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THE EFFECT OF TALKER AGE AND GENDER ON SPEECH PERCEPTION OF PEDIATRIC COCHLEAR IMPLANT USERS

by

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submitted in partial fulfillment of the
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Abstract: Most clinically-employed speech materials for testing hearing impaired individuals are recordings made by adult male talkers. The author examined the possible effect of talker age and gender on the speech perception of children through the use of 1) two speech perception tests, each with four talker types (adult males, adult females, 10-12 year olds, 5-7 year olds), and 2) two groups of pediatric listeners: normal-hearing (NH) and cochlear implant users (CI).

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Abbreviations

AB	Advanced Bionics
ANSD	Auditory Neuropathy Spectrum Disorder
Bilateral	CI at each ear (CI + CI)
Bimodal	CI at one ear, HA at the other ear (CI + HA)
CI	Cochlear Implant
HA	Hearing Aid
HI	Hearing Impaired
LVAS	Large Vestibular Aqueduct Syndrome
NH	Normal hearing
Unilateral	One CI only, no device at the other ear

Introduction

Cochlear implants (CI) and hearing aids (HA) can be used to provide auditory information to hearing impaired individuals. One of the primary goals of these devices is to maximize perception of the speech signal. Audiologically, speech perception abilities of CI and HA users are tracked over time to gather information about performance and to monitor progress of auditory skill development.

There are numerous speech perception tests that are employed clinically. Each measure ultimately aims to give insight into the everyday auditory function of hearing impaired individuals. Results on such measures have shown great variation in performance across and between patients. The disparity in scores depend, in part, on factors such as the test given, testing conditions, and patient-specific characteristics including cause and onset of hearing loss and devices used. In addition, when considering the results of speech perception measures, we must take into account the signal used for testing. The majority of speech perception tests have been recorded by adult talkers, and mostly adult male talkers. The Consonant Nucleus-Vowel Consonant (CNC) and Phonetically Balanced Kindergarten (PBK) monosyllabic word tests are examples of commonly used measures recorded by adults.

Acoustically, speech characteristics vary substantially amongst different age and gender talkers (Eguchi *et al*. 1969, Lee *et al.* 1999). Among these differences, the most obvious to the untrained ear may be the variation in both fundamental and formant frequencies for different talkers. The average fundamental frequency of adult males is 125 Hz, adult females 220 Hz, and children 300 Hz. Speech produced by adult females encompasses a wider and higher frequency range than that of males (Byrne *et al*., 1994). Speech produced by children has energy at higher frequencies than that of adults. These spectral differences are largely due to anatomical and

physiological differences between genders as well as developmental changes that occur during childhood (Eguchi *et al*., 1969).

Lee *et al*. (1999) described a set of acoustic parameters from a database of 436 subjects, ages 5 through 18 years old. They found that differences between male and female fundamental and formant frequencies begin to appear at approximately 11 years old, and by age 13, girls have nearly the same fundamental frequency as adult females. The convergence on adult values occurs at approximately 15 years of age for boys.

Aside from frequency specific acoustic parameters, there are additional differences between speech produced by children and adults. One of these is the consistency of the signal. Until up to approximately 12 to 14 years of age, speech produced by children is more variable than that of adults. This is due to the complicated skills of precise articulatory timing and control that continue to develop through early adolescence. There is a decrease in within-subject variability of temporal and spectral parameters with increasing age. This trend is associated with the process of normal speech development in children (Lee *et al*., 1999).

Eguchi and Hirsh (1969) reported that in addition to the significant variations in the speech signal for different age and gender talkers, there are also differences in the perception of these signals. Twenty normal hearing adults were asked to identify vowels spoken by different age talkers. The talker types consisted of 3, 5, 7 and 9 year olds; as well as 11, and 13 year olds and adults. The latter type contained half females and half males. Results showed an increase in accuracy of vowel identification with the increasing age of the talker. This increase in intelligibility with age suggests that speech production is more consistent with increasing age.

When a child is unable to hear specific sounds or phonemes, he/she will have difficulty learning how to produce them. It has been shown that hearing impaired children demonstrate a

delay in morphological development relative to their normal-hearing peers, often due to their delay in acquiring certain phonemes (Stelmachowicz *et al.*, 2004). Access to high frequency sounds can prove to be challenging for hearing impaired individuals. The high frequency region contains consonant sounds that are essential for intelligibility as well as for giving words their meanings. Research has shown that the /s/ phoneme, which serves several linguistic purposes such as a plural and possessive marker, is one of the most frequently misperceived phonemes by hearing impaired individuals (Bilger *et al.*, 1976). Even when utilizing cochlear implants and/or hearing aids, it is often difficult for these individuals to perceive such high frequency sounds due to certain technological limitations. An example is the limited bandwidth of microphones and receivers used in HAs and CIs compared to the bandwidth of the original signal (Pittman *et al*., 2003). Thus, it can be hypothesized that hearing impaired children may have trouble perceiving speech from specific talker types, such as women and children.

Stelmachowicz *et al.* (2002) demonstrated that pediatric hearing aid users require a wider frequency bandwidth to perceive speech well compared to both their normal hearing peers and hearing impaired adults. Audibility of the mid-frequencies (2-4 kHz) proved to be most important for the perception of speech sounds /s/ and /z/ produced by male talkers, while a wider and higher frequency range (2-8 kHz) was need for optimal perception of these same speech sounds spoken by female talkers.

A study by Stelmachowicz *et al*. (2001) focused on the perception of the /s/ phoneme, spoken by different age and gender talkers, by normal hearing (NH) and hearing-impaired (HI) children and adults. Significant talker effects for /s/ were observed. Optimum performance for the perception of /s/ spoken by the adult male talker was reached at a bandwidth of 4000 Hz for NH subjects, and at a bandwidth of 5000 Hz for HI subjects. For the female talker, a steep

increase in performance was seen as the bandwidth widened to 6 kHz for the NH subjects and to 9 kHz for the HI subjects, with optimum performance reached at a bandwidth of 9 kHz for all subjects. For the child talker, optimum performance was also seen at a bandwidth of 9 kHz for all subjects. Results indicated that children (both NH and HI) performed worse than their adult counterparts at similar bandwidths, and that HI subjects performed more poorly than their NH counterparts. These results highlight the importance of children's access to the entire frequency range of the speech signal.

Only a handful of studies have examined the effect of talker age and gender on listeners' overall speech perception scores. These studies employed adult listeners with both normal hearing and impaired hearing, and normal hearing children (Assmann *et al.* 2000, Bradlow *et al*. 1999, Cox *et al.* 1987, Eguchi *et al*. 1969, Green *et al.* 2007, Hazan *et al.* 2004, Hillenbrand *et al.* 1995, Loizou *et al.* 1998). Many of these perceptual studies used word stimuli, namely CNCs, recorded by adults. We know of no published reports of studies using non-adult (child) talkers using the CNC word lists.

Unlike most earlier studies that used only a single male talker, a study by Loizou *et al*. (1998) focused on the vowel recognition abilities of adult cochlear implant users using four talker types (men, women, boys and girls). Five post-lingually deafened adults were asked to identify 11 vowels in the /hVd/ context (recordings made by Hillenbrand *et al.*, 1995). The CI users were presented vowels from the four different talker types (men, women, boys and girls) for identification. Results revealed that vowels produced by men were easier to identify than other types (average of 80% correct across subjects), and vowels from girls were more difficult to identify than any other talker type (average of 63% correct across subjects). They speculated that the main factor contributing to this effect was the poor resolution in the CI processors of

vowel formants that are high in frequency, as found for females' and young girls' speech. Conclusions drawn from this experiment support a potential overestimation of speech perception skills and everyday performance if only male talkers' speech is used as the test signal for audiologic assessment. Currently, it is not known whether a similar result would be obtained with pediatric CI users, or with speech materials other than hVd stimuli.

Other research with adult cochlear implant users has examined the effect of various frequency allocation tables on speech perception scores. A frequency allocation table assigns the overall frequency range (bandwidth) transmitted by the CI system as well as the frequency ranges assigned to individual electrodes. Altering the frequency allocation table changes the amount of energy provided to specific neural regions. Certain CI companies allow these parameters to be adjusted by the clinician in the software. Fourakis *et al.* (2004, 2007) evaluated the use of different frequency allocation tables with post-lingually deafened adult CI users to examine the possibility of improving speech recognition. Performance was evaluated, in part, by using vowel materials (hVd) recorded by adult males, adult females, and children, and word materials (CNC) recorded by adult males. Results from these studies suggest that speech recognition by adult CI users, specifically vowel perception, can be improved by altering frequency allocation tables from the manufacturers default settings. By distributing the spread of information in a specific manner (7-8 electrodes <1000 Hz, majority of remaining electrodes 1100-3000 Hz, 2-3 electrodes >3000 Hz), resolution in the frequency range most important for speech perception of all talker types was maximized. Results also indicated that limiting the upper bandwidth to 6 kHz, rather than 8 kHz, resulted in better performance for vowel perception, no detriment to CNC performance, and subjective sound quality improvements for adults. This finding for adult CI users is inconsistent with findings of Stelmachowicz *et al.*

(2001), who demonstrated increased performance for perception of /s/ at a widened bandwidth (up to 9kHz) for NH adults and children, and HI adults and children using HAs.

However, a similar experiment has not yet been reported with pediatric CI users as subjects. From aforementioned published findings by authors such as Stelmachowicz *et al.*, it is known that HI children have different requirements (such as a wider and higher bandwidth) for optimized perception of /s/ and /z/ compared to both NH children and HI adults. Factors that differentiate adult from pediatric CI users, and may influence research findings, include time of onset of deafness (pre vs. post-lingual) and different needs for audition (such as the goal of auditory language learning). Therefore, it is possible that the conclusions drawn from research on altering frequency allocation tables with HI adults may not apply to the pediatric population.

The typical clinical tests and materials used for evaluating speech perception of hearing impaired individuals using CIs and/or HAs have been recorded by adult talkers, and mostly adult males. The speech perception abilities of individuals with CIs and/or HAs using male-recorded CNC word lists have been studied extensively. However, most children, regardless of their hearing status, do not listen primarily to adult males during the course of their day. They probably hear adult females (mothers, caregivers and teachers), as well as their peers (both young girls and boys) for a majority of their day. Also, children learn to self-monitor their own voice for production through audition. Fewer studies have examined these abilities using female- or child-recorded CNC word lists. As the goal of speech perception testing is to estimate how patients perform in their everyday listening situations, we may consider expanding this standard protocol to obtain a better representation of "real world" environments, with an interest in further optimizing their device settings and possibly improving performance.

The primary aim of this study is to examine whether talker type, specifically talker age and gender, affects speech perception for pediatric cochlear implant users. The questions to be addressed are: 1) Will talker-type effects be observed for either pediatric NH or pediatric CI subjects? and 2) How well do CI children perform compared to NH children? Performance across talker types for both groups of listeners will be compared using repeated-measures analysis of variance (ANOVA). Performance between the two groups will be compared using ANOVA.

Methods and Materials

The research protocol and informed consent for this study were reviewed and approved by the Institutional Review Board and the Human Studies Committee at Washington University School of Medicine. Participants were recruited through collaborators' patient populations and word of mouth. Remuneration of $15 per session was provided for all study participants.

Design: This was a cross-sectional observational study.

Subjects: All CI subjects satisfied the following requirements: chronological age of 7-12 years old, hearing loss as a primary disability, CI user for at least two years, full insertion of the electrode array with at least 15 electrodes activated in the CI map, education in an oral communication setting (either mainstream or oral deaf education classroom), 20% or greater score on open-set word recognition, and English as their primary language. Inclusion criteria for the normal-hearing group were as follows: chronological age of 7-12 years old, normal hearing defined by pure-tone thresholds of ≤15 dB HL at octave frequencies from 250 to 8000 Hz, normal tympanograms, no significant history of middle-ear disease, no reported speech or language delays, education in mainstream setting, and English as their primary language.

Ten hearing-impaired children who use CIs were recruited and participated (5 females, 5 males). The CI subject group (CI 1-10) ranged in age from 7;3 to 12;0 years;months (mean, 9;6;

SD = 1.8) with a minimum of 2;7 years;months of listening experience for their first ear implanted. Five subjects wore a CI at each ear (Bilateral CI), three subjects wore a CI at one ear and a hearing aid at the other ear (Bimodal), and two subjects wore a CI at one ear and no device at the other ear (Unilateral CI). Seven subjects utilized Cochlear Corporation devices and three subjects utilized Advanced Bionics devices. All testing for CI subjects was completed using their current device settings. Settings for each user were reported to be optimized by each subject's audiologist. The highest frequency band assigned to the electrode array is dependent upon the number of active electrodes in the MAP. By default, the upper limits are 7938 Hz and 8000 Hz for Cochlear and Advanced Bionics, respectively. Detailed demographic characteristics and device information of the CI subject group are reported in Tables I and II.

Ten normal-hearing (NH) children were also recruited and participated (4 females, 6 males). The NH subject group (NH 11-20) ranged in age from 7;5 to 11;2 years;months (mean, 9;10; SD = 1.3). All subjects had bilateral thresholds of 15 dB HL or better at all frequencies at octave intervals from 250 to 8000 Hz, verified at the test session. All subjects, except Subject 20, presented with normal tympanograms (normal pressure, compliance and volume). Subject 20 had pressure equalization (PE) tubes, with tympanometric results indicating patent PE tubes, and hearing thresholds within normal limits. Further details of the NH subject group are reported in Table III.

Stimuli: Two sets of speech materials were employed. Each set of materials was spoken by four talker types: adult males, adult females, 10-12 year old girls and 5-7 year old girls.

The first set of speech materials was a group of eleven vowels spoken in an /h/-vowel-/d/ context (hVd), namely the words "heed, hayed, hid, had, hod, head, heard, hoed, hood, hud, who'd" which correspond, respectively, to the vowels /i/, /e/, /I/, /æ/, /a/, /ɛ/, /ɝ/, /o/, /ʊ/, /ʌ/,

/u/. There were a total of 132 different vowel waveforms: 3 tokens of each vowel x 11 vowel sounds x 4 talker types = 132. Each vowel token represents an hVd syllable spoken by a different individual within that talker type, and, in general, more than three different talkers represent each talker type. The hVds spoken by adult males, adult females and 10-12 year old girls are from a larger speech database recorded by Hillenbrand *et al.* (1995), and are the same as those used by Fourakis *et al.* (2007). For each vowel sound, three different talkers are represented, e.g., three different adult females' productions of /hid/ are the three tokens of /I/ for this talker type, and different talkers' productions are used across the 11 vowel sounds. In total, twenty-one adult males, twenty-five adult females, and fourteen 10-12 year old girls are represented in the hVd stimuli for these three talker types. These particular vowel tokens (talker x vowel sound) were chosen because they were highly intelligible when presented to normal hearing adults (Fourakis *et al*., 2007, Hillenbrand *et al*., 1995). The speech stimuli for the talker type, 5-7 year old girls, were recorded and provided by Assmann & Katz (2000). For these vowels, exactly three 5-7 year old girls recorded the hVd syllables, and for each vowel sound, those same three girls' vowels are represented once. These talkers were recruited from the local community in Dallas and have a Texas dialect. Recordings by the 5-7 year old girls were altered in amplitude to have peak RMS values similar to the recordings from Hillenbrand.

Presentation of the tokens was grouped into experimental block by talker type. Random selection was used to assign the order in which talker types were presented for each subject (see Appendix: Tables A10-A12). The CONDOR-ID (Version 2.c) auditory identification program, developed by the House Ear Institute's Department of Auditory Implants and Perception, was used to present the hVd stimuli and to record responses. The program randomly selected the order of tokens within each talker type. All signals from the adult males, adult females and 10-12

year old girls were identified in quiet with 90-100% accuracy by normal-hearing listeners in Hillenbrand *et al.* (1995). One normal hearing adult identified stimuli from all four talker types, in quiet, with 90-100% accuracy at a pilot session conducted at Washington University in St. Louis by the author of this paper (100% for adult males, adult females, 5-7 year old girls, 91% for 10-12 year old girls).

The second set of materials consisted of the CNC open-set monosyllabic word lists (Peterson & Lehiste, 1962). Each of the 10 lists, consisting of 50 words (150 phonemes), exhibits approximately the same phonemic distribution as the English language, and the lists are roughly equivalent with respect to phonemic distribution. In contrast to the hVd speech materials, for the CNC lists only one person represents each talker type. The adult male, adult female, and ten-year-old girl were recorded previously by others. New recordings of these 10 CNC lists were made in November 2009, by a six-year-old girl recruited from the Washington University community. For all talkers, each digital waveform of a CNC word included the carrier word "ready".

One list of CNC words per talker type was presented to each subject (four lists total per subject), for a total of 200 words presented for identification. Windows Media Player was used to present the CNC stimuli. Lists were given only one time per subject, to avoid learning effects. Which lists were given or excluded was based on research completed by Skinner *et al.* (2006). Random selection was used to determine which subject was given which CNC lists, and the order in which talker types were presented for each subject (see Appendix: Tables A13-A18). One normal hearing adult identified CNC stimuli for all four talker types, in quiet, with 98-100% accuracy at a pilot session at Washington University in St. Louis conducted by the author of this paper (100% for adult male and adult female, 98% for 10-year-old girl and 6-year-old girl).

Test Protocol: All testing was completed in a single-walled booth. Stimuli were routed from a laptop computer (Panasonic CF-19 Toughbook) to a GSI 61 audiometer, and presented via a loudspeaker in the soundfield. The listener was positioned approximately 60 inches from the loudspeaker at 0 degrees azimuth. Testing was conducted in quiet for all subjects. Both a one-third-octave noise (centered at 1000 Hz) and a speech-shaped noise (SSN) were used for calibration of the CNCs and of the hVds. The presentation level was 60 dBA at the position of the listener's head, as measured with a Quest Model 2700 sound level meter.

Normal hearing subjects participated in one test session and unilateral CI subjects also participated in only one test session. However, CI subjects who used two devices (Bilateral CIs or Bimodal) participated in two test sessions. For these subjects, the first session was completed using their "Everyday Listening" set-up (both devices) while the second session was completed using their first CI or CI only. Each test session was completed within 1 – 1½ hours.

The test order was the following: two talker types of CNCs, two talker types of hVds, two talker types of CNCs, and then two talker types of hVds. Subjects were instructed to repeat aloud the word heard for the CNCs, and to touch a screen, that showed eleven hVd words on different buttons of the screen display, in response to the hVd syllable. A break was given at the halfway point and at other times throughout the test session if needed. This protocol was implemented in order to start with a simpler and more familiar task, and to avoid boredom.

Results

Everyday Listening: Results from all subjects (10 CI, 10 NH) were examined.

hVd: The hVd perceptual data were subjected to a mixed between-within subjects analysis of variance with listener group and talker type as main factors. There was a significant main effect of talker type ($F [3,54] = 8.26$, $p < 0.001$). Bonferroni corrected post hoc tests showed that scores for females (mean=85.2%, Standard Error (SE)=±2.59) were significantly higher that those for 5-

7 year old girls (mean=75.8%, SE=±2.9). All other comparisons were not statistically significant. This significant effect of talker type for both groups of listeners is of interest. There was also a significant main effect of listener group ($F [1,18] = 7.91$, $p = 0.012$); the mean hVd percent correct scores are 87.4 (±6.7, 80.7 to 94.0 95% confidence interval) and 74.7 (± 6.7, 68.0 to 81.4 95% confidence interval), for the NH and CI subjects respectively. As expected, NH listeners obtained higher scores than similarly aged CI listeners. There was no significant interaction between listener group and talker type ($F [3,54] = 1.96$, $p = 0.13$). Figure 1 shows hVd data for listener group and talker type. Details on individual and average subject scores for hVds for all subjects can be found in the Appendix (Tables A1-A2).

CNCw: The CNC word scores were similarly subjected to a mixed between-within subjects analysis of variance with listener group and talker type as main factors. Again, as seen with hVds, there was a significant main effect of talker type ($F [3,54] = 10.23$, $p < 0.001$). Bonferroni corrected post hoc tests showed that scores for the female talker (mean=81.8%, SE=±1.8) were not significantly different from those for the male talker (mean=81.9%, SE=±1.9) and scores for the 10 year old girl talker (mean=76.5%, SE±1.8) were not significantly different from those for the 6 year old girl talker (mean=77.0%, SE=±2), but scores for the male and female were significantly higher than the scores for the 10 year old girl and 6 year old girl. In other words, the adult talkers were more accurately understood than both younger talkers. There was also a significant main effect of listener group ($F [1,18] = 76.22$, $p < 0.001$); the mean CNC word percent correct scores are 94.4 (±5.1, 89.3 to 99.5 95% confidence interval) and 64.2 (±5.1, 59.1 to 69.3 95% confidence interval), for the NH and CI subjects respectively. As expected, similar to the hVds, NH listeners obtained higher scores than the similarly aged CI listeners. Unlike the hVds, for the CNC word scores, there was a significant interaction between talker type and

listener group (F [3,54] = 3.78, p = 0.016). The mean CNCw ±SE for NH listeners per talker group are as follows: male = 95.6 ±2.7, female = 95.2 ±2.5, 10 year old girl =93.2 ±2.7, and 6 year old girl =93.6 ±2.8. The mean CNCw ±SE for CI listeners per talker group are as follows: male =68.2 ±2.7, female =68.4 ±2.5, 10 year old girl =59.8 ± 2.7, and 6 year old girl =60.4 ±2.8. Figure 2 shows CNC word data for listener group and talker type. Details on individual and average subject scores for CNC words by CI and NH subjects can be found in the Appendix (Tables A7-A8).

CNCph: The CNC phoneme scores were also subjected to a mixed between-within subjects analysis of variance with listener group and talker type as main factors. Again, as seen with hVds and CNC words, there was a significant main effect of talker type (F [3,54] = 11.49, p < 0.001). Bonferroni corrected post hoc tests showed that scores for the female talker (mean=92.0%, SE=±1.0) were not significantly different from those of the male talker (mean=92.7%, SE=±0.9), and scores for the 10 year old girl (mean=89.7%, SE=±1.1) and 6 year old girl (mean=89.2%, SE=±1.1) were not significantly different from each other. However, scores for the male and female were significantly higher than scores for the 10 year girl and 6 year old girl. Similar to the CNC words, the adult talkers were more accurately understood than both younger talkers. There was also a significant main effect of listener group (F [1,18] = 54.93, p < 0.001); the mean CNC phoneme percent correct scores are 97.9 (±2.8, 95.1 to 100.7 95% confidence interval) and 83.9 (±2.8, 81.1 to 86.7 95% confidence interval), for the NH and CI subjects respectively. Again, as expected, NH listeners obtained higher scores than similarly aged CI listeners. Similar to the CNC word scores, there was a significant interaction between talker type and listener group (F [3,54] = 4.97, p = 0.004) for the CNC phoneme scores. The mean CNCph ±SE for NH listeners per talker group are as follows: male =98.5 ±1.3, female =98.4 ±1.5, 10 year old girl =97.2 ±1.5,

and 6 year old girl =97.5 ±1.6. The mean CNCph ±SE for CI listeners per talker group are as follows: male =86.9 ±1.3, female =85.6 ±1.5, 10 year old girl =82.2 ±1.5, and 6 year old girl =80.8 ±1.6. Figure 3 shows CNC phoneme data for listener group and talker type. Details on individual and average subject scores for CNC phonemes by CI and NH subjects can be found in the Appendix (Tables A7-A8).

Everyday Listening vs. 1st CI only: Results from the 8 CI subjects who use two devices, and thus participated in two test sessions, were examined separately (Unilateral CI users, i.e., subjects CI5 and CI6, are omitted from these analyses). Normal hearing listeners did not participate in a second session. For "Everyday Listening" (Session 1), device conditions were the following: Bilateral subjects used CI + CI, Bimodal subjects used CI + HA. For 1st CI only (Session 2), device conditions were the following: Bilateral subjects used 1st implanted CI, Bimodal subjects used only CI.

hVd: A two-way repeated measures ANOVA was conducted with talker type and device condition as main factors. There was a significant main effect of talker ($F [3,21] = 15.18$, $p < 0.001$). Bonferroni corrected post hoc tests showed that scores for 5-7 year old girls (mean=61.6%, SE=±3.8) were significantly lower than scores for female talkers (mean=73.6%, SE=±3.3) and significantly lower than scores for male talkers (mean=77.9%, SE=±3.8). All other comparisons were not statistically significant. These data, showing the main effect of talker, are illustrated in Figure 4. There was no significant main effect of device condition ($F [1,7] = 2.89$, $p = 0.133$). There was no significant interaction between device condition and talker type ($F [3,21] = 1.28$, $p = 0.307$). Figure 12 shows individual hVd subject scores, averaged across the four talkers, Session 1 ("Everyday Listening") vs. Session 2 (1st CI only). Details on individual and average subject scores for hVds (Session 2) can be found in the Appendix (Table A3).

CNCw: A two-way repeated measures ANOVA was conducted with talker type and device condition as main factors. Similar to the hVds, there was a significant main effect of talker ($F [3,21] = 9.74$, $p < 0.001$). Bonferroni corrected post hoc tests showed that scores for the 10 year old girl talker (mean=55.4%, SE=±4.8) were significantly lower than scores for the male talker (mean=64.0%, SE=±5.6) and scores for the female talker (mean=62.0%, SE=±4.7), but were not significantly different from scores for the 6 year old girl talker (mean=55.9%, SE=±6.1). These data, showing the main effect of talker, are illustrated in Figure 5. Unlike the hVds, there was a significant main effect of device condition ($F [1,7] = 14.3$, $p = 0.007$). In other words, on average, subjects utilizing two devices performed significantly better on CNC words with both devices (CI + CI or CI + HA) compared to using their 1st or only CI alone. Figure 13 shows individual CNCw subject scores, averaged across the four talkers, Session 1 ("Everyday Listening") vs. Session 2 (1st CI only). There was no significant interaction between device condition and talker type ($F [3,21] = 1.04$, $p = 0.397$). These data, showing the main effect of device condition, are illustrated in Figure 6. Details on individual and average subject scores for CNC words (Session 2) can be found in the Appendix (Table A9).

CNCph: A two-way repeated measures ANOVA was conducted with talker type and device condition as main factors. Similar to the hVds and CNCw, there was a significant main effect of talker ($F [3,21] = 7.01$, $p = 0.002$). Bonferroni corrected post hoc tests showed that scores for the male talker (mean=83.4%, SE=±3.4) were significantly higher from those for the 10 year old girl talker (mean=79.4%, SE=±3.1) and scores for the 6 year old girl talker (mean=77.9%, SE=±3.9), but were not significantly different from those for the female talker (mean=81.9%, SE=±2.8). These data, showing the main effect of talker, are illustrated in Figure 7. Similar to the CNC words, there was a significant main effect of device condition ($F [1,7] = 8.44$, $p = 0.023$). In

other words, on average, subjects utilizing two devices performed significantly better on CNC phonemes with both devices (CI + CI or CI + HA) compared to using their 1st or only CI alone. These data, showing the main effect of device condition, are illustrated in Figure 8. There was no significant interaction between device condition and talker type ($F [3,21] = 1.06$, $p = 0.386$). Details on individual and average subject scores for CNC phonemes (Session 2) can be found in the Appendix (Table A9).

Individual Data CI- Everyday Listening: Individual CI subjects' hVd, CNCw and CNCph percent correct identification scores, according to chronological age, were not examined statistically. Visual inspection seems to indicate that age is not a significant factor. Much variability is seen across CI listeners on all measures (i.e., for hVds the oldest CI listener showed the smallest variation across talkers [6 percentage points] compared to the youngest CI listener [34 percentage points]). Figures 9, 10, and 11 show individual subject scores, by age, for hVd, CNCw, and CNCph, respectively, across the 10 CI participants.

Discussion

This study investigated effects of talker age and gender on speech perception for normal hearing children and pediatric cochlear implant users. In summary, significant differences were found between the performance of NH and CI pediatric listeners on CNC and vowel (hVd) measures, with NH subjects performing better than CI subjects. Consistent with results from studies using adult CI users as subjects, a significant talker effect was found for pediatric subjects on vowels (hVds) and CNCs, with better performance for adult talker types compared to child talker types (Loizou *et al.* 1998, Green *et al.*, 2007).

Fourakis *et al.* (2007) found a statistically significant effect of voice when analyzing performance on hVds across talker types. The same hVd recordings of adult males, adult females, and 10-12 year old girls were used for the current study, and recordings of 5-7 year old

girls were only used in the current study. Their results with adult CI users are remarkably similar to results from the current study with pediatric CI users, in which a main effect of talker was also found. Across their eight post-lingually deafened adult CI subjects, average scores were 74% for adult females, 72.7% for adult males and 69.1% for girls. Across the eight pediatric CI subjects using two devices in the current study, average scores (across both sessions) were 73.6% for adult females, 77.9% for adult males, 68.6% for 10-12 year old girls, and 61.6% for 5-7 year old girls. Average vowel identification scores for NH and CI subjects can be found in the Appendix (Tables A4-A6).

In Fourakis *et al.* (2007), hVd perceptual results were analyzed to obtain the 'amount of information transmitted' for several vowel features. One of the best perceived vowel features for the adult CI subjects were "r-colored" vowels. Interestingly, in the current study, /ɝ/ ("heard") was also the best perceived token (out of the 11 vowels) across talker types for all subjects (99% NH, 90% CI). Vowel confusion matrices for NH and CI subjects, and information on most common errors and misperceived tokens can be found in the Appendix (A19-A22).

Results were analyzed separately for the 8 CI subjects who use two devices (5 Bilateral, 3 Bimodal). Surprisingly, there was no significant main effect of device condition for the hVds. As seen in Figure 12, for the hVds, variation was seen across the five Bilateral subjects, with performance (on average) similar between sessions (CI + CI vs. 1st CI only). However, all three Bimodal subjects performed better on the hVd task when using both of their devices (CI + HA) compared to using their CI alone. This result was expected from the Bimodal subjects, since hearing aids provide low frequency acoustic information that is important for vowel identification. Conversely, a significant effect of device condition was seen for the CNCs. As seen in Figure 13, for the CNC words, all subjects (5 Bilateral and 3 Bimodal) performed better

(or equally well) in the "Everyday Listening" device condition (CI + CI or CI + HA) compared to their 1st or only CI alone. These results point to the well-established conclusion that having input from both ears is generally advantageous.

The different sets of test materials should be taken into consideration when examining the results. The CNCs are a broader measure compared to the hVds, in that whole words are required for a response (both vowels and consonants), while hVds focus solely on vowels. Another important difference between these two sets of speech materials was the number of talkers per talker type. There was only one talker per talker type for the CNC stimuli (i.e.: one adult female recorded all ten CNC lists) while there were several talkers per talker type for the hVd stimuli (i.e.: twenty-five adult females recorded the hVd tokens). This relates to two main issues: i) the ability of listeners to adapt to different talkers, and ii) the generalizability of results.

Both adults and children can "train" their ears to adapt to a particular voice—known as "talker normalization" (Ryalls *et al.* 1997, Kishon-Rabin *et al.* 2009). In this study, auditory learning may have occurred with the CNC stimuli—as may occur with commonly used audiologic speech stimuli that use a single talker. However, the possibility of calibrating to a specific talker's voice was most likely eliminated for the hVd stimuli since there was a set of talkers within each talker type; a situation more similar to most real world environments. A ceiling effect was seen for the NH subjects' performance on the CNC task, while it was not seen for the hVd task. This may point to the fact that the hVd task, which used multiple talkers, was more challenging than the CNC task. Additionally, talker intelligibility differences are known to exist amongst individual talkers (Green *et al.* 2007, Hazan *et al.* 2004). However, it is unknown whether these particular talkers, i.e., the adult male, adult female, 10-year-old girl and 6-year-old girl who served as the talkers for the CNC lists, are typical representative talkers of their age and

gender. Therefore, the hVds may be a more robust measure compared to the CNCs, in that results could be more readily generalized to other talkers of the same talker type.

The mode of response also differed between the two measures. For the CNCs, the subject listened to the stimulus and repeated what he/she heard aloud to the examiner. For the hVd task, the subject listened to the stimulus and then touched a button on the screen corresponding to what he/she heard (e.g.: "hood", "heed", "who'd"). The subjects were oriented to this task through a verbal review, first receptively and then expressively, for each vowel sound (with a corresponding picture of the computer screen). In addition, a "preview" was provided before each talker sub-test to familiarize the patient with the talker type. For the CNCs, the subjects had the opportunity to self-correct before the examiner recorded their response. However, for the hVds, if the subject made an error by acting too quickly or accidently pressing the wrong button on the screen, then this could not be corrected. Observations made by the examiner in the test booth found the combination of the task and interface for hVds to be more challenging for all subjects compared to the response format for the CNC test. A few of the subjects (both NH and CI) made comments about the 5-7 year olds' stimuli sounding "different" or "funny", because of their notable accents compared to other talker groups. However, all CI subjects performed well above the chance performance level (9%) for hVds. Despite differences such as number of talkers used per talker type and mode of response between measures, the same general trends were seen in the group data (NH vs. CI) for hVds and CNCs.

Two of the CI subjects (CI 5, CI 6) have the diagnosis of Auditory Neuropathy Spectrum Disorder (ANSD). While ANSD is not an uncommon diagnosis of pediatric CI users, it must be noted that these children may process auditory stimuli differently than children without ANSD. Both of these subjects used one CI only (Unilateral CI), and were therefore not part of the data

set for comparison between test sessions. However, as was true for all CI subjects, each subject's device settings were reported to be optimized for him/her individually.

This pilot study was designed to examine if there was any effect of talker age and gender on speech perception for children with hearing loss using CIs and for children with normal hearing. It is possible that this study did not have sufficient participant numbers to detect significant differences for certain conditions. More subjects should be recruited in future related research, especially to thoroughly examine the effect of device set-up (Bilateral, Bimodal, or Unilateral) on speech perception. Similar measures could also be completed in noise to better replicate a real-world environment. Additionally, the effect of altering MAP parameters (i.e.: frequency allocation tables) and hearing aid settings (i.e.: starting point of frequency compression features) could be explored in related research.

The results of this study indicate that children who use CIs do not perform as well as their NH age mates on selected speech perception measures. Also, more variation is seen with the CI subject's individual data compared to the variation amongst NH subjects. This points to the well-established conclusion that even with optimized devices and a consistent signal in an easy listening environment (quiet, average level speech), listening is more challenging for children with hearing loss (using CIs) compared to normal hearing children. The talker effect seen for CI subjects indicates that pediatric CI users do not hear different age and gender talkers equally well. This finding emphasizes the fact that using male only stimuli for audiologic speech perception testing may overestimate performance and may not represent typical speech environments for children. The patterns of performance seen across the talker types may have implications for speech perception and performance in the real world. Speech, language, and self-monitoring skills are developing during this critical time for children. It is very important

that their devices (both CIs and HAs) are optimized to achieve the best possible perception of all talker types.

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Tables & Figures

TABLE I: Demographic information on CI subjects.

Subject	Age*	Gender	Age ID of HL	Age CI, ear**	Contralateral ear	Etiology of HL
CI 1	8; 8	F	1;0	3;8 R	CI at 6;8 L	Unknown
CI 2	11; 2	M	1;9	2;9 R	CI at 8;4 L	Connexin 26
CI 3	9; 4	F	1;2	3;4 L	HA R	LVAS
CI 4	11; 5	M	2;6	3;7 L	CI at 7;9 R	LVAS
CI 5	8; 4	M	0;4	2;8 L	Not used	Connexin 26, ANSD
CI 6	12; 0	M	1; 1	2; 6 L	Not used	Unknown, ANSD
CI 7	8; 1	F	1;9	5;6 L	HA R	Unknown
CI 8	11; 3	F	1;0	7;11 L	CI at 10;3 R	Unknown
CI 9	7; 4	F	0;11	1;6 R	CI at 4;5 L	Unknown
CI 10	7; 3	M	1;11	2;11 L	HA R	Unknown

*Age = years; months
**First, or only, CI

TABLE II: Devices used by CI subjects.

Subject	Type of CI	Right Ear	Left Ear
CI 1	Cochlear	CI24RCA, Freedom	CI24RECA, CP810
CI 2	Cochlear	CI24R(CS), Freedom	CI24RECA, Freedom
CI 3	Advanced Bionics	Oticon Adapto P (HA)	HiFocus, Harmony
CI 4	Advanced Bionics	Hi Focus, Harmony	HiFocus, Harmony
CI 5	Cochlear	(No device used)	CI24RCA, Freedom
CI 6	Advanced Bionics	(No device used)	HiFocus, Harmony
CI 7	Cochlear	Phonak Naida V UP* (HA)	CI24RECA, CP810
CI 8	Cochlear	CI24RECA, CP810	CI24RECA, CP810
CI 9	Cochlear	CI24R(CS), Freedom	CI24RECA, Freedom
CI 10	Cochlear	Phonak Naida V UP** (HA)	CI24RCA, Freedom

*=Frequency compression active, **=Frequency compression not active

TABLE III: Demographic data on NH subjects.

Subject	Age*	Gender
NH 11	10; 6	M
NH 12	9; 9	M
NH 13	8; 7	F
NH 14	10; 6	M
NH 15	11; 8	M
NH 16	8; 2	F
NH 17	10; 1	M
NH 18	7; 5	M
NH 19	11; 0	F
NH 20	10; 6	F

*Age = years; months.

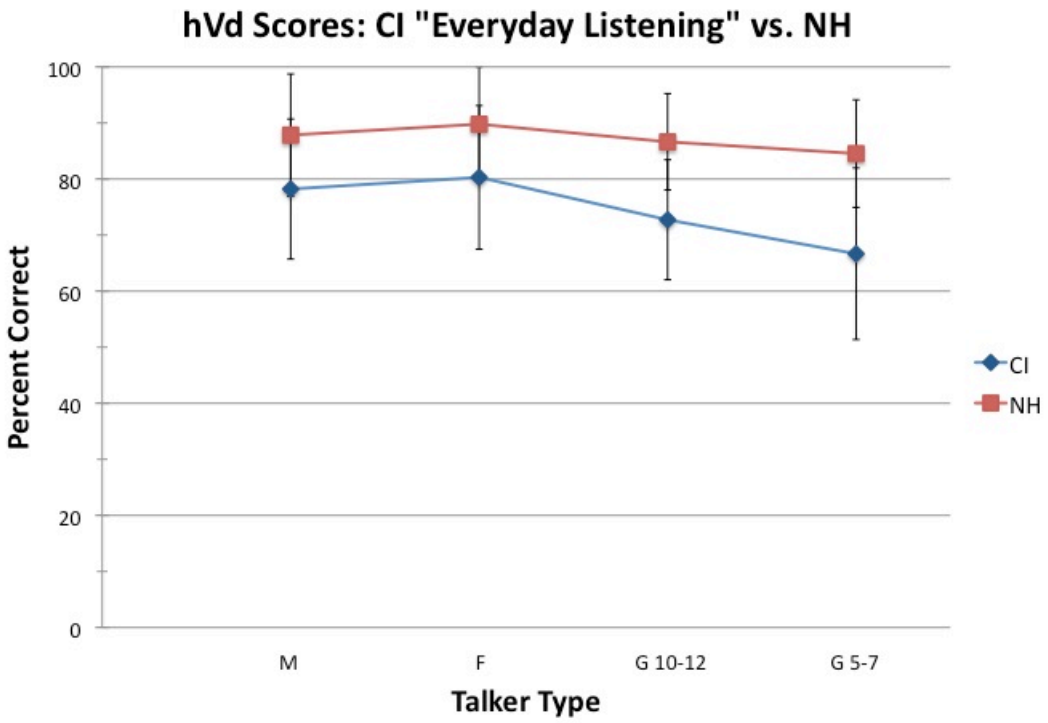

Figure 1. Group mean scores, ±95% confidence interval, (percent correct, calculated from a total of 33 tokens- 11 vowels, 3x each per listener) for the closed-set vowel test (hVd) for males (M), females (F), 10-12 year old girls (G 10-12), and 5-7 year old girls (G 5-7) voices across the 20 participants (10 CI, 10 NH).

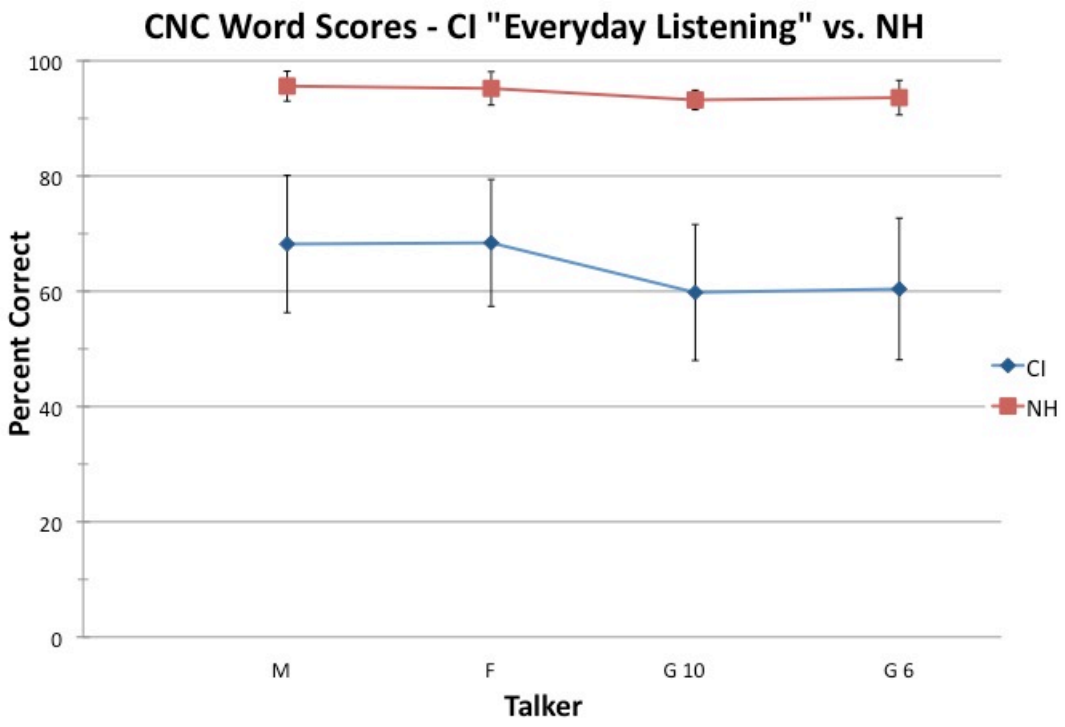

Figure 2. Group mean scores, ±95% confidence interval, (percent words correct, calculated from a total of 50 words per listener) for the open-set word test (CNC) for male (M), female (F), 10-year-old girl (G 10), and 6-year-old girl (G 6) voices across the 20 participants (10 CI, 10 NH).

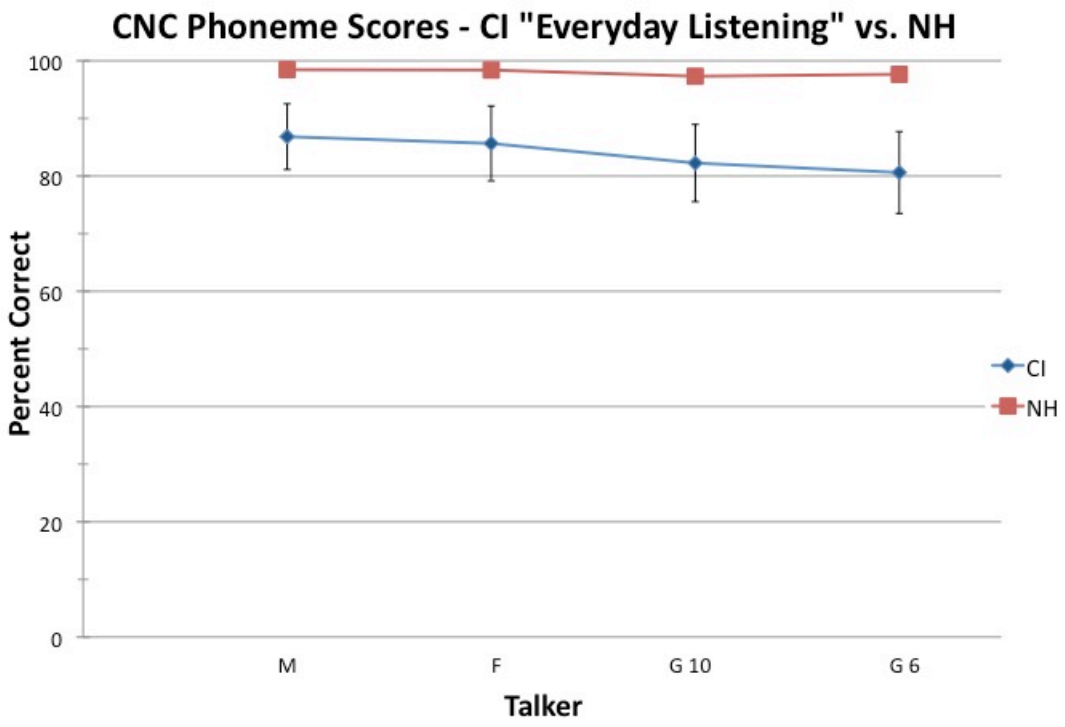

Figure 3. Group mean scores, ±95% confidence interval (percent phonemes correct, calculated from a total of 150 phonemes per listener) for the open-set word test (CNC) for male (M), female (F), 10-year-old girl (G 10), and 6-year-old girl (G 6) voices across the 20 participants (10 CI, 10 NH).

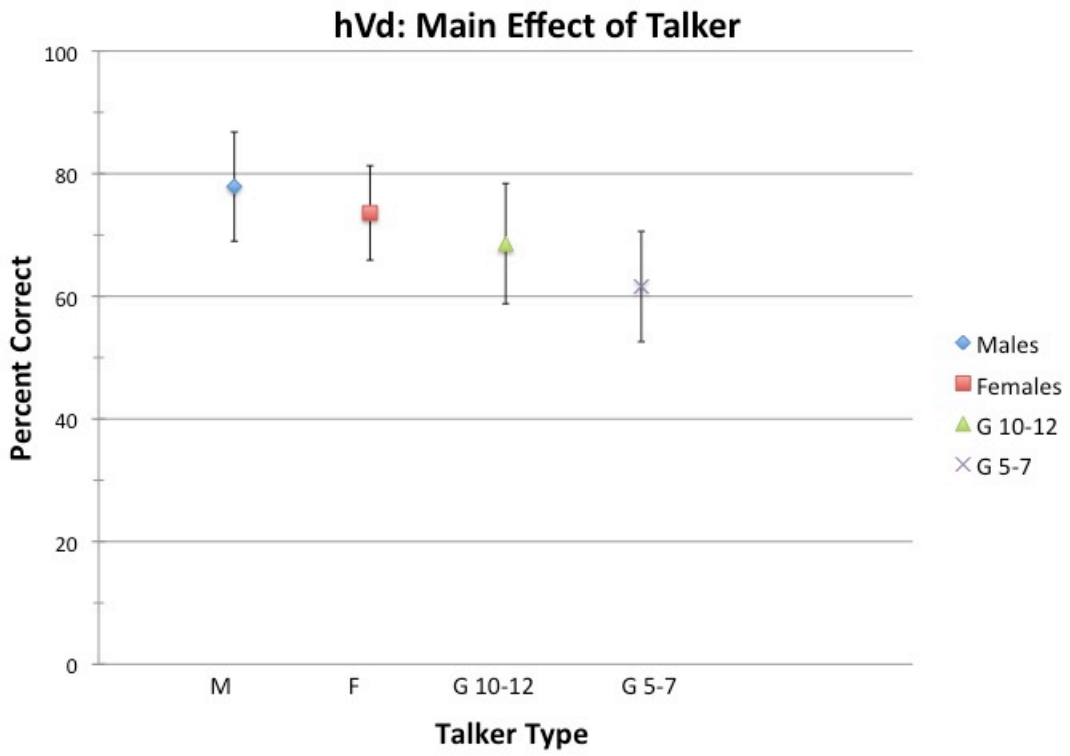

Figure 4. Group mean scores, ±95% confidence interval, (percent correct, calculated from a total of 33 tokens- 11 vowels, 3x each per listener) for the closed-set vowel test (hVd) for males (M), females (F), 10-12 year old girls (G 10-12), and 5-7 year old girls (G 5-7) voices across the 8 CI participants who utilize two devices. Data are combined across Session 1 and Session 2.

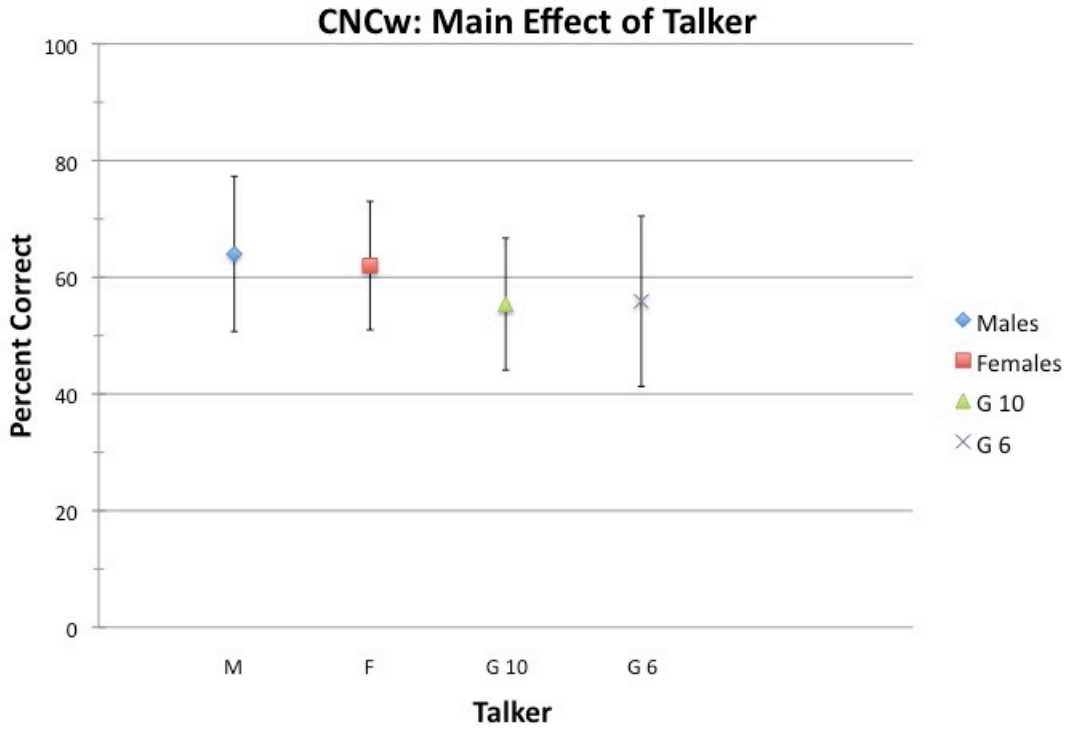

Figure 5. Group mean scores, ±95% confidence interval, (percent words correct, calculated from a total of 50 words per listener) for the open-set word test (CNC) for male (M), female (F), 10-year-old girl (G 10), and 6-year-old girl (G 6) voices across the 8 CI participants who utilize two devices. Data are combined across Session 1 and Session 2.

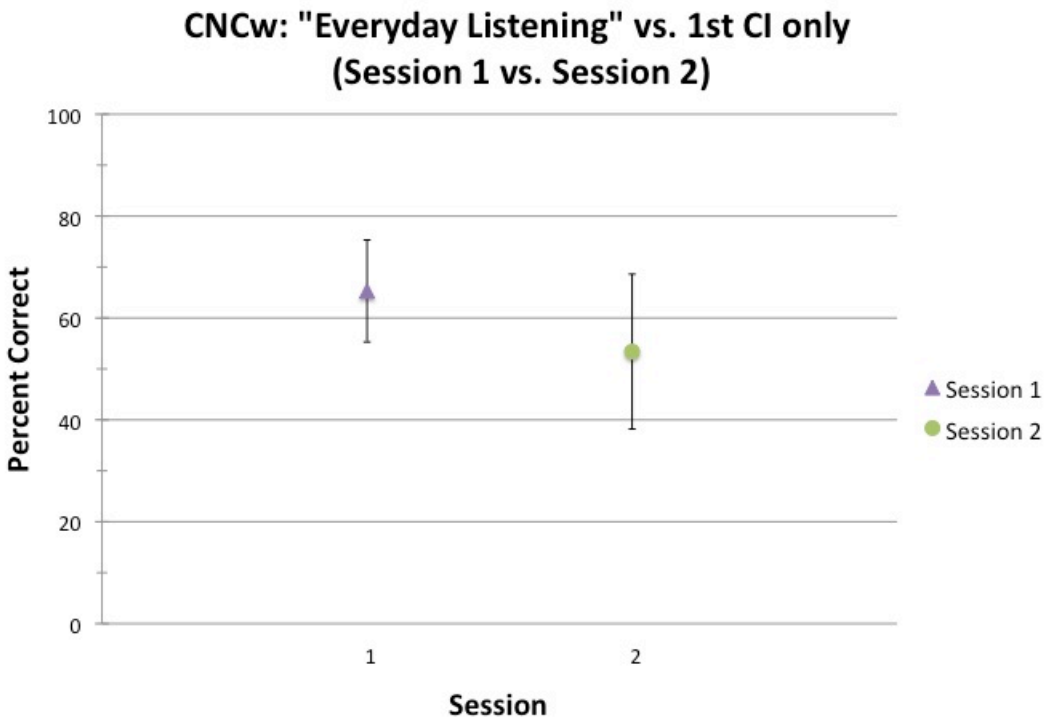

Figure 6. Group mean scores, ±95% confidence interval, (percent words correct) for the open-set word test (CNC) averaged across 4 talkers (male, female, 10-year-old girl, and 6-year-old girl) and across the 8 CI participants who utilize two devices. Bilateral subjects used CI + CI for Session 1, and 1st implanted CI only for Session 2. Bimodal subjects used CI + HA for session 1, and CI alone for Session 2.

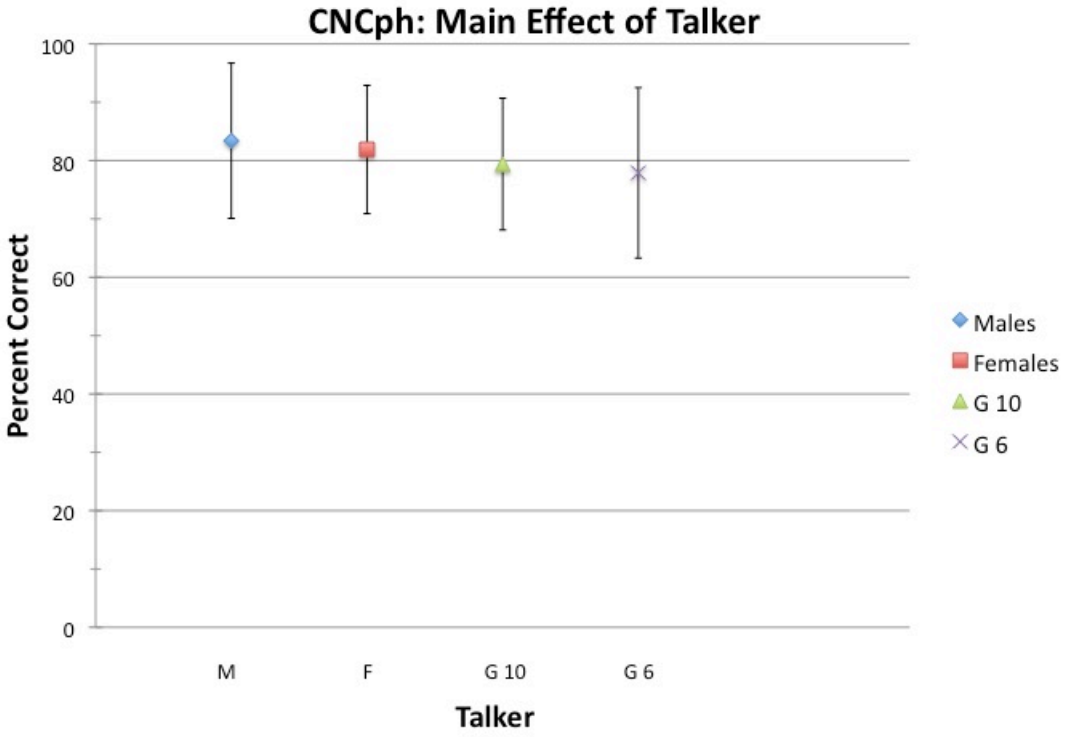

Figure 7. Group mean scores, ±95% confidence interval, (percent phonemes correct, calculated from a total of 150 phonemes per listener) for the open-set word test (CNC) for male (M), female (F), 10-year-old girl (G 10), and 6-year-old girl (G 6) voices across the 8 CI participants who utilize two devices. Data are combined across Session 1 and Session 2.

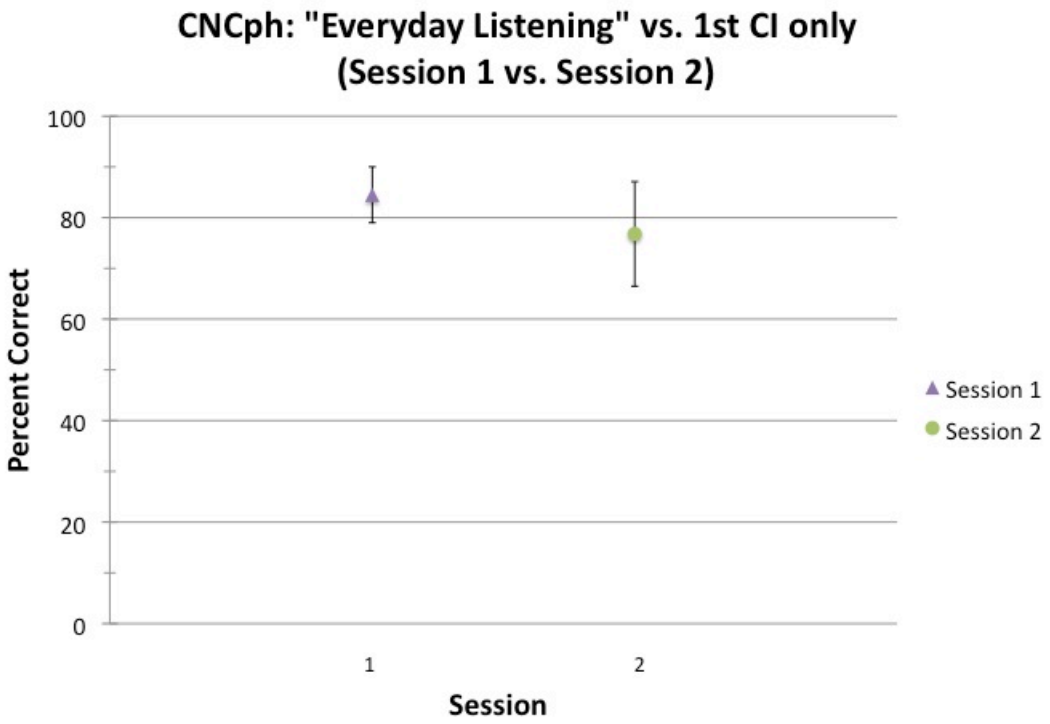

Figure 8. Group mean scores, ±95% confidence interval, (percent phonemes correct) for the open-set word test (CNC) averaged across 4 talkers (male, female, 10-year-old girl, and 6-year-old girl) and across the 8 CI participants who utilize two devices. Bilateral subjects used CI + CI for Session 1, and 1st implanted CI only for Session 2. Bimodal subjects used CI + HA for session 1, and CI alone for Session 2.

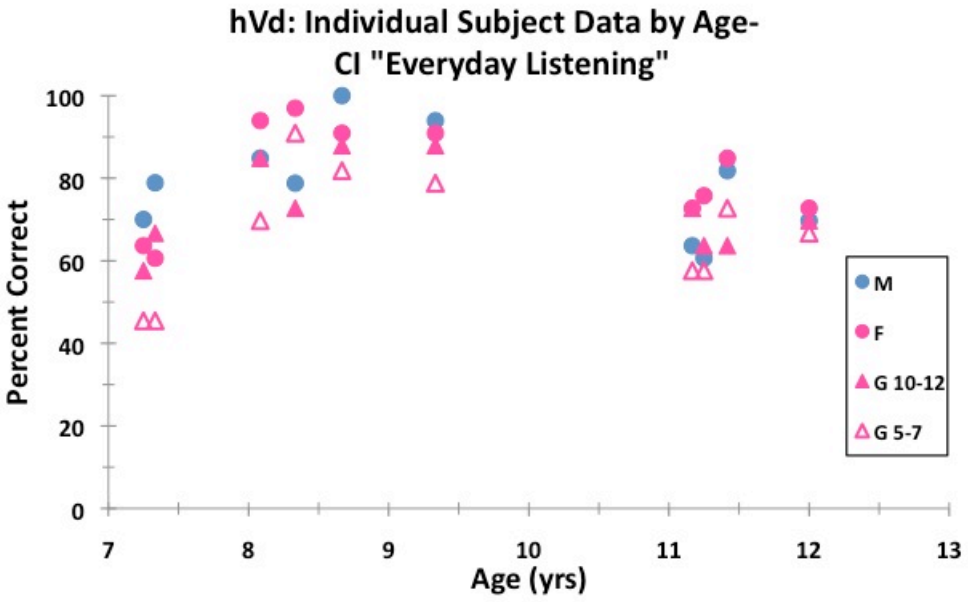

Figure 9. Individual subject scores, by age, (percent correct, calculated from a total of 33 tokens-11 vowels, 3x each) for the closed-set vowel test (hVd) for males, females, 10-12 year old girls, and 5-7 year old girls voices across the 10 CI participants, "Everyday Listening". CI subjects, from youngest to oldest, are CI 10, CI 9, CI 7, CI 5, CI 1, CI 3, CI 2, CI 8, CI 4, CI 6.

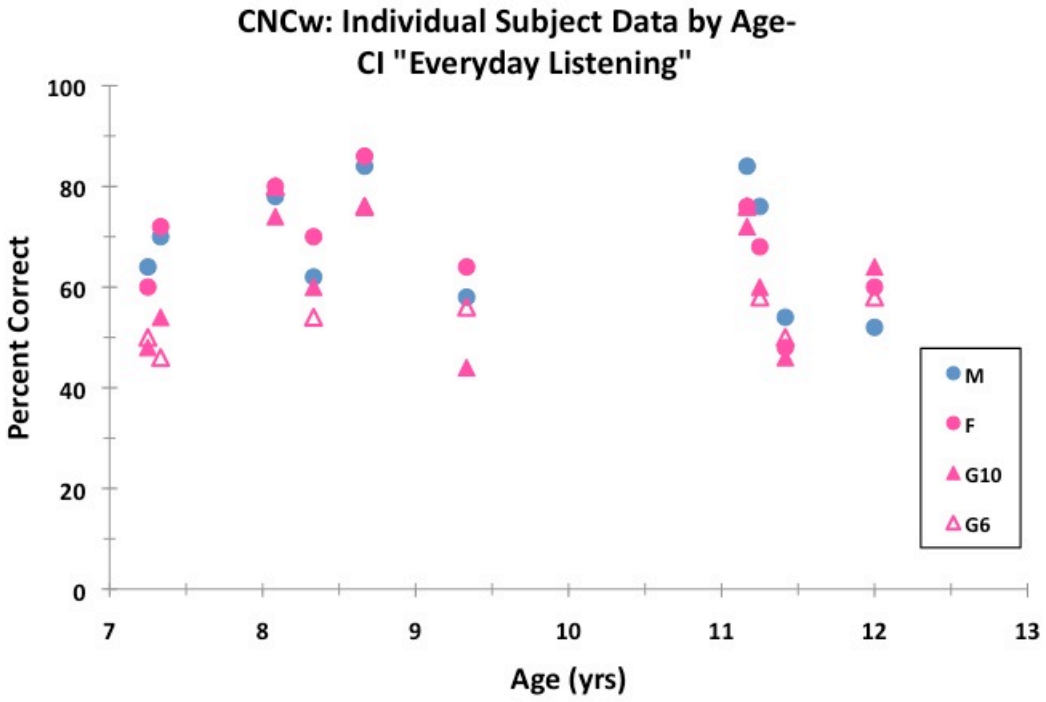

Figure 10. Individual subject scores, by age, (percent words correct, calculated from a total of 50 words) for the open-set word test (CNC) for male, female, 10-year-old girl, and 6-year-old girl voices across the 10 CI participants, "Everyday Listening". CI subjects, from youngest to oldest, are CI 10, CI 9, CI 7, CI 5, CI 1, CI 3, CI 2, CI 8, CI 4, CI 6.

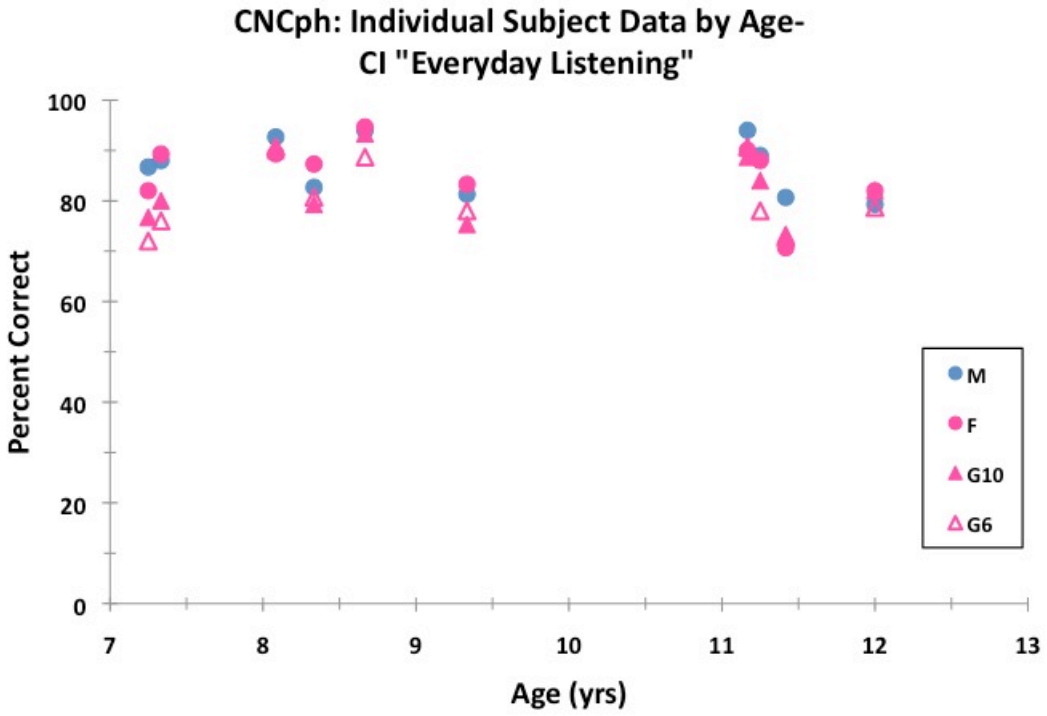

Figure 11. Individual subject scores, by age, (percent phonemes correct, calculated from a total of 150 phonemes) for the open-set word test (CNC) for male, female, 10-year-old girl, and 6-year-old girl voices across the 10 CI participants, "Everyday Listening". CI subjects, from youngest to oldest, are CI 10, CI 9, CI 7, CI 5, CI 1, CI 3, CI 2, CI 8, CI 4, CI 6.

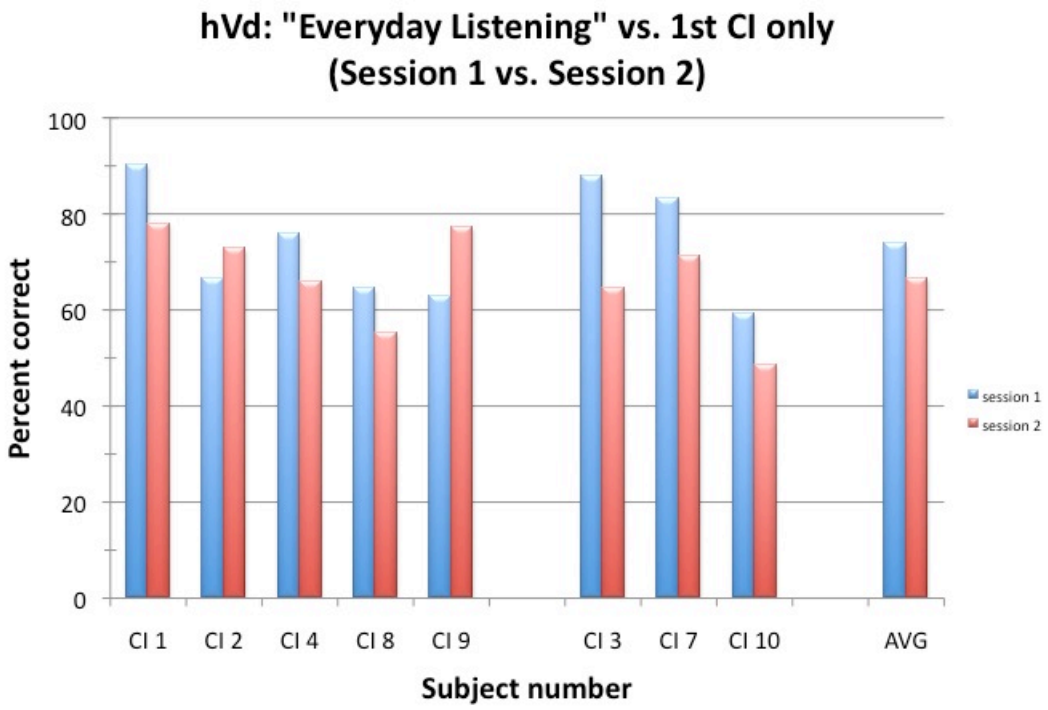

Figure 12. Individual subject scores, averaged across 4 talker types (percent correct, calculated from a total of 132 tokens- 11 vowels, 3x each, 4 talkers) for the closed-set vowel test (hVd) across the 8 CI participants using two devices, Session 1 ("Everyday Listening") vs. Session 2 (1st CI only). CI subjects 1, 2, 4, 8, 9 (Bilateral) wore CI + CI for session 1 and 1st implanted CI only for session 2. CI subjects 3, 7, 10 (Bimodal) wore CI + HA for session 1 and only CI for session 2.

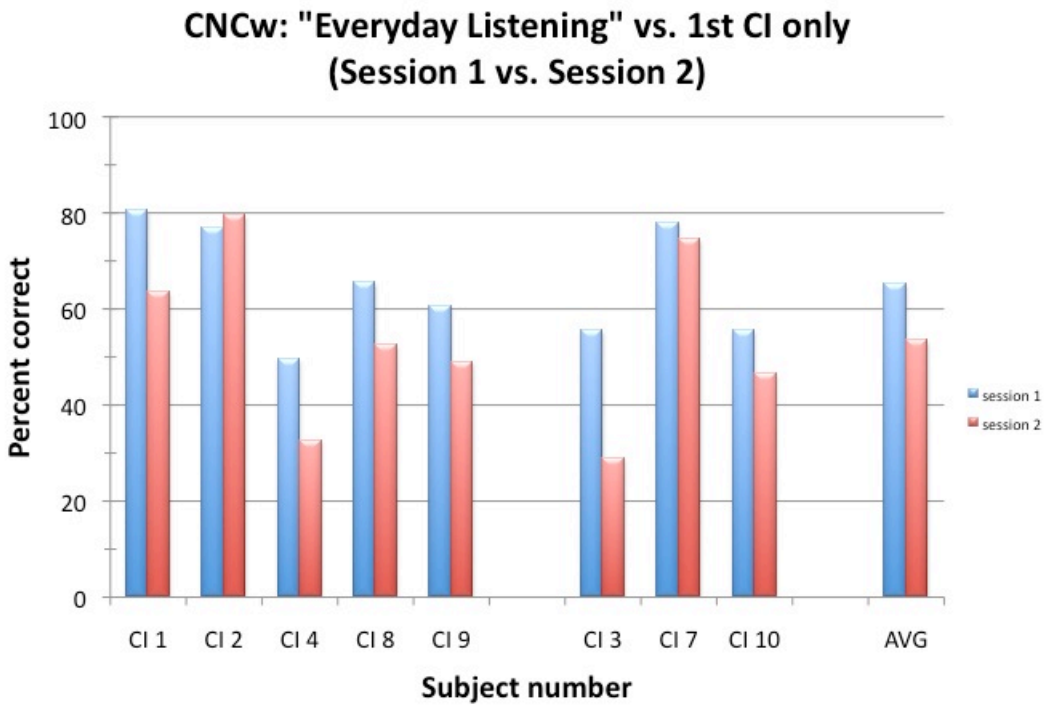

Figure 13. Individual subject scores, averaged across 4 talker types (percent correct, calculated from a total of 200 words) for the open-set word test (CNC) across the 8 CI participants using two devices, Session 1 ("Everyday Listening") vs. Session 2 (1st CI only). CI subjects 1, 2, 4, 8, 9 (Bilateral) wore CI + CI for session 1 and 1st implanted CI only for session 2. CI subjects 3, 7, 10 (Bimodal) wore CI + HA for session 1 and only CI for session 2.

Appendix

Table A1: Vowel identification scores on hVd (% correct): NH subjects. Data are per subject (N=33 trials per cell in table; 11 vowels x 3 presentations per vowel for each talker type). *=Individual subject averages and standard deviations.

Subject	M	F	G 10-12	G 5-7	***NH Avg**	***NH StDev**
NH 11	100	91	97	85	93	7
NH 12	97	94	85	88	91	6
NH 13	85	94	76	76	83	9
NH 14	97	97	91	94	95	3
NH 15	79	85	91	91	86	6
NH 16	64	67	70	67	67	2
NH 17	85	100	94	94	93	6
NH 18	88	79	82	73	80	6
NH 19	97	94	94	85	92	5
NH 20	88	97	88	94	92	5
NH Avg	88	90	87	85		
NH StDev	11	10	9	10		

Table A2: Vowel identification scores on hVd (% correct): CI subjects, "Everyday Listening". Data are per subject (N=33 trials per cell in table; 11 vowels x 3 presentations per vowel for each talker type). *=Individual subject averages and standard deviations.

Subject	M	F	G 10-12	G 5-7	***CI Avg**	***CI StDev**
CI 1	100	91	88	82	90	8
CI 2	64	73	73	58	67	7
CI 3	94	91	88	79	88	7
CI 4	82	85	64	73	76	10
CI 5	79	97	73	91	85	11
CI 6	70	73	70	67	70	2
CI 7	85	94	85	70	83	10
CI 8	61	76	64	58	64	8
CI 9	79	61	67	45	63	14
CI 10	70	64	58	45	59	10
CI Avg	78	80	73	67		
CI StDev	13	13	11	15		

Table A3: Vowel identification scores on hVd (% correct): CI subjects, 2nd session (1st CI only). Data are per subject (N=33 trials per cell in table; 11 vowels x 3 presentations per vowel for each talker type). *=Individual subject averages and standard deviations.

Subject	M	F	G 10-12	G 5-7	***CI Avg**	***CI StDev**
CI 1	76	82	85	70	78	7
CI 2	73	76	79	64	73	6
CI 3	82	70	52	55	65	14
CI 4	91	52	61	61	66	17
CI 5	N/A	N/A	N/A	N/A	N/A	N/A
CI 6	N/A	N/A	N/A	N/A	N/A	N/A
CI 7	76	70	67	73	72	4
CI 8	67	61	55	39	56	12
CI 9	88	79	73	70	78	8
CI 10	58	52	39	45	49	8
CI Avg	76	68	64	60		
CI StDev	11	12	15	12		

Table A4: Average vowel identification scores on hVd (% correct): NH subjects. Data are combined across the 10 CI subjects, for each talker type and vowel. (N=30 trials per cell in table; 10 subjects x 3 vowel presentations per talker type).

Talker Type	Heed	Hid	Head	Had	Hod	Hood	Who'd	Hud	Heard	Hayed	Hoed	**AVG**
M	93	97	100	100	80	87	53	83	97	90	87	88
F	97	100	93	100	70	97	77	80	100	90	83	90
G 10-12	93	100	100	100	73	93	57	67	100	77	97	87
G 5-7	97	100	60	93	87	90	70	70	97	93	73	85
AVG	95	99	88	98	78	92	64	75	99	88	85	

Table A5: Average vowel identification scores on hVd (% correct): CI subjects, "Everyday Listening". Data are combined across the 10 CI subjects, for each talker type and vowel. (N=30 trials per cell in table; 10 subjects x 3 vowel presentations per talker type).

Talker Type	Heed	Hid	Head	Had	Hod	Hood	Who'd	Hud	Heard	Hayed	Hoed	**AVG**
M	77	87	83	97	77	87	70	53	87	83	60	78
F	93	93	80	87	77	93	63	47	100	70	80	80
G 10-12	90	90	60	93	73	93	63	50	87	50	50	73
G 5-7	87	73	57	73	73	67	80	37	87	77	23	67
AVG	87	86	70	88	75	85	69	47	90	70	53	

Table A6: Average vowel identification scores on hVd (% correct): CI subjects, 2nd session (1st CI only). Data are combined across the 8 CI subjects utilizing two devices, for each talker type and vowel. (N=24 trials per cell in table; 8 subjects x 3 vowel presentations per talker type).

Talker Type	Heed	Hid	Head	Had	Hod	Hood	Who'd	Hud	Heard	Hayed	Hoed	**AVG**
M	70	60	73	73	57	60	50	40	77	57	53	61
F	67	63	60	77	40	57	30	37	67	50	47	54
G 10-12	63	53	50	67	43	57	57	37	53	37	43	51
G 5-7	50	63	40	53	50	40	63	23	63	60	17	47
AVG	63	60	56	68	48	54	50	34	65	51	40	

Table A7: Identification scores on CNCs (% correct words, % correct phonemes): NH subjects. (N=50 words; 150 phonemes). *=Individual subject averages and standard deviations.

Subject	M	F	G 10	G 6	***NH Avg**	***NH StDev**
NH 11	96, 99	94, 98	94, 97	92, 97	94, 98	2, 1
NH 12	94, 98	90, 97	90, 96	90, 97	91, 97	2, 1
NH 13	92, 97	94, 98	92, 97	92, 97	93, 97	1, 1
NH 14	98, 99	100, 100	96, 97	98, 99	98, 99	2, 1
NH 15	100, 100	96, 99	92, 97	94, 97	96, 98	3, 1
NH 16	94, 98	92, 97	94, 97	98, 100	95, 98	3, 1
NH 17	92, 97	96, 99	94, 98	90, 96	93, 97	3, 1
NH 18	96, 99	96, 98	94, 98	94, 97	95, 98	1, 1
NH 19	96, 99	98, 99	94, 98	96, 98	96, 98	2, 1
NH 20	98, 99	96, 99	92, 97	92, 97	95, 98	3, 1
NH Avg	96, 98	95, 98	93, 97	94, 98		
NH StDev	3, 1	3, 1	2, 1	3, 1		

Table A8: Identification scores on CNCs (% correct words, % correct phonemes): CI subjects, "Everyday Listening". (N=50 words; 150 phonemes)

Subject	M	F	G 10	G 6	***CI Avg**	***CI StDev**
CI 1	84, 94	86, 95	76, 93	76, 89	81, 93	5, 3
CI 2	84, 94	76, 90	72, 89	76, 91	77, 91	5, 2
CI 3	58, 81	64, 83	44, 75	56, 78	56, 79	8, 4
CI 4	54, 81	48, 71	46, 73	50, 73	50, 74	3, 4
CI 5	62, 83	70, 87	60, 79	54, 81	62, 82	7, 3
CI 6	52, 79	60, 82	64, 82	58, 79	59, 80	5, 2
CI 7	78, 93	80, 89	74, 90	80, 91	78, 91	3, 1
CI 8	76, 89	68, 88	60, 84	58, 78	66, 85	8, 5
CI 9	70, 88	72, 89.3	54, 80	46, 76	61, 83	13, 6
CI 10	64, 87	60, 82	48, 77	50, 72	56, 79	8, 6
CI Avg	68, 87	68, 86	60, 82	60, 81		
CI StDev	12, 6	11, 7	12, 7	12, 7		

Table A9: Identification scores on CNCs (% correct words, % correct phonemes): CI subjects, session 2 (1st CI only). (N=50 words; 150 phonemes)

Subject	M	F	G 10	G 6	***CI Avg**	***CI StDev**
CI 1	66, 85	54, 79	64, 87	70, 87	64, 84	7, 4
CI 2	86, 95	78, 91	72, 87	82, 93	80, 91	6, 4
CI 3	28, 53	38, 62	30, 54	20, 52	29, 55	7, 5
CI 4	32, 64	36, 67	34, 69	28, 59	33, 65	3, 4
CI 5	N/A	N/A	N/A	N/A	N/A	N/A
CI 6	N/A	N/A	N/A	N/A	N/A	N/A
CI 7	82, 93	80, 91	62, 83	74, 91	75, 89	9, 4
CI 8	60, 85	62, 83	50, 77	38, 73	53, 80	11, 5
CI 9	54, 79	42, 73	52, 78	48, 73	49, 76	5, 3
CI 10	48, 73	48, 77	48, 74	42, 71	47, 74	3, 3
CI Avg	57, 78	55, 78	52, 76	50, 75		
CI StDev	21, 14	17, 10	14, 11	23, 15		

Table A10: hVd- Order of presentation for NH subjects. 1= Male, 2= Female, 3= 10-12 year old girls, 4= 5-7 year old girls.

Subject #	**1st**	**2nd**	**3rd**	**4th**
NH 11	2	4	3	1
NH 12	4	3	1	2
NH 13	3	4	2	1
NH 14	1	2	4	3
NH 15	1	3	4	2
NH 16	4	1	2	3
NH 17	4	1	2	3
NH 18	4	2	3	1
NH 19	3	2	1	4
NH 20	1	3	4	2

Table A11: hVd- Order of presentation for CI subjects, "Everyday Listening". 1= Male, 2= Female, 3= 10-12 year old girls, 4= 5-7 year old girls.

Subject #	**1st**	**2nd**	**3rd**	**4th**
CI 1	1	2	3	4
CI 2	3	4	2	1
CI 3	1	3	4	2
CI 4	3	4	1	2
CI 5	3	1	2	4
CI 6	1	4	2	3
CI 7	2	1	3	4
CI 8	3	2	4	1
CI 9	2	3	1	4
CI 10	1	2	4	3

Table A12: hVd- Order of presentation for CI subjects, 2nd session (1st CI only). 1= Male, 2= Female, 3= 10-12 year old girls, 4= 5-7 year old girls.

Subject #	**1st**	**2nd**	**3rd**	**4th**
CI 1	1	4	3	2
CI 2	4	1	2	3
CI 3	1	2	4	3
CI 4	2	3	4	1
CI 5	N/A	N/A	N/A	N/A
CI 6	N/A	N/A	N/A	N/A
CI 7	4	1	2	3
CI 8	1	4	2	3
CI 9	3	4	1	2
CI 10	4	3	1	2

Table A13: CNCs- Order of presentation for NH subjects. 1= Male, 2= Female, 3= 10 year old girl, 4= 6 year old girl.

Subject #	**1st**	**2nd**	**3rd**	**4th**
NH 11	2	3	4	1
NH 12	4	1	2	3
NH 13	4	3	1	2
NH 14	1	4	2	3
NH 15	2	1	3	4
NH 16	4	3	1	2
NH 17	3	1	2	4
NH 18	1	3	4	2
NH 19	2	3	1	4
NH 20	2	1	3	4

Table A14: CNCs- Lists (#1-10) used for NH subjects, per talker type.

Subject #	M	F	G10	G6
NH 11	2	5	3	8
NH 12	8	3	4	7
NH 13	4	1	6	3
NH 14	6	7	3	4
NH 15	2	7	4	1
NH 16	10	1	7	2
NH 17	3	5	8	6
NH 18	6	10	7	5
NH 19	6	4	3	1
NH 20	8	4	5	3

Table A15: CNCs- Order of presentation for CI subjects, "Everyday Listening". 1= Male, 2= Female, 3= 10 year old girl, 4= 6 year old girl.

Subject #	1st	2nd	3rd	4th
CI 1	3	2	1	4
CI 2	1	4	2	3
CI 3	4	3	2	1
CI 4	4	2	3	1
CI 5	3	2	4	1
CI 6	3	4	2	1
CI 7	1	2	3	4
CI 8	3	2	4	1
CI 9	2	3	4	1
CI 10	1	4	3	2

Table A16: CNCs- Lists (#1-10) used for CI subjects, "Everyday Listening", per talker type.

Subject #	M	F	G10	G6
CI 1	8	6	7	10
CI 2	2	5	6	7
CI 3	7	5	2	6
CI 4	3	4	6	10
CI 5	1	5	4	3
CI 6	1	10	8	2
CI 7	7	4	8	10
CI 8	7	10	1	5
CI 9	4	8	2	5
CI 10	8	3	2	4

Table A17: CNCs- order of presentation for CI subjects, 2nd session (1st CI only). 1= Male, 2= Female, 3= 10 year old girl, 4= 6 year old girl.

Subject #	**1st**	**2nd**	**3rd**	**4th**
CI 1	1	2	4	3
CI 2	2	4	1	3
CI 3	4	2	1	3
CI 4	4	3	2	1
CI 5	N/A	N/A	N/A	N/A
CI 6	N/A	N/A	N/A	N/A
CI 7	2	3	1	4
CI 8	2	3	4	1
CI 9	3	1	4	2
CI 10	4	3	2	1

Table A18: CNCs- Lists (#1-10) used for CI subjects, 2nd session (1st CI only) per talker type.

Subject #	**M**	**F**	**G10**	**G6**
CI 1	3	4	1	2
CI 2	4	8	1	3
CI 3	1	10	4	8
CI 4	1	7	2	8
CI 5	N/A	N/A	N/A	N/A
CI 6	N/A	N/A	N/A	N/A
CI 7	3	6	2	1
CI 8	3	8	4	6
CI 9	3	1	7	10
CI 10	5	6	1	7

A19: hVd Matrices-
CI "Everyday Listening": data combined from all CI subjects (CI 1-10)

MALES

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**23**	1	–	–	–	–	–	1	–	–	–
hid:	3	**26**	1	–	2	–	–	1	–	1	–
head:	3	1	**25**	1	–	–	–	–	2	2	1
had:	–	–	1	**29**	3	–	–	1	–	–	–
hod:	–	–	2	–	**23**	2	1	5	–	–	6
hood:	–	1	–	–	–	**26**	7	6	1	–	1
who'd:	–	–	–	–	–	–	**21**	–	1	–	3
hud:	–	–	–	–	2	2	–	**16**	–	–	1
heard:	–	–	1	–	–	–	–	–	**26**	–	–
hayed:	1	1	–	–	–	–	–	–	–	**25**	–
hoed:	–	–	–	–	–	–	1	–	–	2	**18**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	25	34	35	34	39	42	25	21	27	27	21

FEMALES

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**28**	1	–	–	–	–	–	1	–	1	–
hid:	2	**28**	–	–	1	–	–	–	–	4	–
head:	–	1	**24**	–	–	–	–	3	–	2	–
had:	–	–	2	**26**	5	–	–	–	–	1	–
hod:	–	–	–	2	**23**	–	2	8	–	–	3
hood:	–	–	3	–	–	**28**	8	–	–	–	1
who'd:	–	–	–	–	–	–	**19**	1	–	1	2
hud:	–	–	–	–	1	1	–	**14**	–	–	–
heard:	–	–	1	–	–	–	1	1	**30**	–	–
hayed:	–	–	–	2	–	–	–	–	–	**21**	–
hoed:	–	–	–	–	–	1	–	2	–	–	**24**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	31	35	30	34	38	40	23	16	33	23	27

10-12 girls

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**27**	1	–	–	–	–	–	–	–	–	–
hid:	2	**27**	2	–	–	–	–	–	1	11	–
head:	1	1	**18**	–	–	–	–	1	1	2	–
had:	–	–	9	**28**	5	–	–	–	–	–	–
hod:	–	–	–	1	**22**	–	1	7	–	–	5
hood:	–	–	–	–	–	**28**	10	7	2	–	4
who'd:	–	–	–	–	–	1	**19**	–	–	–	2
hud:	–	1	–	–	1	–	–	**15**	–	1	2
heard:	–	–	–	–	–	1	–	–	**26**	–	2
hayed:	–	–	1	1	2	–	–	–	–	**15**	–
hoed:	–	–	–	–	–	–	–	–	–	1	**15**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	28	43	24	42	36	51	22	20	29	19	16

5-7 girls

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**26**	1	–	–	–	–	–	1	–	2	–
hid:	3	**22**	2	–	1	2	–	2	–	2	1
head:	–	6	**17**	1	–	2	–	–	–	–	–
had:	–	–	8	**22**	2	–	–	2	–	–	–
hod:	–	–	–	4	**22**	1	1	10	–	1	4
hood:	–	–	2	–	–	**20**	4	2	–	–	7
who'd:	–	1	–	–	–	2	**24**	–	–	1	1
hud:	–	–	–	2	5	1	–	**11**	3	–	2
heard:	–	–	1	–	–	2	–	–	**26**	–	8
hayed:	1	–	–	1	–	–	–	–	1	**23**	–
hoed:	–	–	–	–	–	–	1	2	–	–	**7**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	30	35	26	34	43	35	29	24	37	26	10

A20: hVd Matrices-
NH: data combined from all NH subjects (NH 11-20)

MALES

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**28**	–	–	–	–	–	–	–	–	–	–
hid:	–	**29**	–	–	–	–	–	–	–	–	–
head:	2	1	**30**	–	–	–	–	–	–	2	–
had:	–	–	–	**30**	4	–	–	–	–	1	–
hod:	–	–	–	–	**24**	1	2	4	–	–	–
hood:	–	–	–	–	–	**26**	7	1	–	–	4
who'd:	–	–	–	–	–	–	**16**	–	1	–	–
hud:	–	–	–	–	1	2	1	**25**	–	–	–
heard:	–	–	–	–	–	–	–	–	**29**	–	–
hayed:	–	–	–	–	–	–	–	–	–	**27**	–
hoed:	–	–	–	–	1	1	4	–	–	–	**26**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	28	29	35	35	31	38	17	29	29	27	32

FEMALES

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**29**	–	–	–	–	–	–	–	–	–	–
hid:	–	**30**	–	–	–	–	–	–	–	1	–
head:	1	–	**28**	–	–	–	–	–	–	–	–
had:	–	–	–	**30**	6	–	–	1	–	2	1
hod:	–	–	–	–	**21**	–	2	4	–	–	–
hood:	–	–	1	–	2	**29**	5	–	–	–	3
who'd:	–	–	–	–	–	–	**23**	–	–	–	1
hud:	–	–	–	–	–	1	–	**24**	–	–	–
heard:	–	–	1	–	–	–	–	–	**30**	–	–
hayed:	–	–	–	–	–	–	–	–	–	**27**	–
hoed:	–	–	–	–	1	–	–	1	–	–	**25**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	29	31	29	40	27	40	24	25	31	27	27

10-12 girls

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**28**	–	–	–	–	–	–	–	–	–	–
hid:	–	**30**	–	–	–	–	–	–	–	7	–
head:	2	–	**30**	–	–	–	–	–	–	–	–
had:	–	–	–	**30**	4	–	–	–	–	–	–
hod:	–	–	–	–	**22**	2	3	3	–	–	–
hood:	–	–	–	–	1	**28**	7	6	–	–	1
who'd:	–	–	–	–	–	–	**17**	–	–	–	–
hud:	–	–	–	–	–	–	–	**20**	–	–	–
heard:	–	–	–	–	–	–	–	–	**30**	–	–
hayed:	–	–	–	–	1	–	–	–	–	**23**	–
hoed:	–	–	–	–	2	–	3	1	–	–	**29**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	28	37	32	34	30	43	17	20	30	24	35

5-7 girls

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**29**	–	–	–	–	–	–	–	–	–	–
hid:	–	**30**	9	–	–	–	–	–	–	–	–
head:	1	–	**18**	2	–	–	–	–	1	–	–
had:	–	–	1	**28**	–	–	–	–	–	1	–
hod:	–	–	–	–	**26**	1	2	5	–	–	4
hood:	–	–	2	–	–	**27**	7	3	–	1	4
who'd:	–	–	–	–	–	1	**21**	–	–	–	–
hud:	–	–	–	–	1	1	–	**21**	–	–	–
heard:	–	–	–	–	–	–	–	–	**29**	–	–
hayed:	–	–	–	–	–	–	–	–	–	**28**	–
hoed:	–	–	–	–	3	–	–	–	–	–	**22**
Sent:	30	30	30	30	30	30	30	30	30	30	30
Heard:	29	39	22	30	37	44	22	13	29	28	25

A21: hVd Matrices-
CI 2nd session (first CI only): data combined from CI subjects with 2 devices (CI 1-10, excluding CI 5 & CI 6).

MALES

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**21**	–	–	–	–	–	–	–	–	1	–
hid:	3	**18**	–	–	2	–	–	1	1	1	–
head:	–	5	**22**	1	–	–	–	3	–	4	–
had:	–	–	1	**22**	3	–	–	–	–	–	–
hod:	–	–	–	–	**17**	–	1	3	–	–	3
hood:	–	–	–	–	–	**18**	5	3	–	–	3
who'd:	–	–	–	–	–	4	**15**	–	–	1	1
hud:	–	1	–	–	1	–	–	**12**	–	–	–
heard:	–	–	1	–	–	1	3	1	**23**	–	1
hayed:	–	–	–	1	–	–	–	–	–	**17**	–
hoed:	–	–	–	–	1	1	–	1	–	–	**16**
Sent:	24	24	24	24	24	24	24	24	24	24	24
Heard:	22	26	35	26	23	29	20	14	30	18	19

FEMALES

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**20**	1	–	–	–	–	–	–	–	–	–
hid:	2	**19**	2	–	3	–	1	–	1	3	–
head:	–	3	**18**	–	–	–	1	2	–	1	1
had:	–	–	2	**23**	7	2	–	2	–	3	–
hod:	–	–	–	–	**12**	2	–	8	–	–	3
hood:	–	1	–	–	–	**17**	11	–	2	–	3
who'd:	–	–	–	–	–	–	**9**	1	–	–	3
hud:	–	–	–	1	1	–	–	**11**	–	–	–
heard:	1	–	1	–	–	1	–	–	**20**	1	–
hayed:	–	–	1	–	1	1	–	–	–	**15**	–
hoed:	1	–	–	–	–	1	2	–	1	1	**14**
Sent:	24	24	24	24	24	24	24	24	24	24	24
Heard:	21	31	26	39	25	34	13	13	24	18	20

10-12 girls

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**19**	1	–	–	–	–	–	–	–	–	1
hid:	4	**16**	1	–	3	–	–	–	2	7	–
head:	1	3	**15**	2	–	1	–	5	1	5	–
had:	–	–	6	**20**	7	–	–	–	–	–	–
hod:	–	–	–	–	**13**	–	1	4	–	–	4
hood:	–	1	–	–	1	**17**	5	3	4	–	3
who'd:	–	2	–	–	–	4	**17**	–	–	–	2
hud:	–	–	2	–	–	1	–	**11**	–	–	–
heard:	–	–	–	–	–	1	–	1	**16**	–	1
hayed:	–	–	–	1	–	–	–	–	–	**11**	–
hoed:	–	–	–	1	–	–	1	–	1	1	**13**
Sent:	24	24	24	24	24	24	24	24	24	24	24
Heard:	21	34	33	33	22	34	25	14	19	12	17

5-7 girls

	heed	hid	head	had	hod	hood	who'd	hud	heard	hayed	hoed
heed:	**15**	1	2	–	–	–	–	–	1	2	–
hid:	6	**19**	4	2	2	4	–	1	–	3	–
head:	–	3	**12**	3	2	2	–	2	1	–	–
had:	–	–	5	**16**	3	–	–	1	1	–	–
hod:	–	–	1	2	**15**	–	–	11	2	–	4
hood:	–	–	–	–	–	**12**	4	1	–	–	2
who'd:	1	1	–	–	–	3	**19**	–	–	1	–
hud:	–	–	–	–	1	–	–	**7**	–	–	1
heard:	–	–	–	–	–	3	–	1	**19**	–	10
hayed:	1	–	–	–	–	–	–	–	–	**18**	2
hoed:	1	–	–	1	1	–	1	–	–	–	**5**
Sent:	24	24	24	24	24	24	24	24	24	24	24
Heard:	21	41	25	26	35	19	25	9	33	21	9

A22: hVd Data

NH: Data combined across 10 NH subjects (NH 11-20).

	Most misperceived tokens:	*Most common errors:*
M:	who'd, hod, hud	hood/who'd, had/hod, hoed/who'd
F:	hod, who'd, hud	had/hod, hood/who'd, hod/hud
G10-12:	who'd, hud, hayed	hood/who'd, hood/hud, had/hod
G5-7:	hud, head, who'd	hid/head, hood/who'd, hod/hud

CI session 1: "Everyday Listening". Data combined across 10 CI subjects (CI 1-10).

	Most misperceived tokens:	*Most common errors:*
M:	hud, hoed, who'd	hood/who'd, hood/hud, hod/hoed
F:	hud, who'd, hayed	hod/hud, hood/who'd, had/hod
G10-12:	hud, hayed, hoed	hid/hayed, hood/who'd, had/head
G5-7:	hoed, hud, head	hod/hud, heard/hoed, had/head

CI session 2: Data combined across the 8 CI subjects utilizing 2 devices, 1st CI only (CI 1-10, excluding CI 5 &6).

	Most misperceived tokens:	*Most common errors:*
M:	hud, who'd, hoed	hood/who'd, head/hid, who'd/hood
F:	who'd, hud, hod	hood/who'd, hod/hud, had/hod
G10-12:	hud, hayed, hod, hoed	hid/hayed, had/hod, had/head
G5-7:	hoed, hud, hood, head	hod/hud, heard/hoed, hid/heed

A23: CNC Data- Most commonly misidentified consonants. Number of errors combined across all 10 CI subjects, "Everyday Listening".

	P	**V**	**N**	**L**	**F**	**M**	**G**	**D**	**S**
M	23	16	15	14	14	10	10	9	1
F	11	8	15	14	11	23	8	6	7
G10	20	8	20	16	18	11	13	15	11
G6	7	10	14	26	8	15	6	26	8

*Since CNC lists have approximately the same phonemic distribution as the English language (and therefore an unequal number of phonemes/list), data can be roughly compared across talker types.