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A potential neurophysiological correlate of electric-acoustic pitch matching in adult cochlear implant users: Pilot data

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Abstract

The overall goal of this study was to identify an objective physiological correlate of electric-acoustic pitch matching in unilaterally implanted cochlear implant (CI) participants with residual hearing in the non-implanted ear. Electrical and acoustic stimuli were presented in a continuously alternating fashion across ears. The acoustic stimulus and the electrical stimulus were either matched or mismatched in pitch. Auditory evoked potentials were obtained from nine CI users. Results indicated that N1 latency was stimulus-dependent, decreasing when the acoustic frequency of the tone presented to the non-implanted ear was increased. More importantly, there was an additional decrease in N1 latency in the pitch-matched condition. These results indicate the potential utility of N1 latency as an index of pitch matching in CI users.

Keywords

Electric-acoustic pitch matching; Auditory evoked potential; N1 latency

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Introduction

One fundamental function of cochlear implants (CIs) is to mimic the natural tonotopic frequency-position function of a normal hearing (NH) cochlea, in which lower frequency sounds stimulate locations closer to the apex and higher frequency sounds stimulate locations closer to the base. CI speech processors analyze the incoming acoustic signals into frequency bands and assign them to the implanted electrodes in the form of a frequency allocation table (FAT). In the FAT, apical electrodes are stimulated in response to low-frequency sounds and basal electrodes are stimulated in response to high-frequency sounds in an attempt to mimic the tonotopicity of a normal cochlea. Implanted electrodes are activated in response to acoustic energy within the passband of each filter (as specified in the FAT). However, the characteristic frequency of the spiral ganglion neurons that are stimulated may not align with the acoustic stimulus frequency due to variation in array insertion depth and cochlear place of stimulation. Therefore, in postlingually deaf patients there is likely a mismatch between the pitch percept elicited by the CI electrode in response to a given acoustic stimulus and the pitch percept elicited by the same stimulus in a contralateral ear with acoustic hearing. This mismatch, present in CI users with asymmetric hearing loss as those participating in this study, maybe even more prominent in patients with single-sided deafness. The characteristic frequency of the stimulated neurons could be higher, similar, or lower than the frequency of the acoustic stimulus, depending on the FAT, the size of the cochlea and the location of each electrode in the cochlea.

As a result of this position-frequency mismatch, uni-lateral CI users with contralateral residual hearing need to both adapt to the frequency mismatch in the implanted ear and integrate the acoustic information from the non-implanted ear when they listen. The existence of this group of CI users permits direct matching of the pitch perceived in response to stimulation of intracochlear electrodes to the pitch elicited by an acoustic frequency. This measure (electric-acoustic pitch matching) can be useful to determine whether listeners show adaptation to the frequency mismatch described above after different amounts of listening experience with the CI (Francart *et al.*, 2008; McDermott *et al.*, 2009; Reiss *et al.*, 2007, 2008, 2014, 2015; Svirsky *et al.*, 2012; Tan *et al.*, 2012; Vermeire *et al.*, 2015). The neural basis for this type of adaptation may involve a combination of basic neural encoding in the auditory system and additional higher level processing. In a previous study (Tan *et al.*, 2017), we showed that the pitch-matching functions obtained in 16 CI subjects were generally 0.9–1.2 octaves lower than the spiral ganglion functions and 0.2–0.27 octaves higher than the FAT functions, much closer to the FAT functions than the spiral ganglion functions. These findings are consistent with the possibility that adaptation to the frequency-position function imposed by CIs is not always complete. The present study examines a potential neurophysiological correlate of electric-acoustic pitch matching by examining scalp-recorded auditory evoked potentials (AEPs) in unilateral CI subjects when they are presented with alternating stimulation to one intracochlear electrode and different acoustic tones, some of which were pitch matched to the stimulation electrode while others were not.

P1-N1-P2 is an ‘obligatory’ or ‘sensory’ evoked potential complex that is commonly used to examine sound processing in the central auditory system in NH listeners (Naatanen and Picton, 1987; Steinschneider and Dunn, 2002). In recent years, this AEP complex has been

applied to CI users (e.g. Beynon *et al.*, 2005; Dorman *et al.*, 2007; Eggermont and Ponton, 2003; Firszt *et al.*, 2002; Jiwani *et al.*, 2013; Kelly *et al.*, 2005; McLaughlin *et al.*, 2013; Pantev *et al.*, 2006; Ponton *et al.*, 1996; Sharma *et al.*, 2014; Thai-Van *et al.*, 2010; Zhang *et al.*, 2009). The P1-N1-P2 complex is sensitive to changes in the physical features of a stimulus in a highly reliable and repeatable manner (Martin *et al.*, 2008; Naatanen and Picton, 1987; Stapells, 2002; Tremblay *et al.*, 2003). For instance, lowering stimulus intensity will result in reduced amplitudes and increased latencies (Hyde, 1997; Lightfoot and Kennedy, 2006; Stapells, 2002). The P1-N1-P2 complex is also sensitive to changes in stimulus frequency (e.g. Martin *et al.*, 2008; Naatanen and Picton, 1987; Naatanen *et al.*, 1988; Stapells, 2002). The N1 component of the AEP, a prominent negative deflection that peaks at approximately 100 milliseconds after the onset of the stimulus, decreases in latency as the frequency of a tone burst stimulus increases (Pantev *et al.*, 1988; Picton *et al.*, 1978). N1 amplitude decreases for high-frequency tones beyond 2 kHz even for signals of the same intensity (Picton *et al.*, 1978). P1-N1-P2 can be elicited not only in response to stimulus onset but also in response to a change in the stimulus. This is known as the acoustic change complex (ACC) (Martin and Boothroyd, 1999, 2000; Ostroff *et al.*, 1998). In this study, the 'change' is both across the two ears (acoustic and implanted) and across modality (electric and acoustic). The ACC served as a neurophysiological correlate of electroacoustic pitch matching in CI users.

Adaptation to the frequency-position relationship imposed by CIs is not always complete in CI users as previously shown in our electric-acoustic pitch-matching study (Tan *et al.*, 2017). Comparison of AEP responses to electrical and acoustic stimuli that are either matched or mismatched in pitch might provide insight into the neural mechanisms underlying the adaptation process. The aim of this study is to investigate whether N1 latency can serve as a possible objective index of electroacoustic pitch matching in CI users. In this initial look, N1 latency was chosen based on pilot data indicating that it was less variable than N1 amplitude in CI users. The hypothesis is that the N1 latencies recorded with pitch-matched and mismatched stimuli will be different. Thus, this study will determine whether N1 latency can index pitch matching of electrical and acoustic stimulation, and be considered as a possible metric to track the adaptation process of CI users over time after cochlear implantation.

Method

Participants

Nine postlingually deafened adults participated. Each used a CI in one ear and had useable hearing in the non-implanted ear. Seven of these subjects were implanted with Cochlear devices and the remaining two participants were implanted with Advanced Bionics Corp. (AB) devices. All intracochlear electrodes in the devices were active. Participants were implanted at the Cochlear Implant Center in the Department of Otolaryngology at New York University. The degree of functional hearing in the non-implanted ear as well as additional demographic information is shown in Table 1. An electrode with reliable behavioral pitch matching for each individual was selected for the experiment. Most subjects had much better residual hearing in the low frequencies (particularly in the vicinity of 500 Hz) than in the high frequencies and the center frequency in their clinical FAT for the third most apical

electrode is 500 Hz for Cochlear device and 540 Hz for AB device, therefore the third most apical electrode was selected. This electrode was pitch matched between 217 Hz and 830 Hz by different subjects (Tan *et al.*, 2017).

Experimental setup: behavioral pitch matching—Before AEP testing was performed, pitch matching data were obtained in each participant by presenting pure tones to the non-implanted ear via a headphone and electrical stimulation of a single electrode in the implanted ear. Electrical stimulation of the single electrode was accomplished via streaming hardware for Cochlear devices and direct audio connection for AB devices. To present electrical stimulation centered at the single electrode for AB devices, a pure tone set to a frequency equivalent to the center frequency of the analysis band associated with the electrode was presented to the speech processor via direct audio connection. We have previously shown that this results in stimulation of the desired electrode with very little stimulation delivered to adjacent electrodes (Tan *et al.*, 2017). Five hundred milliseconds bursts of electrical stimulation delivered to the CI ear were interspersed with 500 milliseconds of acoustic stimulation to the non-implanted ear. In other words, acoustic and electrical stimulation were alternated using a 500-millisecond duty cycle across two ears (Fig. 1). The acoustic frequency was adjusted by the listener until it was perceived as matched in pitch to the electrical stimulation. This setup was implemented in C++ for both Cochlear and AB devices. Under this setup, one intracochlear electrode was electrically stimulated at the participant's maximum comfortable level with the desired rate and pulse width. For Cochlear devices, a single electrode was electrically stimulated at a rate and pulse width as specified in the participant's clinical map using our program via the Nucleus Implant Communicator (NIC) research software library provided by Cochlear Ltd. The stimulation pulses were sent via a standard Freedom™ speech processor. For AB devices, the electrical stimulation was delivered by a Harmony™ speech processor in response to a 500-millisecond tone whose frequency was the same as the center frequency of the analysis band associated with the electrode of interest. The tone was delivered using a direct audio interface cable connected to the Harmony™ speech processor. The speech processor was fitted with the participant's latest clinical map by SoundWave 2.1™. The speech processor was switched to auxiliary input only mode.

The acoustic tones for the non-implanted ear were amplified using the gain function prescribed using the NAL-RP fitting formula based on the participant's pure tone audiogram (Byrne and Dillon, 1986; Byrne *et al.*, 1990). All acoustic stimuli were sampled at 22.05 kHz with 16-bit resolution using a Sound Blaster Audigy SZ soundcard and amplified by a Sony amplifier, before being presented to patients via a Sennheiser HD580 headphone. The acoustic tone was weighted by a trapezoidal window with a rise/fall of 20 milliseconds to prevent spectral splatter. Prior to testing, the participant was asked to confirm that they could hear the test tones.

Procedure for behavioral matching pitch between electric and acoustic stimuli

CI participants were instructed to adjust the intensity of the acoustic tone (presented to the non-implanted ear) to a level perceived as 'loud, but comfortable' and close to the perceived loudness elicited by the electrode stimulation. They were then instructed to adjust the

frequency of that tone until it matched the pitch elicited by electrical stimulation of the single electrode in the contralateral ear. All adjustments of the acoustic tone were either self-driven by the participant or by the experimenter under the participant's verbal instruction via a slider on a computer screen. CI participants were also instructed to listen to acoustic tones that were higher or lower than the electrical stimulation in pitch percept, before they decided upon the pitch-matched tone.

As described in (Tan *et al.*, 2017), CI participants were required to complete six pitch-matching trials for one single-electrode stimulation. The starting frequency of the acoustic tone was randomized over a range of 20 to 10 000 Hz for each trial to assess the presence of non-sensory bias effects using the two 'checks' proposed by Carlyon *et al.* (2010). Frequency values obtained from trials were also fit to a standard normal distribution and values outside a 99.5% confidence interval were discarded. The final pitch-matched value to be used in the pitch-matched condition for AEP testing was the average of the remaining trials. At the 99.5% confidence level, 8 out of 9 participants did not have any outliers. For the remaining 1 participant, 1–3 trials were discarded.

Experimental setup: AEP recording—The same experimental setup used for behavioral pitch matching was used to present both acoustic and electric stimuli for AEP recording (Fig. 2). The acoustic stimulus was amplified in the same manner used in behavioral pitch matching with an input level of 70-dB sound pressure level. In addition, CI participants confirmed that both the acoustic and electric stimuli were audible prior to each test condition. AEPs from all CI participants were obtained with electrical stimulation of the third most apical electrode of the implanted electrode array as shown in Table 2. Please note that to be consistent across different brands of CIs, and to be consistent with Tan *et al.* (2017), electrodes were numbered from apex to base even though Cochlear Ltd. manuals use the opposite order (base to apex). The center frequency of the analysis band allocated to the electrode selected for electrical stimulation and the corresponding average pitch-matched frequency are included in Table 2. All participants watched a muted video during the recordings.

Cochlear device users

The center frequency of the analysis band associated with electrode 3 was 500 Hz for all Cochlear CI participants in this study in accordance with their clinical FATs. All AEP recordings for Cochlear CI participants were obtained with electrical stimulation of Electrode 3 and an acoustic tone was presented sequentially to the contralateral ear in 6 test conditions listed as follows:

1. 250 Hz – one octave below the target 500 Hz tone,
2. 375 Hz – center frequency of analysis band associated with the adjacent apical electrode 2,
3. 500 Hz – center frequency of analysis band associated with electrode 3,
4. 625 Hz – center frequency of analysis band associated with the adjacent basal electrode 4,

5. 1000 Hz – one octave higher than the target 500 Hz tone, and
6. pitch-matched condition – the average pitch-matched frequency of the electrode obtained from the behavioral pitch-matching experiment.

CI 4 had a steeply sloping hearing loss and was not able to hear the tone at 1000 Hz. Hence, Condition 5 was changed to 800 Hz (which was audible to the subject) and Condition 1 was changed to 300 Hz to have Conditions 1 and 5 be about the same distance from 500 Hz in a logarithmic scale, as was done with the other subjects.

AB device users

For the two CI participants using AB devices, electrode 3 was stimulated. The acoustic tones were presented to the non-implanted ear as listed in the following six test conditions:

1. 270 Hz – center frequency of the analysis band associated with electrode 1,
2. 385 Hz – center frequency of the analysis band associated with electrode 2,
3. 540 Hz – center frequency of the analysis band associated with electrode 3,
4. 642 Hz – center frequency of the analysis band associated with electrode 4,
5. 906 Hz – center frequency of the analysis band associated with electrode 5, and
6. pitch-matched condition – the average pitch-matched frequency of the electrode obtained from the behavioral pitch-matching experiment.

All AEPs were recorded using a Neuroscan system with continuous, interleaved presentation of single-electrode electrical stimulation followed by a contralateral acoustic tone. Thus, auditory stimulation was continuous and alternated between ears. Each pair of electric and acoustic stimuli was presented 500 times, and the AEP in response to the onset of the tone was recorded. Acoustic signals were presented to the patient via an ER2 insert earphone. The maximum output level did not exceed 93.6 dB, which is well within the range that these earphones can deliver without distortion. Again, it was confirmed that the participant was able to hear the tones before the recording was started. The trigger was inserted at the onset of the acoustic stimulus (the offset of the electrical stimulation). The onset and offset of the acoustic stimuli were enveloped using a trapezoidal weighting window of 20 milliseconds.

AEP responses were recorded from 64 channels referenced to electrode Cz. Vertical and horizontal electrooculographic channels were used to monitor eye movements and eliminate eye blinks. The ongoing electroencephalography was digitized at 1000 Hz, amplified 1000 times, and filtered between 0.15 and 200 Hz. The AEP responses were processed offline into 991-millisecond epochs after ocular artifact reduction. The responses in each epoch were baseline corrected and filtered using a low delay, zero phase-shift filter between 1 and 30 Hz at 24 dB/octave. After artifact rejection (+100 microvolts) and averaging, a minimum of 97.4% (487/500) sweeps were accepted for computation of the averaged waveform in each condition for each participant. The decay of the electrical stimulus after turn-off did not aggressively affect the cortical evoked potentials at some midline-central electrodes. Re-referencing to the contralateral mastoid electrode (M1/M2) helped to reveal the physiological response.

Results

Pitch matching

The reliability of the pitch-matched frequencies at the selected electrode (shown in Table 2 for each CI participant) was checked by subjecting them to the non-sensory bias checks proposed by Carlyon *et al.* (2010) presented in Table 3. None of the p -STD values was lower than 0.05, suggesting that the standard deviation of starting frequencies is significantly greater than that of the final pitch-matched frequencies. Overall reliability was good.

As shown in Table 4, all participants other than CI 1, and CI 9 perceived a higher pitch than the frequencies imposed by the FAT function at the tested electrode. In other words, six participants experienced ‘basalward shift’ in pitch percept and two participants experienced ‘apicalward shift’ at the selected electrode. CI 5 experienced ‘no shift’ in pitch percept. On average, the pitch percept is consistent with the results reported in our previous study (Tan *et al.*, 2017).

Auditory evoked potentials—Typical AEP waveforms at electrode site Cz are shown for a typical subject (CI 3) in each of the six test conditions (Fig. 3). The P1-N1-P2 complex was clearly evoked by the onset of acoustic stimulation. In this study, the focus was on the latency of N1, the most prominent negative peak in the P1-N1-P2 complex. The latency of N1 was measured at the center of the peak relative to acoustic stimulus onset (i.e. 0 millisecond). For bifurcated or distorted peaks, the centroid of the peak was estimated after the AEP response was smoothed, but the measure was made using the original (non-smoothed) waveform.

Two patterns in N1 latency

Table 4 presents the N1 latencies in each participant at Cz for all six test conditions. Grand mean N1 latencies and corresponding standard errors as a function of frequency are shown in Fig. 4. A regression line was fitted to the grand mean N1 latencies from the first five test conditions (without the pitch-matched condition) to highlight two general patterns. First, grand mean N1 latencies decreased as the frequency of the acoustic tone increased, as would be expected (Picton *et al.*, 1978). Second, N1 latency in the pitch-matched condition was shorter than predicted by the non-linear regression of the data from the other five conditions. Table 4 shows that the pattern of N1 latency decrease with increasing frequency also occurs in individual participants. This result was statistically significant, as confirmed by a multiple linear regression of N1 latency as a function of frequency and subject. The factor ‘frequency’ predicted a decrease in N1 latency ($P = 0.036$). Subject CI5 had much longer N1 latencies than the other subjects, but it is worth mentioning that he had the longest duration of deafness of all 9 subjects in the implanted ear (43 years) and was implanted for less than a year at the time of testing. It is unclear that typical characteristic N1 latencies can be fully restored in every individual by electrical stimulation in the implanted ear after a period of listening with one ear. There is an emerging literature indicating that aided AEPs do not always show the patterns one might expect and it is likely that similar interactions with device will be present for CIs (e.g. Billings *et al.*, 2011; Chun *et al.*, 2016; Tremblay and Miller, 2014). In the individual participants, the first pattern of decreasing N1 latency as

acoustic frequency increases from the lowest to the highest value was observed in 7 out of 9 CI participants, the two exceptions being CI 4 and CI 8.

The frequency-N1 latency data from each individual CI participant was fitted to a non-linear, three-parameter exponential function. The data from CI 7, however, did not converge and was fitted with a two-parameter exponential function instead. These results are shown in Table 5. The last column of Table 5 shows that, even though the exact pitch-matched frequency differed across the CI participants, N1 latency for every participant was shorter in the pitch-matched condition than predicted by the non-linear regression estimate. These difference values (from the predictions) averaged -5.3 millisecond for the pitch-matched frequencies. This effect was statistically significant, as confirmed by a two-way analysis of variance that was carried out on the data shown in Table 5. The two factors were subject and frequency (which could assume two values: pitch matched or non-pitch matched). The difference in N1 latency regression residuals was significantly shorter for pitch-matched frequencies [$F(1, 8) = 5.175$; $P = 0.029$]. The subject factor ($P = 0.648$) and subject-frequency interaction (also $P = 0.648$) were not statistically significant. This shortening of N1 latency in the pitch-matched condition (see Fig. 4 and Table 5) is superimposed on the first N1 latency pattern, which generally decreased in value as frequency increased.

Responses obtained from odd and even trials

To provide a sense of within-subject repeatability in the pitch-matched condition averaged responses to odd and even-numbered trials were examined. Figure 5 shows results from all CI participants. N1 latency was reasonably stable, more so than N1 amplitude. This provides some support for our selection of N1 latency as the metric for the study. Table 6 shows values of N1 latency for all subjects based on odd-and even-numbered trials. The results were satisfactory in that test-retest reliability was high (2 milliseconds or better, as indicated in Table 6) and the effect size was clearly greater than that (5.3 milliseconds on average, as indicated in Table 5).

Discussion

This study presents a novel application of the ACC (Martin and Boothroyd, 1999, 2000; Ostroff *et al.*, 1998). ACC N1 latency served as a correlate of pitch matching and was elicited in response to a stimulus that continuously alternated between ears that were either matched or mismatched in pitch. In this study, the change is both across the two ears (acoustic and implanted) and across modality (electric and acoustic). N1 latency was elicited by the onset of the tones in this study, in the context of a change from preceding stimulation of a single electrode in the CI. In general, N1 latencies decreased as the acoustic tone increased in frequency, which is consistent with observations reported in studies of NH listeners (Pantev *et al.*, 1988, 1989; Picton *et al.*, 1978; Woods, 1995; Woods *et al.*, 1993). The additional N1 shortening in the pitch-matched condition suggests that a binaural electric-acoustic integration process was involved, because a strictly monaural process should have shown results that were independent from the stimulus previously provided to the implanted ear. In other words, if the process had been strictly monaural, N1 latency values for the pitch-matched condition should have fallen squarely on the non-linear

regression line as a function of frequency rather than being significantly below it (Table 5 and Fig. 4). Integration across ears has been shown to occur in the superior olivary complex (e.g. Moore, 1991). In this study, this integration was reflected centrally at the level of auditory cortex. This study demonstrated that N1 latency, which showed additional shortening in the pitch-matched condition when the stimuli alternate between the non-implanted and implanted ears has potential utility as an objective physiological correlate of electroacoustic pitch matching in CI users. More specifically, N1 latency in the pitch-matched condition is shorter than would be predicted from the latency-frequency function obtained with the non-pitch-matched data.

A reduction in ACC N1 latency in the pitch-matched condition was clearly present, on average, but the magnitude of this reduction was small and there was considerable variability across subjects. If this small effect (reduction of N1 latency at pitch-matched stimuli) holds in a larger dataset, this would be an interesting and novel finding with potential clinical application. Further work will be conducted to expand this initial, exploratory study to seek ways to better assess the magnitude of this reduction. In addition, the search for relevant physiological correlates of pitch matching will not be restricted solely to the N1 component. Future studies will examine amplitude, latency and topography of N1 alone and in combination with other AEPs in response to each stimulus separately, together, and sequentially. This may present an opportunity to further validate that the current AEP is not solely evoked by onset of stimulus in the non-implanted ear but by stimulus change across the ears.

The finding of a useful, objective correlate of pitch matching has potential utility for understanding the mechanisms underlying pitch matching and may provide a means to constrain hypotheses about the neurophysiological mechanisms underlying pitch matching changes over time. It will be of interest to determine whether the behavioral changes that have been observed over time in electroacoustic pitch matching correlate with concomitant changes in this novel neurophysiological correlate. In addition, the technique developed could be used to investigate how the processing of sounds is altered when the context in which they have presented changes. For example, how is processing affected by monaural versus binaural versus sequential processing across ears? If the technique can be optimized, it might have utility in the future to monitor the adaptation process in CI users who cannot provide a reliable behavioral index (for instance, young children).

This study marks the first attempt at finding a neurophysiological correlate of electroacoustic pitch matching in CI users with functional residual hearing in the non-implanted ear. N1 latency is identified as a potential candidate as a neurophysiological correlate of electroacoustic pitch matching. The two unique patterns in N1 latency observed in pitch-matched and mismatched conditions were clear in the majority of the participants in this study. Despite some individual differences, this neurophysiological phenomenon appears to merit attention and further exploration. Previous studies on electroacoustic pitch matching (e.g. Reiss *et al.*, 2007, 2008; Tan *et al.*, 2017) have shown that many CI users do not completely adapt to the frequency-place function imposed by their devices and continue to perceive higher pitched sounds despite years of listening experience after cochlear

implantation. Further research is needed to compare NI latency patterns in CI users with complete and incomplete adaptation.

The existence of a population of unilateral CI users with residual hearing in the non-implanted ear presents a unique opportunity to explore electroacoustic pitch matching across two ears, and which may shed light on the adaptation process that takes place after cochlear implantation. The neurophysiological correlate of electroacoustic pitch matching identified in this study may provide a metric to evaluate and monitor this process.

Summary

This work presents our first attempt to explore the potential relationship between electroacoustic pitch matching and AEPs. The main findings were that N1 latency in CI participants decreased when the acoustic frequency of tones presented to the non-implanted ear increased, and there was additional shortening of N1 latency in the pitch-matched condition. Both patterns were statistically significant. Thus, N1 latency could potentially provide a neurophysiological correlate of pitch matching across ears in CI participants and may serve as a metric to monitor the adaptation process of CI users to their devices.

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Figure 1.

Pitch-matching setup for CI participants using Cochlear device. For CI participants using AB device, the electrical stimulation is replaced by the acoustic tone at a center frequency of the analysis band allocated to the electrode in same duty cycle.

Figure 2.
Experimental setup for AEP recordings.

Figure 3. Typical AEP responses recorded at Cz in CI 3. The AEP response recorded in the pitch-matched condition is indicated by the black line.

Figure 4.

Mean AEP N1 latencies in CI participants at electrode site Cz. The green solid line indicates the non-linear regression trend. The black solid star marker indicates the grand mean N1 latency in the pitch-matched condition, and grand mean pitch-matched frequency across all participants. The frequency for each round marker indicates the grand mean frequency in each test condition across all participants. Note that the meaning of the circles and star symbols are not identical. Circles represent average N1 latency obtained at one particular frequency whereas the star represents average N1 latency at the pitch-matched frequency, which varied across subjects.

Figure 5.

N1 recorded at Cz is shown for each CI participant in response to all trials (black), odd-numbered trials (light gray), and even-numbered trials (dark gray) in the pitch-matched condition.

Table 1

Participant demographics

Participant	Etiology	Age at testing Years- months	Duration of implant use Years-months	Implanted ear	Time since onset of hearing loss Years	Pure tone threshold (dBHL) in the non-implant ear			Manufacturer	Implant	Processor
						250 Hz	500 Hz	1000 Hz			
1	Unknown	32-0	1-3	Left	Unknown	35	25	10	Cochlear	CI24R(CA)	Freedom
2	Unknown; possible vestibular schwannoma AS (side with NH)	64-8	2-2	Right	3	15	15	25	Cochlear	N512	CP810
3	Unknown	76-6	0-6	Left	26	35	50	55	Cochlear	N512	CP810
4	Unknown	75-1	0-8	Right	36	20	60	100	Cochlear	CI 24RE	CP810
5	Unknown	70-0	0-1	Left	43	15	15	40	Cochlear	N512	CP810
6	Unknown; perhaps antibiotic	37-2	0-8	Left	10	15	10	5	Cochlear	CI 24RE (CA)	CP810
7	Noise-induced hearing loss-military	70-0	7-1	Left	unknown	20	20	20	Cochlear	CI 24RE (CA)	Freedom
8	Unknown; per pt. report sinusitis	77-4	1-4	Right	32	65	65	80	Advanced Bionics	HR90K	Harmony
9	Noise-induced hearing loss-military	64-4	1-2	Right	12	35	40	85	Advanced Bionics	HR90K	Harmony

Table 2

Electrode selected for AEP recording with each CI participant and the corresponding center frequency and pitch-matched frequency for the selected electrode

Participant	Electrode selected for AEP recording	Center frequency of selected electrode (Hz)	Average pitch-matched frequency (Hz)
<i>Cochlear</i>			
CI 1	3	500	397
CI 2	3	500	809
CI 3	3	500	580
CI 4	3	500	512
CI 5	3	500	500
CI 6	3	500	553
CI 7	3	500	572
<i>Advanced Bionics</i>			
CI 8	3	540	517
CI 9	3	540	385

Table 3

Non-sensory bias checks for each individual CI participant in the pitch-matching experiment. ‘pSTD’ in the second column is the *P*-value of the difference between the standard deviation of the starting and final match frequencies ‘Corr’ in the third column is the correlation between the starting and final matched frequency and the corresponding ‘pCorr’ in the fourth column is the *P*-value of the correlation. ‘Corr’ value would only be considered if ‘pCorr’ is < 0.05

Participant	Check one p-STD	Check two	
		Corr	p-Corr
1	<0.001	0.042	0.634
2	<0.001	0.073	0.408
3	<0.001	0.224	0.371
4	<0.001	-0.037	0.847
5	<0.001	-0.086	0.329
6	<0.001	-0.039	0.657
7	<0.001	0.032	0.716
8	<0.001	0.118	0.252
9	<0.001	0.179	0.081

Table 4

AEP N1 latencies (millisecond) at electrode site Cz

N1 latency (millisecond) at Cz						<i>Pitch matched</i>	Reference electrode
Test condition	1	2	3	4	5		
Acoustic tone (Hz)	250	375	500	625	1000	397	M2
CI 1	104	95	97	93	92	96	
Acoustic tone (Hz)	250	375	500	625	1000	809	M1
CI 2	121	118	114	114	109	108	
Acoustic tone (Hz)	250	375	500	625	1000	580	M2
CI 3	139	154	119	104	105	99	
Acoustic tone (Hz)	300	375	500	625	800	521	M1
CI 4	108	117	107	107	131	106	
Acoustic tone (Hz)	250	375	500	625	1000	500	M2
CI 5	179	173	157	145	114	157	
Acoustic tone (Hz)	250	375	500	625	1000	553	M2
CI 6	152	116	97	100	103	98	
Acoustic tone (Hz)	250	375	500	625	1000	572	M2
CI 7	136	119	127	116	116	122	
Acoustic tone (Hz)	270	455	540	642	1080	517	M1
CI 8	104	102	101	117	108	98	
Acoustic tone (Hz)	270	455	540	642	906	385	M1
CI 9	109	100	93	114	91	100	
Mean acoustic frequency (Hz)	260	392	508	628	976	537	
Mean	128.0	121.6	112.4	112.2	107.7	109.3	
Standard error	24.3	24.3	19.0	13.9	11.6	18.5	

Table 5

Differences between AEP N1 latencies (millisecond) and non-linear three-parameter exponential regression estimates are shown. A negative value indicates that the N1 latency is lower than the corresponding non-linear regression estimate. In the pitch-matched condition, N1 latency values were systematically lower than would be predicted by the non-linear regression

Difference between N1 latency and non-linear exponential regression estimate (millisecond) at Cz						
Test condition	1	2	3	4	5	<i>Pitch matched</i>
CI 1	0.3	-1.8	2.7	-0.4	-0.9	-0.2
CI 2	0.0	0.3	-1.1	0.9	-0.2	-2.8
CI 3	-8.6	20.1	-4.4	-11.4	4.2	-19.0
CI 4	1.0	7.6	-6.4	-10.3	8.1	-8.1
CI 5	-1.9	3.8	-0.8	-1.5	0.4	-0.8
CI 6	-0.4	3.0	-5.9	-0.3	3.5	-3.4
CI 7	0.6	-0.7	0.3	-0.5	0.3	0.0
CI 8	1.6	-3.6	-5.6	9.4	-1.9	-8.3
CI 9	1.7	-3.6	-8.9	14.2	-3.5	-5.0
Mean	-0.6	2.8	-3.3	0.0	1.1	-5.3
Standard deviation	3.2	7.5	3.8	8.1	3.6	6.0

Table 6

N1 latencies (millisecond) obtained from even and odd trials in the pitch-matched condition are shown

Pitch-matched condition	<u>N1 latency (millisecond) at Cz</u>	
	Even trials	Odd trials
CI 1	98	95
CI 2	108	109
CI 3	52	50
CI 4	99	98
CI 5	106	107
CI 6	156	156
CI 7	98	99
CI 8	122	123
CI 9	97	97
CI 10	98	100