Published in final edited form as:

Cochlear Implants Int. 2017 January ; 18(1): 36–48. doi:10.1080/14670100.2016.1263406.

The Impact of Electric Hearing on Children's Timbre and Pitch Perception and Talker Discrimination

Kristin M. Sjoberg,

School of Music, The University of Iowa

Virginia D. Driscoll,

Iowa Cochlear Implant Clinical Research Center, Department of Otolaryngology, The University of Iowa

Kate Gfeller,

Iowa Cochlear Implant Clinical Research Center, School of Music, Department of Communication Sciences and Disorders, The University of Iowa

Anne E. Welhaven,

Department of Biostatistics, The University of Iowa

Karen Iler Kirk, and

Department of Speech and Hearing Science, University of Illinois Urbana-Champaign, The University of Iowa

Lindsay Prusick

Iowa Cochlear Implant Clinical Research Center, Department of Otolaryngology, The University of Iowa

Introduction

Present-day cochlear implant (CI) processing strategies typically remove the temporal fine-structure information in the stimulus waveform and preserve the temporal envelope, resulting in coarse spectral cues and poor frequency resolution. This degraded signal is sufficient for supporting perception of segmental features of speech in quiet, but is poorly suited for perception of those aspects of musical or spoken communication for which temporal fine structure is especially salient (Galvin, Fu, & Nogaki, 2007; Limb & Roy, 2014; Looi, Gfeller, & Driscoll, 2012; See, Driscoll, Gfeller, Kliethermes, & Oleson, 2013). To what extent does the degraded representation in electric hearing (hearing through a CI) undermine accurate perception of several spectrally complex features of music and speech (i.e., timbre, pitch, and talker discrimination) in pediatric CI users? Are there experiential factors (e.g., acute vs. long-term exposure to electric hearing; age at time of testing, music instruction) and the characteristics of the auditory signal (e.g., timbre, pitch, talker discrimination) that have a significant influence on perceptual accuracy for spectrally complex music and speech sounds? These questions have implications for establishing

realistic user expectations for pediatric CI users, as well as evaluating accuracy of research of using simulation methodology in predicting CI benefit.

These questions are informed by several strands of research regarding CI benefits: timbre, pitch and speech perception of CI users, the relations between music and speech in electric hearing, as well as the use of simulation testing in CI research. Related studies are outlined below.

Timbre Perception and CIs

According to the Acoustical Society of America, timbre is “that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar” (1960). In musical terms, timbre is sometimes referred to as the tone quality that characterizes each musical instrument. The unique timbre of an instrument results from combined onset transients, steady state, and decay of harmonics. Without the ability to differentiate timbral features, instrument recognition is difficult, and aesthetic qualities of music suffer (Gfeller, Witt, Adamek, et al., 2002).

The CI provides sufficient spectral information to support discrimination if the instruments have sufficiently different spectral characteristics, but instrument recognition is problematic (for reviews, see Limb & Roy, 2014; Looi et al., 2012). Most published studies on timbre perception of CI recipients have been conducted with postlingually deaf adults, who compare the sound of an instrument through the CI with their recollections of timbre when they had normal or near-normal hearing. Adult CI users differ from NH listeners in overall accuracy and patterns of errors. NH adults are more likely to confuse instruments from the same instrumental family, while CI recipients are more likely to have diffuse errors, confusing even dissimilar instruments (Gfeller, Witt, Woodworth, Mehr, & Knutson, 2002). Although individual adult CI users have reported improved timbre perception or appraisal as the result of upgrading signal processing strategies, group comparisons of persons who use conventional CIs (long electrodes) have failed to show significant differences as a function of internal array design or processing strategies (for review, see Looi et al., 2012).

To date, few studies have examined timbre perception of pediatric CI users, many who have developed their mental representation of musical instruments through electric hearing. These studies indicate pediatric CI recipients can often discriminate between two sounds with distinctly different temporal cues, but are less accurate when sound production and spectral features are more similar (e.g., saxophone vs. a clarinet) (Driscoll, 2012; Gfeller, Driscoll, Kenworthy, & Van Voorst, 2011). Jung et al. (2012) found timbre discrimination of pediatric users was significantly poorer than adult CI users ($p=0.039$), albeit significantly higher than chance level ($p=0.027$). Innes-Brown, Marozeau, Storey, and Blamey (2013) found children using CIs who were enrolled in special music classes were less accurate than NH children in instrument recognition; however, the differences between groups were less distinct in recognition of percussion instruments. In addition to instrumental sound characteristics, poorer recognition accuracy of pediatric CI users can be a function of less exposure to different musical instruments compared with NH children (Gfeller, Witt, Spencer, Stordahl, & Tomblin, 1999).

In summary, the spectrally complex nature of timbre is not ideally represented by CI processors though life experiences may also have an impact on timbre recognition. Another spectrally complex element of music, pitch, is the focus of the following section.

Pitch Perception and CIs

Pitch, how high or low a note sounds, has been described as the most basic organizing structure in most musical cultures (Patel, 2008). We often associate sequential and concurrent patterns of pitch with the creation of melodies and harmony. CI users as a group are significantly less accurate than NH on many pitch tasks, though individual accuracy can vary considerably (Galvin et al., 2007; Gfeller, Knutson, Woodworth, Witt, & DeBus, 1998; Gfeller, Oleson, Knutson, Driscoll, & Olszewski, 2008; Gfeller et al., 2007; Gfeller, Turner, et al., 2002; Limb & Roy, 2014; Looi et al., 2012). Group comparisons with relatively large sample sizes (N=129 or 209) of adult users of conventional long electrodes have not revealed significantly more accurate pitch perception as a function of device or strategy (Drennan et al., 2015; Gfeller, Jiang, Oleson, Driscoll, & Knutson, 2010; Gfeller et al., 2008; Looi et al., 2012). On a temporally more rapid level, pitch and timbre are integrally related because the unique timbre of a musical instrument is a function of temporal and intensity parameters of fundamental frequency and upper harmonics, which make up the complex tone associated with a sound source. Prior research has shown significant correlations between pitch-based tasks and timbre perception of adult CI users (Drennan et al., 2015).

Hearing History, CIs, and Music Perception

Although adult and pediatric CI users receive similar electrical stimulation, there are several reasons why perceptual studies of adults should not be presumed to predict outcomes for pediatric CI users (Hsiao & Gfeller, 2012). First, postlingually deafened adults have a mental representation of pitch relations within musical scales acquired as well as the spectral shapes of instrumental timbres through a normal or near-normal hearing mechanism. Postlingually deafened adults can use memory of musical sounds prior to deafness to help make sense of sounds through an implant (Gfeller & Driscoll, 2010; Olszewski, Gfeller, & Driscoll, 2006). The auditory pathways of prelingually deaf children have developed primarily as a result of electric stimulation, and their mental conceptualization of pitch and timbre has formed in response to degraded stimuli.

Adults and children also differ in acclimatization to the CI signal. While neural plasticity is present throughout life, children have greater plasticity than adults; their brains may adapt to stimuli at a faster rate. Given these important differences, more research is needed with children to better understand the impact of electric hearing on perception of timbre and pitch discrimination in relation to different hearing histories.

As noted previously, the removal of fine structure during signal processing has a negative impact on spectrally complex sounds. These include not only music, but several features of speech, such as speech prosody (See et al., 2013), speech recognition in background noise (Gfeller, Turner, Oleson, Kliethermes, & Driscoll, 2012), and talker discrimination, which is the focus of the following section.

Talker discrimination and CIs

Talker discrimination is the ability to differentiate between two or more talkers. NH individuals, including children, can easily differentiate talkers. By age five, NH children can identify two sentences as being from same or different talkers at an 87% accuracy rate (Cleary & Pisoni, 2002).

While an implant greatly increases ability to understand speech, it is less effective in portraying indexical properties of the acoustic signal that give information about the talker, including age, emotional state, gender and regional background—features that contribute to talker discrimination and recognition (Cleary & Pisoni, 2002). The more listeners are able to perceive indexical properties, the more accurate they will be in understanding linguistic content (McDonald, Kirk, Houston, Sprunger, & Krueger, 2003).

Cleary and Pisoni (2002) tested children with CIs on talker discrimination. The children decided if two sentences were spoken by the same, or different, talkers. In one condition, the sentences varied; in another condition, sentences were fixed. The pediatric CI users, ages 8–9, were 57% accurate in the varied condition, and 67% accurate in the fixed condition. These results were less accurate than those of younger NH children (age 5) who achieved 87% accuracy on the varied sentence condition. Additionally, talker discrimination performance was highly correlated with word recognition (speech recognition fixed condition, $p=.01$ and varied condition, $p=.05$) (Cleary & Pisoni, 2002).

There are a number of reasons talker discrimination is challenging through a CI. First, the voices of talkers have different fundamental frequencies. As noted, CIs are poorly suited for transmitting pitch information (McDonald et al., 2003). Furthermore, the lack of fine spectral cues can make it difficult to tell if differences in productions are simply part of an individual talker's ordinary fluctuation, caused by co-articulation, or indicate a change in the sound source, that is, a second talker (Cleary, Pisoni, & Kirk, 2005; McDonald et al., 2003). Also, talker discrimination is influenced by the sound environment and characteristics of the talker (Cleary et al., 2005).

Although there are important differences between functional uses of speech and music, as well as those features most salient to perceptual processing in electric hearing, there are also interesting overlaps between music and speech perception. The following section focuses on spectrally complex aspects of speech that may also be implicated in perception of timbre and pitch by CI recipients.

CI users and relations between music and speech perception tasks

Perception of fundamental frequency and upper harmonics is important not only to timbre recognition but also speech perception tasks, such as discriminating or identifying the unique qualities of a speaker's voice. Ability to discriminate timbre in speech and music is dependent on the amount of variance in F0 between two sounds. Research points up the role of pitch perception in talker discrimination or recognition. The average spectral characteristics of two utterances must differ by at least 11%–16% (2–2.5 semitones) for NH children to perceive the voices as belonging to different talkers. Unfortunately, a 2 to 2.5 semitone difference is not often discriminated by CI users (Cleary et al., 2005). The

relationships between talker discrimination and timbre, both which involve tone quality, has not received similar attention in research regarding CI recipients.

Several measures of speech recognition by CI users have been correlated with music perception measures. Though results may vary, depending upon environmental testing methods, CI users often struggle on music or speech perception tasks when pitch becomes a factor. For example, in a study by Fu, Chinchilla, Nogaki, and Galvin (2005), adult users were highly accurate at identifying gender of talkers (93.8% correct) until the F0 overlapped between average male and female talkers. Then, performance declined to 67.91%.

To date, studies examining the relationships between perception of timbre, pitch and different features of speech in CI users have yielded mixed results. Speech recognition does appear to impact music perception, especially when lyrics are present (Gfeller et al., 2008). Fu, Chinchilla, and Galvin (2004) reported that pitch perception was an important factor in the ability to discern talker sex. Several studies indicate that pitch perception predicted speech recognition in noise (Gfeller et al., 2007), perception of affective speech prosody (See et al., 2013), and recognition of lexical tones (e.g., Li, Wang, Li, Zhang, & Liu, 2014). Conversely, some studies reported weak correlations between speech recognition and speech timbre perception with music timbre recognition or pitch perception (Cullington & Zeng, 2011; Gfeller et al., 1998; Gfeller et al., 2008; Gfeller, Witt, Woodworth, et al., 2002).

While the skills of musical timbre perception, pitch perception, and speech timbre perception appear interrelated, and it has been posited that performance on one may be predictive of the others, these relationships are far from clear cut, especially with pediatric CI users. Prior studies have also indicated non-auditory variables (e.g., age of listener, extent of musical training) that contribute to variability among CI users on measures of pitch, timbre, and speech perception. Further, some of these variables may be highly correlated, further complicating predictions. Consequently, more research is needed examining each variable, but using analyses that permit examination of multiple factors. However, there are pragmatic challenges associated with testing pediatric CI recipients. These challenges, along with methodological options for research are discussed in the following section

The use of simulations to examine electric hearing—A number of challenges are associated with researching perceptual abilities of pediatric CI recipients. Because development of speech and language is such a critical end point for pediatric CI benefit, children with CIs are often tested on a host of linguistic measures in order to determine progress, need for remediation, or accommodation. It can be difficult to find time for testing music perception as well as all components of speech. The competing priorities for testing are further impacted by the limited attention spans of younger children. Testing a child who is tired or inattentive can have a negative impact on test reliability. Furthermore, researchers may not have the option of requiring additional visits because testing is likely to be arranged around educational priorities. Given that extensive testing with children as well as access to adequate sample sizes of pediatric CI users can be problematic, researchers have looked to alternative methods for examining potential outcomes.

One methodological option that has been used to estimate CI benefit is simulation testing. Simulations have been used by many researchers to investigate how specific characteristics of the CI signal impact perception and understanding of speech and music (Driscoll, Oleson, Jiang, & Gfeller, 2009; Fu et al., 2005; Fu & Nogaki, 2004; Loizou, Dorman, & Tu, 1999; Moore & Tan, 2003; Nogaki, Fu, & Galvin, 2007; Torppa et al., 2012; Wright & Uchanski, 2012). Simulations allow for precise control over acoustical parameters, while ascertaining the impact of specific signal characteristics on perception. Simulations also permit an investigation of electric hearing without having to account for the influence of factors known to contribute to variability among CI users (e.g., hearing history, device characteristics).

Practically speaking, testing with simulations provides an opportunity to examine test protocols and estimate the impact of electric hearing on the perceptual tasks prior to engaging CI patients. For example, Wright and Uchanski (2012) found that NH adults listening to CI simulations performed similarly to CI adult users on many music tests, including the UW-CAMP timbre test. Similarly, Fu et al. (2005) tested NH individuals listening to CI simulations; NH performed similarly to the CI group when simulations included 4–8 channels. In summary, prior research suggests that using simulations can help predict some aspects of performance of CI users on speech and music perception, which can assist the formulation of suitable research inquiries with CI recipients (Fu et al., 2005; Fu & Nogaki, 2004; Moore & Tan, 2003; Wright & Uchanski, 2012).

That having been said, despite the methodological advantages of simulations, this method does not take into account acclimatization to the CI signal over time, differences in auditory development as a function of electrical stimulation during critical periods, or the effect of individual differences (e.g., training, life experiences) that influence perception of auditory input. Therefore, it is of interest to examine how simulations compare and contrast with outcomes from experienced CI users to better understand the impact of different factors on perceptual outcomes.

To summarize, at present, few systematic studies have examined timbre or pitch perception of pediatric CI recipients. Because perception of both of these musical elements requires sufficient access to fine structure in the waveform, these perceptual tasks provide us with greater insights into the impact of electric hearing on two important elements of music. From a developmental standpoint, the accuracy of children in comparison with published studies of adult CI users helps to clarify the role of auditory development through acoustic vs. electric hearing in perceptual accuracy of spectrally complex parameters. Furthermore, the perceptual accuracy on timbre and pitch may have implications for spectrally complex aspects of speech perception, such as talker discrimination. Additional research is needed to better understand relations among these perceptual tasks, and how they are influenced by group and individual characteristics. This study asks the following questions regarding participant's perception of spectrally complex tasks:

1. Does electric hearing (simulation of electric hearing or CI use) have a significant impact upon perception of spectrally complex features of music (timbre recognition, pitch perception) and speech (talker discrimination)?

2. How accurately does testing of simulations of electric hearing with NH children predict outcomes with pediatric CI recipients?
3. What are the relations among timbre, pitch perception and talker discrimination?
4. What are the relations between perception of pitch, timbre, talker discrimination, and speech reception with and without background noise?
5. Do individual listener characteristics (e.g., age at testing, musical training) predict outcomes on timbre, pitch, and talker discrimination?

Method

Participants

Participants included 35 NH, typically developing children and 30 pediatric CI recipients. The NH participants (17 female, 18 male) had a mean age of 10.43 years (range 8–14 years) and all spoke English as their primary language. All participants passed a hearing screening, confirming pure-tone thresholds of 20 dB HL at 250, 500, 1000, 2000 and 4000 Hz. The auditory pathways of NH had developed in response to acoustic stimulation. NH participants, recruited through advertisement, were volunteers and received compensation. The study was approved by the Institutional Review Board and each participant and their guardian provided informed consent.

The pediatric CI recipients were enrolled in a large Midwestern research hospital for their implantation and follow-up services and tested during their annual research and clinical visits. The CI recipients (19 F, 11 M) all spoke English as their first language and had a mean age of 12.07 years (range of 7 to 17 yrs.). They were pre- or peri-lingually deaf with average age of onset 0.82 years (SD =1.21, min =0, max = 4); average age of implant was 4.83 years (SD=4.38, min=.92, max=16.08). Most or all development of the auditory pathways of the CI group was in response to electric stimulation. All used oral communication. Table 1 describes demographics and auditory profile characteristics of the CI users.

Measures

Instrument Timbre Recognition Task (ITRT)—The primary dependent variable for this study was the Instrument Timbre Recognition Task (ITRT). This task was developed expressly for this study because many of the prior experimental tasks for timbre recognition were either devised for adult users (e.g., test protocols that may be inappropriate with regard to test length, instructions, or response requirements), or required sufficient prior familiarity with the targeted musical instruments as part of selection criteria (see review in (Looi et al., 2012)) Prior pediatric studies indicate that for various reasons (e.g., Individual Education Plans eliminating participation in music instruction), some pediatric CI users have little if any knowledge about music instruments (Gfeller et al., 1999). Therefore, this task included brief training (direct exposure) of the selected instrumental timbres prior to testing. The acute training also provided the NH group with some practice in listening to and making paired associations between the novel representation through the CI and each instrument tested.

The timbral stimuli were prepared and presented in two listening conditions: (a) unprocessed ('normal') musical instrument digital interface (MIDI) sound files of commonly known musical instruments, and (b) a processed version (simulation of electric hearing through CI) of MIDI sound files used in the 'unprocessed' listening condition. The NH group was tested under both the unprocessed and processed (simulation) conditions. The pediatric CI users were tested only under the unprocessed condition. The creation of stimuli is described in the following section.

Creation of the sound stimuli

The MIDI sound files included six different musical instruments created with professional composition software, Finale SongWriter®: flute, clarinet, violin, cello, trombone, and piano. These six instruments were selected because previous research indicated they are familiar to many children (Gfeller & Driscoll, 2010; Olszewski et al., 2006) (an important consideration in a recognition task) and because they represented four musical instrument families based upon different principles of sound production, thus comprising different spectral characteristics. Because prior research indicates that perceptual acuity of CI recipients can vary as a function of frequency range (Gfeller, Witt, Woodworth, et al., 2002), instruments were chosen to represent different frequency ranges: cello and trombone represented the lowest range, piano and clarinet represented the medium range, and flute and violin represented the highest range.

Each of the MIDI files consisted of a brief four-note melodic pattern that was composed for this study, but based upon prior studies of timbre recognition (for review, see Looi et al., 2012). The starting pitch for each MIDI file was 130 Hz for low, 260 Hz for medium, and 520 Hz for high range. The frequency range for each instrument was within typical performance range. MIDI files were used rather than live instrument recordings in order to maintain control over spectro-temporal and intensity cues.

Pilot testing of instrument discrimination and recognition was conducted prior to final testing in order to evaluate feasibility. Because a timbre discrimination task resulted in ceiling effects, a closed-set identification task was chosen for the dependent variable in the finalized ITRT.

After MIDI items were produced for each of the six instruments, a processed version, simulating the signal conveyed by a CI, was prepared. The simulations were created using AngelSim™ software (Fu, 2012). The simulation used a white noise vocoder, and audio files were band passed into 8 frequency channels. As described on the AngelSim™ website (Fu, 2012), at each frequency, the temporal envelope was extracted, using half-rectification and low-pass filtering. The cut-off frequency was 160 Hz with 24 dB/octave filter slope with the filter type based on the Greenwood function, with the analysis filter design of 200 to 7000 Hz at 24 dB/octave and carrier filter design of the same range. The extracted envelope was used to modulate a wide-band white noise, which was then filtered with a bandpass filter. The modulated noise bands were summed and presented at equal root mean squared (RMS).

The simulation condition permitted assessment of the impact of electric hearing on timbre recognition, without the influence of factors known to contribute to variability among CI

recipients. Simulation testing also examined the feasibility of the testing protocol (e.g., understanding instructions, length of test) with the target population prior to enrolling CI patients in testing beyond their typical protocol for annual testing. Subsequent comparisons between the simulation condition and testing with CI users permitted an evaluation of how closely simulation testing predicts actual CI outcomes (Research Question 2).

Prior to initiating the experiment, test methods and language used in instructions were examined by three speech-language pathologists for appropriate level of difficulty, task length, and clarity for children. After pilot testing with 15 NH listeners confirmed the format and content of the ITRT were suitable, the task was finalized. Pilot data were not included in the final data analyses.

Test administration of the ITRT

The finalized protocol included two practice items with musical instruments not used in formal testing to ensure that participants understood the task. After the practice items were completed, formal testing commenced. The ITRT for NH participants included three sections. Part 1 introduced each of the six instrumental sounds in the electric (simulation) condition along with pictures of the source (e.g., photographs of a flute, piano, etc.). The computer screen instructions stated that six musical instruments would be played through a special machine so the instruments would not sound like they normally sound. Each instrument simulation was presented with pictures of the musical instrument that played. Each instrument simulation was presented twice.

After the introduction of the six instruments, Part 2 commenced in which each processed file of the six instruments from Part 1 was presented randomly two times. Part 2 required the NH participant to match each item with the picture of the correct musical instrument. No feedback was given on accuracy. Participants were encouraged to guess if unsure.

Part 3 asked the NH listener to identify each instrument from unprocessed MIDI sound files. This section helped to ascertain how accurately the instruments could be recognized under normal acoustic listening conditions and whether or not each of the six instruments was familiar to each participant. Instruments in this section were also presented twice, randomly. All three parts took approximately 15 minutes.

The CI recipients completed a version of the ITRT-CI that included Parts 1 and 3 using only unprocessed MIDI files. No simulations were presented to the CI participants.

Pitch Discrimination Task (PDT)—In order to better understand the relations between pitch and timbre perception, a pitch discrimination task was administered. The Pitch Discrimination Task (PDT) tested the listener's ability to determine from two different pitches whether the second pitch was higher or lower than the first. The PDT used complex pitches produced using MIDI acoustic piano, which permitted control of the acoustic parameters of the stimuli. The tones spanned three octaves, ranging from 73–553 Hz. Participants heard two complex MIDI piano tones separated by one second of silence. An adaptive algorithm was used to determine the number of semitones (smallest interval on the piano, in the scale for western music) necessary for an individual to accurately discriminate

a difference between two pitches. This algorithm was an adaptation of the staircase method (Cornsweet, 1962; Treutwein, 1995) and required nine correct choices before the interval decreased and three errors for the level to increase. The number of presentations varied, depending on response accuracy. The minimum number of representations was 24, with maximum of 54. On average, a participant heard around 40 presentations before threshold was determined. This measure is further described in research with adult cochlear implant recipients and normal-hearing adults (Gfeller, Turner, et al., 2002).

Children’s Music Background Questionnaire (CMBQ)—Because prior research indicates how the extent of formal or informal musical experience or training could influence accuracy (Gfeller et al., 2008), a music background assessment was administered to participants. This measure, described in detail by Gfeller et al. (1999), provided a numerical index of how much music experience (music classes, etc.) each child had prior to testing. This measure was examined as a possible predictor of the dependent variables in the study in research question 5.

Talker Discrimination Task (TDT)—In order to examine the relations among timbre recognition, pitch perception, and talker discrimination, the *Talker Discrimination Task* (TDT) (McDonald et al., 2003) was administered to all participants. This task used a same-different paradigm in which participants heard a sentence spoken twice, and responded whether the same or different talkers spoke the sentences. Participants responded by clicking “same” or “different” on the computer screen. Final outcomes were scored as percent correct.

The stimuli in the TDT were produced by ten adult talkers (half female, half male). The sentence used in this task was “He ran halfway to the hardware store.” This sentence, taken from the Indiana Multi-Talker Sentence Database, and talkers’ presentations covered a wide range of frequencies.

The TDT included a set of five practice pairs. Participants did not receive feedback on the practice items or actual task. For 50% of the sentence pairs, the talker was the same; for the other 50%, the talkers were different. All talkers were paired with every other talker an equal number of times and presentations were randomly ordered. For the NH participants, all sentence presentations were converted to 8-channel CI simulations as described earlier, representing electric hearing.

Multimodal Lexical Sentence Test for Children (MLST-C)—Previous research indicates a significant relationship between some aspects of speech and timbre recognition abilities (Gfeller, Turner, et al., 2002). However, these studies have examined relations in adult CI users, who have mapped the novel sounds heard through their CI onto a mental representation of spoken and musical sounds. This study provided an opportunity to better understand this relationship in pediatric CI users, whose hearing history has been primarily through a device that provides poor spectral resolution. Therefore, speech recognition was included as a variable in this study. The *MLST-C* is a speech recognition measure developed by Kirk et al. (2012). This test used 100 semantically neutral sentences, each five to seven words long, with three keywords. The keywords were controlled for lexical density and word

frequency. All words were common productions of 3 to 5 year-old typically developing children. Sentences were spoken by five female and five male talkers. For the NH participants, all sentence presentations had been converted to 8-channel CI simulations, representing electric hearing.

Because NH children were unaccustomed to speech testing (which the CI users experienced annually) and electrically-produced speech, each NH participant heard ten practice sentences, five during which the participant merely listened, and five in which they repeated what they heard. After the practice section, the participant heard four lists of sentences. Two lists were presented in quiet and two in speech-shaped noise at a SNR of +10. The noise used for this test was created based on 100 concatenated sentences from the corpus. Specifics regarding the noise creation can be found in Krull, Choi, Kirk, Prusick, and French (2010). Each list contained eight sentences equivalent for the following parameters: balanced in talker gender, equal numbers of sentences from all lexical categories, at least two female and two male talkers, and strong list equivalency. The lists were counterbalanced over participants, and order of lists presented in quiet or in noise was randomized. After hearing each sentence, participants repeated what they heard, and were encouraged to guess if unsure. Responses were scored by the percent correct of keywords repeated correctly.

Testing Protocol—Testing was completed at a university hospital in the United States. NH participants first completed the hearing screening. The CI participants were tested as part of their annual visits for device maintenance and assessment of speech and language development.

After the consent and confirmation process, each participant completed the Pitch Discrimination Task (PDT) (unprocessed) followed by both speech measures and the Instrument Timbre Recognition Task (ITRT). For the NH group, speech and ITRT testing included simulation testing. Participants were tested individually in sound field in a double-walled sound booth. The items for all tests were presented at 60 dBC SPL through an Alessis amplifier to two speakers placed one meter away at 5 degrees azimuth. Finally, participants completed the Children's Musical Background Questionnaire (CMBQ) (Gfeller et al., 1999). Frequent breaks were offered. All measures were completed in one two-hour session. Table 2 provides a summary of the conditions under which the stimuli were presented for each group and test.

Statistical Analysis

A variety of statistical methods were employed to address the research questions. The first research question investigated the impact of electric hearing upon perception of spectrally complex features of music and speech. This analysis comprised two sample t-tests for independent groups, assuming equal variances for each of the comparisons between CI users and NH subjects summarized in Tables 3a, b, and c. In order to compare the outcomes on the ITRT for the NH subjects in the simulated and unprocessed conditions, a paired t-test was used.

The second research question addressed how accurately the simulation condition with NH listeners predicted the outcomes of the pediatric CI users. For this research question,

multiple linear regressions were used. A regression model was built based upon data from NH children who listened to CI simulated sound. Using the estimated regression coefficients from this regression model, data from the children using CIs was plugged into the fitted regression model to predict the CI users' timbre recognition (ITRT). This predicted ITRT was compared to the CI users' actual ITRT values to assess how well the NH children listening to simulations predict CI users' scores. Accuracy was assessed by fitting a regression model using predicted ITRT to predict actual ITRT values and plotting the corresponding 95% prediction and confidence intervals.

Research questions 3 and 4 elucidated the relationships between perceptions of timbre, pitch perception, talker discrimination, and speech reception with and without background noise. Pearson's correlation was used to quantify the strength and significance of the relationships.

Finally, the 5th research question examined the relations between individual listener characteristics and the outcomes of timbre recognition, pitch perception, and talker discrimination. Multiple linear regression models using CMBQ, age, and group (either NH or CI) as predictor variables were used to evaluate these relations. The large number of devices and strategies reported in conjunction with well-documented variability of CI users on other influential factors (for review, see Looi et al., 2012), precluded a meaningful analysis of the impact of device or strategy with the sample size tested in this study.

Results

In order to determine the impact of electric hearing upon perception of spectrally complex features of music and speech, comparisons were made between groups (CI vs. NH) and within groups (NH, acoustic vs simulations) using t-tests. Table 2 summarizes the comparisons examined in each test. Conditions in which both NH and CI groups heard unprocessed sound represented the typical listening condition for each group. The simulation condition represented acute exposure to electric hearing, as opposed to the long-term acclimatization of CI users. Tables 3a, b, c describe the results of these tests.

On pitch (PDT), the mean of NH participants was significantly different and more accurate (Mean of 3 semitones) than CI subjects (Mean of 9 semitones) on threshold discrimination ($p < .0001$). On the unprocessed version of timbre recognition (ITRT), the NH mean was significantly more accurate (86.2%) than the CI mean (65.8%) ($p < .0001$). On timbre, mean accuracy for the NH group was significantly better ($p < .0001$) on the acoustic (unprocessed) condition (86.2% correct) than the simulation condition (53.1%). Thus, for pitch perception and timbre recognition, acoustic hearing was superior to electric hearing conveyed through either simulations or CIs.

Our second research question examined how acute simulation testing with NH children compared to outcomes of pediatric CI recipients. NH children in the simulation conditions (acute electric hearing) performed less accurately than CI children (acclimatized long-term electric hearing), on timbre recognition (ITRT, $p = 0.0067$) and the Multimodal Lexical Sentence Test for Children (MLST-C), both in quiet ($p < 0.0001$) and in noise ($p = 0.0007$). On the Talker Discrimination Task (TDT), there was no significant difference between NH

(simulations) and CI (unprocessed) talker discrimination performance; however, CI users showed considerably more variability than the NH group in the acute simulation condition. Thus, on at least two of the measures (timbre recognition, speech recognition), the simulation conditions underestimated the accuracy that a pediatric CI user would achieve after acclimatization to the CI signal.

In order to determine if general trends from the simulation condition were similar to CI users, a linear regression model was used to model the percent correct for instrumental timbre recognition (ITRT) in NH children under the simulation condition. Then, this model was used to predict the CI users' ITRT score; these predicted ITRT scores were compared to the CI users' actual ITRT scores. Predictor variables were pitch (PDT), age, MLST-C (quiet, noise), talker discrimination (TDT), music background scores (CMBQ), and gender.

To estimate this regression model, 32 NH observations were used. No model selection was conducted, as the goal was to describe the most variance possible, not to select important predictor variables. The resulting model was used to ascertain predicted the timbre recognition (ITRT) value for each of the CI participants within complete data sets for the relevant variables ($N = 21$). The predicted ITRT value was then compared to the actual ITRT percent correct. Figure 1 shows the actual ITRT percent correct versus the predicted ITRT percent correct. A 45-degree line was added to the plot as a reference line. If NH outcomes predicted the scores of CI children, then the points would fall on the line. Figure 1 shows that most points are above the line, meaning the model underestimates ITRT scores for the CI users.

When a regression line was fitted to this data (using predicted ITRT to predict actual ITRT), the coefficient was not significant ($p\text{-value} = 0.0935$, $\text{adj } R^2 = 0.09572$) (see Figure 2). Along with the regression line, 95% prediction bands and 95% confidence bands have been plotted. This was done to examine how well the predicted ITRT (NH simulations) could predict the ITRT scores of the CI users (see Figure 3). Since many of the points did not fall within the confidence bands, this indicated that the predicted ITRT was not a good predictor of the ITRT scores for the CI group. Furthermore, if the predicted ITRT accurately predicted the actual ITRT, the 95% Prediction Interval would be narrow (see Figure 4). On the plot, this interval was extremely wide, containing a large range of values. This is another indication that the predicted ITRT from the NH simulation data did not accurately predicting actual ITRT outcomes.

Our third and fourth research questions examined the relations among the following variables for the two groups (NH, CI): Timbre recognition (ITRT), Pitch (PDT), Talker discrimination (TDT), and the Multimodal Lexical Sentence Test for Children (MLST-C) in quiet and noise. For the NH group in the simulation condition, there was a significant Pearson correlation between TDT and speech recognition, MLST-C in quiet ($r = 0.41597$, $p = 0.0179$) and between MLST-C in quiet and in noise ($r = 0.57423$, $p = 0.0005$). No other correlations were significant.

For CI group, there was a significant Pearson correlation between TDT and PDT ($r = -0.42028$, $p = 0.0325$), TDT and MLST-C in noise ($r = 0.38700$, $p = 0.0461$), and MLST-C

in noise and quiet ($r = 0.86434$, $p < 0.0001$). No other correlations for the CI group were significant. Thus, the relations among these variables differed between the NH and CI groups.

Finally, we examined whether individual characteristics such as age, hearing status (NH, CI), and prior music experience (CMBQ) predicted performance on the ITRT, PDT, and TDT. Regression models were used to determine which characteristics account for differences among the participants on ITRT, PDT and TDT. The predictor variables were CMBQ, age, and group (CI, NH). For ITRT, the overall model was significant ($p=0.0017$), but the only variable with a significant coefficient was group (NH or CI) (-13.125 , $p=0.0130$). More specifically, for NH children in the acute simulation condition, we can expect the mean ITRT will be 13.125% lower than in the CI group.

The model was also significant for PDT (unprocessed for both groups) with significant coefficients for both group (NH, CI) (-5.813 , $p=0.0009$) and CMBQ (-0.402 , $p=0.0073$). Thus, on average the participants with NH would be expected to have a mean PDT score 5.813 lower (which indicates more accurate performance) than those in the CI group. More specifically, for every unit increase of music experience measured using the CMBQ, we would expect a decrease (thus better performance) of 0.402 in PDT on average. For TDT, the overall model was significant ($p=0.0175$). Only the coefficient for CMBQ was significant (0.486 , $p=0.0497$). Thus, for every unit increase in music training/experience, (CMBQ), we would expect an increase of 0.486 units in talker discrimination percent correct. For both NH and CI groups, music training was predictive of better performance on both PDT and also on the TDT, but not for ITRT.

Discussion

The primary purposes of this study were to compare, in a pediatric population, electric vs. acoustic hearing for transmission of spectrally complex aspects of music and speech, to examine how the results of simulations of electric hearing compare with results of pediatric CI users, and to determine which factors predict outcomes. Whether comparisons were between groups who have acoustic hearing (NH) or electric hearing (CI), or within-subject comparisons (NH in acoustic vs. simulation conditions), electric hearing resulted in significantly less accurate perception on pitch perception and timbre recognition. This is consistent with many prior studies (for reviews, see Limb & Roy, 2014; Looi et al., 2012) documenting that electric hearing is less effective in conveying spectrally complex features of music (timbre, pitch) and speech (talker discrimination)..

Our second research question examined how accurately CI simulations with NH children estimate how well pediatric CI users are able to perceive spectrally complex aspects of music and speech. Neither t-test comparisons nor the regression model indicated that the simulations provided an accurate prediction of outcomes for the pediatric CI group on these measures; rather, the results underestimated the performance. Consequently, the use of acute simulation testing as conducted in this study did not offer a useful prediction of how accurately pediatric CI users could perceive timbre or pitch following months or years of acclimatization. These findings highlight methodological limitations of relying exclusively

on simulation testing. While simulation testing has the advantage of focusing on the impact of the auditory input, and can provide some insights regarding the feasibility of a test protocol, it is important to account for individual differences among users, including life experiences as important influences on CI benefit, above and beyond the auditory input.

There are important differences between the two groups tested (NH with simulations, CI users) that could explain different outcomes. First, the mental representation of structural features of music and speech will be different for children whose auditory pathways developed in response to electric as opposed to acoustic stimulation. On one hand, children using implants from infancy would have an electrodotopic representation of acoustic features such as pitch. Thus, CI recipients, having grown up hearing music and speech through the implant would have developed a unique and less refined mental representation of what various pitches, timbres, and talkers sound like. The NH children, while having a healthy auditory system and more 'normal' and rich representation of spectrally complex sounds, in this testing condition would have to quickly map on to their well-established representation of pitches, timbres, and voice quality of talkers, how these auditory features sound through the simulation. The testing provided only a brief period of acclimatization.

Given these differences, it is not particularly surprising that the CI group was significantly more accurate than the NH group in acute simulation testing. It would be advisable for future studies to test NH children after a greater length of experience with the simulations, and determine whether those results more closely resemble outcomes of long-term CI users. While our results are disappointing with regard to methodological potential of acute simulation testing, our results can be seen in a positive light from a clinical standpoint, namely that children who have grown up with electrical hearing appear able to achieve more accurate outcomes of spectrally complex music and speech perception as a result of long-term usage than acute stimulation testing predicts.

In looking at relations among the music and speech measures, it is interesting to see slightly different patterns between the NH and CI groups. For example, while both NH and CI groups showed strong relations between the two speech tasks of TDT and MLST-C, it was interesting to note that a significant relationship between PDT and TDT existed for only the CI group. Thus, it appears with electric speech, those CI users who are able to extract better pitch percepts may find that information beneficial in differentiating between the gender of speakers as well as two speakers of the same sex. The NH children listening to simulations of TDT may have lacked enough experience to successfully extract and apply pitch cues for that task, or information processing is sufficiently different between the two groups as a result of hearing history that cues are used differently in these perceptual tasks.

As we consider individual characteristics, it is of interest that extent of music training was predictive of more accurate talker discrimination as well as pitch perception. If music training can enhance pitch perception in CI users as well as NH children, and pitch assists CI users in talker discrimination, then music training that includes pitch-based tasks may offer benefits in optimizing CI use for spectrally complex speech as well as music.

In summary, because acoustic hearing was superior on all the tasks in the study, the preservation of acoustic hearing through atraumatic surgical techniques or electrode arrays is important to consider with regard to perception of complex elements in speech as well as music. It would also be interesting to examine possible synergistic benefits of bimodal hearing. However, it is possible that benefits achieved with conventional CIs and individuals with limited residual hearing may be optimized through music training.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors would like to thank all those who took part in this study. This study was supported by grant 2 P50 DC00242, RO1 DC012082-10, and 5 RO1 DC008875-06 from the NIDCD, NIH; and the Iowa Lions Foundation. None of the authors report having a conflict of interest.

References

- American Standards Association, & Acoustical Society of America. American Standards Acoustic Terminology. New York: Acoustical Society of America; 1960.
- Cleary M, Pisoni D. Talker discrimination by prelingually deaf children with cochlear implants: Preliminary results. *The Annals of Otolaryngology, Rhinology, and Laryngology Supplement*. 2002; 189:6.
- Cleary M, Pisoni DB, Kirk KI. Influence of voice similarity on talker discrimination in children with normal hearing and children with cochlear implants. *Journal of Speech, Language, and Hearing Research*. 2005; 48(1):204–223.
- Cornsweet TN. The staircase-method in psychophysics. *American Journal of Psychology*. 1962; 75:485. [PubMed: 13881416]
- Cullington HE, Zeng FG. Comparison of bimodal and bilateral cochlear implant users on speech recognition with competing talker, music perception, affective prosody discrimination, and talker identification. *Ear and Hearing*. 2011; 32(1):16. [PubMed: 21178567]
- Drennan WR, Oleson JJ, Gfeller K, Crosson J, Driscoll VD, Won JH, ... Rubinstein JT. Clinical evaluation of music perception, appraisal and experience in cochlear implant users. *International Journal of Audiology*. 2015; 54(2):114–123. [PubMed: 25177899]
- Driscoll V. The effects of training on recognition of musical instruments by adults with cochlear implants. 2012; 33(4):410.
- Driscoll V, Oleson J, Jiang D, Gfeller K. The effects of training on recognition of musical instruments presented through cochlear implant simulations. *Journal of the American Academy of Audiology*. 2009; 20(1):71–82. [PubMed: 19927684]
- Fu, Q. AngelSim™ Cochlear Implant Hearing Loss Simulator (Version 1.05.05). 2012. Retrieved from <http://www.tigerspeech.com/angelsim/>
- Fu Q, Chinchilla S, Galvin J. The role of spectral and temporal cues in voice gender discrimination by normal-hearing listeners and cochlear implant users. *Journal of the Association for Research in Otolaryngology*. 2004; 5(3):8.
- Fu Q, Chinchilla S, Nogaki G, Galvin J. Voice gender identification by cochlear implant users: The role of spectral and temporal resolution. *The Journal of the Acoustical Society of America*. 2005; 118(3):1711. [PubMed: 16240829]
- Fu Q, Nogaki G. Noise susceptibility of cochlear implant users: The role of spectral resolution and smearing. *Journal of the Association for Research in Otolaryngology*. 2004; 6(1):19.
- Galvin JJ, Fu Q, Nogaki G. Melodic contour identification by cochlear implant listeners. *Ear and Hearing*. 2007; 28(3):302.doi: 10.1097/01.aud.0000261689.35445.20 [PubMed: 17485980]

- Gfeller, K., Driscoll, V. The effect of training on melody and timbre recognition by pediatric CI recipients. Paper presented at the 11th International Conference on Cochlear Implants and Other Implantable Auditory Technologies; Stockholm, Sweden. 2010.
- Gfeller K, Driscoll V, Kenworthy M, Van Voort T. Music Therapy for Preschool Cochlear Implant Recipients. 2011; 29(1):39.
- Gfeller K, Jiang D, Oleson J, Driscoll V, Knutson JF. Temporal stability of music perception and appraisal scores of adult cochlear implant recipients. *Journal of the American Academy of Audiology*. 2010; 21(1)
- Gfeller K, Knutson JF, Woodworth G, Witt S, DeBus B. Timbral recognition and appraisal by adult cochlear implant users and by normal-hearing adults. *Journal of the American Academy of Audiology*. 1998; 9(1):1. [PubMed: 9493937]
- Gfeller K, Oleson J, Knutson JF, Driscoll V, Olszewski C. Multivariate predictors of music perception and appraisal by adult cochlear implant users. *Journal of the American Academy of Audiology*. 2008; 19(2)
- Gfeller K, Turner C, Oleson J, Kliethermes S, Driscoll V. Accuracy of cochlear implant recipients on speech reception in background music. *Annals of Otology, Rhinology and Laryngology*. 2012; 121(12):782.
- Gfeller K, Turner C, Oleson J, Zhang X, Gantz B, Froman R, Olszewski C. Accuracy of cochlear implant recipients on pitch perception, melody recognition and speech reception in noise. *Ear and Hearing*. 2007; 28(3):412. [PubMed: 17485990]
- Gfeller K, Turner C, Woodworth G, Mehr M, Fearn R, Witt S, Stordahl J. Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. *Cochlear implants international*. 2002; 3:31.
- Gfeller K, Witt S, Adamek M, Mehr M, Rogers J, Stordahl J, Ringgenberg S. Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. *Journal of the American Academy of Audiology*. 2002; 31:132.
- Gfeller K, Witt S, Woodworth G, Mehr M, Knutson JF. Effects of frequency, instrumental family, and cochlear implant type on timbre recognition and appraisal. *Annals of Otology, Rhinology, and Laryngology*. 2002; 111:349.
- Gfeller K, Witt SA, Spencer L, Stordahl J, Tomblin JB. Musical involvement and enjoyment of children using cochlear implants. *Volta Review*. 1999; 100(4):213.
- Hsiao F, Gfeller K. Music perception of cochlear implant recipients with implications for music instruction: A review of literature. Update: applications of research in music education. 2012; 30:5. [PubMed: 23469365]
- Innes-Brown H, Marozeau JP, Storey CM, Blamey PJ. Tone, rhythm, and timbre perception in school-age children using cochlear implants and hearing aids. *Journal of the American Academy of Audiology*. 2013; 24(9)doi: 10.3766/jaaa.24.9.4
- Jung KH, Won JH, Drennan WR, Jameyson E, Miyasaki G, Norton SJ, Rubinstein JT. Psychoacoustic performance and music and speech perception in prelingually deafened children with cochlear implants. *Audiology & Neurotology*. 2012; 17(3):189.doi: 10.1159/000336407 [PubMed: 22398954]
- Kirk K, Prusick L, French B, Gotch C, Eisenberg LS, Young N. Assessing spoken word recognition in children who are deaf or hard of hearing: A translational approach. *Journal of the American Academy of Audiology*. 2012; 23(6):12.
- Krull V, Choi S, Kirk KI, Prusick L, French B. Lexical effects on spoken word recognition in children with normal hearing. *Ear and Hearing*. 2010; 31(1):102. [PubMed: 19701087]
- Li A, Wang N, Li J, Zhang J, Liu Z. Mandarin lexical tones identification among children with cochlear implants or hearing aids. *International Journal of Pediatric Otorhinolaryngology*. 2014; 78(11):1945–1952. [PubMed: 25234731]
- Limb CJ, Roy AT. Technological, biological, and acoustical constraints to music perception in cochlear implant users. *Hearing Research*. 2014; 123(7)doi: 10.1002/lary.23752
- Loizou P, Dorman M, Tu Z. On the number of channels needed to understand speech. *Journal of the Acoustical Society of America*. 1999; 106(4):7.

- Looi V, Gfeller K, Driscoll V. Music appreciation and training for cochlear implant recipients: A review. *Seminars in Hearing*. 2012; 33(4)
- McDonald, CJI., Kirk, KI., Houston, DM., Sprunger, AB., Krueger, TJ. Talker discrimination by adults with cochlear implants. Paper presented at the Association for Research in Otolaryngology 26th Midwinter Meeting; Daytona Beach, FL. 2003.
- Moore BCJ, Tan C. Perceived naturalness of spectrally distorted speech and music. *Journal of the Acoustical Society of America*. 2003; 114(1):408. [PubMed: 12880052]
- Nogaki G, Fu Q, Galvin JJ. Effect of training rate on recognition of spectrally shifted speech. *Ear and Hearing*. 2007; 28(2):132. [PubMed: 17496666]
- Olszewski, C., Gfeller, K., Driscoll, V. Effect of training on music perception by pediatric CI recipients. Paper presented at the 9th International Conference on Cochlear Implants; 2006 Jun 16.
- Patel, A. *Music, language, and the brain*. Ny: Oxford Press; 2008. p. 9
- See RL, Driscoll VD, Gfeller K, Kliethermes S, Oleson J. Speech intonation and melodic contour recognition in children with cochlear implants and with normal hearing. *Otology & Neurotology*. 2013; 34(3):490–498. doi:410.1097/MAO.1090b1013e318287c318985. [PubMed: 23442568]
- Torppa R, Salo E, Makkonen T, Loimo H, Pykäläinen J, Lipsanen J, ... Huottilainen M. Cortical processing of musical sounds in children with Cochlear Implants. *Clinical Neurophysiology*. 2012; 123(10):1966. [PubMed: 22554786]
- Treutwein B. Mini review. Adaptive psychophysical procedures. *Vision Research*. 1995; 35:2503. [PubMed: 8594817]
- Wright R, Uchanski RM. Music perception and appraisal: Cochlear implant users and simulated CI listening. *Journal of the American Academy of Audiology*. 2012; 23(5):350. [PubMed: 22533978]

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Table 1

Int ID	Device 1	Device 2	Strategy	Processor	Rate/Channel	Length of use	Age @ implant	Current Age
1	CI24RE(CA)		ACE	CP810	900 Hz	35	12	15
2	CI24RE(CA)		ACE	Freedom	1200 Hz	45	1.83	9
3	HR90K/HiFocus 1J		HiRes Optima-S	Harmony	2560 pps	35	4.42	7
4	Hybrid S12	CI24RE(CA)	ACE	CP810; CP910	900 Hz	72;58	1.25	7
5	CI24R(CS)		ACE	CP810	1200 Hz	168	1.69	15
6	CI24RE(CA)	CI24RE(CA)	ACE	Freedom; Freedom	1800 Hz	108;72	5	14
7	CI24RE(CA)	CI24RE(CA)	ACE	Freedom; Freedom	900 Hz; 1200 Hz	95	0.92	8
8	CI24RE(CA)	CI24RE(CA)	ACE	Freedom; Freedom	900 Hz	73	1.08	7
9	Hybrid L24		ACE	CP910	900 Hz	35	12.08	15
10	CI24RE(CA)	CI24RE(CA)	ACE	CP810; CP810	900 Hz	96	2.58	10
11	CI24M		ACE	CP810	900 Hz	191	1.58	17
12	CI24R(CS)		ACE	CP810	1200 Hz	155	2.33	14
13	CI24R(CS)	CI512	ACE	CP810; CP810	1200 Hz	155; 48	3.42	16
14	CI24RE(CA)	CI24RE(CA)	ACE	CP910; CP910	900 Hz	96; 89	6.83	14
15	CI24RE(CA)	CI24RE(CA)	ACE	CP810; CP810	2400 Hz	120;93	3.92	13
16	HR90K/HiFocus 1J	HR90K/HiFocus 1J	HiRes-S w/Fidelity 120	Harmony; Harmony	3712 pps, 2855 pps	126;107	2.33	12
17	CI24R(CA)	CI422	ACE	CP810; CP910	900 Hz	131;7	1.33	12
18	CI24RE(CA)	CI24RE(CA)	ACE	CP810; CP810	900 Hz	38;32	7.92	12
19	HR90K Advantage/HiFocus 1J		HiRes Optima-P	Naida Q70	2250 pps	23	13.08	15
20	CI512	CI422	ACE	CP810; CP810	900 Hz	47;31	3.92	7
21	CI24RE(CA)	CI512	ACE	CP810; CP810	900 Hz	47;38	4	7
22	Hybrid L24		ACE	CP910	900 Hz	18	16.08	17
23	CI24RE(CA)	CI422	ACE	CP910; CP910	1200 Hz	80;7	1.08	7
24	Hybrid L24		ACE	CP910	900 Hz	24	13.5	15
25	CI512		ACE	CP810	900 Hz	59	4.58	9
26	CI512		ACE	CP810	900 Hz	47	9.92	13
27	CI24RE(CA)	CI24RE(CA)	ACE	CP810; CP810	1200 Hz	168;40	1.6	15
28	CI24M		ACE	Freedom	1200 Hz	192	1.58	17

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Int ID	Device 1	Device 2	Strategy	Processor	Rate/Channel	Length of use	Age @ implant	Current Age
29	CI24RE(CA)		ACE	CP810	1800 Hz	120	1.17	10
30	CI24R(CA)		ACE	CP920	900 Hz	135	1.83	13

Table 2

	PDT	ITRT	ITRT	ITRT	TDT	MLST-C In quiet	MLST-C In noise
NH [Acoustic hearing]	unprocessed	unprocessed	Unprocessed vs. simulation	simulation	simulation	simulation	simulation
CI [Electric hearing]	unprocessed	unprocessed	-----	unprocessed	unprocessed	unprocessed	unprocessed

PDT=Pitch Discrimination Test
ITRT=Instrument Timbre Recognition Test
TDT=Talker Discrimination Test
MLST-C= Multimodal Lexical Sentence Test for Children

Table 3a

CI Users						
Variable	Condition	N	Mean	Std Dev	Minimum	Maximum
PDT	Unprocessed	29	9.31	8.43	1	24
TDT	Unprocessed	27	82.97	13.44	49.1071	100
MLST-C in quiet	Unprocessed	29	77.16	18.93	18.7500	95.8333
MLST-C in noise	Unprocessed	29	62.07	20.79	10.4167	93.75
ITRT Unprocessed	Unprocessed	30	65.83	17.42	33.3333	91.6667

Table 3b

NH Subjects						
Variable	Condition	N	Mean	Std Dev	Minimum	Maximum
PDT	Unprocessed	34	2.47	3.48	1	19
TDT	Simulation	34	86.90	5.94	74.1071	94.6429
MLST-C in quiet	Simulation	33	56.94	15.96	18.75	89.5833
MLST-C in noise	Simulation	33	45.52	15.43	10.4167	68.75
ITRT Unprocessed	Unprocessed	35	86.19	17.73	25	100
ITRT-CI Sim	Simulation	35	53.10	18.97	8.3333	91.6667

Table 3c

Test	Group 1	Condition	Group 2	Condition	p-values
PTD	NH	Unprocessed	CI	Unprocessed	< 0.0001
ITRT	NH	Unprocessed	CI	Unprocessed	< 0.0001
ITRT	NH	Unprocessed	NH	Simulated	< 0.0001
ITRT	NH	Simulated	CI	Unprocessed	0.0067
TDT	NH	Simulated	CI	Unprocessed	0.1318
MLST-C in Quiet	NH	Simulated	CI	Unprocessed	< 0.0001
MLST-C in Noise	NH	Simulated	CI	Unprocessed	0.0007