 2019), and possibly neural health and/or density (DeVries et al., 2016; Goldwyn et al., 2010; Jahn & Arenberg, 2020a, 2020b). An electrode that is placed in a suboptimal position in the cochlea (i.e., relatively distant from auditory neurons) (DeVries et al., 2016; Jahn & Arenberg, 2019; Long et al., 2014) or that stimulates a population of degenerated or dead auditory neurons (Bierer, 2007; Shepherd & Javel, 1997), or a combination of the two, requires relatively high current levels to elicit auditory percepts. Higher current levels may lead to lost and/or smeared spectral information, which is believed to occur when electrical current from adjacent channels stimulates overlapping populations of auditory neurons (reviewed by Bierer, 2010). In fact, multiple studies have shown that channels with relatively high focused thresholds have steeper loudness growth (Bierer & Nye, 2015), indicating a smaller dynamic range and poorer sensitivity to variation in the intensity of the auditory signal. In contrast to auditory detection thresholds measured with monopolar (broad) electrode configurations, channels with relatively high focused thresholds are more likely to have broader psychophysical tuning curves (PTCs) (Bierer & Faulkner, 2010; Long et al., 2014), lower intracochlear resistance values (DiNino et al., 2019), smaller evoked potential amplitudes (DeVries et al., 2016), steeper evoked potential growth functions (Jahn & Arenberg, 2020b), and higher wave V thresholds in the electrically evoked auditory brainstem response (Bierer et al., 2011). These findings demonstrate that single-channel focused thresholds have the potential to be used as a proxy measure for the quality of the interface between each channel and its target auditory neurons, the sensitivity of that channel to different stimulation levels, and its degree of frequency selectivity or channel interaction.

ENI Quality and Vowel Identification

Vowel sounds are suitable stimuli for understanding the transmission and perception of spectral information through CI channels, as their identification relies largely on the resolvability of distinct formant frequencies (Neel, 2008; ter Keurs et al., 1994; Arjmandi et al., 2018). Vowels are also the nucleus of a syllable, wherein their identification contributes to successful word segmentation and speech understanding (e.g., Johnson & Jusczyk, 2001; Jusczyk et al., 1999), and

they carry a substantial portion of the information necessary for speech perception (e.g., Kewley-Port et al., 2007), although speech intelligibility may be better explained by nonlinguistic measures of uncertainty such as cochlea-scaled spectral entropy (Stilp & Kluender, 2010) or simply by the relative intensity of speech (Oxenham et al., 2017) rather than on the basis of a distinction between vowel and consonant. Nevertheless, vowel identification has been extensively used to understand patterns of speech perception in listeners with CIs (e.g., DiNino et al., 2016; Giezen et al., 2010; Jahn et al., 2019; Jahn et al., 2018; Lane et al., 2001). Vowel identification scores significantly decrease when relevant frequency components are distorted (e.g., DiNino et al., 2016; ter Keurs et al., 1994). Therefore, CI listeners' vowel identification performance may provide an indication of how across-array (across electrodes) and site-specific (at the electrode level) ENI quality relate to the transmission of spectral cues that are important for accurate speech perception.

Each electrode in the CI array is responsible for carrying a specific frequency band. Loss or distortion of spectral information in each band (i.e., channel) due to factors such as channel interaction can potentially interfere with a listener's ability to successfully distinguish different vowel sounds. Analysis of the relative channel importance for phoneme identification (i.e., perceptual weight) showed varying perceptual weighting across channels for vowel identification, whereas weights were equal across consonants (e.g., Kasturi et al., 2002). Those results suggest that vowel identification is particularly sensitive to the quality of spectral information provided by each channel or frequency band. Moreover, listeners with normal hearing perform more poorly in the identification of vocoded vowels with low-frequency spectral holes (setting the output of particular band-pass filters to zero) than those with mid-, and high-frequency holes (DiNino et al., 2016; Shannon et al., 2002; Throckmorton & Collins, 2002), suggesting that loss or distortion of spectral information in channels that convey key formant frequency information is more detrimental to vowel identification than other channels.

Thus, single or combined effects of poor electrode placement or poor neural health could degrade the faithful transmission of spectral information through a CI channel, likely leading to an elevated focused threshold and reduced ability to identify vowel sounds. Although focused thresholds have proven to be useful for identifying channels with poor ENIs, the relationship between focused thresholds and vowel identification has not yet been established. There is also limited evidence from CI listeners about how ENI quality near apical (low-frequency), mid-, and basal (high-frequency) channels (frequency bands) would differentially impact vowel identification. This study aims to exploit the sensitivity of focused stimulation to ENI quality by quantifying the relationship between focused thresholds and vowel identification in adult and pediatric CI listeners. Understanding this relationship is important because specific

patterns in estimates of ENI quality such as relatively elevated focused thresholds in specific frequency regions (e.g., apical, middle, or basal regions) may differentially impact vowel identification and contribute to poor speech outcomes with a CI.

Age-Related Variability in ENI Quality

There is both psychophysical (DiNino et al., 2019) and electrophysiological (Brown et al., 2010; Jahn & Arenberg, 2020a; Jahn & Arenberg, 2020b) evidence suggesting that the quality of the ENI differs between adults and children with CIs. For instance, DiNino et al. (2019) found that focused behavioral thresholds were lower for children than for adults. As the cochlea is adult-sized at birth, these global age-related differences in ENI quality may be related to differences in cochlear resistivity, spiral ganglion integrity, or a combination of the two. In fact, multiple studies have shown that children demonstrate steeper electrophysiological growth functions than adults, which are suggestive of denser underlying neural populations in the children (Brown et al., 2010; Jahn & Arenberg, 2020a, 2020b). There is also evidence that children with CIs have higher levels of intracochlear bone and tissue growth than adults (Busby et al., 2002; DiNino et al., 2019; Molisz et al., 2015). These age-related differences in the quality of the ENI may lead to differences in frequency resolving abilities between children and adults with CIs, potentially leading to different performance across adult and pediatric CI listeners in discrimination between speech sounds. However, prior studies on the differences between children and adults in their spectral resolving abilities and speech recognition have reported mixed findings (Gifford et al., 2018; Horn et al., 2017; Landsberger et al., 2018). It is not yet clear how age-related factors related to ENI quality contribute to speech perception in children and adults with CIs.

In this work, we examined how variation in focused thresholds relates to vowel identification performance in pediatric and adult CI listeners, and whether such a relationship differs between the two age groups. First, we compared focused thresholds between children and adults to estimate the quality of the ENI and to replicate previous work (DiNino et al., 2019). Second, we examined the relationship between focused thresholds and vowel identification for children and adults. Addressing this question allows us to determine the role of age-related differences in estimated ENI quality in vowel identification. We hypothesized that higher focused thresholds would correspond to poorer vowel identification scores. We also hypothesized that children would perform better than adults in vowel identification because of their lower average focused thresholds. Third, we asked how average focused thresholds in different regions of the cochlea (e.g., apical, middle, and basal) relate to vowel identification scores. We expected that higher focused thresholds in apical and middle regions would correspond to poorer

vowel identification because those channels carry the main frequency information relevant to distinguishing most vowel contrasts (i.e., first and second formant frequencies). The findings from this study will further elucidate the relationship between focused thresholds and vowel identification and compare such relationship between children and adults. This study also investigates how those relationships are influenced by the global (across-array) and regional measures (apical, middle, and basal regions). If single-channel focused thresholds relate to vowel identification, that measure has the potential to be incorporated to optimize CI programming and to improve speech perception in CI listeners.

Materials and Methods

Participants

Table 1 displays the demographic profiles of the participants. Thirty-six CI listeners participated in this study. Fifteen participants were children (7 females) and twenty-one were adults (9 females), as identified by their age at implantation (older or younger than age 18 years, respectively). Eleven children had bilateral CIs and four had unilateral CI (26 ears). Five adults had bilateral CIs and 16 had unilateral CI (26 ears). Overall, data from 52 ears were analyzed. Mean age of implantation was 4.8 years for 26 ears from the children group ($SD=3.5$ years; range = 1 to 13.86 years) and 52.6 years for 26 ears from the adult group ($SD=16.8$ years; range = 19.24 to 85.69 years). For children, the mean age of implantation was 3.39 years for their first implanted ears ($SD = \pm 2.66$ years) and 6.72 years for their second implanted ears ($SD = \pm 3.71$ years). For adults, the mean age of implantation was 51.39 years for their first implanted ears ($SD = \pm 16.43$ years) and 59.11 years for their second implanted ears ($SD = \pm 18.19$ years). All participants received Advanced Bionics HiRes 90k devices. All participants used oral communication and they were all native speakers of American English. Adults gave written informed consent prior to participation. Children gave written informed assent and a parent or legal guardian provided written consent for their participation. Studies were approved by the University of Washington Institutional Review Board.

Single-Channel Detection Thresholds in Response to Focused Electrode Configuration

Single-channel auditory detection thresholds were measured in response to a spatially focused electrode configuration (steered quadrupolar, sQP), with a current focusing coefficient (σ) of 0.9 (Bierer et al., 2015). sQP stimulation involves four intracochlear electrodes, in which the two middle electrodes are stimulated as active electrodes and the two outer electrodes carry the return current. The fraction of current returning through the two intracochlear electrodes is

Table 1. Demographic Information for all 52 Ears from 36 Participants (15 Children and 21 Adults), Including Participants' ID, Gender (M = Male and F = Female), Ear Implanted (R = Right and L = Left), Age Group (P = Pediatric and A = Adult), Etiology (if Known), Duration of Deafness, Age at Implantation, Age at Testing, and Electrode Array Type. HF = HiFocus; EVA = Enlarged Vestibular Aqueduct. Children and Adult CI Listeners are Indicated by "P" and "S" Letters in Their IDs, Respectively.

ID	Ear	Etiology	Duration of Deafness	Age at Implantation	Age at Testing	Length of CI Use	Electrode Array
P01	R	Unknown	2.3	2.3	15.70	13.4	HF IJ
P01	L	Unknown	12.1	12.1	15.70	3.6	HF IJ
P02	R	EVA	1.05	1.05	11.80	10.75	HF IJ
P02	L	EVA	3.04	3.05	11.80	8.75	HF IJ
P03	R	Unknown	1.39	1.39	12.90	11.51	HF IJ
P03	L	Unknown	5.59	5.59	12.90	7.31	HF IJ
P04	R	Unknown	1.67	1.67	13.20	11.53	HF IJ
P04	L	Unknown	4.67	4.67	13.20	8.53	HF IJ
P05	R	Connexin-26	4.1	4.1	17.70	13.6	HF IJ
P05	L	Connexin-26	9.9	13.86	17.70	3.84	HF IJ
P06	R	Unknown	1.84	4.34	17.20	12.86	HF IJ
P06	L	Unknown	8.46	10.96	17.20	6.24	HF IJ
P07	L	Unknown	4.91	4.91	13.30	8.39	HF IJ
P07	R	Unknown	1.86	1.86	13.30	11.44	HF IJ
P08	L	EVA	2.9	2.94	15.30	12.36	HF IJ
P09	L	Unknown	1.33	2.58	13.50	10.92	HF IJ
P09	R	Unknown	2.68	3.93	13.50	9.57	HF IJ
P10	L	Connexin-26	1.1	1.08	13.30	12.22	HF IJ
P10	R	Connexin-26	5.1	5.11	13.30	8.19	HF IJ
P13	L	EVA	6.35	9.17	NA	3.83	HF IJ
P14	L	Unknown	5.67	5.42	13.80	8.38	HF IJ
P14	R	Unknown	3.9	7.17	13.80	6.63	HF IJ
P15	R	EVA	4.93	7.93	8.50	0.57	Mid-scala
P16	L	DFNBI	1	1	14.56	13.56	HF IJ
P16	R	DFNBI	4.5	4.5	14.56	10.06	HF IJ
P58	R	Genetic	2.42	2.42	NA	19.50	HF IJ
S22	R	Genetic	11.81	66.69	78.20	11.51	IJ Helix
S23	L	Idiopathic	3.92	61.95	73.40	11.45	IJ Helix
S23	R	Idiopathic	6.5	64.54	73.40	8.86	HF IJ
S28	R	Autoimmune Disease	7	69.69	76.00	6.31	HF IJ
S29	R	Noise exposure	39.19	85.69	87.80	2.11	Mid-scala
S29	L	Noise exposure	30.3	76.79	87.80	11.01	HF IJ
S38	R	Otosclerosis	1	46.22	50	3.78	HF IJ
S39	R	Genetic	8	30.12	54.41	24.29	HF IJ
S39	L	Genetic	18	40.12	54.79	14.67	HF IJ
S40	R	EVA	46.4	50.36	56.200	5.84	HF IJ
S41	R	Maternal Rubella	1	42.90	49.00	6.1	HF IJ
S42	R	Unknown	1	51.21	64.00	12.79	HF IJ
S43	R	Noise exposure	18.73	67.89	72.50	4.61	Mid-scala
S45	L	Genetic	18	61.02	65.50	4.48	Mid-scala
S45	R	Genetic	10.99	54.00	65.50	11.5	HF IJ
S46	R	Genetic	25.09	64.17	69.40	5.23	HF IJ
S47	R	Unknown	10.33	36.40	40.40	4	Mid-scala
S48	R	Auto Immune	22	55.3	59.00	3.7	HF IJ
S49	L	Genetic	42.75	44.19	45.80	1.61	Mid-scala
S49	R	Genetic	42.09	43.53	45.80	2.27	Mid-scala
S50	R	Unknown	53.01	71.01	76.50	5.49	HF IJ
S52	R	Unknown	6.09	65.97	71.20	5.23	HF IJ
S53	R	Meningitis	42.88	44.05	56.00	11.95	IJ Helix
S54	R	EVA	16.69	23.69	27.80	4.11	Mid-scala
S59	L	Ototoxicity	18.91	30.91	32.10	1.19	Mid-scala
S60	R	Meningitis	19.10	19.24	22.40	3.16	Mid-scala

specified by the current focusing coefficient of sigma (σ), while the remaining current is passed through an extracochlear ground. Sigma can range from 0 (the lowest degree of current focusing) to 1 (the highest degree of current focusing), corresponding to delivering all return current through the extracochlear electrode (monopolar stimulation) to passing all return current through the intracochlear electrodes (i.e., each of the two return electrodes deliver 50% of the return current), respectively. We used a sigma value of 0.9 to present current at perceptible levels that were below the voltage compliance limits of the device for most participants. Thresholds were obtained on channels 2 through 15 using a sweep procedure based on Békésy tracking principles (Bierer et al., 2015; Şek et al., 2005). Stimuli were swept across the electrode array by implementing current steering between two adjacent, active electrodes by varying the steering coefficients (α) from 0 to 1 in step sizes of 0.1 (Bierer et al., 2015; Şek et al., 2007). Setting $\alpha=0$ corresponds to delivering all electrical current through the more apical of the two active electrodes, whereas $\alpha=1$ means all current is steered through the basal active electrode.

All electrical stimuli were biphasic, charge-balanced pulse trains with the cathodic phase leading and presented directly to the internal device. Electric pulses were 97 microseconds (μs) in duration with a 0- μs interphase gap and were presented at a rate of 997.9 pulses per second. The duration of each pulse train was 200.4 milliseconds. Most comfortable listening levels (MCLs) were measured on channels 2 through 15 in response to the same focused stimuli to set the upper limit of stimulation prior to each threshold sweep, assuring that the current level never exceeded MCL. MCLs were measured behaviorally for each channel using the Advanced Bionics clinical loudness scale (Advanced Bionics, LLC), which ranged from “1” (just noticeable) to “10” (“too loud”). Current level was increased manually until participants rated the loudness as “7”, defined as “Loud but comfortable” and then reduced back down to a “6”, defined as “Most Comfortable” level. Once the MCLs were obtained, they were set as the upper stimulation limit and threshold measurements proceeded. Pulse trains were presented starting at 6 dB below MCL and swept across the electrode array in one forward sweep from apical to basal electrodes (channels 2 to 15) and one backward sweep from basal to apical electrodes (channels 15 to 2). Listeners continuously held down the spacebar on the computer keyboard when they could hear the stimuli and released the spacebar when they could not. The final single-channel threshold levels were the weighted average of consecutive current levels across the forward and backward sweeps at integer channel numbers (Bierer et al., 2015). The presentation and manipulation of stimuli as well as recording participants’ responses were performed via custom software in MATLAB (The MathWorks, Inc.), while controlling the Bionic Ear Data Collection System (BEDCS, version

1.18315; Advanced Bionics, LLC). Further details can be found in Bierer et al. (2015).

Vowel Identification Task

Vowel identification performance was evaluated using a closed set of ten vowels presented in \hVd\ contexts (/i/ in “HEED”; /e/ in “HAYED”; /ɪ/ in “HID”; /ɛ/ in “HEAD”; /æ/ in “HAD”; /ɑ/ in “HOD”; /ʌ/ in “HUD”, /oʊ/ in “HOED”; /ʊ/ in “HOOD”; /u/ in “WHO’D”) in quiet. Participants who achieved a score of 70% or higher in quiet also completed the test in the presence of a 4-talker babble noise at a +10 dB signal-to-noise ratio (SNR). Vowels were naturally spoken recordings of a female talker who was native to the Pacific Northwest region of the United States. They were presented at 60 dBA through speakers, one meter away from the listener, who was seated in a sound-attenuating booth. The contralateral CI in bilateral listeners and hearing aid in bimodal listeners were turned off during the tests. If participants had residual hearing in the non-implanted ear, that ear was plugged. Participants completed the testing using their everyday listening programs. Participants completed one practice run and at least two test runs, with each run consisting of 3 presentations of each vowel. After presenting each vowel stimulus, participants used a computer mouse to select their responses from ten boxes labeled with each of the ten \hVd\ tokens (“HEED”, “HID”, etc.). During the practice run, participants could choose to repeat each vowel multiple times and they received feedback as to the correct response. Participants then performed at least two test runs, which contained three repetitions of each vowel with no option to repeat the vowels and no feedback. A third test run was conducted if the percent correct score on the first two test runs differed from each other by more than 10%. All two or three test runs were averaged to calculate the final score (in percent correct). Scores were converted to rationalized arcsine units (RAU) to normalize error variance (Studebaker, 1985). ListPlayer software (Version 2.2.11.52, Advanced Bionics, LLC) was used to present the vowel stimuli and to record the participants’ responses.

Results

Focused Thresholds

The first analysis assessed whether focused thresholds were lower in pediatric than in adult CI listeners, as in our previous study (DiNino et al., 2019). Figure 1A shows the average focused thresholds for children (in blue) and adults (in red) across the electrode array. The standard error means are shown as shaded regions. A linear mixed-effects model was constructed such that focused threshold was the dependent variable and age group (two levels of pediatric or adult coded as categorical variable) and electrode number (coded as categorical

variable) were independent variables. Participant ID and ear were included as two random effects to account for the non-independence of repeated measurements within the same listener. We also controlled for the effect of electrode array type in the model. On average, children had lower focused thresholds than adults ($\beta = -2.01$, $p = 0.036$, see Table 2 for details). There was no significant interaction between age group and electrode site. Figure 1B shows the distributions of average focused thresholds, obtained across the electrode array (across-array average focused threshold), for children and adults. The mean across-array average focused threshold was 2.27 dB lower for children compared to adults (Figure 1B).

Duration of Deafness and Focused Thresholds

The second analysis examined the relationship between the duration of deafness and across-array average focused

threshold. The scatter plot in Figure 2 shows the relationship between the duration of deafness for each ear and its across-array average focused threshold. Data for adults are shown in red circles and children in blue squares. For bilaterally-implanted CI listeners, the data for the first (unfilled) and second implanted ear (filled) are connected by a thin line (children in blue and adults in red line). A linear mixed-effect model was built on all data to examine how the duration of deafness relates to across-array average focused thresholds. Duration of deafness was an independent variable and average focused threshold was included as a response variable, while controlling for the effect of electrode array type. Participant ID and ear were included as random intercepts. The results of the linear mixed-effects analysis showed that the duration of deafness significantly predicted average focused thresholds ($\beta = 0.13$, $p = 0.005$). Because the durations of deafness were shorter and the range was

Table 2. Results of the Mixed-Effects Analysis Testing Whether Focused Thresholds Differ Across Age Group (Adults Versus Children) and for Different Electrodes.

Parameter	Estimate (β)	SE	t	p
Intercept	42.92	1.09	39.3	< 0.001
Age Group	2.01	0.99	2.10	0.036
Electrode Number	0.05	0.05	1.03	0.31
Age Group \times Electrode Number	-0.07	0.05	-1.58	0.11

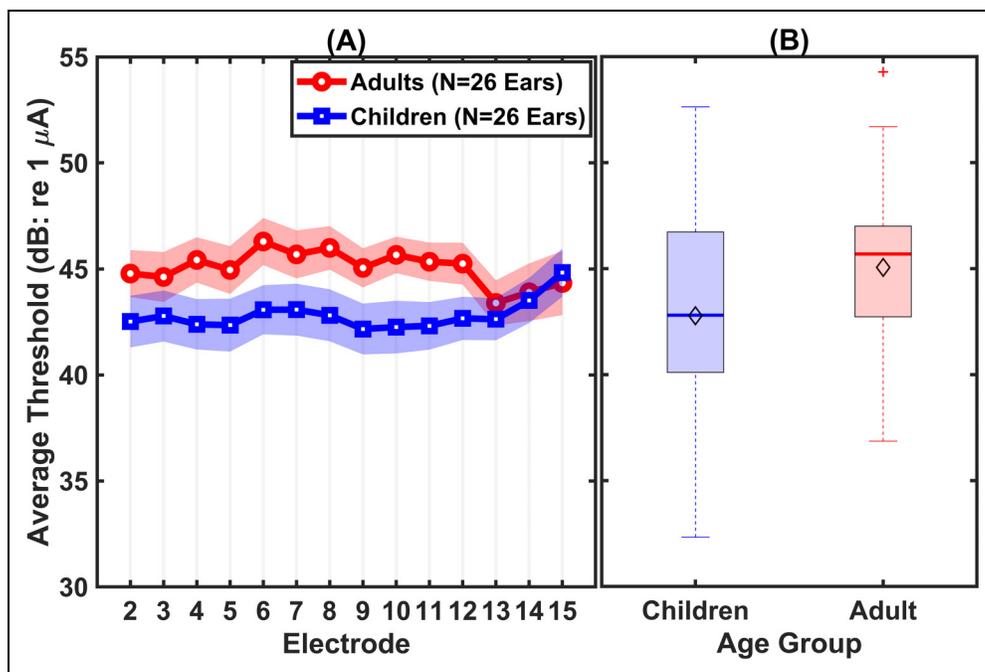


Figure 1. (A) mean (solid lines) and ± 1 standard error mean (shaded areas) of focused thresholds (in dB re: 1 μ A) for children (blue squares) and adults (red circles) with CIs. (B) Boxplots showing the distribution of across-array average focused thresholds for two age groups. The solid red and blue horizontal lines on the boxes show the median values and the diamonds show the average values. The bottom and top edges of the boxes indicate the 25th and 75th percentiles, respectively.

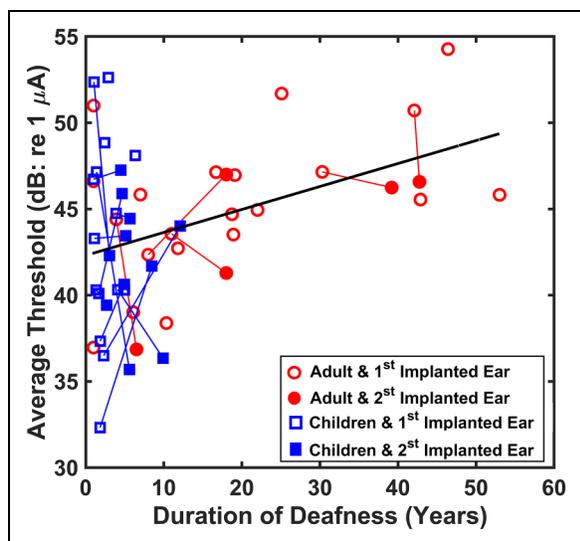


Figure 2. Scatterplot showing the relationship between duration of deafness and across-array average focused thresholds for children (blue squares) and adults (red circles). Unfilled squares indicate the first implanted ears and filled squares show the second implanted ears. The data for the first and second implanted ears of bilateral CIs users are connected by a line.

narrower for the children than the adult group (adult: $M = 20.03 \pm 15.63$ years, children: $M = 4 \pm 2.8$ years, $t(50) = 5.13$, $p < 0.0001$), we also built two linear mixed-effect models to examine this relationship for each group separately. The results of these linear mixed-effects analyses showed that the duration of deafness significantly predicted average focused thresholds in adults ($\beta = 0.14$, $p = 0.01$), but not for children ($\beta = 0.06$, $p = 0.58$). These results suggest that the significant relationship between the duration of deafness and average focused threshold was driven by the adult data.

Average Focused Threshold and Vowel Identification in Children and Adults

The goal of this analysis was to examine the relationship between across-array average focused threshold and vowel identification in quiet and background noise. We also evaluated whether that relationship differs between pediatric and adult CI listeners. Two separate linear mixed-effects models were built, one for quiet and one for noise, to test the relationship between average focused thresholds (as fixed-effect factor) and vowel identification as response variable. Age group was also included as a fixed factor in the models. Participant IDs and ear were included in the models as random intercepts. Figure 3 shows a negative relationship between average focused thresholds and vowel identification scores for children and adults in quiet (panel A) and in background noise (panel B), suggesting that higher average focused thresholds correspond with poorer vowel identification scores ($\beta = -2.92$, $p = 0.002$). The results of

the second mixed-effects model showed that the average focused threshold was a significant predictor of vowel identification in noise ($\beta = -1.19$, $p = 0.02$). It should be noted that this effect for noise would likely have been stronger if the poorer-performing CI listeners had also been tested in noise. There was neither an effect of age group nor a significant interaction between average focused thresholds and age group on vowel identification scores, either in quiet or in noise (see Table 3). The least-squares regression models fitted on all data (in black) in Figure 3 show an approximately 4.8 RAU points drop in average vowel identification score in quiet and 3.4 RAU points drop in average vowel identification score in noise for each 1 dB increase in focused threshold, suggesting that individual differences in their average focused thresholds can have meaningful implications for clinical assessment of global ENI quality.

We further examined the change in vowel identification scores as a function of listening condition (quiet vs. noise) for children and adults. Only participants who were tested in both quiet and noise conditions were included in this analysis (18 ears from 14 adults (4 bilateral CIs) and 20 ears from 11 children (9 bilateral CIs)). Figure 4 shows the vowel identification scores of children and adults for the two listening conditions. Vowel identification score dropped significantly from an average of 99.3 RAU in quiet to 69.5 RAU in noise for children, approximately a 30-point decrease in vowel identification ($\beta = -29.84$, $p < 0.0001$). Vowel identification score also dropped in adults from 101.3 RAU in quiet to 62.6 RAU in noise, corresponding to a 38.7-point decrease ($\beta = -38.7$, $p < 0.0001$). The results of the linear mixed-effects analysis with age group and listening conditions as independent variables and vowel identification as dependent variable showed a strong, significant effect of listening conditions on vowel identification ($\beta = -38.7$, $p < 0.0001$). Note that the performance dropped 8% more for the adults compared to children, but this was not a significant difference as the statistical model showed no effect of age group or an interaction between age group and listening condition.

Average Apical, Middle, and Basal Focused Thresholds and Vowel Identification

The goal of this analysis was to determine how average focused thresholds in apical, middle, and basal regions of the electrode array may differentially relate to vowel identification scores in quiet and in noise. We also examined whether those relationships varied between children and adults. Average apical, middle, and basal focused thresholds were defined as the mean of focused thresholds obtained across electrodes 2 to 6, 7 to 11, and 12 to 15, respectively. The scatterplots in Figure 5 show the average focused thresholds obtained from apical, middle, and basal electrodes plotted against vowel identification performance in quiet (panel A; the first row) and in noise

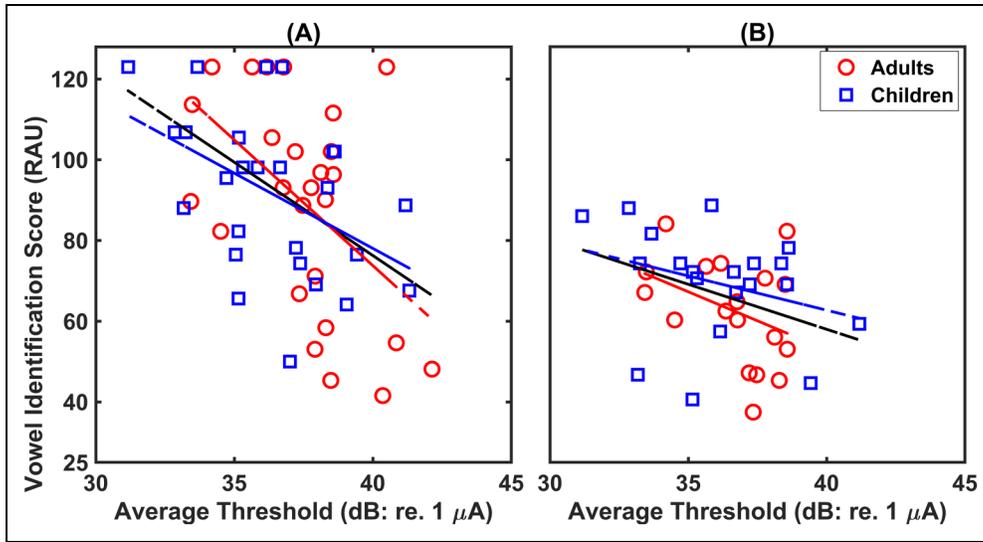


Figure 3. Scatterplots showing the relationship between average focused thresholds and vowel identification scores for children (blue squares) and adults (red circles) in (A) quiet and in (B) noise. The trend lines are the least squares regression lines for children (red lines) and adults (blue lines). The black lines show trend lines for all children and adults data.

Table 3. Results of Linear Mixed-Effects Analysis in Testing the Effects of Average Focused Thresholds and Age Group on Vowel Identification in Quiet and in Noise.

Parameter	Estimate (β)		SE		t		p	
	Quiet	Noise	Quiet	Noise	Quiet	Noise	Quiet	Noise
Model predicting vowel identification score								
Intercept	219.76	116.97	42.16	21.69	5.21	5.39	< 0.0001	< 0.0001
Average Threshold	-2.92	-1.19	0.93	0.50	-3.14	-2.37	0.002	0.02
Age Group	-37.82	-14	53.26	21.69	-0.71	-0.64	0.48	0.52
Average Threshold \times Age Group	0.79	0.39	1.19	0.50	0.66	0.77	0.51	0.44

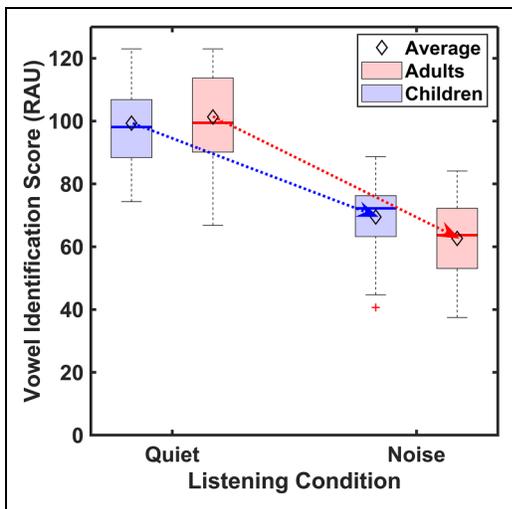


Figure 4. Boxplots showing the distributions of vowel identification scores for children (blue boxes) and adults (red boxes) CI listeners in quiet and in background noise. The horizontal blue and red lines on the boxes show the median values and the diamonds show the average values. The average values for each age group in quiet and noise are connected by dotted arrows.

(panel B; the second row). A linear mixed effect analysis was conducted to test whether there was a significant effect of average focused thresholds on vowel identification and whether those relationships were affected by the electrode location (apical or middle or basal) and age group (children or adults). The results showed a significant effect of average thresholds on vowel identification in quiet ($\beta = -1.17$, $p = 0.0003$) and in noise ($\beta = -0.436$, $p = 0.01$). However, there was no significant interaction effect between age group or electrode location (apical, middle, or basal average focused thresholds) and focused thresholds in predicting vowel identification scores.

Discussion

The present study investigated how ENI quality, as estimated via focused thresholds, relates to vowel identification performance in pediatric and adult CI listeners. Patterns of focused thresholds and vowel identification scores were examined across age groups, as a function of the duration of hearing loss, for different listening conditions (quiet and noise), and by region of the cochlea to understand how these

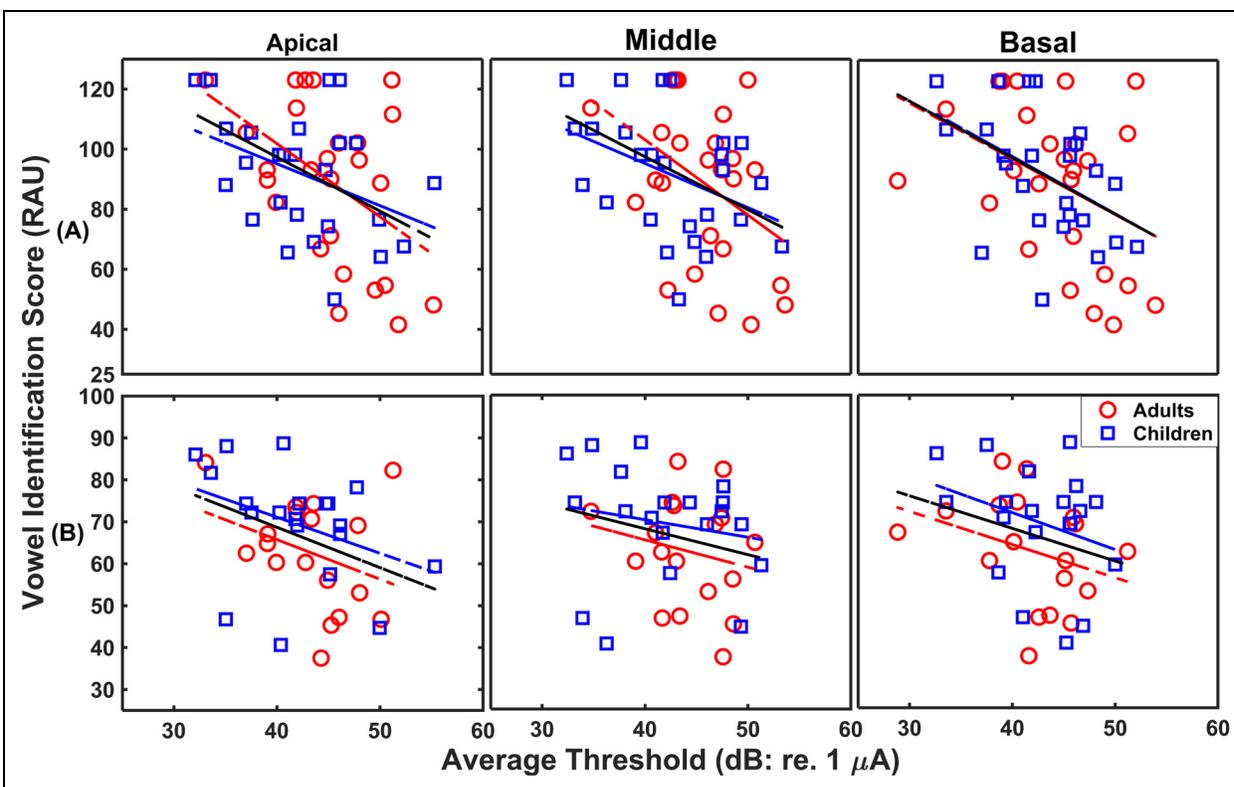


Figure 5. Scatterplots showing the relationship between average apical, middle, and basal focused thresholds and vowel identification scores for children (blue squares) and adults (red circles) in (A) quiet and in (B) noise. The trend lines are the least squares regression lines for children (red lines) and adults (blue lines). The black lines show trend lines for all children and adults data.

factors may explain the relationship between focused thresholds and vowel identification.

Age-Related Variation in Estimated ENI Quality

We observed that children had lower focused thresholds than adults, consistent with prior findings (DiNino et al., 2019). In the prior study, listener groups were highly controlled and included only early implanted children and adult-deafened and late-implanted adults, whereas the current study did not control the groups as tightly and still replicated the result of lower thresholds for children. Because the cochlea is adult-sized at birth and we controlled for electrode array type (proxy for electrode-neuron distance), the lower thresholds most likely reflect healthier and higher-density spiral ganglion neuron populations in the children than in the adults. Findings from multiple studies using evoked potentials have also suggested that children have greater integrity of auditory neurons than adults (e.g., Brown et al., 2010; Jahn & Arenberg, 2020a, 2020b). Furthermore, studies using CT-imaging found no between-group difference in their estimates of poorly positioned electrodes between adults and children (Noble et al., 2017; Noble et al., 2014). Human temporal bone studies show that spiral ganglion neuron counts decline with advancing age (Makary et al., 2011), which

could also contribute to the higher focused thresholds observed in adults compared to children.

Relationship Between Duration of Deafness and Estimated ENI Quality

We also observed that adults with longer durations of deafness had higher average focused thresholds, suggesting that long periods of auditory deprivation have negative consequences for the health of the auditory neurons. The negative effect of auditory deprivation on neural health has been demonstrated in human temporal bone studies (Otte et al., 1978) and in animal models (e.g., Leake & Hradek, 1988). Specifically, lower numbers of spiral ganglion neurons were found in individuals with severe hearing loss than in those with normal hearing (Otte et al., 1978), and a lack of auditory stimulation was associated with greater spiral ganglion neuron degeneration in deaf cats (e.g., Leake & Hradek, 1988). Evidence from these studies suggests that the longer the duration of deafness, the poorer the spiral ganglion survival, which could be reflected in higher auditory detection thresholds. Most adults in the current study had long periods of deafness prior to receiving their CIs, which likely negatively impacted their neural health and increased the current levels required to elicit auditory percepts with

focused stimulation. Our results also showed that average across-array focused thresholds were highly variable for both children and adults, as shown in prior studies (Bierer et al., 2015; Bierer, 2007). Considering the short period of deafness for children, this large range of variability could be associated with variation in other demographic factors such as hearing loss etiology (e.g., Jahn et al., 2020) or a combination of multiple demographic factors that is currently challenging to disentangle. Regardless, it is important to understand how children and adult CI listeners differ in their quality of ENIs and its connection to their ability to perceive speech sounds.

Relationships Between Estimated ENI Quality and Vowel Identification

We further examined the relationship between focused thresholds and vowel identification to understand whether and how estimated ENI quality may relate to vowel identification in quiet and in noise. Our results showed that children and adults who had higher across-array average focused thresholds performed more poorly on the vowel identification task. Although prior studies showed that greater across-array variation in focused threshold was associated with poorer speech recognition scores (Bierer & Faulkner, 2010; DeVries et al., 2016; Long et al., 2014; Pfungst et al., 2004), our results show that the absolute threshold level also predicts vowel identification scores. The negative relationship between focused thresholds and vowel identification suggests that spectral cues required for accurate vowel identification may have been distorted or lost due to poor interfaces between electrodes and their target neurons, as reflected by the elevated focused thresholds. Although children and adults had different focused threshold levels, this difference did not differentially impact their vowel identification. Arenberg and DeVries (2018) showed that children and adults with CIs were not different in their frequency tuning (i.e., spatial selectivity), which may explain the similar vowel identification performance. But children had lower focused thresholds than adults, suggesting a higher-quality ENI in the children. One possible explanation for similar vowel identification scores between children and adults in this study is that channel interaction is more detrimental to phoneme perception in children than it is for adults (Jahn et al., 2019), irrespective of estimated ENI quality. These results together demonstrate that focused thresholds can be used to capture a good portion of the variability in vowel identification that is most likely derived by across-listener variability in global ENI quality and transmission of frequency information through CIs.

Evidence from prior studies showed that a loss of frequency information in specific regions of the cochlea can systematically alter vowel identification (e.g., DiNino et al., 2016; Throckmorton & Collins, 2002). Our investigation of the relationship between average focused thresholds in

apical, middle, and basal regions and vowel identification showed that poorer vowel identification performance can be predicted by focused thresholds in apical, middle, and basal regions. This pattern suggests that poor ENI quality can impact frequency information relevant to vowel identification in all regions across the electrode array that is not solely limited to the frequency regions that transmit the main vowel-related acoustic cues such as first and second formant frequencies. This relationship was weaker in noise, likely because only a subset of high-performing participants was tested in noise. The observed significant relationship between focused thresholds and vowel identification in the present study underscores the potential for incorporating focused thresholds to develop more effective fitting strategies for pediatric and adult CI recipients. For instance, as most channels with high focused thresholds are expected to be located farther from the target auditory neurons (DeVries et al., 2016), an investigation of improving vowel identification using a dynamically focused electrical field for those channels is warranted (Arenberg et al., 2018). Compared to adult CI listeners, this is particularly important for children as they can likely take advantage of combining their plastic auditory neural pathways with an effective electrode configuration that could maximize the advantage of using CI in learning speech sounds.

Conclusion

In summary, the current study has provided new evidence about how focused thresholds, as an estimate of ENI quality, relate to vowel identification and how this relationship varies for adult and pediatric CI listeners. Single-channel focused thresholds were lower for children than for adults, suggesting a higher-quality interface between electrodes and the auditory neurons in children. In addition, listeners with higher across-array average focused thresholds performed more poorly on vowel identification, which suggests a relationship between poor ENI quality and resolvability of frequency information, as well as vowel identification. Future studies could explore the use of vowel identification errors and vowel confusion patterns (e.g., DiNino et al., 2016; Munson et al., 2003) to elucidate how the quality of the ENI at certain electrode sites (frequency regions) involved in transmitting certain cues, such as formant frequencies and transitions, may contribute to errors in identification of specific vowels (Munson et al., 2003; Neel, 2008; Winn et al., 2012) and relate to specific error patterns in vowel confusions (i.e., vowel advancement and vowel height; e.g., DiNino et al., 2016).

Findings from the current study suggest a relationship between focused thresholds, a proxy for the quality of ENI, and the identification of vowel sounds that is important for speech perception (e.g., Kewley-Port et al., 2007). Focused thresholds can be measured reliably and swiftly through a

fast sweep procedure (Bierer et al., 2015). Therefore, they can be potentially used for diagnostic purposes and ultimately provide information about programming decisions in clinical practice. Future studies could use average focused thresholds in apical, middle, and basal regions to identify subsets of electrodes with poor ENIs and examine if alterations of those electrodes, either channel deactivation or applying focused stimulation, will improve speech perception. Further studies are also required to fully assess the clinical significance of focused thresholds in reflecting the quality of ENI, the ability to resolve frequency information, and vowel identification in children and adult CI listeners.

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References

- Arenberg J. G., & DeVries L. A. (2018). The effects of auditory experience on psychophysical tuning curves in pediatric and adult cochlear implant listeners. *Acta Acustica United with Acustica*, *104*(5), 830–834. <https://doi.org/10.3813/AAA.919255>
- Arenberg J. G., Parkinson W. S., Litvak L., Chen C., Kreft H. A., & Oxenham A. J. (2018). A dynamically focusing cochlear implant strategy can improve vowel identification in noise. *Ear and Hearing*, *39*(6), 1136–1145. <https://doi.org/10.1097/AUD.0000000000000566>
- Arjmandi M. K., & Dilley L. & Wagner C., S. E. (2018). Investigation of acoustic dimension use in dialect production: Machine learning of sonorant sounds for modeling acoustic cues of African American dialect. 11th International Conference on Voice Physiology and Biomechanics, 12–13. East Lansing, USA.
- Arjmandi M. K., Houston D. M., & Dilley L. C. (2021). Variability in quantity and quality of early linguistic experience in children with cochlear implants : evidence from analysis of natural auditory environments. *Ear and Hearing*, *43*(2), 685–698. <https://doi.org/10.1097/AUD.0000000000001136>
- Bierer J. A. (2010). Probing the electrode-neuron interface with focused cochlear implant stimulation. *Trends in Amplification*, *14*(2), 84–95. <https://doi.org/10.1177/1084713810375249>
- Bierer J. A., Faulkner K. F., & Tremblay K. L. (2011). Identifying cochlear implant channels with poor electrode-neuron interface: Electrically-evoked auditory brainstem responses measured with the partial tripolar configuration. *Ear and Hearing*, *32*(4), 436. <https://doi.org/10.1038/jid.2014.371> <https://doi.org/10.1097/AUD.0b013e3181ff33ab>
- Bierer J. A., Bierer S. M., Kreft H. A., & Oxenham A. J. (2015). A fast method for measuring psychophysical thresholds across the cochlear implant array. *Trends in Hearing*, *19*, 1–12. <https://doi.org/10.1177/2331216515569792>
- Bierer J. A. (2007). Threshold and channel interaction in cochlear implant users: evaluation of the tripolar electrode configuration. *The Journal of the Acoustical Society of America*, *121*(3), 1642–1653. <https://doi.org/10.1121/1.2436712>
- Bierer J. A., Deeks J. M., Billig A. J., & Carlyon R. P. (2015). Comparison of signal and gap-detection thresholds for focused and broad cochlear implant electrode configurations. *JARO - Journal of the Association for Research in Otolaryngology*, *16*(2), 273–284. <https://doi.org/10.1007/s10162-015-0507-y>
- Bierer J. A., & Faulkner K. F. (2010). Identifying cochlear implant channels with poor electrode-neuron interface: partial tripolar, single-channel thresholds and psychophysical tuning curves. *Ear and Hearing*, *31*(2), 247–258. <https://doi.org/10.1097/AUD.0b013e3181c7daf4>
- Bierer J. A., & Nye A. D. (2015). Comparisons between detection threshold and loudness perception for individual cochlear implant channels. *Ear and Hearing*, *35*(6), 641–651. <https://doi.org/10.1097/AUD.0000000000000058>. Comparisons
- Brown C. J., Abbas P. J., Etlar C. P., O'Brien S., & Oleson J. J. (2010). Effects of long-term use of a cochlear implant on the electrically evoked compound action potential. *Journal of the American Academy of Audiology*, *21*(1), 5–15. <https://doi.org/10.3766/jaaa.21.1.2>
- Busby P. A., Plant K. L., & Whitford L. A. (2002). Electrode impedance in adults and children using the nucleus 24 cochlear implant system. *Cochlear Implants International*, *3*(2), 87–103. <https://doi.org/10.1179/cim.2002.3.2.87>
- DeVries L., & Arenberg J. G. (2018). Psychophysical tuning curves as a correlate of electrode position in cochlear implant listeners. *JARO - Journal of the Association for Research in Otolaryngology*, *19*(5), 571–587. <https://doi.org/10.1007/s10162-018-0678-4>
- DeVries L., Scheperle R., & Bierer J. A. (2016). Assessing the electrode-neuron interface with the electrically evoked compound action potential, electrode position, and behavioral thresholds. *JARO - Journal of the Association for Research in Otolaryngology*, *17*(3), 237–252. <https://doi.org/10.1007/s10162-016-0557-9>
- Dilley L., Lehet M., Wieland E. A., Arjmandi M. K., Kondaurova M., Wang Y., Reed J., Svirsky M., Houston D., & Bergeson T. (2020). Individual differences in mothers' spontaneous infant-directed speech predict language attainment in children with cochlear implants. *Journal of Speech, Language, and Hearing Research*, *63*(7), 2453–2467. https://doi.org/10.1044/2020_JSLHR-19-00229
- DiNino M., O'Brien G., Bierer S. M., Jahn K. N., & Arenberg J. G. (2019). The estimated electrode-neuron interface in cochlear

- implant listeners is different for early-implanted children and late-implanted adults. *Journal of the Association for Research in Otolaryngology*, 20(3), 291–303. <https://doi.org/10.1007/s10162-019-00716-4>
- DiNino M., Wright R. A., Winn M. B., & Bierer J. A. (2016). Vowel and consonant confusions from spectrally manipulated stimuli designed to simulate poor cochlear implant electrode-neuron interfaces. *The Journal of the Acoustical Society of America*, 140(6), 4404–4418. <https://doi.org/10.1121/1.4971420>
- Giezen M. R., Escudero P., & Baker A. (2010). Use of acoustic cues by children with cochlear implants. *Journal of Speech, Language, and Hearing Research*, 53(6), 1440–1457. [https://doi.org/10.1044/1092-4388\(2010/09-0252\)](https://doi.org/10.1044/1092-4388(2010/09-0252))
- Gifford R. H., Noble J. H., Camarata S. M., Sunderhaus L. W., Dwyer R. T., Dawant B. M., Dietrich M. S., & Labadie R. F. (2018). The relationship between spectral modulation detection and speech recognition: adult versus pediatric cochlear implant recipients. *Trends in Hearing*, 22, 1–14. <https://doi.org/10.1177/2331216518771176>
- Goldwyn J. H., Bierer S. M., & Bierer J. A. (2010). Modeling the electrode-neuron interface of cochlear implants: effects of neural survival, electrode placement, and the partial tripolar configuration. *Bone*, 23(1), 1–7. <https://doi.org/10.1161/CIRCULATIONAHA.110.956839>
- Holden L. K., Finley C. C., Firszt J. B., Holden T. A., Brenner C., Potts L. G., Gotter B. D., Vanderhoof S. S., Mispagel K., & Heydebrand G., Skinner M. W. (2013). Factors affecting open-set word recognition in adults with cochlear implants. *Ear and Hearing*, 34(3), 342–360. <https://doi.org/10.1097/AUD.0b013e3182741aa7>
- Horn D. L., Dudley D. J., Dedhia K., Nie K., Drennan W. R., Won J. H., Rubinstein J. T., & Werner L. A. (2017). Effects of age and hearing mechanism on spectral resolution in normal hearing and cochlear-implanted listeners. *The Journal of the Acoustical Society of America*, 141(1), 613–623. <https://doi.org/10.1121/1.4974203>
- Jahn K. N., Bergan M. D., & Arenberg J. G. (2020). Auditory detection thresholds and cochlear resistivity differ between pediatric cochlear implant listeners with enlarged vestibular aqueduct and those with connexin-26 mutations. *American Journal of Audiology*, 29(March), 1–42. <https://doi.org/10.1680/jdare.20.00019>
- Jahn K. N., & Arenberg J. G. (2019). Evaluating psychophysical polarity sensitivity as an indirect estimate of neural status in cochlear implant listeners. *Journal of the Association for Research in Otolaryngology*, 20(4), 415–430. <https://doi.org/10.1007/s10162-019-00718-2>
- Jahn K. N., & Arenberg J. G. (2020a). Electrophysiological estimates of the electrode-neuron interface differ between younger and older listeners with cochlear implants. *Ear and Hearing*, 41(4), 948–960. <https://doi.org/10.1097/AUD.0000000000000827>
- Jahn K. N., & Arenberg J. G. (2020b). Identifying cochlear implant channels with relatively poor electrode-neuron interfaces using the electrically evoked compound action potential. *Ear and Hearing*, 41(4), 961–973. <https://doi.org/10.1097/AUD.0000000000000844>
- Jahn K. N., DiNino M., & Arenberg J. G. (2019). Reducing simulated channel interaction reveals differences in phoneme identification between children and adults with normal hearing. *Ear and Hearing*, 40(2), 295–311. <https://doi.org/10.1097/AUD.0000000000000615>
- Jahn K. N., DiNino M., Winn M., Hulswit J., & Arenberg J. G. (2018). Vowel confusion patterns in children and adults with cochlear implants. *The Journal of the Acoustical Society of America*, 144(3), 1794–1794. <https://doi.org/10.1121/1.5067915>
- Johnson E. K., & Jusczyk P. W. (2001). Word segmentation by 8-month-olds: when speech cues count more than statistics. *Journal of Memory and Language*, 44(4), 548–567. <https://doi.org/10.1006/jmla.2000.2755>
- Jusczyk P. W., Houston D. M., & Newsome M. (1999). The beginnings of word segmentation in English-learning infants. *Cognitive Psychology*, 39(3–4), 159–207. <https://doi.org/10.1006/cogp.1999.0716>
- Kasturi K., Loizou P. C., Dorman M., & Spahr T. (2002). The intelligibility of speech with “holes” in the spectrum.” *The Journal of the Acoustical Society of America*, 112(3), 1102–1111. <https://doi.org/10.1121/1.1498855>
- Kewley-Port D., Burkle T. Z., & Lee J. H. (2007). Contribution of consonant versus vowel information to sentence intelligibility for young normal-hearing and elderly hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 122(4), 2365–2375. <https://doi.org/10.1121/1.2773986>
- Landsberger D. M., Padilla M., Martinez A. S., & Eisenberg L. S. (2018). Spectral-Temporal modulated ripple discrimination by children with cochlear implants. *Ear and Hearing*, 39(1), 60–68. <https://doi.org/10.1097/AUD.0000000000000463>
- Lane H., Matthies M., Vick J. P. J., & Zandipour M. (2001). The effects of changes in hearing status in cochlear implant users on the acoustic vowel space and CV coarticulation. *Journal of Speech, Language, and Hearing Research*, 44(3), 552–563. [https://doi.org/10.1044/1092-4388\(2001/043\)](https://doi.org/10.1044/1092-4388(2001/043))
- Leake P. A., & Hradek G. T. (1988). Cochlear pathology of long term neomycin induced deafness in cats. *Hearing Research*, 33(1), 11–33. [https://doi.org/10.1016/0378-5955\(88\)90018-4](https://doi.org/10.1016/0378-5955(88)90018-4)
- Long C. J., Holden T. A., McClelland G. H., Parkinson W. S., Shelton C., Kelsall D. C., & Smith Z. M. (2014). Examining the electro-neural interface of cochlear implant users using psychophysics, CT scans, and speech understanding. *JARO - Journal of the Association for Research in Otolaryngology*, 15(2), 293–304. <https://doi.org/10.1007/s10162-013-0437-5>
- Makary C. A., Shin J., Kujawa S. G., Liberman M. C., & Merchant S. N. (2011). Age-related primary cochlear neuronal degeneration in human temporal bones. *JARO - Journal of the Association for Research in Otolaryngology*, 12(6), 711–717. <https://doi.org/10.1007/s10162-011-0283-2>
- Molisz A., Zarowski A., Vermeiren A., Theunen T., De Coninck L., Siebert J., & Offeciers E. F. (2015). Postimplantation changes of electrophysiological parameters in patients with cochlear implants. *Audiology and Neurotology*, 20(4), 222–228. <https://doi.org/10.1159/000377615>
- Munson B., Donaldson G. S., Allen S. L., Collison E. A., & Nelson D. A. (2003). Patterns of phoneme perception errors by listeners with cochlear implants as a function of overall speech perception ability. *The Journal of the Acoustical Society of America*, 113(2), 925–935. <https://doi.org/10.1121/1.1536630>
- Neel A. T. (2008). Vowel space characteristics and vowel identification accuracy. *Journal of Speech, Language, and Hearing Research*, 51(3), 574–585. [https://doi.org/10.1044/1092-4388\(2008/041\)](https://doi.org/10.1044/1092-4388(2008/041))
- Niparko J. K., Tobey E. A., Thal D. J., Eisenberg L. S., Wang N.-Y., Quittner A. L., & Fink N. E. (2010). Spoken language

- development in children following cochlear implantation. *Jama*, 303(15), 1498–1506. <https://doi.org/10.1001/jama.2010.451>
- Noble J. H., Hedley-Williams A. J., Sunderhaus L., Dawant B. M., Labadie R. F., Camarata S. M., & Gifford R. H. (2017). Initial results with image-guided cochlear implant programming in children. *Physiology & Behavior*, 176(1), 139–148. <https://doi.org/10.1097/MAO.0000000000000909>.Initial
- Noble J. H., Gifford R. H., Hedley-Williams A. J., Dawant B. M., & Labadie R. F. (2014). Clinical evaluation of an image-guided cochlear implant programming strategy. *Audiology and Neurotology*, 19(6), 400–411. <https://doi.org/10.1159/000365273>
- Otte J., Schuknecht H. F., & Kerr A. G. (1978). Ganglion cell populations in normal and pathological human, implications for cochlear implantation. *The Laryngoscope*, 88(8), 1231–1246. <https://doi.org/10.1288/00005537-197808000-00002>
- Oxenham A. J., Boucher J. E., & Kreft H. A. (2017). Speech intelligibility is best predicted by intensity, not cochlea-scaled entropy. *The Journal of the Acoustical Society of America*, 142(3), EL264–EL269. <https://doi.org/10.1121/1.5002149>
- Pfingst B. E., Xu L., & Thompson C. S. (2004). Across-site threshold variation in cochlear implants: relation to speech recognition. *Audiology and Neuro-Otology*, 9(6), 341–352. <https://doi.org/10.1159/000081283>
- Sek A., Alcántara J., Moore B. C. J., Kluk K., & Wicher A. (2005). Development of a fast method for determining psychophysical tuning curves. *International Journal of Audiology*, 44(7), 408–420. <https://doi.org/10.1080/14992020500060800>
- Sek A., Wicher A., & Drgas S. (2007). A fast method for the determination of psychophysical tuning curves: further refining. *Archives of Acoustics*, 32(3), 707–728.
- Shannon R. V., Galvin J. J., & Baskent D. (2002). Holes in hearing. *JARO - Journal of the Association for Research in Otolaryngology*, 3(2), 185–199. <https://doi.org/10.1007/s101620020021>
- Shepherd R. K., & Javel E. (1997). Electrical stimulation of the auditory nerve. I. Correlation of physiological responses with cochlear status. *Hearing Research*, 108(1–2), 112–144. [https://doi.org/10.1016/S0378-5955\(97\)00046-4](https://doi.org/10.1016/S0378-5955(97)00046-4)
- Stilp C. & Kluender E., K. R. (2010). Cochlea-scaled entropy, not consonants, vowels, or time, best predicts speech intelligibility. *Proceedings of the National Academy of Sciences of the United States of America*, 107(27), 12387–12392. <https://doi.org/10.1073/pnas.0913625107>
- Studebaker G. A. (1985). A “rationalized” arcsine transform. *Journal of Speech and Hearing Research*, 28(3), 455–462. <https://doi.org/10.1044/jshr.2803.455>
- ter Keurs M., Festen J. M., & Plomp R. (1994). Effect of spectral envelope smearing on speech reception. I. *Journal of the Acoustical Society of America*, 95(2), 1053–1064. <https://doi.org/10.1121/1.408467>
- Throckmorton C. S., & Collins L. M. (2002). The effect of channel interactions on speech recognition in cochlear implant subjects: predictions from an acoustic model. *The Journal of the Acoustical Society of America*, 112(1), 285–296. <https://doi.org/10.1121/1.1482073>
- Winn M. B., Chatterjee M., & Idsardi W. J. (2012). The use of acoustic cues for phonetic identification: effects of spectral degradation and electric hearing. *The Journal of the Acoustical Society of America*, 131(2), 1465–1479. <https://doi.org/10.1121/1.3672705>