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Effects of sequential bilateral cochlear implantation in children with severe to profound hearing loss

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EFFECTS OF SEQUENTIAL BILATERAL COCHLEAR IMPLANTATION IN CHILDREN WITH SEVERE TO PROFOUND HEARING LOSS

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Abstract: The aim of this study was to evaluate the effects of asymmetry in auditory performance and asymmetry in hearing history on bilateral outcomes in children. Specifically, bilateral benefit was compared to a) individual ear performance on speech recognition and localization measures, and b) the hearing history of each ear.

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ABBREVIATIONS

AAI: Age at Implantation

AOSPHL: Age at Onset of Severe to Profound Hearing Loss

ANOVA: Analysis of Variance

BICI: Bilateral Cochlear Implant

BOR: Branchio-Oto-Renal Syndrome

CI: Cochlear Implant

CI1: First Ear to Receive a Cochlear Implant

CI2: Second Ear to Receive a Cochlear Implant

CMV: Cytomegalovirus

CNC: Consonant-Nucleus-Consonant Test

dB: Decibel

HA: Hearing Aid

HINT: Hearing in Noise Test

LOD: Length of Deafness

LOU: Length of Use

RMS: Root Mean Square

SD: Standard Deviation

SNHL: Sensorineural Hearing Loss

SPL: Sound Pressure Level

TBS: Time Between Surgeries

INTRODUCTION

Children with normal hearing receive bilateral auditory input from birth, allowing for the development of binaural sound processing from infancy. Binaural sound processing provides listeners with several advantages including detection of sound at a lower intensity level (binaural summation), improved speech understanding in background noise (binaural squelch), and improved abilities to localize sounds in space (Levitt & Rabiner, 1967; Marks, 1978; Nittrouer, Caldwell-Tarr, Lowenstein, Rice & Moberly, 2013). Because binaural sound processing requires auditory access from both ears, bilateral cochlear implantation is often recommended for children with severe to profound bilateral sensorineural hearing loss (SNHL) who are unable to benefit from hearing aid use. Many of these children have received cochlear implants sequentially (first and second ear surgeries separated by time) rather than simultaneously (both ears implanted during the same surgery procedure). The impact of the age at which a child receives their second cochlear implant (CI) on the ability to benefit from bilateral hearing is not entirely understood. Children who received their second CI before the age of eight exhibited faster rates of improvement and higher speech perception scores in quiet in the second ear than those who received their second CI after eight years of age (Peters, Litovsky, Parkinson & Lake, 2007). Similarly, shorter inter-implant delays and thus shorter duration of unilateral auditory deprivation has been associated with improved speech perception in quiet (Peters et al., 2007).

Bilateral cochlear implantation has also been shown to improve speech perception abilities in noise. Understanding speech in noise requires the listener to compare the auditory signal from both ears. Both children and adults listening in the bilateral cochlear implant (BICI) condition performed better for speech in noise tasks than in either unilateral condition (Buss et al., 2008; Gordon & Papsin, 2009; Vincent et al., 2012; Strom-Roum, Laurent & Wie, 2012).

Binaural auditory input is also vital for sound localization accuracy. To correctly identify the location of a sound source in space, the central auditory system compares time and intensity cues of the signal arriving at each ear. Without binaural auditory access, a listener is unable to compare signals, and thus localization accuracy decreases. Normal hearing children around the age of 5 are able to identify the location of a sound source within 30 degrees of its origin (RMS error ranging from 8.9-29.2 degrees) (Grieco-Calub & Litovksy, 2010). Bilaterally implanted children were able to localize better than those with one cochlear implant. However, their scores were significantly poorer than children with normal hearing (RMS error ranging from 19-56 degrees versus 8.9-29.2 degrees) (Vincent et al., 2012; Grieco-Calub & Litovksy, 2010). Shorter inter-implant intervals and previous acoustic experience have also correlated with improved localization abilities in children (Grieco-Calub & Litovsky, 2010; Strom-Roum, Rodvik, Osnes, Fagerland & Wie, 2012).

The improvement seen in the BICI condition over the performance of the best unilateral condition is often defined as bilateral benefit. Children receiving bilateral cochlear implants exhibit a wide range of performance on outcome measures that assess bilateral benefit. Researchers have investigated reasons behind this variability. In adult bilateral CI recipients, it has been suggested that the amount of bilateral benefit observed may relate to the symmetry in performance between the two implanted ears. For example, Yoon et al. found listeners had the greatest bilateral benefit when the performance of the two CIs alone was comparable (Yoon, Li, Kang, & Fu, 2011). Similarly, Mosnier and colleagues reported that individuals with symmetric speech scores between the two ears showed a significant bilateral advantage, whereas, those with asymmetric performance did not (Mosnier et al., 2008). Less is known about the relation between symmetry between ears and bilateral CI benefit in children.

The aim of this study was to evaluate the effects of asymmetry in auditory performance and asymmetry in hearing history on bilateral outcomes in children. Specifically, bilateral benefit was compared to a) individual ear performance on speech recognition and localization measures, and b) the hearing history of each ear. Speech perception abilities in both quiet and noise as well as localization abilities were compared between each unilateral condition and the bilateral listening condition. In doing so, measurements of binaural benefit were made. Factors that may influence binaural benefit were investigated and included age at onset of severe to profound hearing loss (AOSPHL), hearing aid use prior to cochlear implantation, age at cochlear implantation and symmetry of performance between ears.

METHODS

This study followed procedures approved by the Human Research Protection Office at Washington University School of Medicine. Inclusion criteria included participants between the ages 6 to 21, who had received bilateral cochlear implants at St. Louis Children's Hospital, having received their first cochlear implant by four years of age. Eighteen participants with bilateral cochlear implants enrolled who ranged in age at the time of testing from 7.48 to 21.38 years (mean 12.24 years; SD 4.32). Length of deafness ranged from .45 to 4.44 years (mean 1.80 years, SD 1.05) in the first ear and ranged from .92 to 12.37 years (mean 4.58 years, SD 3.51) in the second ear. Five participants underwent simultaneous cochlear implantation, and thirteen participants were sequentially implanted, with an average inter-implant interval of 2.83 years (SD 3.02). At the time of testing, all participants had experience listening with two cochlear implants for at least one year (mean length of bilateral use 7.16 years; SD 2.03). Tables 1 and 2 provide additional demographic information for each participant.

Prior to enrollment in the study, participants were seen by their primary audiologist. During this clinical appointment, loudness balancing was completed by asking the child if speech originating from the front was perceived equally loud between the two ears. Additionally, each participant's programs were optimized to maximize audibility and comfort for soft, average and loud speech. Programming optimization was confirmed by ensuring soundfield audiometric thresholds of 30 dB HL or better for each ear and completing a listening check to assess microphone quality. Participants completed all outcome measures using their everyday speech processor program and everyday settings for each ear. Tables 3 and 4 provide information about the cochlear implant devices and programming parameters used for each participant.

One three-hour test session was conducted with breaks as needed. Participants were tested in three conditions; with their first cochlear implant alone (CI1), with their second cochlear implant alone (CI2), and in the bilateral condition (BICI). The order of test conditions was randomized and maintained for all outcome measures included in the study protocol. Testing was completed in a double-walled sound booth and speech recognition stimuli were presented from a speaker at 0 degree azimuth, approximately 1 meter from the participant.

Word recognition in quiet was assessed at two intensity levels; at an average conversational level of 60 dB SPL and a soft conversational level of 50 dB SPL. Lists of 50 Consonant-Vowel-Consonant (CNC) (Peterson & Lehiste, 1962) recorded words spoken by a male talker were presented to the listener at each intensity level. Word lists were scored as a percent correct in each of the three conditions; CI1, CI2 and BICI. CNC word lists were randomized for each participant to reduce potential learning effects. Word recognition in noise was also assessed with CNC words presented at 60 dB SPL with 4-talker babble and a signal-to-noise (SNR) ratio of +8 dB. In this test condition, the words and background noise were

presented from the same loudspeaker. Similarly, word lists were scored as a percent correct in each of the three listening conditions.

Sentence recognition in noise was also assessed using Hearing In Noise Test (HINT) sentences (Nilsson, Soli, & Sullivan, 1994) in the R-Space (Revit, Schulein, & Julsrom, 2002; Compton-Conley, Neuman, Killion, & Levitt, 2004). The R-Space set up was designed to simulate a realistic noisy environment with eight speakers arranged in a circle surrounding the participant, each speaker 45 degrees apart. One list of HINT sentences (20 sentences) was presented to the listener in each of the three conditions from a loudspeaker at a 0 degree azimuth at a fixed level of 60 dB SPL. The level of the recorded restaurant noise presented from all eight speakers varied adaptively throughout the test, yielding the SNR at which the participant could correctly repeat back 50% of the sentences. The first sentence was presented to the listener at an SNR of +16 dB. If the participant could not correctly repeat back the sentence, the SNR was increased until a correct response was obtained. After the initial correct response, the SNR of the next sentences was decreased with correct responses and increased with incorrect responses. The SNR was adapted in 4 dB steps for the first 4 sentences presented, and in 2 dB steps for the remaining 17 sentences. The final SNR was calculated by averaging the SNR presentation level for the last 17 sentences. Adaptive HINT testing was completed in all three listening conditions.

Following adaptive HINT testing, roving HINT testing was completed in the R-Space set up. For this measure, HINT sentences were presented from one of five speakers in front of or to the sides of the listener (180 degree configuration). The restaurant noise was presented from all other speakers that were not delivering the sentence stimuli. The presentation level of the HINT sentences remained constant at 60 dB SPL with a fixed SNR that was 2 dB easier than the lowest SNR obtained in the adaptive R-space task. One list of HINT sentences (20 sentences) was

presented to the listener in two conditions; the best CI condition and the bilateral condition. The best CI condition was defined as the CI ear with the best performance during testing, including the lowest SNR identified in the adaptive R-Space task. For the five simultaneous participants, the best CI condition was defined as the preferred ear, based on performance during testing and subjective preference by the child. For each condition, the sentence lists were scored as percent correct of the total number of words correctly repeated back for the 20 sentences.

Localization was evaluated with participants seated facing a 15 loudspeaker array positioned in an arc from -70 degrees to +70 degrees, with 10 degrees separation between each speaker (Potts, Skinner, Litovsky, Strube, & Kuk, 2009). The participant was seated 1.5 meters from the center speaker. Two CNC word lists (100 total words) were presented in each condition at 60 dB SPL (+/- 3 dB). Ten words were presented randomly from one of ten active loudspeakers, 5 loudspeakers were inactive (unknown to the listener). Participants were instructed to identify the number of the speaker (visibly marked from 1 to 15) from which the stimulus was presented, participants were not asked to repeat the word. Scores were reported as a root-mean-square (RMS) error score based on the source location and participant response for each condition.

For each participant, a calculation was made to estimate the length of time they had good auditory access in each ear. To make this assessment, auditory access was analyzed for each participant from birth to test date for both ears. Auditory access was split into four categories; no auditory access (aided thresholds in the severe to profound hearing loss range), poor access (aided thresholds in the moderately severe hearing loss range), fair access (aided thresholds in the low frequencies at 30 dB or better, sloping into the moderate/moderately severe hearing loss range) and good access (aided thresholds 30 dB or better). Estimates were made for the length

of time the participants experienced each of the four categories. Furthermore, the length of time spent in each category was factored into the final calculation at varying degrees, based on the amount of auditory access (time spent with good access counted at 100%, fair access counted at 50%, poor access counted at 25% and no access counted at 0%). For example, participant 6 was identified with bilateral profound hearing loss at birth. P06 was fit with hearing aids at 2.5 months of age and implanted in the first ear at 14 months of age. It was estimated P06 experienced no auditory access for approximately 76 days prior to amplification, poor auditory access for 355 days while aided and good auditory access for 2,596 days while wearing their first CI. To estimate the percent of life with good hearing in the first ear, the number of days with no access was factored into the calculation at 0% (0 x 76), the number of days with poor auditory access was counted at 25% (.25 x 355), and the number of days with good auditory access was counted at 100% (1 x 2596). This number was then divided by the total number of days. [((0 x 76) + (.25 x 355) + (1 x 2596)) / 3027) = 89% of life with good hearing in the first ear. Estimates for percent of life with good hearing for each participant are displayed in Table 5.

Data Analysis

Mean scores were compared between the three listening conditions (CI1, CI2 and BICI) for each speech perception and localization measure. A repeated measure one-way analysis of variance (ANOVA) was completed to compare group scores. Following determination of significance, a post-hoc analysis using Bonferroni corrections was applied. If the data violated the assumption of sphericity, Greenhouse-Geisser values were reported. For roving HINT testing, mean scores were compared between the two listening conditions (the best unilateral CI condition and BICI). A paired sample t-test was completed to compare group statistics. The

effects of demographic variables were examined using correlational analyses.

RESULTS

Figure 1 displays the average soundfield thresholds for CI1 and CI2 prior to testing. Mean thresholds for frequency modulated (FM) tones were 21 dB HL or better for each ear and suggested good audibility across the frequency range of .25 to 6 kHz.

CNC Words

Figure 2 displays the individual participant and average scores in percent correct for CNC words in quiet at 60 dB SPL for all three listening conditions; light green for the first implanted ear (CI1), purple for the bilateral condition (BICI), and blue for the second implanted ear (CI2). In this figure and those that follow, participant results are ordered left to right based on the bilateral score from lowest (poorest) to highest. Results from ANOVA revealed a significant difference based on CI condition [$F(2, 34) = 14.00$, $p < 0.001$]. Pairwise comparisons revealed scores in the BICI were significantly higher than in the CI2 condition ($p < 0.001$), and CI1 scores were significantly higher than CI2 ($p < 0.05$). Though BICI scores tended to be higher than CI1, this result was not statistically significant. The mean score obtained for CNC words in quiet at 60 dB SPL in the BICI condition was 80.00% correct (range 58.00-96.00%; SD, 9.28), compared to 74.67% (range 44.00-96.00%; SD 13.02) in the CI1 condition and 66.56% correct (range 38.00-92.00%; SD 14.01) for the CI2 condition. While listening in the bilateral condition, all participants but one achieved speech perception scores at or greater than 70% correct. In the CI2 unilateral condition, all but one participant achieved scores of 40% correct or greater.

Figure 3 displays the individual and average scores in percent correct for CNC words in quiet at a soft level of 50 dB SPL. Results from ANOVA revealed a significant difference based on CI condition [$F(2, 34) = 15.40$, $p < 0.001$]. Pairwise comparisons revealed scores in the BICI condition were significantly higher than those in both the CI1 and CI2 conditions ($p < 0.01$; $p < 0.001$). While scores obtained in the CI1 condition tended to be higher than those in the CI2 condition, this result did not reach statistical significance. The mean score obtained for CNC words in quiet at 50 dB SPL in the BICI condition was 69.89% correct (range 52.00-92.00%; SD, 12.28), compared to 59.22% (range 26.00-84.00%; SD 14.41) in the CI1 condition and 52.56% (range 30.00-76.00%; SD 15.29) for the CI2 condition. In the bilateral listening condition, all participants achieved scores greater than 50% correct.

Figure 4 displays the individual and average scores in percent correct for CNC words in the presence of background noise (four talker babble with a +8 dB SNR). Results from ANOVA revealed a significant difference based on CI condition [$F(2, 34) = 17.47$, $p < 0.001$]. Pairwise comparisons revealed scores in the BICI condition were significantly higher than those in both the CI1 and CI2 conditions ($p < 0.05$; $p < 0.001$). The mean score obtained for CNC words in background noise in the BICI condition was 53.33% (range 26.00-92.00%; SD 15.54), compared to 46.22% (range 14.00-84.00%; SD 15.54) in the CI1 condition and 39.00% (range 10.00-74.00%; SD 16.25) for the CI2 condition. Sixteen of the eighteen children tested achieved bilateral scores greater than 40% correct when listening in noise.

HINT Sentences in the R-Space

Figure 5 displays the individual participant and average SNR obtained during adaptive HINT sentence testing completed in the R-Space for all three listening conditions. Results from ANOVA revealed a significant difference based on CI condition [$F (2, 34) = 35.48$, $p < 0.001$]. Pairwise comparisons revealed the bilateral condition yielded significantly lower SNR scores compared to both the CI1 and CI2 conditions ($p < 0.001$; $p < 0.001$). The mean SNR obtained for adaptive HINT sentences in the R-Space in the BICI condition was +5.98 dB (range -.82 - +13.88 dB; SD 3.98), compared to +9.37 dB (range +2 - +21.18 dB; SD 5.01) in the CI1 condition and +10.61 dB (range +5.76 - +21.18 dB; SD 4.76) for the CI2 condition. In the bilateral listening condition, more than half of the participants obtained SNR scores less than +5 dB. One participant, P18, obtained a negative SNR score in the BICI condition and similarly, obtained some of the best scores in each unilateral CI condition. This participant had congenital bilateral severe to profound SNHL and was implanted simultaneously at the age of one.

Figure 6 displays the individual participant and average scores obtained for roving HINT sentences completed in the R-Space for two listening conditions, the best unilateral CI condition (in grey) and BICI (in purple). Results from the paired t-test revealed a significant difference based on CI condition [$t (17) = 7.76$, $p < 0.001$]. Pairwise comparisons revealed scores in the BICI condition were significantly higher than those in the best unilateral condition ($p < 0.001$). The BICI mean score obtained for roving HINT sentences in the R-Space was 78.61% (range 42.00-96.00%; SD 14.69) compared to 63.06% (range 32.00-86.00%; SD 15.30). Participants completed HINT testing at SNRs ranging from +1.2 – 15.88 dB.

Localization

Figure 7 displays the individual participant and average RMS values obtained for localization testing. Results from ANOVA revealed a significant difference based on CI condition [$F(2, 34) = 20.32$, $p < 0.001$]. Pairwise comparisons revealed the bilateral condition yielded significantly lower RMS values compared to both the CI1 and CI2 conditions ($p < 0.01$; $p < 0.001$). Lower RMS values indicate better accuracy for localization of a sound in space. The mean bilateral RMS score obtained for localization was 33.83 degrees (range 10.30-55.00; SD 12.85), compared to 55.07 (range 35.40-76.23; SD 11.23) in the CI1 condition and 55.61 (range 40.20-81.78; SD 10.35) for the CI2 condition. The participants displayed significant variability in terms of bilateral benefit. Several participants, including P14, P13 and P16, do not show any bilateral benefit, whereas 12 participants show a large bilateral benefit. The four top performers for this task were able to localize within 20 degrees. The top performer, P15, performs near chance (59 degrees) when listening in either unilateral condition. Their score improves significantly to 10.3 degrees when listening in the BICI condition.

Correlational Analyses

To investigate the effects of demographic factors on bilateral speech perception and localization skills, correlation analyses were completed. The demographic factors included in the analysis consisted of age at onset of severe to profound hearing loss in each ear, age at implantation in each ear, length of deafness in each ear, length of use of each CI, time between surgeries and percent of life with good hearing in each ear. Table 6 details the correlational coefficients and probability values for each of the test measures.

Figure 8 displays the correlation between the scores for BICI CNC words in quiet at 60 dB SPL and several significant demographic factors. A significant correlation was found

between the age at implantation for the second CI and CNC words in quiet at 60 dB SPL in the bilateral listening condition ($r = -.754$, $p < 0.001$). Scores for BICI CNC words in quiet increased as the age at implantation for the second ear decreased. A similar correlation was found for several other demographic factors, including the length of deafness in the second ear ($r = -.821$, $p < 0.001$) and the time between implant surgeries ($r = -.771$, $p < 0.001$) when compared to BICI CNC words in quiet at 60 dB SPL. As the length of deafness of the second ear and time between surgeries decreased, the bilateral scores for CNC words increased.

Similarly, a significant correlation was found between adaptive HINT testing in the R-Space in the bilateral condition and the age at implantation of the second CI ($r = .492$, $p = 0.038$), length of deafness in the second ear ($r = .592$, $p = 0.010$) and time between surgeries ($r = .569$, $p = 0.014$). The three significant correlations are displayed in scatterplots in Figure 9. For this listening task, lower SNRs indicate better performance in noise. Those children who received their second CI at a younger age, experienced shorter lengths of deafness in the second ear and had a shorter time between surgeries tended to obtain lower SNR scores in the R-Space.

The three demographic factors discussed, that is age at implantation of the second CI, length of deafness in the second ear, and time between surgeries were highly correlated. All three of these factors are related to time of implantation. A child who receives their second CI at a young age will also have a shorter length of deafness in the second ear and a shorter time between surgeries. Therefore, a similar pattern of significance was expected for these three demographic factors and their effect on speech perception outcomes.

Figure 10 demonstrates statistically significant correlations between length of use of the first CI compared to bilateral scores for CNC words in quiet at 60 dB SPL ($r = -.603$, $p = 0.008$) and adaptive HINT testing in the R-space ($r = .635$, $p = 0.005$). For both of these measures, as

the length of use with the first CI increased, performance on these tasks tended to decrease. This result indicates that children with longer periods of use with their first CI performed poorer for CNC words in quiet at 60 dB SPL and showed poorer performance in noise in the R-Space when tested in the bilateral condition. Length of use with the first CI is highly correlated with time between surgeries. Therefore, these children with longer use of their first CI tended to wait longer to receive their second CI and had longer periods of unilateral CI experience.

A significant correlation was also found between the percent of life with good hearing in the second ear and CNC words in quiet at 60 dB SPL ($r = .805$, $p < 0.001$) as well as adaptive HINT testing in the R-Space ($r = -.542$, $p = 0.020$) when listening bilaterally. Those participants who experienced a longer period of good hearing in their second ear tended to have higher speech perception scores in the BICI listening condition and performed better in noise. These relations are displayed in Figure 11.

Correlational analyses were also completed to investigate the relationship between bilateral benefit and asymmetry in performance between the two unilateral conditions for each speech perception and localization measure. To calculate bilateral benefit, the CI1 score was subtracted from the BICI score. A positive number indicated a significant improvement in the bilateral condition, whereas, a negative number indicated a decrement in the bilateral condition compared to CI1. To measure the asymmetry in performance between each ear, the difference in scores obtained in the CI1 condition was compared to that obtained in the CI2 condition. No statistically significant correlation was found between bilateral benefit and asymmetry in performance between ears for any of the speech perception and localization measures.

Furthermore, bilateral benefit was compared to the asymmetry found in percent of good hearing in each ear. To calculate the asymmetry in percent of life with good hearing, the percent

of life score for CI1 was compared to that of CI2. This calculation is displayed in Table 5. For the localization task only, a significant correlation was found between bilateral benefit and the asymmetry in the percent of life with good hearing ($r = .646$, $p = 0.004$). This correlation is displayed in a scatterplot in Figure 12. The graph suggests that children with more symmetric hearing histories between the two ears were able to identify the location of a sound source with greater accuracy than those with more asymmetric histories.

DISCUSSION

The aim of this study was to evaluate the effects of asymmetry in auditory performance and asymmetry in hearing history on bilateral outcomes in children. Specifically, bilateral benefit was compared to a) individual ear performance on speech recognition and localization measures, and b) the hearing history of each ear. All of the participants included in this study received their first cochlear implant by 4 years of age, with varying lengths of time between their first and second surgeries.

Results for CNC word testing in quiet and in noise revealed a significant difference between the three listening conditions. For CNC words in quiet at 60 dB SPL, scores were significantly higher in the CI1 condition compared to that of CI2, as well in the bilateral condition compared to CI2, suggesting that bilateral auditory input enhances speech perception in quiet. For CNC words in quiet at 50 dB SPL as well as in background noise, speech perception scores were highest in the bilateral condition compared to scores obtained in either unilateral condition. These two tasks, listening to soft speech and speech in the presence of background noise, are significantly more difficult than listening to speech at an average conversational level. As the tasks became increasingly more difficult, a more pronounced

bilateral advantage was seen, suggesting binaural auditory input increases one's speech perception abilities in difficult listening environments.

To evaluate each participant's speech understanding in a more realistic noisy environment, testing was completed in the R-Space. Results for adaptive HINT testing demonstrated that participants obtained significantly lower SNRs when listening in the bilateral condition. Seventeen of the eighteen participants obtained a lower SNR when in the BICI condition over either unilateral condition. One participant of note, P18, obtained a negative SNR in the BICI condition. In a study conducted by Reeder et al., normal hearing listeners between the ages 7.5-17.8 years obtained a mean SNR of -4.6 dB (SD 1.7 dB) in the R-Space (Reeder, Cadieux, & Firszt, 2015). When listening with two implants, P18 is just outside of the range of SNRs obtained by normal hearing children. Furthermore, roving HINT testing in the R-Space compared speech perception in noise for the best unilateral CI condition compared to the BICI condition. Speech perception scores were significantly higher in the BICI condition than in the best unilateral CI condition. Fifteen participants obtained scores greater than 70% correct in the BICI condition, whereas only five participants scored above 70% correct in the unilateral condition. Taken together, these results demonstrate the importance of binaural auditory access for speech understanding in noise when the noise source surrounds the listener.

Localization testing revealed a significant bilateral advantage compared to either unilateral condition. Participants were able to identify the location of a sound source with significantly greatly accuracy when listening with both implants. Thirteen participants obtained RMS error values of 40 degrees or less, whereas only two participants were able to achieve this level of accuracy in the unilateral condition. RMS values obtained on this task varied widely between participants. In this study, RMS error values ranged from 10.30-55.00 degrees (average

33.83 degrees). This result is in agreement with a previous study conducted by Grieco-Calub and Litovsky (2010), who reported RMS values ranging from 19-56 degrees in pediatric BICI users.

Age at Implantation, Length of Deafness and Time Between Surgeries

A significant correlation was found between age at implantation of the second CI, length of deafness in the second ear and time between surgeries with several of the speech perception measures, including CNC words in quiet at 60 dB SPL and adaptive HINT testing in the R-Space. The correlations demonstrate that participants who received their second CI at a younger age, and thus had shorter periods of deafness in the second ear and shorter interimplant intervals, performed significantly better on speech perception tasks both in quiet and in noise than those who received their second CI at an older age. This observed trend supports previously published studies, where shorter interimplant delays and shorter periods of auditory deprivation were associated with improved speech perception scores in both quiet and noise (Peters et al., 2007; Gordon & Papsin, 2009). Children with longer interimplant delays experience greater periods of time with unilateral auditory stimulation. It has previously been suggested that extended periods of unilateral implant use may negatively affect later speech perception abilities in the second ear (Gordon & Papsin, 2009).

Length of Use of CI1

A significant association was also observed between the length of use with the first CI and CNC words in quiet at 60 dB SPL and adaptive HINT testing in the R-Space. The correlation revealed that those listeners with longer periods of use with their first CI tended to perform

poorer on speech perception tasks in quiet and in noise than those with less CI1 experience. Length of use with CI1 is highly correlated with the time between surgeries. Those with more experience with CI1 tended to have longer inter-implant intervals, and thus longer periods of deafness in the second ear. As mentioned previously, shorter inter-implant intervals have been associated with greater speech perception performance (Peters et al., 2007; Gordon & Papsin, 2009).

Bilateral Benefit versus Symmetry in Performance Between Ears

Correlational analyses were completed to investigate the relationship between the amount of bilateral benefit observed for each test measure compared to the symmetry in performance between the two implanted ears on each speech perception and localization task. However, a significant correlation was not observed between these two factors. This result is contrary to that published by Mosnier et al. (2008) and Yoon et al. (2011). In 2008, Mosnier found that individuals with more symmetric speech scores between the two ears showed a larger bilateral benefit than those with more asymmetric scores. Similarly, in 2011 Yoon et al. reported that listeners experienced the largest bilateral benefit when the performance of the two CIs alone was comparable. In the current study, a similar trend for bilateral benefit and symmetric speech perception scores for CNC words in noise was observed, however, this result did not reach statistical significance. Five participants included in this study were simultaneously implanted, and though they experienced very similar hearing histories between their two ears, performance was variable on speech perception and localization tasks.

Percent of Life with Good Hearing

A significant correlation was found between percent of life with good hearing in the second ear and speech perception tasks in quiet and in noise, CNC words in quiet at 60 dB SPL and adaptive HINT testing the R-Space. For both speech perception measures, participants who experienced a greater percentage of their life with good hearing in the second ear tended to perform better in both quiet and in noise, while those with less favorable listening histories in the second ear tended to perform poorer.

Asymmetry of Percent of Life with Good Hearing

A significant relationship was observed between asymmetry of percent of life with good hearing and bilateral benefit seen in localization testing. Participants with more symmetric hearing histories tended to experience greater bilateral benefit for localization testing. The two participants with identical hearing histories between the two ears (asymmetry = 0.00) observed the greatest amount of bilateral benefit during localization testing, indicating their localization accuracy was significantly better when listening in the bilateral condition over either unilateral condition. Whereas the two participants with the most asymmetric hearing histories (approximately 50% difference in symmetry) both experienced bilateral decrements during localization, suggesting they were able to localize the origin of a sound source with greater accuracy in the unilateral condition than in the bilateral condition. Taken together, these results suggest that those listeners with more symmetric hearing histories are able to identify the location of a sound source with greater accuracy than those with more asymmetric histories. This result is in agreement with results published by Grieco-Calub and Litovsky (Grieco-Calub & Litovsky, 2010). The authors suggested that localization accuracy requires a long period of bilateral listening experience to develop. Therefore, the participants in this study with symmetric

hearing histories experienced similar auditory input binaurally throughout their lives, allowing them to develop more accurate spatial awareness.

Overall, group data from this study reveal a significant bilateral advantage for the speech perception tasks completed in quiet for soft speech and in noise, as well as for localization. Greater performance was associated with earlier age at implantation in the second ear as well as shorter length of deafness in the second ear and a shorter inter-implant interval.

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Table 1. Individual Hearing History Information

Participant No.	Age at test	AOSPHL 1st Ear	AOSPHL 2nd Ear	Age HA 1st Ear	Age HA 2nd Ear	Etiology
P01	11.05	0	0	0.25	0.25	unknown
P02	8.42	1.66	1.66	1.67	1.67	CMV
P03	8.9	0	0	0.16	0.16	unknown
P04	16.47	2	2	2	2	unknown
P05	9.58	0	0	0.08	0.08	BOR
P06	8.29	0	0	0.21	0.21	unknown
P07	14.08	3	4	1.56	1.56	EVA
P08	10.2	0	0	0.66	0.66	unknown
P09	11.58	0	0	1.5	1.5	unknown
P10	21.38	0	0	0.67	0.67	unknown
P11	19	0	0	2.69	2.69	unknown
P12	9.7	0	0	0.34	0.34	unknown
P13	17.33	0	0	0.5	0.5	unknown
P14	12.61	0	0	2.18	2.18	unknown
P15	9.15	0	0	0.21	0.21	unknown
P16	7.68	0	0	0.25	0.25	unknown
P17	17.44	1.5	1.5	0.13	0.13	CMV
P18	7.48	0	0	0.33	0.33	Connexin 26
Mean	**12.24**	**0.45**	**0.51**	**0.89**	**0.89**	
SD	**4.32**	**0.92**	**1.09**	**0.85**	**0.85**	

Note: AOSPHL: Age at onset of severe to profound hearing loss; HA: Hearing aid; CMV: Cytomegalovirus; BOR: Branchio-Oto-Renal Syndrome; SD: Standard deviation.

Table 2. Individual Demographic Information

Participant No.	Age at CI1	Age at CI2	LOD CI1	LOD CI2	LOU CI1	LOU CI2	Time Between CI1 and CI2
P01	3.26	5.96	3.26	5.96	7.80	5.10	2.70
P02	2.11	3.09	0.45	1.43	6.31	5.33	0.98
P03	1.23	2.75	1.23	2.75	7.68	6.16	1.52
P04	2.86	8.57	0.85	6.57	13.61	7.90	5.72
P05	0.92	0.92	0.92	0.92	8.66	8.66	0.00
P06	1.10	2.09	1.10	2.09	7.19	6.20	0.99
P07	5.28	8.39	2.28	4.38	8.80	5.69	3.11
P08	1.79	1.96	1.79	1.96	8.41	8.24	0.17
P09	1.98	2.66	1.98	2.66	9.59	8.92	0.67
P10	2.15	12.37	2.15	12.37	19.23	9.01	10.22
P11	3.29	8.77	3.29	8.77	15.71	10.23	5.48
P12	4.44	8.23	4.44	8.23	5.25	1.47	3.79
P13	1.51	9.52	1.51	9.52	15.82	7.81	8.01
P14	2.47	5.02	2.47	5.02	10.13	7.58	2.55
P15	1.01	1.01	1.01	1.01	8.14	8.14	0.00
P16	0.86	0.86	0.86	0.86	6.82	6.82	0.00
P17	3.22	8.29	1.72	6.79	14.22	9.14	5.08
P18	1.06	1.06	1.06	1.06	6.42	6.42	0.00
Mean	**2.25**	**5.08**	**1.80**	**4.58**	**9.99**	**7.16**	**2.83**
SD	**1.27**	**3.70**	**1.05**	**3.51**	**3.98**	**2.03**	**3.02**

Note: LOD: Length of deafness; LOU: Length of use; SD: Standard deviation.

Table 3. Device Parameters

	Internal		External		Active Electrodes	
Participant	**CI1**	**CI2**	**CI1**	**CI2**	**CI1**	**CI2**
P01	HiRes 90K 1j	HiRes 90K 1j	Naida	Naida	1-16	1-15
P02	HiRes 90K 1j	HiRes 90K 1j	Harmony	Harmony	1-16	1-16
P03	HiRes 90K 1j	HiRes 90K 1j	Naida	Naida	1-4, 6-16	1-14
P04	Nucleus 24	Freedom CA	N5	N5	1-22	1-22
P05	HiRes 90K 1j	HiRes 90K 1j	Naida	Naida	1-15	1-15
P06	HiRes 90K 1j	HiRes 90K 1j	Naida	Naida	1-15	1-16
P07	HiRes 90K 1j	HiRes 90K 1j	Naida	Naida	1-7, 11-15	1-15
P08	Pulsar	Pulsar	Sonnet	Sonnet	12	12
P09	Freedom CA	Freedom CA	N6	N6	1-22	1-22
P10	CII Hi Focus 1j	HiRes 90K 1j	Harmony	Naida	1-7, 10-12	1-15
P11	Freedom straight	Freedom CA	N6	N6	1-22	1-22
P12	HiRes 90k 1j	HiRes 90K MidScala	Naida	Naida	1-16	1-16
P13	CII Hi Focus 1j	HiRes 90K 1j	Naida	Naida	1-10	1-13
P14	Freedom CA	Freedom CA	N6	N6	2-22	4-22
P15	Freedom CA	Freedom CA	N5	N5	22	22
P16	HiRes 90k 1j	HiRes 90k 1j	Naida	Naida	1-16	1-8, 10, 11
P17	Freedom CA	Nucleus CA	N5	N5	1-8, 10-15, 17, 18, 20-22	1-15, 17-19, 21, 22
P18	Nucleus CI 513	Nucleus CI 513	N5	N5	1-22	1-22

Table 4. Programming Parameters

Participant	Strategy CI1	Strategy CI2	Pulse Width (µs) CI1	Pulse Width (µs) CI2	Channel Rate (pps)/Maxima CI1	Channel Rate (pps)/Maxima CI2
P01	HiRes Optima-S	HiRes Optima-S	40.4	40.4	1650	1650
P02	HiRes Optima-S	HiRes Optima-S	40.4	40.4	1650	1650
P03	HiRes Optima-S	HiRes Optima-S	36.8	36.8	1811	1811
P04	ACE	ACE	25	25	900/12	900/12
P05	HiRes Optima-S	HiRes Optima-S	55.7	57.5	1197	1160
P06	HiRes Optima-S	HiRes Optima-S	45.8	38.6	1456	1727
P07	HiRes Optima-S	HiRes Optima-S	62.9	62.9	1061	1061
P08	FSP	FSP	30.4-60.4	33.8-67.1	980	850
P09	ACE	ACE	25	25	1200/12	1200/12
P10	HiRes-S	HiRes-S	34.1	21.6	1465	1574
P11	ACE	ACE	25 us	25	900/10	900/10
P12	HiRes Optima-S	HiRes Optima-S	32.3	32.3	2062	2062
P13	HiRes Optima-S	HiRes Optima-S	44.0	44.0	1515	1515
P14	ACE	ACE	25	25	900/8	900/10
P15	ACE	ACE	25	25	1200/12	1200/12
P16	HiRes Optima-S	HiRes Optima-S	42.2	42.2	1580	1580
P17	ACE	ACE	25	25	900/12	900/12
P18	ACE	ACE	25	25	900/8	900/8

Table 5. Percent of Life With Good Hearing

Participant No.	% Life CI1	% Life CI2	Asymmetry for % Life
P01	77	59	18
P02	82	77	5
P03	92	82	10
P04	87	60	27
P05	90	92	2
P06	89	80	9
P07	81	67	4
P08	83	80	3
P09	83	79	4
P10	91	42	49
P11	47	56	9
P12	75	43	32
P13	92	42	50
P14	80	59	21
P15	88	88	0
P16	78	90	12
P17	89	67	22
P18	85	85	0
Mean	83	69	16
SD	10	17	15

Note: Asymmetry for % Life: Percent of life with good hearing = % Life CI1 minus % Life CI2. Values listed in the Asymmetry for % of Life column are absolute values.

Table 6. Demographic Correlation

Condition	CNC Q60 BICI	CNC Q50 BICI	CNC-N BICI	Adp HINT BICI	Rov HINT BICI	Loc BICI
AOSPHL CI1	r = .059 p = .815	r = .186 p = 0.459	r = .046 p = 0.857	r = -.221 p = 0.379	r = -.313 p = 0.206	r = -.223 p = 0.375
AOSPHL CI2	r = .085 p = .738	r = .253 p = 0.311	r = .089 p = 0.725	r = -.235 p = 0.347	r = -.290 p = 0.242	r = -.263 p = 0.292
AAI CI1	r = -.358 p = .144	r = -.160 p = 0.527	r = -.087 p = 0.732	r = .088 p = 0.729	r = -.518 *p = 0.028	r = -.064 p = 0.800
AAI CI2	r = -.754 ***p < 0.001	r = -.355 p = 0.148	r = -.292 p = 0.239	r =.492 *p = 0.038	r = -.388 p = 0.112	r = .322 p = 0.193
LOD CI1	r = -.484 *p = 0.042	r = -.356 p = 0.147	r = -.145 p = 0.567	r = .300 p = 0.227	r = -.350 p = 0.155	r = .117 p = 0.643
LOD CI2	r = -.821 ***p < 0.001	r = -.453 p = 0.059	r = -.336 p = 0.173	r = .592 *p = 0.010	r = -.318 p = 0.198	r = .421 p = 0.082
TBS	r = -.771 ***p < 0.001	r = -.372 p = .128	r = -.327 p = 0.185	r = .569 *p = 0.014	r = -.252 p = 0.314	r = .422 p = 0.081
LOU CI1	r = -.603 **p = 0.008	r = -.230 p = 0.358	r = -.375 p = 0.126	r = .635 ***p = 0.005	r = -.064 p = 0.800	r = .414 p = 0.088
LOU CI2	r = -.030 p = 0.907	r = .097 p = 0.701	r = -.254 p = 0.308	r = .401 p = 0.099	r = .258 p = 0.301	r = .183 p = 0.466
% Life CI1	r = .048 p = 0.851	r = .223 p = 0.374	r = -.096 p = 0.706	r = -.261 p = 0.296	r = .110 p = 0.665	r = -.155 p = 0.539
% Life CI2	r = .805 ***p < 0.001	r = .505 *p = .032	r = .318 p = 0.198	r = -.542 *p = 0.020	r = .345 p = 0.161	r = -.425 p = 0.078

Note: Q: Quiet; N: Noise; Adp: Adaptive; Rov: Roving; Loc: Localization; BICI: Bilateral CI condition CI1: 1st cochlear implant; CI2: 2nd cochlear implant; r: correlation coefficient; p: probability value; % Life: Percent of life with good hearing; LOD: Length of deafness; AOSPHL: Age at onset of severe to profound hearing loss; AII: Age at implantation; LOU: Length of use; TBS: Time between surgeries. * *p < 0.05; *** *p < 0.01; **** *p < 0.005.*

Table 7: Asymmetric Percent of Life with Good Hearing and Bilateral Benefit Correlation

Condition	Bilat. Benefit CNC Q60	Bilat. Benefit CNC Q50	Bilat. Benefit CNC N	Bilat. Benefit Adp HINT	Bilat. Benefit Rov HINT	Bilat. Benefit Loc
Asym. % Life	r = -.234 p = 0.351	r = -.318 p = 0.198	r = .012 p = 0.963	r = -.061 p = 0.810	r = -.138 p = 0.586	r = .646 ***p = 0.004

Note: Q: Quiet; N: Noise; Adp: Adaptive; Rov: Roving; Loc: Localization; Bilat. Benefit: Bilateral benefit; Asym % Life: Asymmetry; % Life: Percent of life with good hearing; r: correlation coefficient; p: probability value. *** $p < 0.005$.

Figure 1: Average Audiometric Thresholds

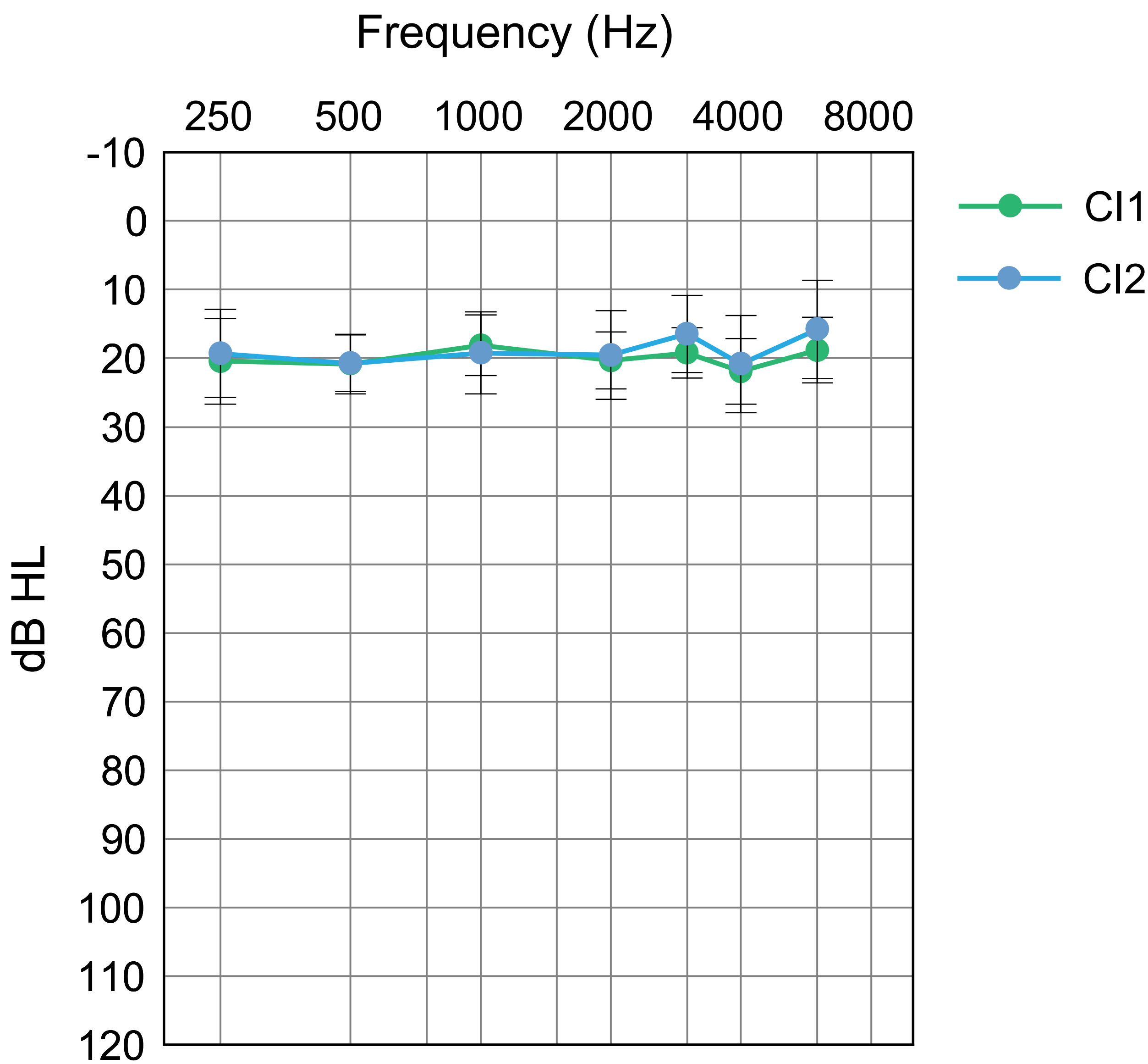
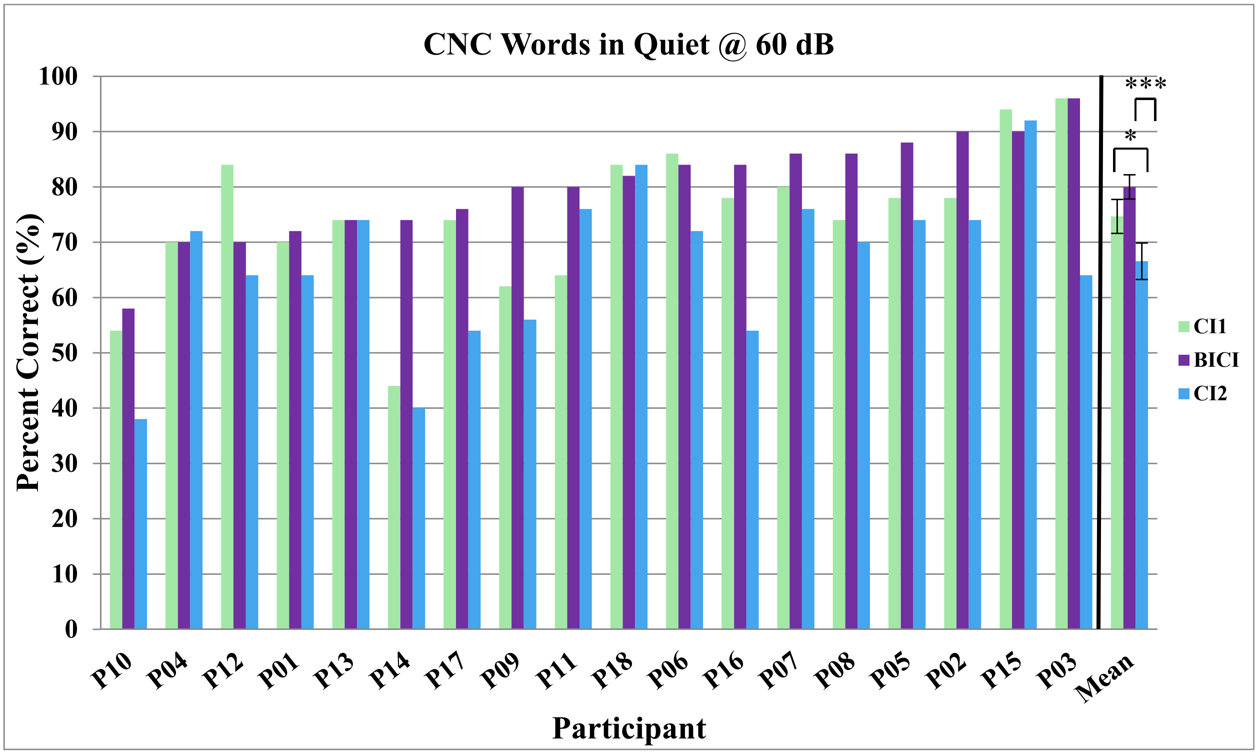
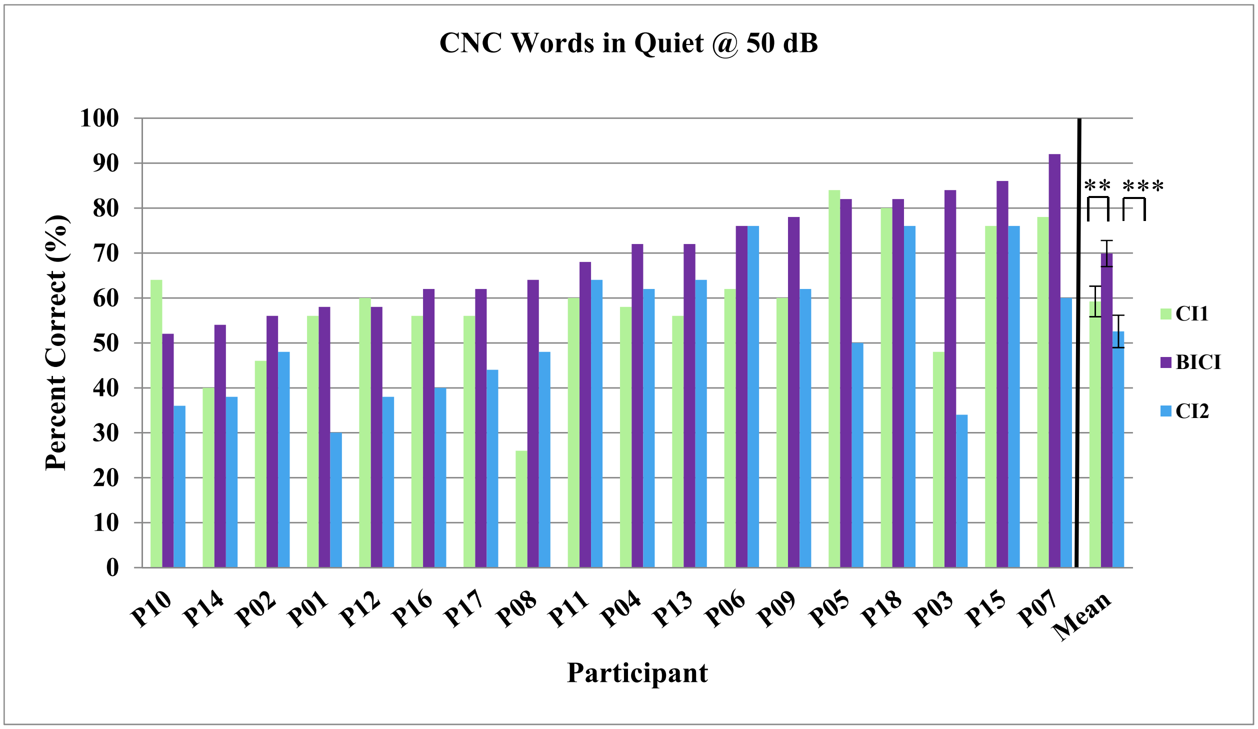


Figure 2. Individual and Average Results for CNC words Presented in Quiet at 60 dB SPL



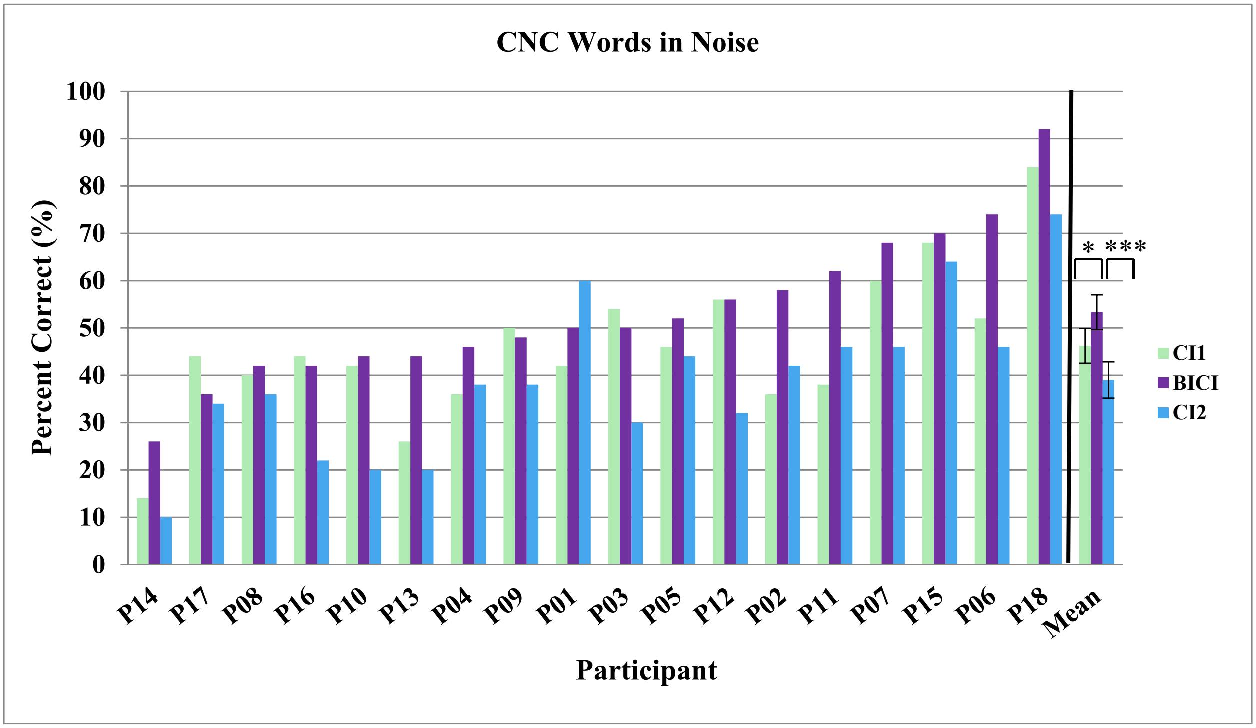
*Error bars indicate SEM. * p < 0.05; *** p < 0.001.*

Figure 3. Individual and Average Results for CNC words Presented in Quiet at 50 dB SPL



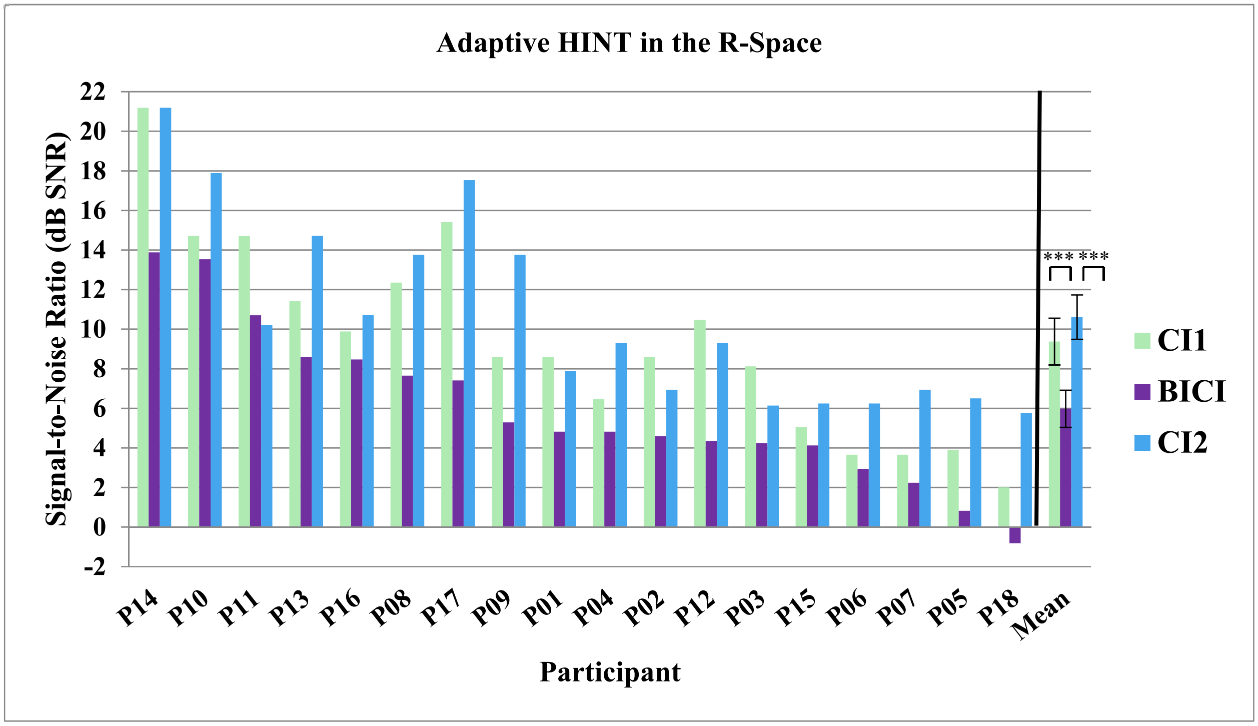
*Error bars indicate SEM. ** p < 0.01; *** p < 0.001.*

Figure 4. Individual and Average Results for CNC words Presented in Noise at 60 dB SPL (SNR +8 dB)



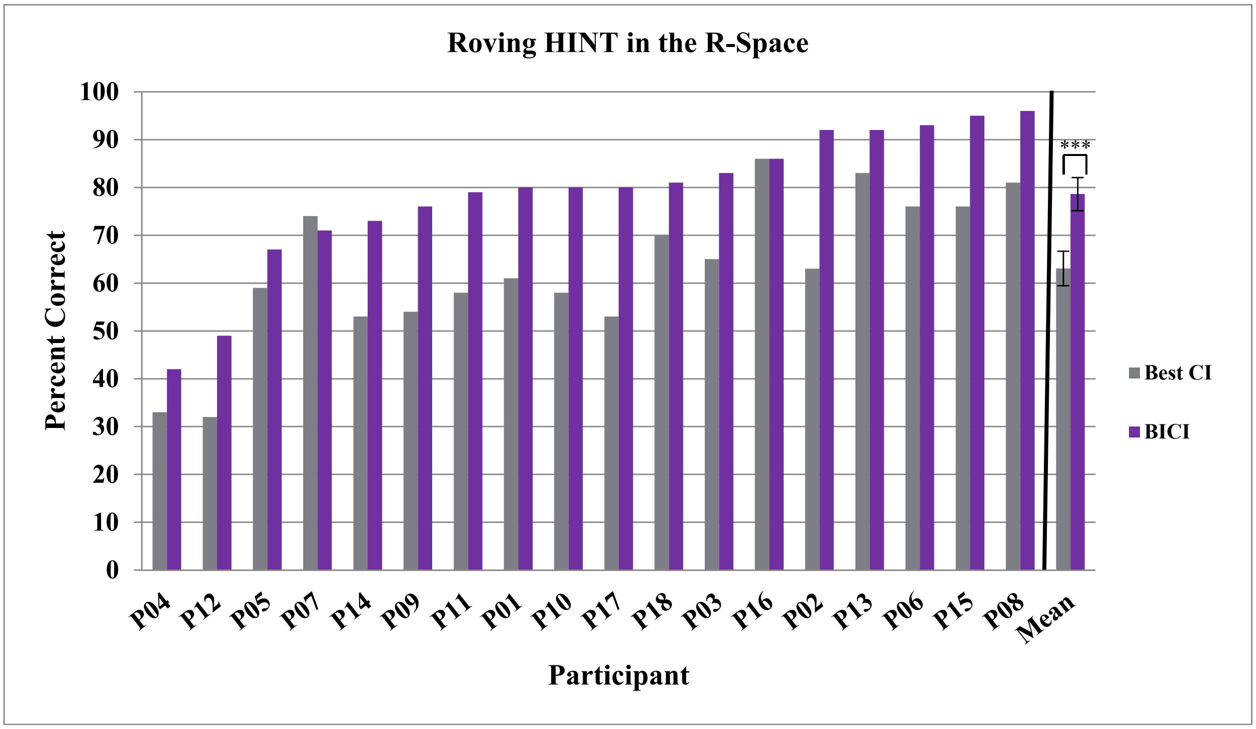
*Error bars indicate SEM. * p < 0.05; *** p < 0.001.*

Figure 5. Individual and Average SNR Scores for Adaptive HINT in R-Space



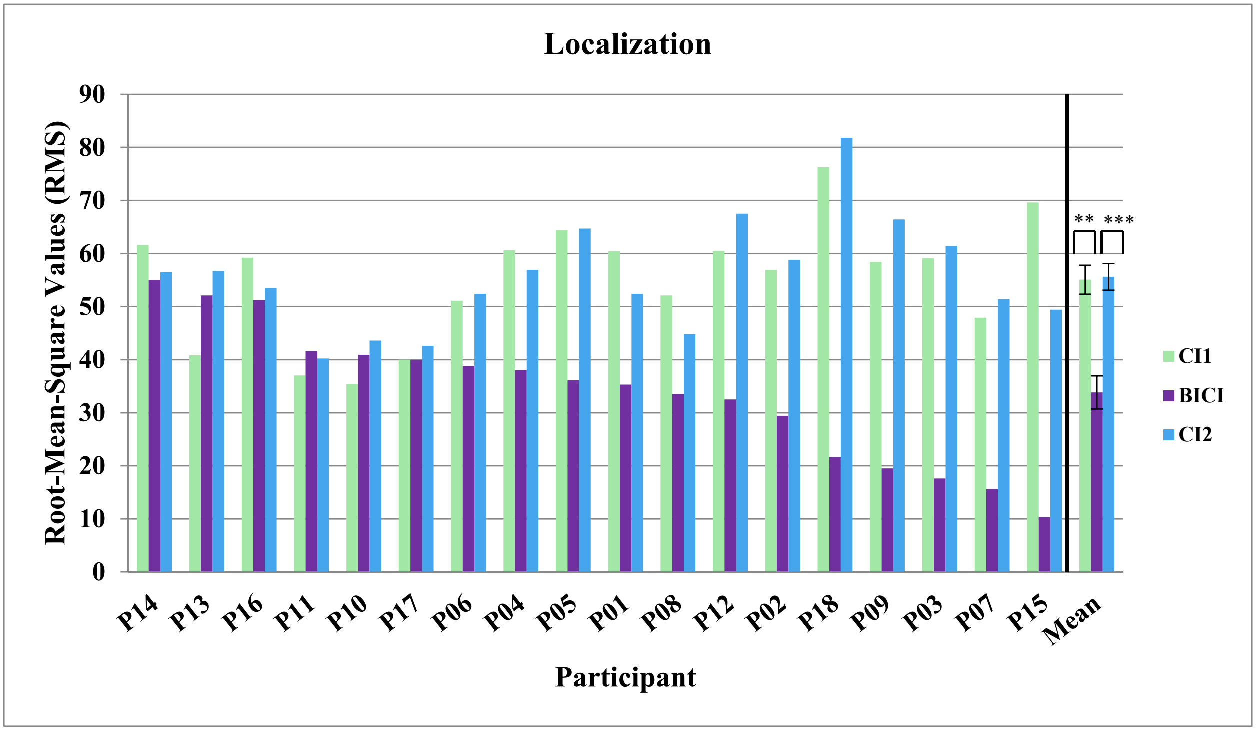
*Error bars indicate SEM. *** p < 0.001.*

Figure 6. Individual and Average Results for Roving HINT in R-Space



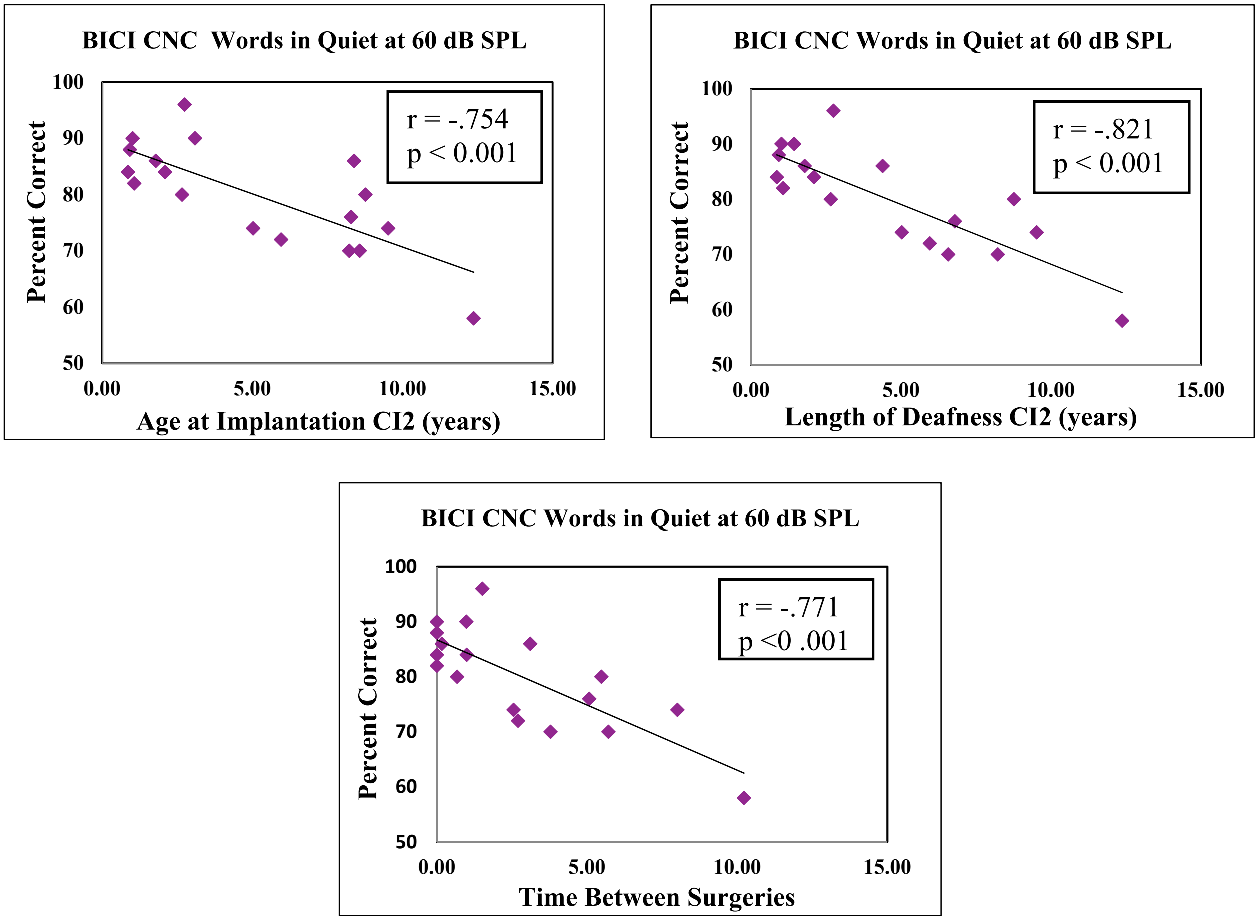
Error bars indicate SEM. *** p < 0.001.

Figure 7. Individual and Average RMS Values for Localization Testing



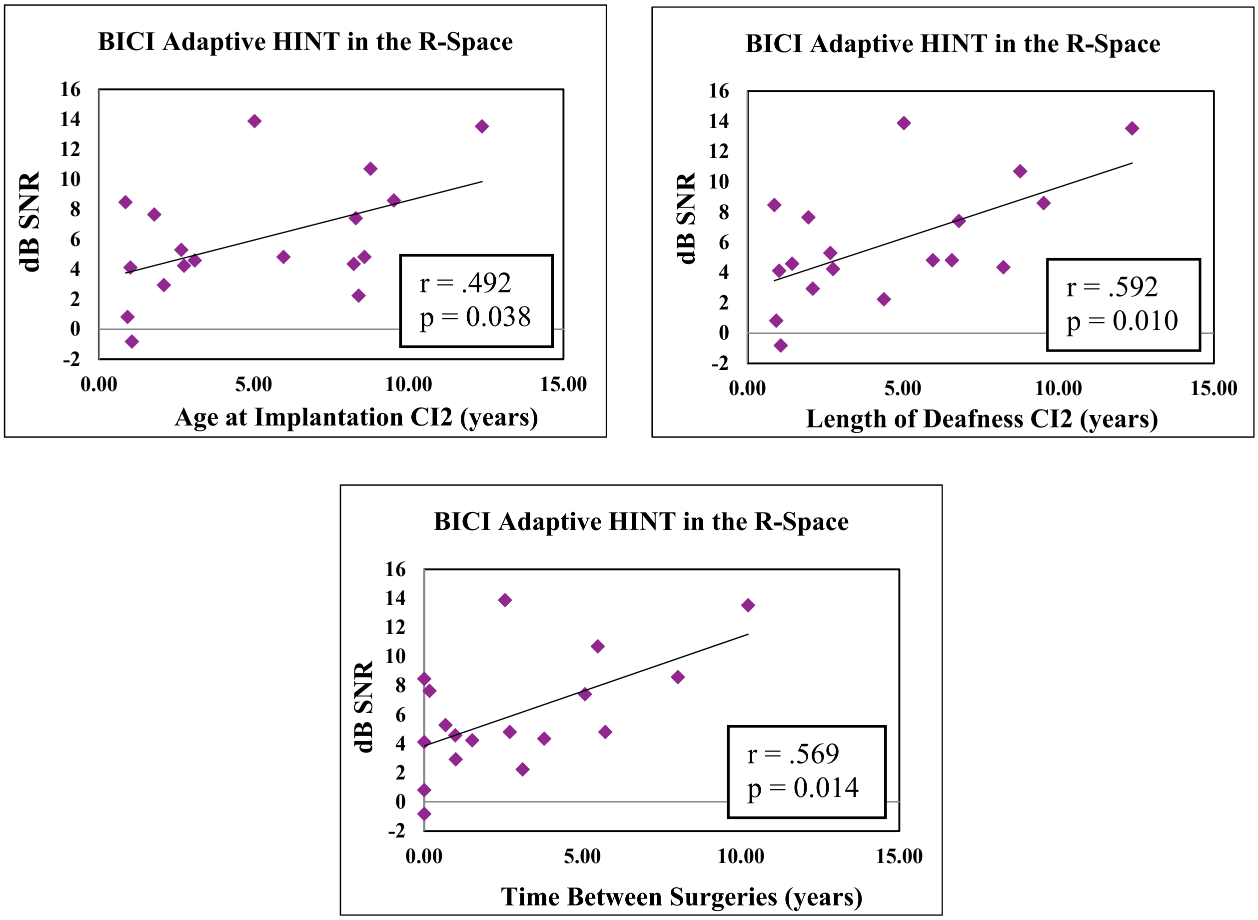
*Error bars indicate SEM. ** p < .01; *** p < 0.001.*

Figure 8: Relation between Demographic Factors and CNC words in Quiet at 60 dB SPL in the Bilateral Condition



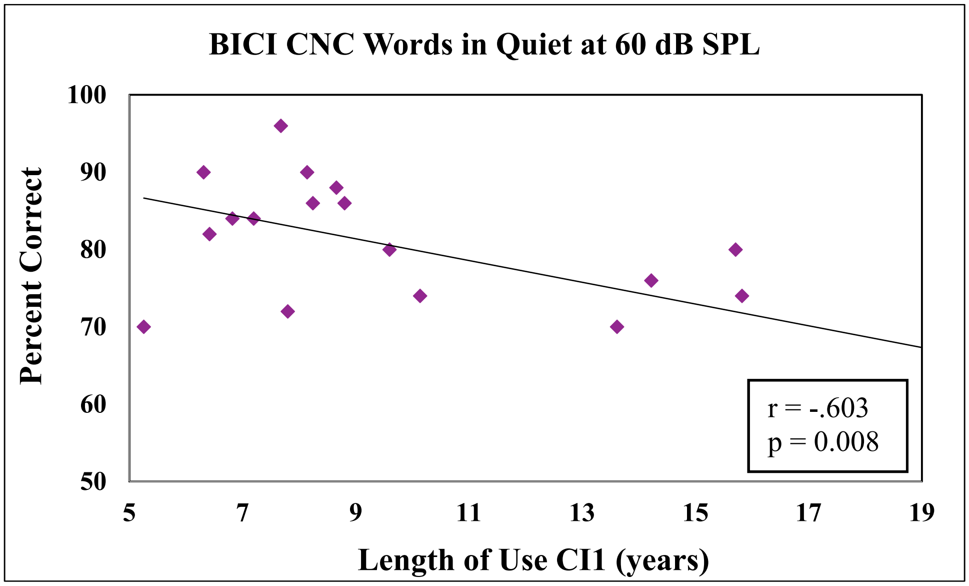
Note: SNR: Signal to noise ratio.

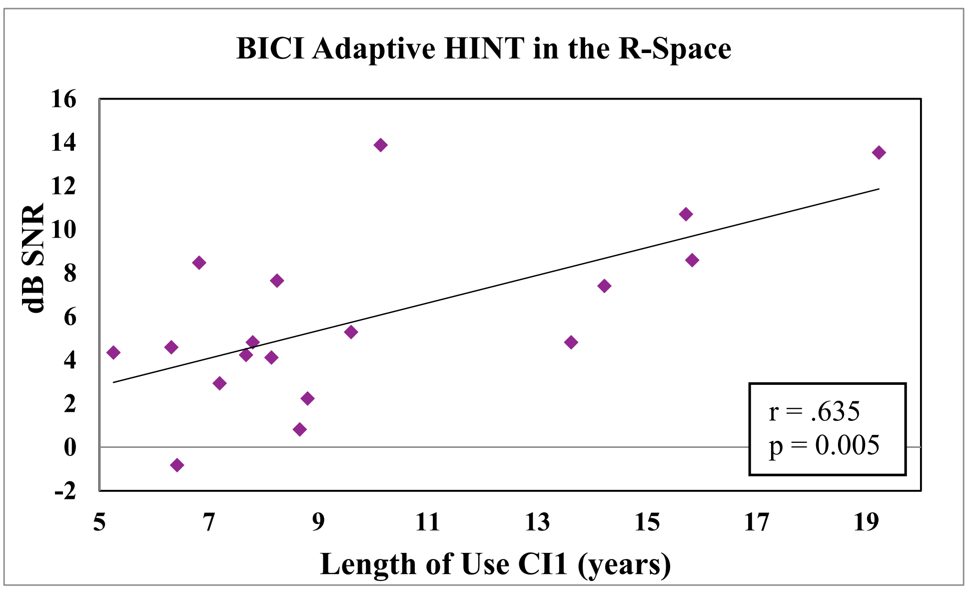
Figure 9: Relation between Demographic Factors and Adaptive HINT in the R-Space in the Bilateral Condition



Note: SNR: Signal to noise ratio.

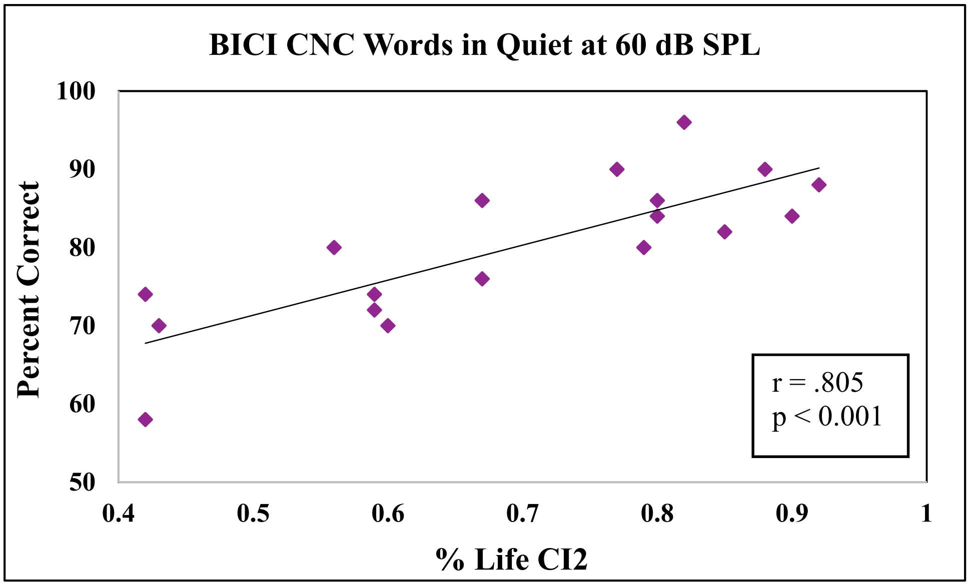
Figure 10: Relation between Length of Use with CI1 and CNC Words in Quiet at 60 dB SPL and Adaptive HINT in the Bilateral Condition

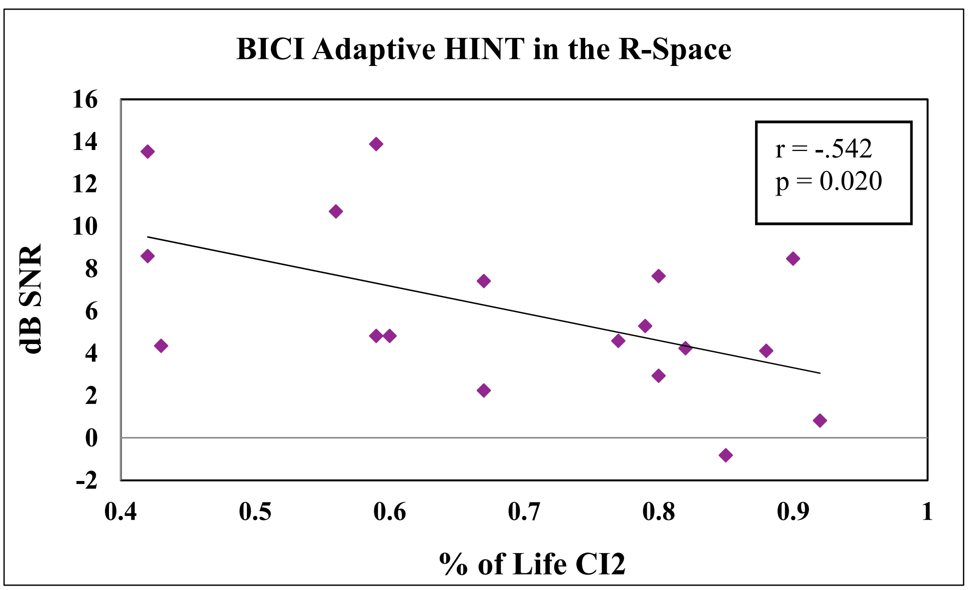




Note: SNR: Signal to noise ratio.

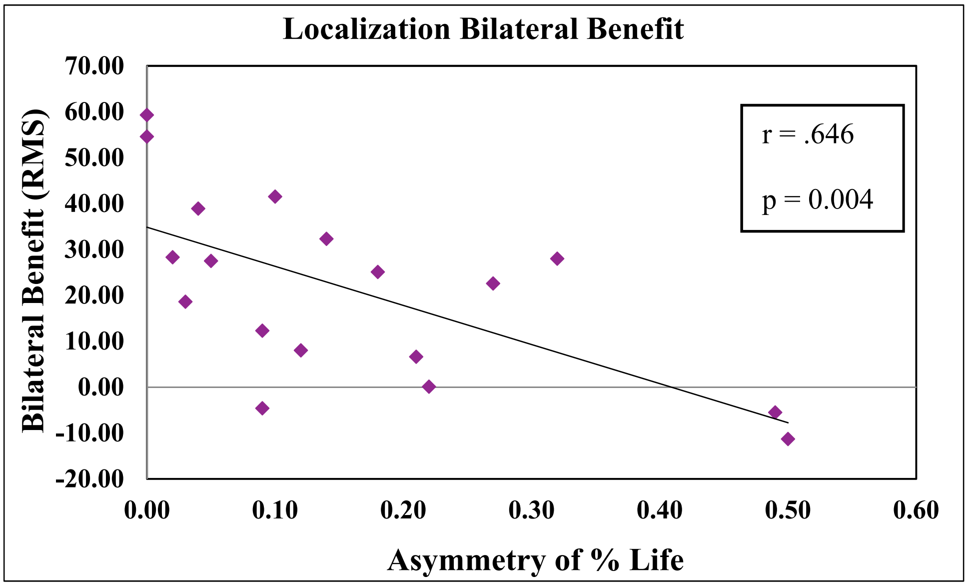
Figure 11: Relation between Percent of Life with Good Hearing CI2 and CNC Words in Quiet at 60 dB SPL and Adaptive HINT in the Bilateral Condition





Note: SNR: Signal to noise ratio; % of Life CI2: Percent of life with good Hearing with CI2.

Figure 12: Relation between Asymmetry of Percent of Life with Good Hearing and Bilateral Benefit in Localization Testing



Note: % Life: Percent of life with good hearing; RMS: Root Mean Square.