

Polarity Sensitivity in Pediatric and Adult Cochlear Implant Listeners

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Abstract

Modeling data suggest that sensitivity to the polarity of an electrical stimulus may reflect the integrity of the peripheral processes of the spiral ganglion neurons. Specifically, better sensitivity to anodic (positive) current than to cathodic (negative) current could indicate peripheral process degeneration or demyelination. The goal of this study was to characterize polarity sensitivity in pediatric and adult cochlear implant listeners (41 ears). Relationships between polarity sensitivity at threshold and (a) polarity sensitivity at suprathreshold levels, (b) age-group, (c) preimplantation duration of deafness, and (d) phoneme perception were determined. Polarity sensitivity at threshold was defined as the difference in single-channel behavioral thresholds measured in response to each of two triphasic pulses, where the central high-amplitude phase was either cathodic or anodic. Lower thresholds in response to anodic than to cathodic pulses may suggest peripheral process degeneration. On the majority of electrodes tested, threshold and suprathreshold sensitivity was lower for anodic than for cathodic stimulation; however, dynamic range was often larger for cathodic than for anodic stimulation. Polarity sensitivity did not differ between child- and adult-implanted listeners. Adults with long preimplantation durations of deafness tended to have better sensitivity to anodic pulses on channels that were estimated to interface poorly with the auditory nerve; this was not observed in the child-implanted group. Across subjects, duration of deafness predicted phoneme perception performance. The results of this study suggest that subject- and electrode-dependent differences in polarity sensitivity may assist in developing customized cochlear implant programming interventions for child- and adult-implanted listeners.

Keywords

spiral ganglion, cochlear nerve, auditory threshold, speech perception, pediatric

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Introduction

Physiological and psychophysical responses vary considerably across stimulation sites within individual cochlear implant (CI) listeners (e.g., DeVries & Arenberg, 2018b; DeVries, Schepelerle, & Bierer, 2016; Pfungst & Xu, 2004; Zhu, Tang, Zeng, Guan, & Ye, 2012). Some of this variability may, in part, result from within- and across-subject variation in spiral ganglion neuron (SGN) integrity. Human postmortem temporal bone studies demonstrate that SGN density varies widely across individuals and across the length of the cochlea within an individual ear (Hinojosa & Marion, 1983; Makary, Shin, Kujawa, Liberman, & Merchant, 2011; Nadol, 1997; Nadol, Young, & Glynn, 1989; Otte, Schuknecht, & Kerr, 1978). In those temporal bone analyses, variability in SGN counts is partially explained by demographic variables such as chronological age, duration of deafness, and hearing loss etiology. Animal studies also

indicate that long-term auditory deprivation is associated with reduced SGN survival relative to normal (e.g., Hall, 1990; Heffer et al., 2010; Ramekers et al., 2014; Shepherd & Javel, 1997).

Despite the observed relationships between SGN loss and multiple demographic characteristics, the functional consequences of reduced SGN density remain ambiguous. Signal detection theory analysis suggests that a dramatic loss of SGNs (~75%) may be required to detect

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measurable, albeit small, deficits in psychoacoustic perception (Oxenham, 2016). Similarly, empirical data in humans do not demonstrate consistent relationships between postmortem SGN density and speech perception scores obtained during an individual's lifetime (Fayad & Linthicum, 2006; Khan et al., 2005; Nadol et al., 2001; Otte et al., 1978).

In vivo estimates of neural status may improve our ability to study how the integrity of the SGNs relates to auditory perception with a CI during life. Over the years, several proposed estimates of SGN density have been evaluated in animals and in humans. In animal models, evoked potential responses vary systematically as a function of SGN density; for instance, electrodes near cochlear regions with relatively few surviving SGNs tend to have relatively small evoked potential amplitudes, high evoked potential thresholds, and shallow evoked potential amplitude growth functions (AGFs; Hall, 1990; Pfungst et al., 2015; Ramekers et al., 2014; Shepherd & Javel, 1997). Moreover, psychophysical temporal integration abilities may depend, in part, on local SGN density (Pfungst et al., 2011; Zhou, Kraft, Colesa, & Pfungst, 2015).

In human CI listeners, evoked potential and temporal integration responses vary widely across electrode sites (e.g., Bierer, Faulkner, & Tremblay, 2011; Brown, Abbas, & Gantz, 1990; Cafarelli Dees et al., 2005; DeVries et al., 2016; Eisen & Franck, 2004; Schwartz-Leyzac & Pfungst, 2016; Zhou & Pfungst, 2014). Some evidence suggests that younger participants have larger electrically evoked compound action potential (ECAP) amplitudes and steeper ECAP AGF slopes than older participants (Brown, Abbas, Etlar, O'Brien, & Oleson, 2010; Cafarelli Dees et al., 2005). Relatively shallow ECAP AGF slopes are also associated with relatively long durations of hearing loss (Schwartz-Leyzac & Pfungst, 2016) and poor speech perception scores (Brown et al., 1990; Kim et al., 2010). In bilateral CI listeners, between-ear differences in phoneme perception are partially explained by between-ear differences in ECAP responses (Schwartz-Leyzac & Pfungst, 2018) and temporal integration abilities (Zhou & Pfungst, 2014). Moreover, deactivating CI channels with poor temporal integration performance leads to improved speech perception scores for some adult listeners (Zhou, 2017).

Although indirect estimates of SGN density have been studied extensively in humans, the number of remaining SGNs constitutes only one aspect of neural health. Conceivably, the integrity of the peripheral processes could also influence the fidelity of electrical stimulation by a CI. Recent computational modeling evidence suggests that sensitivity to the polarity of an electrical stimulus may reflect local peripheral process integrity (Joshi, Dau, & Epp, 2017; Rattay, Leao, & Felix, 2001; Rattay, Lutter, & Felix, 2001; Resnick, O'Brien, & Rubinstein, 2018).

Polarity sensitivity refers to the difference in psychophysical or physiological responses to positive (anodic) and negative (cathodic) electrical current. Modeling data suggest that better sensitivity to the anodic polarity than to the cathodic polarity may indicate peripheral process degeneration or demyelination (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018). Differential sensitivity to each polarity is thought to reflect differences in the site of spike initiation in response to anodic and cathodic pulse shapes. Specifically, injecting cathodic current into the extracellular space depolarizes nearby neural membrane while hyperpolarizing distant neural membrane (Rubinstein, 1991). Conversely, anodic current depolarizes distant neural membrane and hyperpolarizes nearby neural membrane (Rubinstein, 1991). When the peripheral processes have degenerated and the electrode is located distal to the soma, higher current levels for cathodic relative to anodic polarities are required in order for cathodic stimuli to overcome the unmyelinated cell body and generate an action potential near the central axon (Joshi et al., 2017; Macherey, Carlyon, Chatron, & Roman, 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018).

Electrophysiological and psychophysical evidence in adult CI listeners suggests that polarity sensitivity has the potential to provide insight into the status of the electrode–neuron interface (Carlyon, Cosentino, Deeks, Parkinson, & Arenberg, 2018; Hughes, Choi, & Glickman, 2018; Hughes, Goehring, & Baudhuin, 2017; Jahn & Arenberg, 2019; Macherey et al., 2017; Macherey, Carlyon, van Wieringen, Deeks, & Wouters, 2008; Macherey, van Wieringen, Carlyon, Deeks, & Wouters, 2006; Spitzer & Hughes, 2017; Undurraga, Carlyon, Wouters, & van Wieringen, 2013; Undurraga, van Wieringen, Carlyon, Macherey, & Wouters, 2010; van Wieringen, Macherey, Carlyon, Deeks, & Wouters, 2008). At suprathreshold stimulation levels, evoked potential amplitudes are generally larger (Bahmer & Baumann, 2013; Hughes et al., 2017, 2018; Macherey et al., 2008; Undurraga et al., 2010), and most comfortable listening levels (MCLs) are generally lower (Macherey et al., 2017), for anodic compared with cathodic stimulation. These findings using suprathreshold stimulation levels suggest that anodic stimulation may be more effective, in general, than cathodic stimulation in adult CI listeners.

On the other hand, recent evidence using low-level stimulation shows that polarity sensitivity at threshold is subject- and electrode-dependent in postlingually deafened adults (Carlyon et al., 2018; Jahn & Arenberg, 2019; Macherey et al., 2017). Moreover, Jahn and Arenberg (2019) demonstrated that the psychophysical polarity effect at threshold varies independently of electrode position relative to the modiolus and intracochlear

resistance. Taken together, these studies provide increasing evidence that polarity sensitivity may reflect neural integrity in CI listeners, and that the measure is relatively independent of non-neural factors that influence the quality of the electrode–neuron interface in humans.

To comprehensively characterize polarity sensitivity in CI listeners and to determine its utility in clinical interventions, it is important to evaluate polarity sensitivity in individuals with diverse hearing histories and to determine whether it relates to CI outcomes. To date, polarity sensitivity has been studied in small samples of largely postlingually deafened adults. Children and adults with CIs typically present with different demographic characteristics that may influence SGN integrity. For instance, adult CI recipients are generally implanted at a more advanced age and experience longer durations of preimplantation auditory deprivation than children. Children and adults with CIs also tend to have different hearing loss etiologies. Human histological studies demonstrate that chronological age, duration of deafness, and hearing loss etiology are each predictive of SGN density (Makary et al., 2011; Nadol, 1997; Nadol et al., 1989; Otte et al., 1978). The primary goal of this study was to expand upon previous literature by characterizing polarity sensitivity and speech perception performance in a relatively large and diverse sample of CI listeners. Two groups of participants with divergent hearing histories were recruited: (a) adolescents who were deafened and implanted during childhood and (b) older adult-implanted listeners.

The primary outcome measure in this study was the polarity effect at threshold, defined as the difference in the magnitude of single-channel behavioral thresholds measured in response to anodic and cathodic polarities (cathodic threshold minus anodic threshold; Carlyon et al., 2018; Jahn & Arenberg, 2019). The polarity effect at threshold was chosen as the primary outcome measure because it has been shown to vary independently of electrode position and tissue impedances in CI listeners (Jahn & Arenberg, 2019). In this study, we also assessed the polarity effect at suprathreshold levels by estimating individuals' MCLs for each pulse shape and calculating the polarity effect at MCL and for dynamic range (DR). Note that spike timing differs between peripheral and central processes; however, the psychophysical measures used in this study and in others are likely not sensitive to those latency differences.

Consistent with prior investigations, we predicted that the polarity effect at threshold would be subject- and electrode-dependent, but that anodic stimulation would generally result in lower MCLs than cathodic stimulation (Carlyon et al., 2018; Jahn & Arenberg, 2019; Macherey et al., 2017). We expected variability in polarity sensitivity to persist across the diverse sample of pediatric and adult CI listeners included in this dataset.

Furthermore, we predicted that (a) long periods of preimplantation auditory deprivation would be associated with lower (i.e., better) threshold sensitivity to anodic stimulation than to cathodic stimulation (i.e., more peripheral degeneration), (b) adult-implanted listeners would have larger polarity effects at threshold (i.e., more peripheral degeneration) than child-implanted listeners, and (c) relatively poor speech perception scores would be associated with relatively large polarity effects at threshold (i.e., more peripheral degeneration). The results of this investigation will provide insight into the characteristics of polarity sensitivity in child- and adult-implanted listeners and may assist in developing hypothesis-driven recommendations for the application of polarity sensitivity to CI programming interventions.

Methods

Subjects

Demographic information for all subjects and ears tested in this study is presented in Table 1. Data were obtained from a total of 41 ears (27 individual subjects, 13 males) implanted with Advanced Bionics HiRes 90K devices. Twenty ears (11 individual subjects) were deafened and implanted during childhood (prior to age 18 years). At the time of testing, subjects in the child-implanted group ranged in age from 13 to 18 years ($M = 15.2$ years, standard deviation [SD] = 1.4 years). Nine of the 11 child-implanted subjects were bilaterally implanted, and data were collected from each ear. Subjects P11 and P12 are fraternal twins. No other subjects are related to one another. Hereafter, this group of subjects will be referred to as the “child-implanted group”, to signify that they were deafened and implanted as children and tested during adolescence. In all figures, data from the child-implanted group are denoted by green symbols.

Twenty-one ears (16 individual subjects) were implanted during adulthood (age 18 or older). Four of the adult-implanted subjects (S40, S49, S53, and S60) were diagnosed with severe-to-profound sensorineural hearing loss as children, and the remaining subjects became deaf as adults. At the time of testing, adult-implanted participants ranged in age from 22 to 87 years ($M = 59.9$ years, $SD = 18.8$ years). Seven of the 16 adult-implanted participants presented with bilateral implants; however, due to time constraints, only five of the bilaterally implanted adults were tested in both ears. Hereafter, this group of subjects will be referred to as the “adult-implanted group”, to signify that they were implanted and tested as adults. In all figures, data from the adult-implanted group are denoted by blue symbols.

All subjects primarily used spoken language to communicate, and all but one subject were native American English speakers. Subject S54 learned English as

Table 1. Demographic Information.

ID	Etiology	Age (years)	First-implanted ear			Second-implanted ear		
			Age implanted (years)	Duration of deafness (years)	Electrode array	Age implanted (years)	Duration of deafness (years)	Electrode array
Child-implanted Listeners								
P02	EVA	13.9	1.1	1.1	HFIJ	3.1	3.1	HFIJ
P03	Unknown	14.7	1.4	1.4	HFIJ	5.6	5.6	HFIJ
P04	Unknown	15.2	1.7	1.7	HFIJ	4.7	4.7	HFIJ
P06	Unknown	18.8	4.3	1.8	HFIJ	10.9	8.5	HFIJ
P07	Unknown	15.4	1.9	1.9	HFIJ	4.9	4.9	HFIJ
P09	Unknown	14.9	2.6	1.3	HFIJ	3.9	2.7	HFIJ
P11	DFNBI	15.3	1.4	1.2	HFIJ	10.2	10.0	HFIJ
P12	DFNBI	15.3	1.7	1.4	HFIJ	10.2	10.0	HFIJ
P13	EVA	13.4	9.2	6.4	HFIJ	—	—	—
P16	DFNBI	14.6	1.0	1.0	HFIJ	4.5	4.5	HFIJ
P17	Unknown	15.5	1.3	1.3	HFIJ	—	—	—
	Mean (SD)	15.2 (1.4)	2.5 (2.4)	1.9 (1.5)		6.5 (3.1)	6.0 (2.8)	
Adult-implanted Listeners								
S22	Unknown	78.2	66.7	11.8	IJ Helix	—	—	—
S23	Unknown	73.4	62.0	3.9	IJ Helix	64.6	6.5	HFIJ
S29	Noise exposure	87.8	76.8	30.3	HFIJ	85.7	39.2	MS
S39	Genetic	54.4	30.1	8.0	HFIJ	40.1	18.0	HFIJ
S40	EVA	56.2	50.4	46.4	HFIJ	—	—	—
S43	Noise exposure	72.5	67.9	18.7	MS	—	—	—
S45	Genetic	65.4	54.0	11.0	HFIJ	61.0	18.0	MS
S46	Unknown	69.4	64.2	25.1	HFIJ	—	—	—
S47	Unknown	40.4	36.4	10.3	MS	—	—	—
S49	Unknown	45.8	43.5	42.1	MS	44.2	42.8	MS
S50	Unknown	76.5	71.0	53.0	HFIJ	—	—	—
S52	Unknown	71.2	66.0	6.1	HFIJ	—	—	—
S53	Meningitis	56.0	44.1	42.9	IJ Helix	—	—	—
S54	EVA	27.8	23.7	16.7	MS	—	—	—
S59	Ototoxicity	32.1	30.9	18.9	MS	—	—	—
S60	Meningitis	22.5	19.2	19.1	MS	—	—	—
	Mean (SD)	59.9 (18.8)	50.4 (18.3)	22.8 (15.6)		59.1 (18.2)	24.9 (15.5)	

Note. Demographic information for all participants, including: hearing loss etiology (if known), chronological age at time of testing (in years), age of implantation for implanted each ear (in years), duration of deafness for each implanted ear (in years), and electrode array for each implanted ear. Duration of deafness is defined as the time between diagnosis of severe-to-profound sensorineural hearing loss and cochlear implant activation. Note that subjects S47 and S59 are bilaterally implanted, but their second-implanted ears were not tested as part of this study. EVA = enlarged vestibular aqueduct; DFNBI = genetic nonsyndromic hearing loss. HFIJ = HiFocus IJ electrode array; MS = mid-scala electrode array; SD = standard deviation.

a second language during early childhood. Each child provided written informed assent, and his or her parents or legal guardians provided written informed consent. Each adult provided written informed consent. All procedures were approved by the University of Washington Human Subjects Division.

Electrical Stimuli

Electrical stimuli were controlled by the Bionic Ear Data Collection System version 1.18.315 (Advanced Bionics,

Valencia, CA) and custom MATLAB scripts (MathWorks, Inc., Natick, MA). Stimuli were presented directly to the internal device. Prior to testing, electrical stimuli were verified using a reference implant and a digital storage oscilloscope.

Channel Selection for Polarity Testing

Advanced Bionics devices have 16 electrode contacts. Due to time and attention constraints, it was not feasible to measure the polarity effect on every electrode in each

ear. Instead, four channels per ear were selected for polarity effect testing. Within a subject, the four channels were selected based on the relative magnitude of single-channel behavioral thresholds measured in response to a spatially focused electrode configuration. Focused behavioral thresholds are believed to reflect the overall quality of the electrode–neuron interface; within a subject, higher threshold channels are thought to interface poorly with the auditory nerve relative to lower threshold channels (for review, see Bierer, 2010). For instance, channels with relatively high focused thresholds are often located farther from the target neurons (DeVries & Arenberg, 2018b; DeVries et al., 2016; Jahn & Arenberg, 2019; Long et al., 2014) and have smaller evoked potential amplitudes (DeVries et al., 2016) than lower threshold channels.

In this study, the two lowest threshold channels and the two highest threshold channels were selected for polarity effect assessment. None of the four channels were directly adjacent to one another. Theoretically, selecting low- and high-threshold channels within a subject allows for assessment of a subset of electrodes that vary in the quality with which they interface with the auditory nerve; low- and high-threshold channels represent “good” and “poor” electrode–neuron interfaces, respectively.

Single-channel-focused behavioral thresholds were assessed using a modified Békésy-style sweep procedure that is 4 times faster than traditional adaptive forced-choice methods (Bierer, Bierer, Kreft, & Oxenham, 2015; Sek, Alcántara, Moore, Kluk, & Wicher, 2005). Using current steering, stimuli were swept across the electrode array by dividing the electrical current between two adjacent intracochlear electrodes and varying the proportion of current directed to each electrode.

Stimuli were biphasic, cathodic-leading pulse trains (102 μ s/phase, 0- μ s interphase gap, 200.4 ms duration, 997.9 pulse per second) presented in a steered quadrupolar (sQP) stimulation mode. A channel was comprised of four adjacent intracochlear electrodes. The two middle electrodes served as active electrodes, and the two outermost electrodes served as return electrodes. The current focusing coefficient (σ) was set to 0.9, indicating that 90% of the return current was delivered through the intracochlear return electrodes (45% to each electrode) and the remaining 10% was delivered through an extracochlear ground. Current focusing coefficients can range from 0 to 1, with 1 representing the highest possible degree of current focusing and, consequently, resulting in the most spatially restrictive electrical field. The higher the current focusing coefficient, the greater the observed channel-to-channel variability in focused thresholds (Bierer & Faulkner, 2010). A highly focused coefficient of 0.9 was selected to capture as much within-subject variability in focused thresholds as possible while

remaining below the voltage compliance limits of the device.

The modified sweep procedure has been described in detail in many other studies from our laboratory (e.g., Bierer et al., 2015; DeVries & Arenberg, 2018b; DeVries et al., 2016; Jahn & Arenberg, 2019). A brief review of the sweep procedure is provided here. To sweep stimuli across the electrode array, current was steered between the two active electrodes by varying the steering coefficient, alpha (α). When $\alpha=0$, all current is delivered through the more apical of the active electrode pair. Conversely, when $\alpha=1$, all current is delivered through the more basal active electrode. Because sQP stimulation requires four adjacent intracochlear electrodes, focused thresholds can only be obtained for Electrodes 2 to 15. Per convention, on Channels 3–15, integer channel numbers refer to the number of the basal active electrode when $\alpha=1$; for Channel 2, an α value of 0 is used to center the current on Electrode 2.

The upper limit of stimulation on each electrode was set to each listener’s electrode-specific MCL, which corresponded to a loudness rating of “6,” or *most comfortable*, on the Advanced Bionics Clinical Loudness Scale (Advanced Bionics, Valencia, CA). Pulse trains were presented starting at a level 6 dB below each listener’s MCL and swept across the electrode array by increasing alpha from 0 to 1 in step sizes of 0.1. The listener was instructed to continuously depress the spacebar on a standard computer keyboard when he or she could hear the stimulus and to release the spacebar when he or she could not hear the stimulus. When the spacebar was depressed, the presentation level of the stimulus decreased. Conversely, the presentation level increased when the spacebar was released. The participants completed one forward sweep that progressed basally (Channels 2–15) and one reverse sweep that progressed apically (Channels 15–2). Final single-channel focused threshold estimates were calculated as the weighted average of consecutive current levels at integer channel numbers along the forward and reverse sweeps (as in Bierer et al., 2015).

Following the threshold measurement, the channels with the two lowest focused thresholds and those with the two highest focused thresholds were identified for each ear. If any of those channels were adjacent to one another, the channel with the next-lowest or next-highest nonadjacent threshold was identified. These four nonadjacent channels (two low-threshold and two high-threshold channels) were used for subsequent polarity effect testing.

Polarity Effect Measurement

Polarity sensitivity was assessed on four nonadjacent channels within each ear: the two channels with the lowest focused thresholds and the two channels with

the highest focused thresholds. Stimuli were 99 pulse per second trains presented in a monopolar stimulation mode (43 μ s/phase, 0- μ s interphase gap, 400 ms duration). A triphasic pulse shape was used, where the central high-amplitude phase was twice the amplitude of the first and third phases. The polarity of the central high-amplitude phase was either anodic (CAC) or cathodic (ACA), depending on the experimental condition. Triphasic pulses concentrate the charge of the polarity of interest into a brief time window while maintaining the requisite charge balance for use in humans. The stimuli were identical to those used in recent investigations of psychophysical polarity sensitivity (Carlyon et al., 2018; Jahn & Arenberg, 2019).

On the four selected channels, behavioral thresholds were measured in response to each of the two triphasic pulses. The polarity effect (in dB) was defined as the ACA threshold minus the CAC threshold (ACA – CAC). A positive polarity effect value indicated that CAC thresholds were lower (i.e., better) than ACA thresholds. Based on modeling data, lower anodic than cathodic thresholds may indicate some degree of peripheral process degeneration (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018). Conversely, a negative polarity effect value indicated lower (i.e., better) ACA thresholds compared with CAC thresholds and may reflect healthy peripheral processes (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018).

To obtain suprathreshold polarity data and to set the upper limit of stimulation for polarity assessment, MCLs were obtained on each of the four channels in response to each polarity. To measure MCL, the current level was gradually increased from a subthreshold level of 50 μ A up until the subject reported a loudness rating of “6,” or *most comfortable* on the Advanced Bionics Clinical Loudness Scale (Advanced Bionics, Valencia, CA). For each channel and polarity, the corresponding MCL was set as the upper limit of stimulation for the threshold measurement procedure.

For 27 of the 328 (8%) total channel/polarity combinations tested, MCL could not be reached at stimulation levels below the voltage compliance limits of the device. This tended to occur for certain subjects and was not related to CI channel or polarity, as follows: P12 (both implanted ears, all electrode/polarity combinations), P13 (first/only-implanted ear, both polarities on Channel 15), P17 (first/only-implanted ear, all electrode/polarity combinations except for the anodic polarity on Channel 2), and S29 (second-implanted ear, cathodic polarity on Channels 8 and 13). In those cases, the upper limit of stimulation was set to the highest current level that could be achieved without exceeding voltage compliance limits. In each case, the upper stimulation level was equivalent to a subjective listening level of

either 4 (*medium soft*) or 5 (*medium*), which was sufficiently high for the subject to accurately perform the threshold measurements. However, those 27 measurements were excluded from any subsequent MCL and DR analyses.

An adaptive one-up/one-down staircase tracking procedure was used to measure single-channel behavioral thresholds for each polarity on each of the four channels. For each adaptive track, the initial presentation level was set to 90% of the MCL; for channel/polarity combinations where MCL could not be reached, the initial presentation level was set to 98% of the upper stimulation level. For subsequent tracks, the initial presentation level was set anywhere from 50 to 98% of the upper stimulation level. A lower starting level was used on electrodes with large DRs to reduce the amount of time necessary to estimate threshold. Higher starting levels were maintained for electrodes with small DRs to ensure that the subject could comfortably hear the stimulus before the first reversal.

The subject was instructed to press the spacebar on the computer keyboard one time whenever he or she heard a sound. The presentation level decreased if the subject responded within 3 s after stimulus presentation and increased if the subject did not respond within 3 s. The initial step size was 0.5 dB. After the first reversal, the step size was reduced to 0.2 dB. Random delays of 0.1 to 0.6 s were incorporated prior to each stimulus presentation. After eight reversals, the adaptive procedure terminated. Threshold was estimated as the average of the final six reversals.

The order of channels and polarities tested was randomized for each subject. Two adaptive threshold tracks were completed for each polarity on each channel. The two threshold estimates were averaged together to calculate a final threshold value. A third and fourth run were completed if the thresholds estimated on the first two runs differed by 1 dB or more. In those cases, threshold estimates from each of the four runs were averaged together.

Speech Perception

Speech perception was assessed using medial vowel and consonant recognition tasks. Phonemes were chosen as the speech perception tasks because they are particularly sensitive to spectral and temporal distortions resulting from CI processing and poor electrode–neuron interfaces (DiNino, Wright, Winn, & Bierer, 2016; Nie, Barco, & Zeng, 2006; Shannon, Fu, & Galvin Iii, 2004; Xu, Thompson, & Pfingst, 2005). Vowel stimuli were a closed set of 10 recorded vowels in /hVd/ context (/i/, “heed”; /I/, “hid”; /eI/, “hayed”; /ε/, “head”; /æ/, “had”; /a/, “hod”; /u/, “who’d”; /ʊ/, “hood”; /oʊ/, “hoed”; and /ʌ/, “hud”) that were spoken by one

female talker native to the Pacific Northwest region of the United States. Consonant stimuli were a closed set of 16 recorded consonants presented in /aCa/ context (/p/, “aPa”; /t/, “aTa”; /k/, “aKa”; /b/, “aBa”; /d/, “aDa”; /g/, “aGa”; /f/, “aFa”; /θ/, “aTHa”; /s/, “aSa”; /ʃ/, “aSHa”; /v/, “aVa”; /z/, “aZa”; /dʒ/, “aJa”; /m/, “aMa”; /n/, “aNa”; and /l/, “aLa”) and spoken by one male talker (stimuli were the same as those used by Shannon, Jansvold, Padilla, Robert, & Wang, 1999). Testing was performed in a double-walled sound-treated booth (IAC RE-243). Stimuli were presented through an external A/D device (SIIF USB SoundWave 7.1) and a Crown D75 amplifier at a calibrated level of 60 dB-A through a Bose 161 speaker placed at 0° azimuth and 1 m from the participant’s head. Custom software (ListPlayer2 version 2.2.11.52, Advanced Bionics, Valencia, CA) was used to present the stimuli and to record responses.

Participants were tested with one ear at a time using their everyday listening programs. Unilateral CI users wore an earplug in the nonimplanted ear during speech perception testing. After each speech token was presented, a graphical user interface with the possible phoneme choices was displayed on a computer screen. The participant selected his or her response using a computer mouse. Participants completed one practice run consisting of three repetitions of each speech token prior to beginning the experiment. Performance feedback was provided during the practice run. During the experiment, two runs consisting of three repetitions of each speech token were conducted, resulting in a total of six presentations of each speech token. Feedback was not provided during the experiment. Stimuli were pseudorandomly interleaved within each run. If scores on the two runs differed by more than 10%, a third run consisting of three additional repetitions was presented. Scores from each run were averaged together to achieve a final percentage correct.

Statistical Analyses

Data were analyzed using R Version 3.3.1 (R Core Team, 2016). Linear mixed-effects models were employed for all analyses to account for clustering of electrode-specific data within ears and for clustering of two ears within the same listener. “Subject” and “ear” were included as random effects in the models, where appropriate. Models were fit using restricted maximum likelihood parameter estimates to minimize small sample estimation bias (McNeish, 2017). An unstructured covariance matrix was specified for each model. An Akaike information criterion with a bias correction for small samples (AICc) was used for model selection (Hurvich & Tsai, 1989).

Note that traditional R^2 values are invalid for multi-level models. Instead, two pseudo- R^2 values, described

by Nakagawa and Schielzeth (2013), are presented where applicable: (a) marginal R^2 (R^2_{marginal}), representing the proportion of the total variance explained by the fixed effects, and (b) conditional R^2 ($R^2_{\text{conditional}}$), representing the proportion of the variance explained by both the fixed and random effects. The difference between the R^2_{marginal} and $R^2_{\text{conditional}}$ reflects the variability in the random effects; here, this would represent across-subject variability. The lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017), MuMIn (Bartón, 2018), and Lattice (Sarkar, 2008) R packages were used to perform statistical analyses and to assess the validity of model assumptions. Bonferroni corrections for multiple comparisons were applied and are noted where appropriate.

Results

Electrode Array Considerations

Subjects presented with a variety of electrode array types (HiFocus 1J, 1J Helix, and Mid-Scala; Table 1). Different electrode arrays are designed to achieve different positions in the cochlea relative to the modiolus (Dhanasingh & Jolly, 2018) and can influence absolute threshold measurements (DeVries & Arenberg, 2018b; DeVries et al., 2016; Jahn & Arenberg, 2019; Long et al., 2014). However, recent evidence suggests that the psychophysical polarity effect varies independently of electrode position relative to the inner wall of the cochlea in CI listeners (Jahn & Arenberg, 2019). This is likely because the polarity effect is a difference score, rather than an absolute threshold measurement. The same stimuli and analysis methods used in Jahn and Arenberg (2019) were used in this study. Prior to data analysis, we confirmed that the polarity effect was not influenced by electrode array type, $F(2, 36.31) = 0.63$, $p = .63$, or electrode cochlear location, $F(1, 129.83) = 0.03$, $p = .86$, in this sample of subjects. Electrode cochlear location was defined as apical (Electrodes 2–8) or basal (Electrodes 9–15). Electrode position is not considered further.

Characterization of the Polarity Effect at Threshold and at Suprathreshold Levels

The first analysis served to characterize the polarity effect at threshold and at suprathreshold levels. Figure 1(a) to (d) shows single-channel thresholds and MCLs measured in response to the ACA and CAC pulses for two child-implanted participants (a and b) and two adult-implanted participants (c and d). Black squares represent responses to the ACA pulse, and red circles represent responses to the CAC pulse. Solid lines connect the threshold responses, and dashed lines connect the MCLs. Based on modeling data, lower thresholds or

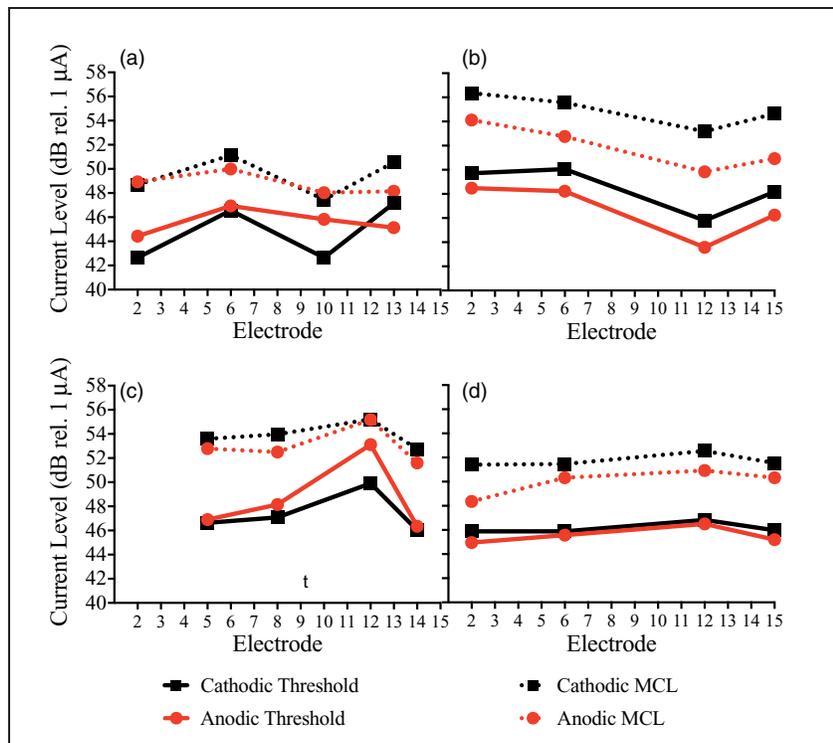


Figure 1. Single-channel auditory detection thresholds and MCLs measured in response to the cathodic (ACA) and anodic (CAC) pulse shapes for two child-implanted ears (a and b) and two adult-implanted ears (c and d). Black squares represent responses to the ACA pulse shape, and red circles represent responses to the CAC pulse shape. Solid lines connect threshold measurements, and dotted lines connect MCL measurements. MCL = most comfortable listening level.

MCLs in response to anodic than to cathodic pulses may reflect peripheral process degeneration (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018).

Positive polarity effect values indicate lower thresholds or MCLs in response to anodic than to cathodic pulses; negative polarity effect values indicate the inverse. The magnitude of the polarity effect at threshold and at MCL varied across- and within-subjects. Across electrodes, the polarity effect at threshold ranged from -4.82 dB to 3.54 dB ($M = 0.25$ dB, $SD = 1.52$ dB), and 102 of the 164 electrodes (62.20%) had lower thresholds for anodic than for cathodic pulses. The polarity effect at MCL was calculated on 149 of the 164 electrodes tested. At MCL, the polarity effect ranged from -2.13 dB to 4.83 dB ($M = 1.12$ dB, $SD = 1.24$ dB) and 133 of the 149 electrodes (89.26%) had lower MCLs for anodic than for cathodic pulses. An electrode with lower threshold sensitivity to anodic stimulation did not necessarily have lower suprathreshold sensitivity to anodic stimulation, and vice versa.

Assessing the polarity effect at threshold and at MCL allowed us to calculate the difference in DR between the two polarities (i.e., DR polarity effect). DR was calculated as the difference between MCL and threshold for

each polarity on each tested electrode. Like threshold and MCL, the DR polarity effect was calculated as the difference in DR for the cathodic (ACA) pulse versus the anodic (CAC) pulse ($ACA - CAC$). Therefore, a positive DR polarity effect value indicates that the DR for the cathodic pulse is larger than the DR for the anodic pulse. A negative DR polarity effect value indicates a larger DR for the anodic than for the cathodic pulse.

The DR polarity effect was assessed on 149 electrodes. The DR polarity effect varied from -2.05 dB to 5.31 dB ($M = 0.87$ dB, $SD = 1.25$ dB), and 115 of the 149 electrodes (77.18%) demonstrated larger DRs for cathodic pulses than for anodic pulses. Like threshold and MCL, the magnitude of the DR polarity effect was subject- and electrode-dependent. Despite the finding that most electrodes had better sensitivity to the anodic polarity at threshold and at MCL, the majority of electrodes exhibited larger DRs for the cathodic polarity than for the anodic polarity.

Relationships between polarity sensitivity at threshold and at suprathreshold levels were evaluated to determine whether polarity effects at low current levels are predictive of those at higher current levels. Initially, “age-group” was included in the models as an independent variable to account for potential differences between

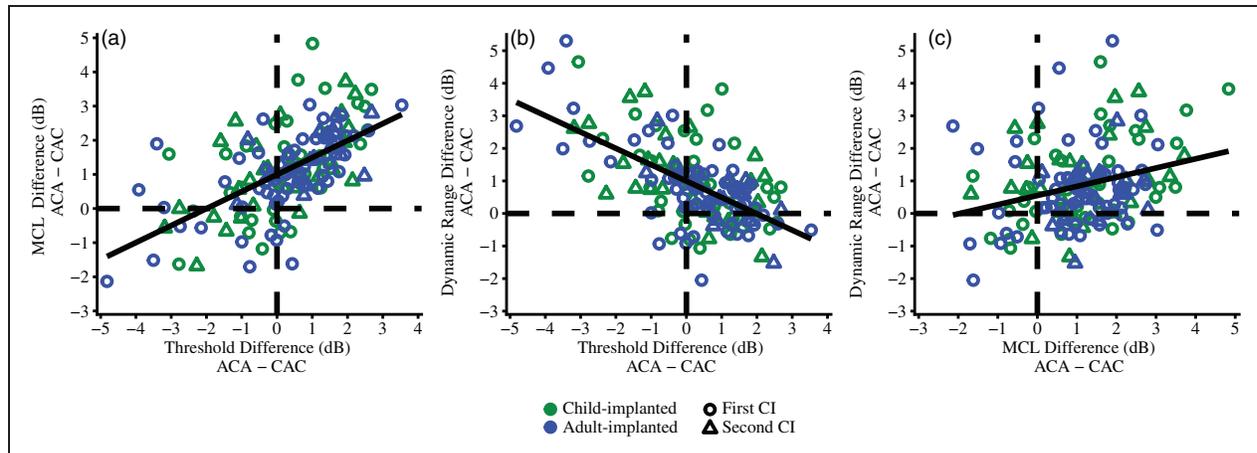


Figure 2. Single-channel data for the relationships between (a) polarity effect at threshold and at MCL, (b) polarity effect at threshold and for dynamic range (DR), and (c) polarity effect at MCL and for DR. Dashed lines split each panel into four quadrants at $y=0$ and $x=0$. Data points that fall in the upper right-hand quadrants and in the lower left-hand quadrants have the same sign (positive or negative, respectively) for both of the measures represented in the figure. Circles indicate data from first-implanted ears, and triangles represent data from second-implanted ears. Green symbols indicate data from child-implanted ears, and blue symbols indicate data from adult-implanted ears. CI = cochlear implant; MCL = most comfortable listening level; ACA = cathodic; CAC = anodic.

child- and adult-implanted ears; however, in each case, more parsimonious model fits (i.e., lower AICc values) were obtained when age-group (i.e., lower AICc values) were obtained when age-group was excluded. Thus, the relationships between polarity sensitivity at threshold and at suprathreshold levels did not differ between child- and adult-implanted listeners, and “age-group” was not included in the final models. To elucidate this finding, data from child- and adult-implanted ears are denoted by separate colors in each figure (green and blue symbols, respectively).

Figure 2(a) to (c) shows single-channel data for the relationships between (a) polarity effect at threshold and at MCL, (b) polarity effect at threshold and for DR, and (c) polarity effect at MCL and for DR. Dashed lines split each panel into four quadrants at $y=0$ and $x=0$. Data points that fall in the upper right-hand quadrants and in the lower left-hand quadrants have the same sign (positive or negative, respectively) for both of the measures represented in the figure.

Polarity effects at threshold, MCL and DR were highly correlated. Therefore, to statistically analyze the relationships between each measure, it was necessary to specify separate mixed-effects models. A Bonferroni adjustment for multiple comparisons was applied (adjusted $\alpha = .017$). The polarity effect at threshold was positively correlated with the polarity effect at MCL, $R^2_{\text{marginal}} = .42$, $R^2_{\text{conditional}} = .67$, $F(1, 139.27) = 132.78$, $p < .001$, wherein positive polarity effect values at threshold were associated with positive polarity effect values at MCL. This suggests that, in general, electrodes that had lower threshold sensitivity to the anodic polarity than to the cathodic polarity also had lower

suprathreshold sensitivity to the anodic polarity than to the cathodic polarity.

Furthermore, the polarity effect at threshold was negatively correlated with the DR polarity effect, $R^2_{\text{marginal}} = .27$, $R^2_{\text{conditional}} = .60$, $F(1, 139.27) = 74.22$, $p < .001$. Specifically, better threshold sensitivity to one polarity was associated with larger DRs for that polarity. However, oftentimes (on 42.28% of electrodes), DR was larger for the cathodic polarity irrespective of polarity sensitivity at threshold. This can be seen in the upper right-hand quadrant of Figure 2(b); many electrodes have larger DRs for the cathodic polarity despite having lower threshold sensitivity to the anodic polarity.

Finally, the polarity effect at MCL was positively correlated with the DR polarity effect, $R^2_{\text{marginal}} = .06$, $R^2_{\text{conditional}} = .23$, $F(1, 119.02) = 8.33$, $p = .005$, indicating that lower suprathreshold sensitivity to anodic stimulation was generally associated with smaller DRs for the anodic than for the cathodic polarity. Overall, the DR in response to each polarity was influenced by both the threshold and the MCL. However, better sensitivity at threshold or at MCL for a particular polarity did not necessarily mean that the DR was larger in response to that polarity. On some electrodes, low-amplitude anodic pulses at MCL may restrict the anodic DR relative to the cathodic DR.

Polarity Sensitivity as a Function of Channel Classification

Recall that channels were selected for polarity testing based on the relative within-subject magnitude of

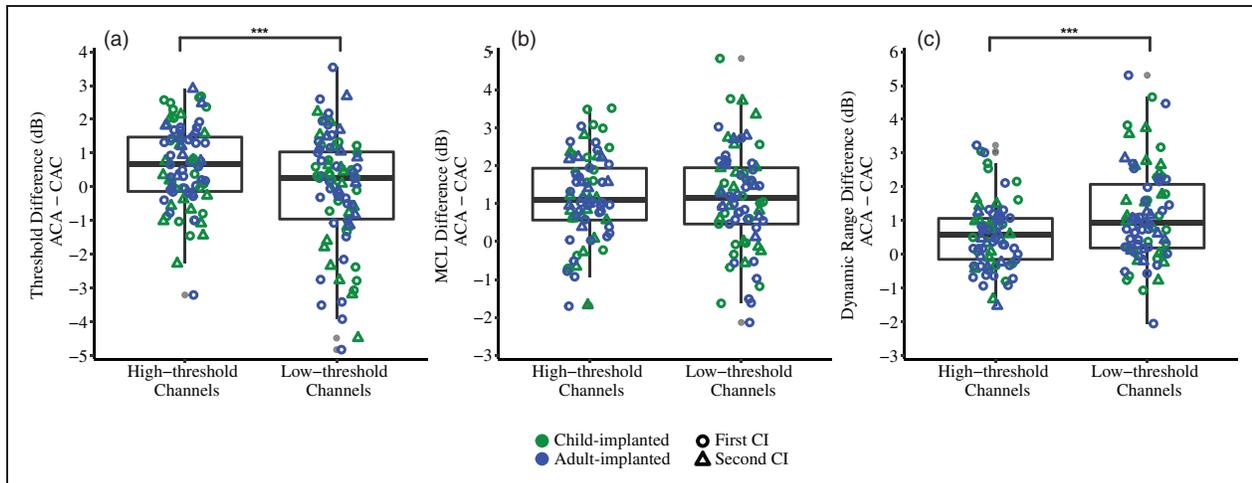


Figure 3. Single-channel polarity effects as a function of channel classification (high-focused-threshold vs. low-focused-threshold channels) for (a) the polarity effect at threshold, (b) the polarity effect at MCL, and (c) the polarity effect for dynamic range. Circles indicate data from first-implanted ears, and triangles represent data from second-implanted ears. Green symbols indicate data from child-implanted ears, and blue symbols indicate data from adult-implanted ears. CI = cochlear implant. *** denotes a statistically significant difference in polarity effect between high- and low-threshold channels at the $p < .001$ level. ACA = cathodic; CAC = anodic; MCL = most comfortable listening level.

single-channel focused behavioral thresholds. The second analysis evaluated differences in polarity sensitivity on low-focused-threshold channels compared with high-focused-threshold channels. Once again, during the model selection procedure, it was determined that polarity sensitivity as a function of channel classification did not differ between child-implanted and adult-implanted listeners, and that including “age-group” in the models resulted in poorer fits (i.e., higher AICc values). Thus, the final models for this analysis did not include “age-group” as an independent variable.

Figure 3 shows single-channel polarity effect as a function of channel classification (low-focused-threshold vs. high-focused-threshold channels) for (a) the polarity effect at threshold, (b) the polarity effect at MCL, and (c) the DR polarity effect. As the polarity effects at threshold, MCL and DR are highly correlated, separate mixed-effects models were specified to assess differences in each measure as a function of channel classification. A Bonferroni adjustment for multiple comparisons was applied (adjusted $\alpha = .017$). On high-focused-threshold channels, the polarity effect at threshold ranged from -3.20 dB to 2.90 dB ($M = 0.61$ dB, $SD = 1.21$ dB). On low-focused-threshold channels, the polarity effect at threshold ranged from -4.82 dB to 3.54 dB ($M = -0.11$ dB, $SD = 1.71$ dB). High-focused-threshold channels had significantly larger polarity effects, on average, than low-focused-threshold channels (Figure 3(a)), $R^2_{\text{marginal}} = .07$, $R^2_{\text{conditional}} = .29$, $F(1, 122) = 12.97$, $p < .001$. This suggests that better threshold sensitivity to anodic stimulation than to cathodic stimulation was more common on the high-focused-threshold channels than on the low-focused-threshold channels.

However, the polarity effect at MCL did not differ between high- and low-focused-threshold channels (Figure 3(b)), $R^2_{\text{marginal}} < .01$, $R^2_{\text{conditional}} = .44$, $F(1, 110.71) = 0.05$, $p = .83$. On high-focused-threshold channels, the polarity effect at MCL ranged from -1.70 dB to 3.52 dB ($M = 1.14$ dB, $SD = 1.16$ dB). On low-focused-threshold channels, the polarity effect at MCL ranged from -2.13 dB to 4.83 dB ($M = 1.11$ dB, $SD = 1.33$ dB). This suggests that suprathreshold polarity sensitivity did not differ as a function of channel classification.

Finally, the DR polarity effect was larger for low-focused-threshold channels than for high-focused-threshold channels (Figure 3(c)), $R^2_{\text{marginal}} = .05$, $R^2_{\text{conditional}} = .30$, $F(1, 110.4) = 11.11$, $p = .001$. In other words, low-focused-threshold channels tended to have larger DRs for the cathodic polarity than for the anodic polarity. On high-focused-threshold channels, the DR polarity effect ranged from -1.52 dB to 3.23 dB ($M = 0.58$ dB, $SD = 1.00$ dB). On low-focused-threshold channels, the DR polarity effect ranged from -2.04 dB to 5.30 dB ($M = 1.15$ dB, $SD = 1.40$ dB). Although the polarity effects at threshold and DR differed significantly between high- and low-focused-threshold channels, note that there is substantial variability in both outcome measures, irrespective of channel classification.

Across-Site Average Polarity Effect, Demographics, and Speech Perception

The final analyses assessed the relationships between the across-site average polarity effect at threshold, demographic characteristics (age and duration of deafness), and speech perception. Table 2 shows the across-site

average polarity effects at threshold for each ear tested. The across-site average polarity effect was calculated by averaging the polarity effects at threshold across the four tested electrodes within each ear. This across-site averaging method has been used in several studies to quantify and relate electrode-specific measures to demographic characteristics (e.g., DeVries et al., 2016; Jahn & Arenberg, 2019; Scheperle, 2017; Schwartz-Leyzac & Pfungst, 2016, 2018). During the model selection procedure, it was determined that more parsimonious model fits (i.e., lower AICc values) were obtained when “age-group” (child-implanted vs. adult-implanted) was included in the model instead of “chronological age.” This is likely because chronological age was bimodally distributed in this sample.

Figure 4 shows the across-site average polarity effects at threshold for the child-implanted and adult-implanted listeners. A mixed-model analysis ($R^2_{\text{marginal}} = .04$, $R^2_{\text{conditional}} = .24$) revealed that the polarity effect at threshold did not vary systematically as a function of age-group, $F(1, 27.00) = 0.03$, $p > .05$, or duration of deafness, $F(1, 32.14) = 0.99$, $p > .05$. There was substantial variability in the across-site average polarity effect for both groups of subjects. For the child-implanted group, the polarity effect at threshold ranged from -4.48 dB to 2.68 dB ($M = 0.13$ dB, $SD = 1.51$ dB). For the adult-implanted group, the polarity effect at threshold ranged from -4.82 dB to 3.54 dB ($M = 0.36$ dB, $SD = 1.53$ dB).

Notably, duration of deafness varied widely for the adult-implanted listeners (range = 3.9–53.0 years) and less so for the child-implanted listeners (range = 1.0–10.1 years). We also previously showed that the polarity effect at threshold differs between low- and high-focused-threshold channels. So, we subsequently evaluated the relationship between duration of deafness and the across-site average polarity effect separately for each age-group and for each channel classification.

Figure 5(a) and (b) shows the relationship between duration of deafness and the across-site average polarity effect on high-focused-threshold channels for (a) the child-implanted group and (b) the adult-implanted group. On high-focused-threshold channels, the average polarity effect increased with increasing durations of deafness for the adult-implanted listeners, $R^2_{\text{marginal}} = .28$, $R^2_{\text{conditional}} = .46$; $F(1, 15.53) = 7.31$, $p = .016$; Bonferroni-adjusted $\alpha = .025$, but not for the child-implanted listeners, $R^2_{\text{marginal}} = .02$, $R^2_{\text{conditional}} = .15$; $F(1, 13.43) = 0.50$, $p = .49$. On low-focused-threshold channels, the polarity effect did not vary as a function of duration of deafness for either group ($ps > .05$).

As many participants were bilaterally implanted, we performed a supplementary demographic analysis to determine whether polarity sensitivity differed between the first- and second-implanted ears. There was no

between-ear difference in the polarity effects for threshold, $F(1, 161.24) < 0.01$, $p = .96$, MCL, $F(1, 136.83) = 0.46$, $p = .50$, or DR, $F(1, 145.27) = 0.06$, $p = .81$.

Finally, relationships between phoneme perception, the across-site average polarity effect at threshold, and demographic variables were evaluated. Table 3 shows phoneme perception scores in percentage correct for each ear tested. Percentage correct scores were converted to rationalized arcsine units prior to statistical analysis to normalize error variance (Studebaker, 1985). The mixed-effects models predicting phoneme perception included fixed effects for across-site average polarity effect, age-group, and duration of deafness (vowels: $R^2_{\text{marginal}} = .23$, $R^2_{\text{conditional}} = .74$; consonants: $R^2_{\text{marginal}} = .22$, $R^2_{\text{conditional}} = .71$). Neither vowel nor consonant perception were predicted by the across-site average polarity effect, $ps > .05$; vowels: $F(1, 26.96) = 2.22$; consonants: $F(1, 26.24) = 1.29$, or age-group, $ps > .05$; vowels: $F(1, 27.21) = 1.83$; consonants: $F(1, 24.52) = 2.12$. However, duration of deafness was inversely related to vowel, $F(1, 33.82) = 9.93$, $p = .003$, and consonant, $F(1, 30.74) = 9.36$, $p = .005$, perception (Figure 6). Specifically, phoneme perception decreased with increasing duration of preimplantation auditory deprivation.

As before, relationships between speech perception and the across-site average polarity effect were also assessed separately for high- and low-focused-threshold channels; however, the relationship between speech perception and polarity sensitivity did not differ as a function of channel classification ($ps > .05$).

Discussion

Modeling evidence suggests that sensitivity to electrical stimulus polarity may reflect the health of the SGN peripheral processes in CI listeners (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018). Specifically, better sensitivity to anodic (positive) current than to cathodic (negative) current may indicate some degree of peripheral process degeneration. The primary aim of this study was to characterize polarity sensitivity in child- and adult-implanted listeners and to determine the relationship between polarity sensitivity and traditional CI outcome measures. Results indicated that polarity sensitivity varied widely within- and across-ears and did not differ between child-implanted and adult-implanted participants. Interestingly, although most electrodes showed better threshold and suprathreshold sensitivity to the anodic polarity than to the cathodic polarity, the psychophysical DR of the cathodic polarity was often larger than that of the anodic polarity. Across subjects, phoneme perception performance was predicted by duration of deafness but not by polarity sensitivity. Moreover, polarity sensitivity at threshold was related to duration of deafness in the

Table 2. Across-Site Average Polarity Effects for Individual Participants.

ID	First CI			Second CI		
	Low-threshold channels M (SD)	High-threshold channels M (SD)	All channels M (SD)	Low-threshold channels M (SD)	High-threshold channels M (SD)	All channels M (SD)
Child-implanted Listeners						
P02	0.80 (0.29)	1.93 (0.80)	1.36 (0.81)	2.08 (0.19)	1.53 (0.42)	1.81 (0.42)
P03	0.56 (0.93)	2.47 (0.15)	1.51 (1.23)	1.36 (0.25)	0.45 (1.59)	0.91 (1.07)
P04	0.86 (0.67)	-0.21 (0.83)	0.32 (0.87)	-0.06 (0.99)	-1.86 (0.59)	-0.96 (1.23)
P06	1.02 (0.32)	-1.01 (0.02)	0.00 (1.19)	-2.49 (0.99)	0.83 (1.70)	-0.82 (2.22)
P07	-2.05 (1.03)	1.05 (0.53)	-0.50 (1.91)	-2.18 (0.82)	-0.04 (0.32)	-1.11 (1.34)
P09	-0.57 (0.21)	0.03 (0.09)	-0.27 (0.37)	1.01 (1.29)	-1.05 (0.05)	-0.02 (1.40)
P11	-2.72 (0.49)	-0.46 (0.57)	-1.59 (1.37)	-0.30 (1.23)	1.47 (0.95)	0.58 (1.36)
P12	0.43 (0.11)	2.34 (0.43)	1.38 (1.13)	-3.41 (1.51)	0.07 (0.90)	-1.67 (2.25)
P13	0.23 (0.04)	-0.66 (1.11)	-0.21 (0.83)	—	—	—
P16	0.15 (0.18)	2.49 (0.27)	1.32 (1.36)	-0.07 (0.74)	0.55 (0.29)	0.24 (0.58)
P17	0.36 (0.05)	0.41 (0.61)	0.38 (0.35)	—	—	—
Mean (SD)	-0.08 (1.22)	0.76 (1.35)	0.34 (0.99)	-0.45 (1.87)	0.21 (1.11)	-0.12 (1.12)
Adult-implanted Listeners						
S22	-2.70 (1.73)	0.97 (0.66)	-0.87 (2.37)	—	—	—
S23	-0.69 (0.54)	-1.74 (2.07)	-1.22 (1.37)	-0.98 (0.22)	0.05 (0.37)	-0.47 (0.64)
S29	0.41 (1.06)	0.95 (0.50)	0.68 (0.74)	-0.03 (0.20)	2.69 (0.30)	1.33 (1.58)
S39	0.55 (0.32)	0.62 (0.44)	0.59 (0.31)	1.27 (0.32)	1.41 (0.30)	1.34 (0.27)
S40	2.86 (0.96)	1.58 (0.13)	2.22 (0.93)	—	—	—
S43	-0.03 (0.66)	-0.39 (0.54)	-0.21 (0.53)	—	—	—
S45	0.21 (0.06)	1.36 (0.06)	0.78 (0.67)	2.19 (0.71)	0.85 (0.13)	1.52 (0.87)
S46	0.28 (0.47)	0.12 (0.23)	0.20 (0.32)	—	—	—
S47	2.22 (0.54)	0.17 (0.79)	1.19 (1.31)	—	—	—
S49	-2.45 (0.42)	1.03 (0.38)	-0.71 (2.03)	0.37 (0.71)	1.63 (0.26)	1.00 (0.85)
S50	-1.97 (2.04)	0.98 (1.10)	-0.49 (2.16)	—	—	—
S52	-0.64 (0.51)	-0.06 (0.14)	-0.35 (0.45)	—	—	—
S53	1.26 (0.99)	0.93 (1.06)	1.09 (0.86)	—	—	—
S54	-1.91 (4.12)	0.29 (0.53)	-0.81 (2.71)	—	—	—
S59	-0.98 (3.56)	1.84 (0.11)	0.43 (2.62)	—	—	—
S60	1.22 (0.16)	-0.57 (0.59)	0.33 (1.09)	—	—	—
Mean (SD)	-0.15 (1.61)	0.50 (0.91)	0.17 (0.92)	0.56 (1.21)	1.33 (0.98)	0.94 (0.81)

Note. Across-site average polarity effects at threshold (in dB) for all ears tested. Average polarity effects are shown for the two low-threshold channels, the two high-threshold channels, and all four channels combined. Low-threshold channels refer to the two nonadjacent channels with the lowest focused behavioral thresholds within an individual ear. High-threshold channels refer to the two nonadjacent channels with the highest focused behavioral thresholds within an individual ear. Focused thresholds were measured with a steered quadrupolar electrode configuration (focusing coefficient = 0.9). CI = cochlear implant; SD = standard deviation.

adult-implanted ears but not in the child-implanted ears. Subject- and electrode-dependent differences in polarity sensitivity may be useful in customizing programming interventions for CI listeners with a variety of hearing histories.

Polarity Sensitivity at Threshold and at Suprathreshold Levels

The primary outcome measure in this study was the psychophysical polarity effect at threshold, which has been

hypothesized to reflect local peripheral process integrity (Carlyon et al., 2018; Jahn & Arenberg, 2019; Macherey et al., 2017) and varies independently of electrode position and intracochlear resistance in CI listeners (Jahn & Arenberg, 2019). The polarity effect was defined as the difference in single-channel behavioral thresholds measured in response to cathodic (ACA) and anodic (CAC) pulse shapes (ACA - CAC). Our data suggest that the polarity effect at threshold is subject- and electrode-dependent in a relatively large sample of child-implanted and adult-implanted listeners ($n = 41$ ears).

These findings are consistent with previous studies in postlingually deafened adults with CIs (Carlyon et al., 2018; Jahn & Arenberg, 2019; Macherey et al., 2017).

In the present sample, the majority of electrodes (62.20%) showed lower threshold sensitivity to the anodic polarity than to the cathodic polarity. Based on modeling data, the proportion of electrodes with lower threshold sensitivity to anodic than to cathodic stimulation reflects the proportion of fibers with some degree of peripheral process degeneration or demyelination

(Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018). This theory assumes that the site of spike initiation differs for anodic and cathodic current. At low current levels, maximum depolarization occurs near the periphery in response to cathodic stimulation, leading to relative hyperpolarization in more central regions of the neuron. The inverse occurs for anodic stimulation, wherein maximal depolarization occurs closer to the central axon.

Thus, in a peripherally degenerated neuron, relatively high current levels are required for cathodic stimulation to overcome the unmyelinated cell body and a region of central hyperpolarization in order to generate an action potential. Theoretically, lower thresholds are expected for anodic stimulation because the action potential would not need to overcome the unmyelinated cell body or a region of strong hyperpolarization to excite the central axon (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018). If polarity sensitivity does reflect peripheral process integrity in humans, then our data indicate that some degree of peripheral degeneration is likely to occur near most electrode sites in child-implemented and adult-implemented listeners.

Our results also indicated that channels with relatively high focused behavioral thresholds are more likely to have lower threshold sensitivity to anodic stimulation than to cathodic stimulation compared with channels with lower focused thresholds. Focused thresholds are believed to reflect the overall quality of the electrode-neuron interface, which is influenced by electrode position (DeVries & Arenberg, 2018b; DeVries et al., 2016; Long et al., 2014), intracochlear bone and tissue growth (Spelman, Clopton, & Pfungst, 1982), and the integrity of

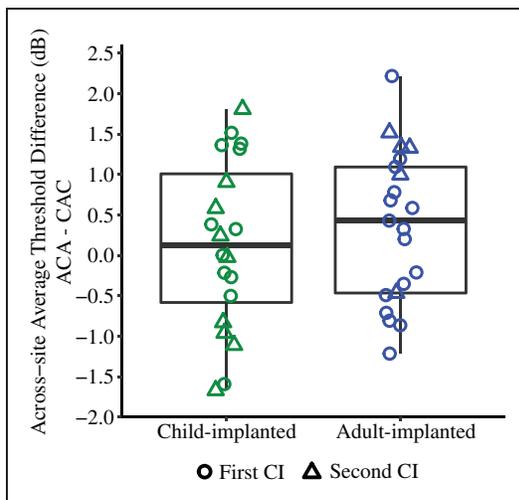


Figure 4. Across-site average polarity effects at threshold (in dB) for the child-implemented ears and the adult-implemented ears. Circles indicate data from first-implemented ears, and triangles represent data from second-implemented ears. CI = cochlear implant; ACA = cathodic; CAC = anodic.

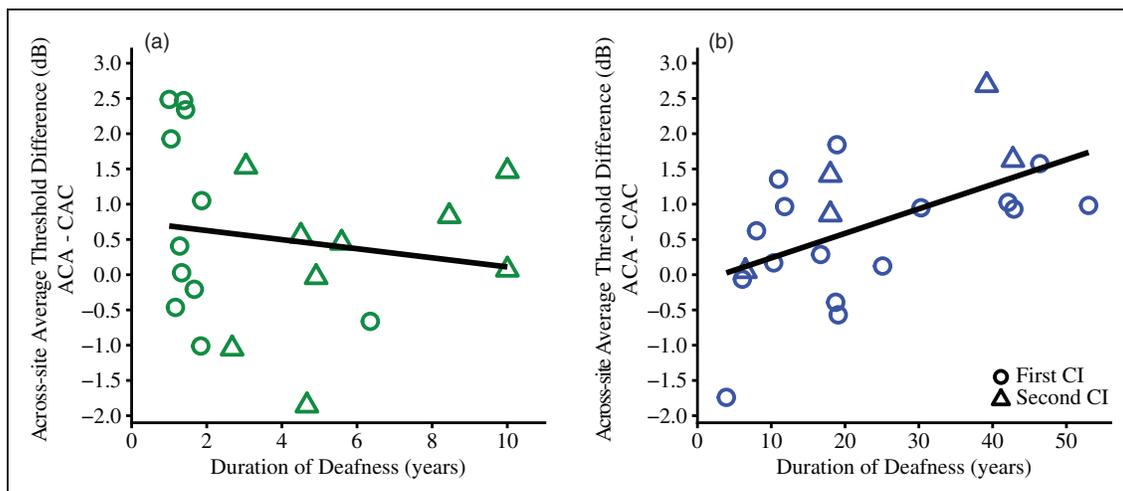


Figure 5. Across-site average polarity effect at threshold (in dB) as a function of duration of deafness (in years) on high-focused-threshold channels for (a) the child-implemented ears and (b) the adult-implemented ears. Circles indicate data from first-implemented ears, and triangles represent data from second-implemented ears. CI = cochlear implant; ACA = cathodic; CAC = anodic.

Table 3. Speech Perception Scores.

ID	Vowel scores (percentage correct)		Consonant scores (percentage correct)	
	First CI	Second CI	First CI	Second CI
Child-implanted Listeners				
P02	97	100	79	84.5
P03	93.5	100	82	82
P04	96.5	97	77	86.5
P06	100	93	—	—
P07	98.5	96	95	72
P09	83	91.5	83	80
P11	63.5	22	60.5	17
P12	53.5	21.5	52	21.7
P13	98.5	—	77	—
P16	90	95	95	75
P17	93.5	—	63.3	—
Mean (SD)	88.0 (15.5)	79.4 (32.8)	76.5 (14.3)	64.9 (28.4)
Adult-implanted Listeners				
S22	96.5	—	80	—
S23	95	87.7	74	75
S29	92	92.3	79	74
S39	100	95	92	91
S40	48	—	35	—
S43	67.7	—	80	—
S45	100	100	80	80
S46	55	—	31	—
S47	100	—	90	—
S49	41	88	41	44
S50	53.3	—	51	—
S52	82	—	55	—
S53	90	—	81	—
S54	98.5	—	85.5	—
S59	90	—	77	—
S60	45	—	41	—
Mean (SD)	78.4 (22.5)	92.6 (5.1)	67.0 (20.9)	72.8 (17.5)

Note. Vowel and consonant perception scores (in percentage correct) for all ears tested. Stimuli were presented in quiet at a level of 60 dB-A. CI = cochlear implant; SD = standard deviation.

the auditory neurons (Goldwyn, Bierer, & Bierer, 2010). Channels with high focused thresholds are believed to interface relatively poorly with the auditory nerve, as they are often located far from the modiolus (DeVries & Arenberg, 2018b; DeVries et al., 2016; Jahn & Arenberg, 2019; Long et al., 2014) and have small evoked potential amplitudes and steep evoked potential growth functions (Bierer et al., 2011; DeVries et al., 2016).

It is unlikely that the polarity effect at threshold was significantly influenced by electrode position relative to the modiolus or intracochlear resistance in this study. In a sample of 11 adult CI listeners, Jahn and Arenberg (2019) demonstrated that the polarity effect at threshold

varies independently of electrode position relative to the modiolus and intracochlear resistance. They also showed that, across listeners, the polarity effect at threshold predicted focused behavioral thresholds (sQP; focusing coefficient = 0.9); specifically, channels with relatively high focused thresholds were more likely to have better sensitivity to anodic than to cathodic stimulation than channels with lower focused thresholds.

The present results agree with those of Jahn and Arenberg (2019), demonstrating that channels with high focused thresholds, on average, had better sensitivity to anodic stimulation relative to cathodic stimulation than low-focused-threshold channels. We also show that this finding is consistent across child-implanted and

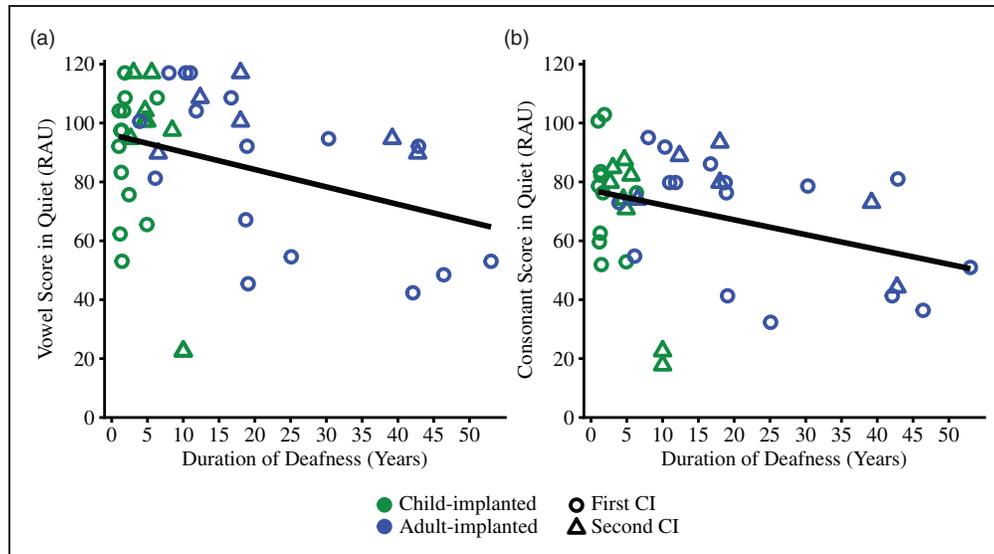


Figure 6. (a) Vowel perception (RAUs) and (b) consonant perception (RAUs) as a function of duration of deafness (in years). Circles indicate data from first-implanted ears, and triangles represent data from second-implanted ears. Green symbols indicate data from child-implanted ears, and blue symbols indicate data from adult-implanted ears. CI = cochlear implant; RAU = rationalized arcsine unit.

adult-implanted listeners. However, it should be noted that although the polarity effect at threshold differed significantly between high- and low-focused-threshold channels, there was substantial variability in the magnitude of the polarity effect, irrespective of channel classification.

Some of the observed variability in polarity sensitivity likely results from the channel selection procedure. Channels were selected based on the relative magnitude of within-subject focused thresholds. It is likely that focused thresholds on many of the selected electrodes were low or high as a result of electrode position and intracochlear bone and tissue growth and not necessarily because of the local status of the auditory nerve (Bierer et al., 2015; DeVries & Arenberg, 2018b; DeVries et al., 2016; Jahn & Arenberg, 2019; Long et al., 2014). Regardless, the present results suggest that channels that are estimated to interface poorly with the auditory nerve are more likely to have lower threshold sensitivity to anodic than to cathodic stimulation than channels with better interfaces. This provides additional evidence that polarity sensitivity reflects an underlying characteristic of the electrode–neuron interface that may be related to SGN integrity in child- and adult-implanted listeners.

If polarity sensitivity reflects peripheral process degeneration, it may have utility in customizing CI programming parameters. Taken together, the results from this study and from Jahn and Arenberg (2019) imply that a comprehensive approach that considers electrode position and polarity sensitivity may help in selecting channels for deactivation or current focusing. DeVries and Arenberg (2018a) demonstrated that some listeners receive speech perception benefit when a subset of

electrodes that are located far from the modiolus are stimulated using a spatially focused electrode configuration; however, some listeners did not benefit, or performed worse, with that type of listening strategy. Others have shown that deactivating channels that are estimated to interface poorly with the auditory nerve improve speech perception scores for some listeners but not others (Bierer & Litvak, 2016; Noble, Gifford, Hedley-Williams, Dawant, & Labadie, 2014; Noble et al., 2016; Noble, Labadie, Gifford, & Dawant, 2013; Zhou, 2017).

An individualized CI programming approach that considers estimates of electrode position and neural integrity may be ideal. For example, it may be desirable to implement current focusing on an electrode that is located far from the modiolus, but that has better threshold sensitivity to cathodic stimulation than to anodic stimulation (possibly indicating that the target neurons are healthy). On the other hand, it may be best to deactivate or employ an anodic pulse shape on an electrode with better threshold sensitivity to anodic stimulation (possibly indicating local peripheral degeneration). Our results, and others (e.g., Noble et al., 2016), indicate that this combined programming approach could be assessed in older children and adults with CIs. For infants and toddlers, it may be possible to assess polarity sensitivity using objective measures such as the ECAP. However, electrophysiological estimates of polarity sensitivity have not yet been evaluated in young children.

In addition to the primary outcome measure (polarity effect at threshold), we assessed the polarity effect at MCL and differences in DR as a function of polarity. A vast majority of electrodes tested (89.26%) had better suprathreshold sensitivity to the anodic than to the

cathodic polarity. This is consistent with prior studies showing that MCLs are often lower for anodic than for cathodic pulse shapes in postlingually deafened adults (Carlyon, Deeks, & Macherey, 2013; Macherey et al., 2006, 2008, 2017). These findings also align with modeling data suggesting a peripheral-to-central shift in the site of spike initiation for cathodic stimulation at high current levels (Joshi et al., 2017; Rattay, Leao, et al., 2001; Rattay, Lutter et al., 2001; Resnick et al., 2018). Moreover, the present results demonstrate that variability in suprathreshold polarity sensitivity is observed in both child- and adult-implanted listeners.

Elevated MCLs for cathodic compared with anodic triphasic pulse shapes may suggest that the anodic phase is generally more effective at exciting the SGNs in human CI listeners. In psychophysical polarity sensitivity studies, lower MCLs have been elicited in response to both pseudomonophasic and triphasic electrical pulse shapes (Carlyon et al., 2013; Macherey et al., 2006, 2008, 2017). However, it should be noted that psychophysical polarity effects in response to triphasic pulses are often smaller in magnitude than those measured in response to pseudomonophasic pulses (Carlyon et al., 2013; Macherey et al., 2006). The difference in polarity effect magnitude between the two pulse shapes may be related to differences in the ratio between the duration of the short and long phases of each stimulus. Yet, Carlyon et al. (2013) demonstrated that the size of the duration effect does not differ markedly between the two waveforms. Moreover, electrophysiological evidence suggests that suprathreshold neural responses are phase locked to the anodic phase of pseudomonophasic and symmetric biphasic electrical pulses (Undurraga et al., 2010, 2013). The present results are consistent with prior behavioral and electrophysiological evidence showing that, for a variety of pulse shapes, anodic stimulation may be more effective than cathodic stimulation at suprathreshold levels in human CI listeners.

If the majority of electrodes are more sensitive at threshold and at MCL to the anodic polarity than to the cathodic polarity, it may be assumed that the DR is simply shifted downward for anodic stimulation. However, although correlated, the magnitude and sign of the polarity effect at threshold did not necessarily correspond to that at MCL. This suggests that DR may also differ between anodic and cathodic polarities in an electrode-dependent manner. In fact, despite generally lower sensitivity for anodic pulses at threshold and at MCL, DR remained larger for cathodic pulses on most electrodes (77.18%). Macherey et al. (2017) demonstrated that loudness tends to grow less steeply as a function of current level for cathodic pulse shapes than for anodic pulse shapes. Thus, if loudness grows less steeply for cathodic than for anodic stimulation, larger DRs would generally be expected for cathodic pulses.

Notably, CI listeners programmed with larger electrical DRs have better speech perception scores (Bento et al., 2005; Fu & Shannon, 2000; Loizou, Dorman, & Fitzke, 2000; Zeng & Galvin, 1999) and better binaural sensitivity (Todd, Goupell, & Litovsky, 2017) than those with smaller electrical DRs. We performed an exploratory regression analysis to determine whether the DRs for cathodic or anodic stimuli were correlated with vowel identification performance in this sample of CI listeners. Linear mixed-effects models were used to account for clustering of two ears within the bilaterally implanted listeners. Results indicated that better vowel identification scores were associated with larger DRs for both the cathodic, $F(1, 132.19) = 8.02, p = .005$, and the anodic, $F(1, 136.46) = 4.38, p = .04$, pulse shapes. The subjects' clinical MAPs were not available for analysis, but it is likely that subjects with larger DRs for the experimental stimuli also had larger DRs in their everyday CI programs.

The results of this investigation suggest that electrode-dependent differences in DR as a function of polarity may have applications to CI programming. It is possible that a pulse shape can be tailored on an electrode-specific basis to maximize DR. For instance, anodic pulse shapes could be implemented on channels with large anodic DRs and cathodic pulse shapes on electrodes with large cathodic DRs. Our results suggest that novel programming interventions based on polarity sensitivity may be attempted in both child- and adult-implanted listeners. Future investigations should also assess the stability of polarity sensitivity at MCL and DR over time.

Polarity Sensitivity as a Function of Age and Duration of Deafness

Another primary hypothesis of this study was that child-implanted listeners would have smaller polarity effects at threshold than adult-implanted listeners. This prediction was based on human temporal bone literature and limited behavioral and electrophysiological evidence. Postmortem temporal bone studies demonstrate a reduction in SGN density with increasing age and duration of hearing loss (Makary et al., 2011; Nadol, 1997; Nadol et al., 1989; Otte et al., 1978). Histopathological data also show that hearing loss etiology, which often differs between child- and adult-deafened individuals, is a strong predictor of SGN density in humans (Nadol, 1997; Nadol et al., 1989; Otte et al., 1978). Available behavioral and electrophysiological evidence supports the temporal bone findings, suggesting that children with CIs have lower focused behavioral thresholds (DiNino, O'Brien, Bierer, Jahn, & Arenberg, 2019) and steeper ECAP AGFs (Brown et al., 2010) than adults. For these reasons, we predicted that the child-implanted listeners would experience less peripheral process

degeneration than adult-implanted listeners, and that this would manifest as larger polarity effects in the adults.

However, results demonstrated that the polarity effect at threshold did not differ between the child- and adult-implanted listeners in this study. Instead, substantial variability in the polarity effect was observed across all subjects and electrodes. If polarity sensitivity does reflect peripheral process integrity, this may suggest that both child- and adult-implanted listeners experience some degree of peripheral degeneration, even if they are implanted early in life. It should also be noted that we did not test infants or young children, and most of the adolescents in this study had been deaf since early childhood. As SGN degeneration begins at the peripheral processes and progresses centrally, some degree of peripheral degeneration should be expected in older children and adults with profound deafness (Johnsson, 1974). Moreover, the initial hypothesis was informed by human temporal bone and animal literature that had assessed SGN density. It is possible that some degree of peripheral process degeneration has occurred in both groups, but that SGN density remains higher in the child-implanted listeners than in the adult-implanted listeners. Future studies will investigate this distinction.

We also hypothesized that individuals with longer periods of auditory deprivation prior to implantation would have larger polarity effects than those with shorter durations of deafness. This hypothesis was confirmed on high-focused-threshold channels for adult-implanted listeners but not for child-implanted listeners. Duration of deafness did not correlate with polarity sensitivity on low-focused-threshold channels in either group of subjects. This finding is somewhat consistent with Jahn and Arenberg (2019) who demonstrated that the across-site average polarity effect was larger in adults with relatively long preimplantation durations of deafness. However, in that study, the polarity effect was averaged across all 16 electrodes in each ear. In this study, the polarity effect was only assessed on four electrodes per ear, which may have limited our ability to detect a relationship with duration of deafness.

It is also possible that limited variability in duration of deafness among the child-implanted listeners obscured a relationship with polarity sensitivity. The longest duration of deafness in the child-implanted group was 10.1 years. In contrast, the adult-implanted ears ranged in duration of deafness from 3.9 to 53 years. However, despite a limited range of preimplantation auditory deprivation, the child-implanted listeners still demonstrated substantial variability in polarity sensitivity. It is possible that hearing loss etiology, which is strongly associated with SGN survival in human temporal bone analyses (Nadol, 1997; Nadol et al., 1989; Otte et al., 1978), is a more robust predictor of peripheral degeneration than age or duration of deafness. Unfortunately, the majority

of our participants presented with unknown etiologies, so its relationship with polarity sensitivity could not be evaluated here. Future investigations should attempt to recruit participants with known hearing loss etiologies.

Phoneme Perception Is Related to Duration of Deafness, But Not to Polarity Sensitivity

A final goal of this study was to evaluate the relationship between polarity sensitivity and phoneme perception scores. We hypothesized that individuals with large polarity effects at threshold would have poorer phoneme perception scores than individuals with smaller polarity effects at threshold. Contrary to this prediction, polarity sensitivity at threshold was not related to either vowel or consonant perception. Instead, duration of deafness predicted phoneme perception. Individuals with relatively short preimplantation periods of auditory deprivation tended to have better phoneme perception scores than individuals with longer durations of deafness. The observed relationship between duration of deafness and speech perception is consistent across many investigations (e.g., Blamey et al., 2013; Green et al., 2007; Holden et al., 2013; Lazard et al., 2012). Changes in the central auditory system as a consequence of auditory deprivation that are not captured by peripheral measures likely play an important role in CI outcomes.

Moreover, signal detection theory analyses suggest that a dramatic loss of SGNs may be necessary in order to detect measurable deficits in auditory discrimination of intensity, frequency, and interaural time differences (Oxenham, 2016). In line with signal detection theory, relationships between indirect estimates of SGN integrity and speech perception are largely inconsistent across studies. Histopathological studies have failed to demonstrate consistent, positive relationships between postmortem SGN density and speech perception scores assessed during life (Fayad & Linthicum, 2006; Khan et al., 2005; Nadol et al., 2001; Otte et al., 1978). A few ECAP analyses have demonstrated that larger peak amplitudes (DeVries et al., 2016; Schepelerle, 2017) and steeper AGF slopes (Brown et al., 1990; Kim et al., 2010) are associated with better speech perception scores. For bilateral CI listeners, between-ear differences in ECAP amplitude and slope measures (Schvartz-Leyzac & Pfungst, 2018) and in temporal integration abilities (Zhou & Pfungst, 2014) may be predictive of between-ear differences in speech perception abilities. However, there are also many studies that have not observed relationships between ECAP responses and speech perception outcomes (e.g., Cosetti et al., 2010; Franck & Norton, 2001; Turner, Mehr, Hughes, Brown, & Abbas, 2002).

If SGN integrity plays a role in CI performance, the relationship is likely complex and extends beyond measuring speech perception scores (Oxenham, 2016).

In fact, modeling data suggest that speech perception tasks may not be the optimal psychophysical tools for assessing the effects of modest peripheral degeneration on auditory perception with a CI. Resnick et al. (2018) proposed that mild-to-moderate peripheral degeneration would not influence perception of relevant speech features, which are generally longer than 20 ms in duration. Instead, modest demyelination is expected to alter coding of fine temporal cues, such as those needed to detect interaural timing differences. An interaural timing difference-based sound localization task might be more appropriate than speech perception for probing the behavioral implications of peripheral degeneration.

Concluding Remarks

Variability in CI outcomes may be related, in part, to within- and between-listener variation in the quality of the electrode–neuron interface. SGN integrity may contribute to the efficacy with which a CI electrode interfaces with the auditory nerve; however, it is difficult to estimate neural health in humans. This study characterized polarity sensitivity, a proposed estimate of SGN peripheral process integrity, in child- and adult-implanted listeners with CIs. We demonstrated that, if polarity sensitivity reflects neural integrity in CI listeners, then both child-implanted and adult-implanted listeners likely experience some degree of peripheral degeneration, even if they are implanted early in life. Future endeavors to apply polarity sensitivity to the study of individualized programming strategies should incorporate both pediatric and adult listeners.

Subsequent investigations may attempt to use polarity sensitivity, in conjunction with estimates of electrode position, to select appropriate CI electrodes for deactivation and current focusing. It may also be possible to selectively stimulate electrode sites with pulse shapes that optimize a listener's DR. We also demonstrated that polarity sensitivity may not predict phoneme perception scores for CI listeners. Instead, future studies, especially those that intend to implement programming adjustments, should consider utilizing psychophysical tasks that assess one's ability to process fine temporal cues.

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Data Accessibility Statement

Data from this study will be made available upon reasonable request.

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