2012

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Recommended Citation

Weberling, Lindsay, "Speech perception and localization abilities in pediatric bilateral sequential cochlear implant recipients" (2012). *Independent Studies and Capstones.* Paper 658. Program in Audiology and Communication Sciences, Washington University School of Medicine. https://digitalcommons.wustl.edu/pacs_capstones/658

Speech Perception and Localization Abilities in Pediatric Bilateral Sequential Cochlear Implant Recipients

by

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A Capstone Project
submitted in partial fulfillment of the
requirements for the degree of:

Doctor of Audiology

Washington University School of Medicine
Program in Audiology and Communication Sciences

May 17, 2013

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Abstract:* *The primary purpose of this study was to evaluate speech perception and localization abilities in children who have received sequential cochlear implants, with the first implant received before age 4 and the second implant received before age 12. Results indicate performance in the bilateral cochlear implant condition is significantly better than listening with each implant alone for the outcome measures used in this study.

ACKNOWLEDGMENTS

I would like to extend a sincere thank you to Dr. Jill Firszt, for her continued insight and mentorship throughout the entirety of this capstone project. It has been a pleasure working in her research lab for the last two years, where I was able to gain invaluable learning experiences as a student. I would also like to thank to Dr. Jamie Cadieux for her endless patience, support, and guidance regarding all aspects of this study and throughout my time working in the Firszt Lab. Ruth M. Reeder provided invaluable assistance with statistical analysis and data interpretation. Thank you to the clinical audiologists at St. Louis Children's Hospital for their assistance in subject recruitment and coordinating clinical appointments with research sessions. Thank you to the clinical audiologists at Washington University for sharing booth space and time. This study could not have been successfully completed without the help from all these individuals. Finally, I would like to expresses genuine appreciation to the families and individuals who participated in the study and for their understanding of the importance of research in this clinical area.

This Capstone Research Project was supported by:

NIH/NIDCD R01 009010 (Firszt)

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

ABBREVIATIONS

ACE	Ace Combination Encoder
AOHL	Age at Onset of Hearing Loss
AOSPHL	Age at Onset of Severe to Profound Hearing Loss
ANOVA	Analysis of Variance
BICI	Bilateral Cochlear Implant
BKB-SIN	Bamford-Kowal-Bench Sentence in Noise
CI	Cochlear Implant
CI1	First Ear Cochlear Implant
CI2	Second Ear Cochlear Implant
CMV	Cytomegalovirus
CNC	Consonant-Nucleus-Consonant Test
dB	Decibel
EVA	Enlarged Vestibular Aqueduct
HA	Hearing Aid
HINT	Hearing in Noise Test
LOD	Length of Deafness
LOU	Length of Use
RMS	Root-Mean-Square
SD	Standard Deviation
SPL	Sound Pressure Level

INTRODUCTION

People with two normal hearing ears develop binaural sound processing, leading to detection of sound at lower intensity levels (binaural summation), better understanding of speech in background noise (binaural squelch), and localization of sounds in space (Levitt et al., 1967; Marks, 1978). Because these binaural advantages cannot develop without hearing in each ear, bilateral rather than unilateral cochlear implantation is often recommended as treatment for individuals with severe to profound sensorineural hearing loss who do not benefit from hearing aids. Bilateral cochlear implants can improve speech perception abilities compared to listening with one device alone, especially in noise, however results are variable and outcome predictors are unknown (Peters et al., 2007; Ramsden et al., 2005; Kuhn et al., 2004; Galvin et al., 2007). In addition, questions remain regarding user success for the second ear in those who are sequentially implanted after a period of unilateral implantation.

Several factors may play a role in determining binaural listening advantages in the sequentially implanted population, such as the time interval between implants, the age at implantation of the second ear, and/or the previous auditory experiences for each ear. Some research has revealed at least some bilateral listening advantages when listening to speech in noise and localization tasks regardless of age at second implant and time between implants (Litovsky et al., 2004; Peters et al., 2007). In comparison, other studies noted higher speech perception scores in noise with each implant alone and in the bilateral condition as well as better localization abilities in children who received the second implant at a younger age (< 4 years of age), experienced shorter duration of deafness and/or shorter intervals between implants, and had a history of using a hearing aid in the non-implanted ear (Gordon et al., 2009; Van Deun et al., 2009; Peters et al., 2007; Steffans et al., 2008).

Studies have shown that children who receive their first implant before the age of 2 years have better success achieving speech perception and communication abilities comparable to age-matched normal hearing children when listening in quiet environments (Kim et al., 2009; Svirsky et al., 2004; Robbins et al., 2004). However, these scores decrease significantly in noise. Similar trends have been reported regarding age of implantation for the second ear and speech perception abilities, suggesting those who receive the second implant at a younger age (< 4 years of age) achieve higher speech perception scores that are more comparable to the first ear (Gordon et al., 2009; Asp et al., 2011; Galvin et al., 2008).

The ability to localize a sound source is dependent on the central auditory system making comparisons of timing (for lower pitches) and intensity (for higher pitches) between ears. These differences cannot be accessed if the auditory signal is not available in each ear. Adding a second cochlear implant to provide auditory access would be expected to improve localization, however, localization abilities are reduced compared to normal hearing listeners. One possible explanation is poorly balanced loudness between devices where one ear receives a louder input than other ear, eliminating the ability to successfully compare individual ear intensities. Continued localization difficulty may arise because the timing cues between the two implants are mismatched, which in turn alters the timing comparisons between ears. In addition, for sequential implantation, a period of auditory deprivation and/or unilateral auditory input occurs before receiving the second implant which may influence adaptation to binaural input.

In a study by Greico-Calub et al. (2010), normal hearing children performed localization tasks at RMS values less than 30° (range: 8.9 - 29.9°). With unilateral cochlear implant users, or in the unilateral condition in bilateral users, localization performance was near or at chance levels (Litovsky et al., 2006; Verschuur et al., 2005; Senn et al., 2005). Although some pediatric bilateral cochlear implant users showed significantly better localization abilties in the bilateral condition compared to that of the unilateral condition, performance varied widely (Greico-Calub et al., 2010; Van Deun et al., 2010; Steffans et al., 2008; Litovsky et al., 2006). Van Deun et al. (2010) found average RMS values of 38° (range of 13-63°) for a population of pediatric bilateral cochlear implant users who received their first implant between the ages of 6 months and 9 years and their second implant between 1.5 and 12 years. These results are similar to those found by Greico-Calub et al. (2010) who reported RMS values ranging from 19 to 56° for pediatric bilateral cochlear implant users who received their first and second implants at 3.65 and 7.6 years, respectively. Collectively, these studies suggest that the variability in localization results may be due to the period of time that young children had no usable hearing or heard with a unilateral cochlear implant and therefore single ear input.

The primary purpose of this study was to evaluate speech perception and localization abilities in children who received sequential bilateral implants, the first cochlear implant received before the age of 4 and the second before the age of 12. Speech perception abilities, both in quiet and noise, as well as localization abilities were examined with the first implant alone (CI1), second implant alone (CI2), and in the bilateral (BICI) condition. Factors such as age at first implant, age at second implant, time between implants, hearing aid use prior to implantation, and length of deafness were considered to identify factors that may be predictive of outcomes in this population.

METHODS

This study was approved by the Human Research Protection Office at Washington University School of Medicine (WUSM).

Fifteen sequentially implanted children ranging in age from 6.10 to 15.98 years (mean 10.19, SD 2.85 years) participated. Inclusion criteria included participants between ages 5 and 18 years who received the first implant by age 4 and the second implant by age 12, with more than 3 months between implants. Hearing history information for each child is provided in Tables 1 and 2. The average age at implantation was 2.52 years (range 1.22 - 4.72 years, SD 1.17 years) and 5.64 (range 2.06 - 11.40 years, SD 2.79 years) for the first and second ears, respectively. There was an average of 3.12 years between the first and second implant surgeries (range 0.18 – 7.82 years, SD 2.34 years). Participants had an average of 4.55 years (range 2.63 - 5.94 years, SD .97 years) of bilateral implant experience. All children were implanted with Cochlear Corporation or Advanced Bionics devices. Device information is provided in Table 3.

Children participated in two test sessions lasting 3 hours each. Outcome measures utilized during the first session were randomized and repeated at the second session in order to allow for averaging of test results and determination of test-retest reliability. Cochlear implant programs were recently optimized at the participants' educational site or at St. Louis Children's Hospital. Speech processors were optimized so that conversational speech was audible, loud sounds were comfortable, and soft sounds were audible, which was confirmed by sound field threshold levels below 35 dB HL with the exception of P2. Loudness balancing between ears was performed by asking the child if speech was equally loud between ears when spoken to at midline. Depending on the child's response, stimulation levels were increased or decreased until the child reported equal loudness between ears. Children wore their everyday speech processor programs throughout the test sessions. Each outcome measure was assessed in three conditions: first cochlear implant received (CI1), second cochlear implant received (CI2), and in the bilateral condition (BICI) at both test sessions. Testing was performed in a double-walled soundproof booth. Listening checks were performed on microphones and sound-field thresholds were measured through each cochlear implant (separately and together) using warble tones prior to completing the test battery. The average group aided soundfield thresholds are shown in Figure 1.

A variety of word and sentence speech perception measures were utilized to assess speech understanding for each ear alone and in the bilateral condition in both quiet and in noise. All speech perception stimuli were calibrated and presented via loudspeaker at 0° azimuth with participants seated approximately 1 meter from the loudspeaker. Speech perception lists were randomized to eliminate participant learning effects**.**

To assess speech perception in quiet, two lists of Consonant-Nucleus-Consonant (CNC) monosyllabic words (Peterson, 1962) using a recorded male's voice were presented at a conversational level of 60 dB SPL. In addition, the Bamford-Kowal-Bench (BKB) sentences (Bench et al., 1979) were presented in quiet at 50 dB SPL using two list pairs per condition. Both CNC words and BKB sentences were reported as percent correct.

To assess speech perception in noise, two lists of CNC words were presented at 60 dB SPL in the presence of four-talker babble with a signal-to-noise ratio (SNR) of +8 dB. The BKB Speech in Noise (BKB-SIN) test (Etymotic Research, 2005) using two list pairs, was also administered at 65 dB SPL in the presence of four-talker babble. Sentences were prerecorded at a starting SNR of +21 dB and decreased in 3 dB steps to reach an SNR of 0 dB; after each sentence, participants repeated what they heard and scoring was based on the number of key words correct. If no words were repeated correctly across all sentences, a score of 23.5 dB was assigned. Otherwise, the calculated score represents the SNR needed for the participant to achieve 50% key word accuracy.

The Hearing in Noise Test (HINT) presented in the R-Space was utilized to assess speech perception in environmental noise. The R-Space aims to provide a real-life noisy listening condition. During R-Space testing, the participant was surrounded by eight loudspeakers playing recorded restaurant noise at a fixed level of 60 dB SPL. Two HINT lists (20 sentences each) were presented at levels that varied adaptively resulting in a score yielding the SNR for 50% sentence recognition. The first sentence was presented at +12 dB SNR. If the participant could not correctly repeat the entire sentence, the SNR was increased until a correct response was obtained. After the initial sentence was repeated back correctly, the SNR was adapted in 4 dB steps for the first four sentences and in 2 dB steps for the remaining 17 sentences. Depending on whether the sentence was repeated back correctly or not, the SNR was decreased or increased in 2 dB steps, respectively. The final SNR was calculated by averaging the final 17 sentence SNR values. If this test paradigm was too difficult for participants, a score of 22 dB was assigned.

Localization abilities were assessed by presenting monosyllabic words roved at a 60 dB SPL (+/- 3 dB) level from an array of 15 loudspeakers that were visibly numbered. Placed in an arc ranging from -70° to +70°, loudspeakers were 10° apart with 10 loudspeakers active and 5 inactive. With the participant seated approximately 1 meter from the center of the array, two CNC word lists were presented for each condition. The participant was instructed to report the loudspeaker number from which he/she thought the stimuli came from, repeating the word was not required. Scores were reported in root-mean-square (RMS) values for each condition.

Data Analysis

Both mean and individual participant scores were compared between the three listening conditions. Analysis of variance (ANOVA) followed by post-hoc analyses was used for comparisons with group data. A binomial distribution model (Thornton et al., 1978; Carney et al., 2007) was used for individual participant condition comparisons for CNC words as well as BKB Sentences in quiet with significant differences defined as 0.05. BKB-SIN testing utilized a critical difference of 3.1 dB based on the 95% confidence intervals available for adult cochlear implant users for 2 list pairs (Etymotic Research, BKB-SIN Test Manual). Normative data for pediatric cochlear implant users are not available for BKB-SIN test scoring. The HINT in the R-Space measure used a critical difference of 1.4 dB based on the 95% confidence interval for this measure (Compton-Conley et al., 2004). For localization measures, a root mean square or RMS calculation was performed per listening condition. Group results were analyzed with ANOVA. Responses were also calculated for individuals based on the mean and SD of the participant responses relative to the source. Slopes of the fitted lines were compared using ordinary least squares regression (with unequal variance of SEM corrections).

RESULTS

Displayed in Figures 2-6 are the scores in the three listening conditions indicated by light green for the first implanted ear (CI1), purple for the bilateral condition (BICI), and blue for second implanted ear (CI2). In Figure 2, participants are ordered based on CNC scores in quiet for CI2 scores for low performers, mid performers, and high performers. In the subsequent figures, the CI condition indicators as well as order of participants are the same for the speech perception and localization figures.

CNC Words

Figures 2 and 3 display the average individual and group results in percent correct for CNC words in quiet at 60 dB SPL and in the noise (four talker babble with a +8 dB SNR) for all participants in the three test conditions, respectively. A 2 (session) by 3 (CI condition) repeated measures ANOVA revealed a significant difference based on CI condition for both CNC words in quiet [F (1.2, 16.6) = 9.418, $p < 0.01$] and for CNC words in noise [F (1.3, 18.1) = 8.055, $p < 0.05$]. In addition, a significant session effect was seen for CNC words in noise [F (1, 14) = 5.473, $p < 0.05$], indicating CNC scores in noise for CI1 and CI2 were higher in the second test session compared to the first test session. Pairwise comparisons revealed BICI scores were significantly higher than CI2 scores for CNC words in quiet as well as in noise ($p = 0.02$). Results demonstrated the BICI condition tended to be higher than CI1 scores, however, this difference was not significant ($p = 0.06$).

The average BICI score for CNC words in quiet for this group of participants was approximately 83%. Four of the 15 participants showed statistically different scores between the

CI1 and BICI scores in quiet. BICI CNC word scores were greater than 80% for 11 of 15 participants while only 6 reached 80% or greater for the CI1 listening condition.

For CNC word testing in noise, the average BICI score was roughly 60%. Similar to CNC words in quiet, four participants exhibited a significant difference between CI1 and BICI scores. More than half of the participants (9 of 15) scored 60% or greater in the BICI condition while only four reached 60% in the CI1 condition.

BKB Sentences

Figure 4 plots the mean individual and group data in percent correct for the BKB Sentences presented at 50 dB SPL. A 2 (session) by 3 (CI condition) repeated measures ANOVA found a significant difference for CI condition [$F(1.1, 14.7) = 7.804$, $p < 0.05$]. A pairwise comparison indicated the BICI scores were significantly higher than both the CI1 scores ($p = 0.001$) and CI2 scores ($p = 0.021$).

The average BKB Sentence score in the BICI condition for this group was approximately 90%; 10 of the 15 children reached 90% or greater in the BICI condition. For this outcome measure, only one individual exhibited a significant difference between the CI1 and BICI conditions. Ten of the 15 participants scored equal to or greater than 80% in the CI1 condition whereas only six individuals reached 80% in the CI2 condition.

BKB-SIN

Figure 5 provides the SNR scores for the average individual and group results for assessment on noise using the BKB-SIN. A lower SNR score indicates better performance. A 2 (session) by 3 (CI condition) repeated measures ANOVA revealed a significant difference based on CI condition [F (1.2, 15.061) = 14.605, $p < 0.01$]. Pairwise comparisons demonstrated the BICI condition was significantly lower (better) than both the CI1 ($p = 0.023$) and CI2 SNR scores ($p < 0.001$). In addition, the CI1 scores were significantly lower than the CI2 scores ($p = 0.019$).

BKB-SIN testing revealed an average SNR value of 4.78 dB in the BICI condition indicating a mild SNR loss (Etymotic Research, BKB-SIN Test Manual). All participants in this study received an SNR value of less than 10 dB in the BICI condition while 11 participants showed SNR values less than 5 dB. Significant differences between the CI1 and BICI conditions were observed for four participants. Two participants were assigned a dB SNR value of 23.5, indicating the task was too difficult.

HINT in the R-Space

Figure 6 displays the average individual and group SNR scores for HINT in the R-Space. A 2 (session) by 3 (CI condition) repeated measures ANOVA revealed a significant difference based on CI condition [F (1.2, 15.019) = 16.122, $p < 0.01$]. Pairwise comparisons showed the BICI condition yielded significantly lower SNR scores compared to that of the CI1 condition ($p = 0.017$) and CI2 condition ($p = 0.000$). CI1 scores were significantly lower than CI2 scores ($p = 0.020$). The mean differences between CI conditions for the HINT in R-Space are similar to those found for the BKB-SIN testing.

HINT in the R-Space testing revealed an average SNR value of 4.16 dB in the BICI condition, similar to that of the BKB-SIN testing. In comparison to BKB-SIN testing, about half (8 of 15) of the participants demonstrated statistically significant differences between the BICI and CI1 listening conditions. Nine of 15 participants in this group received SNR values of 5 dB or less.

L*ocalization Testing*

Figure 7 provides the average RMS values for individual and group localization testing. Lower RMS values indicate better accuracy for localization of a sound source in space. As with the speech perception measures, a 2 (session) by 3 (CI condition) repeated measures ANOVA revealed a significant difference for CI condition [$F (1.3, 14.472) = 14.773$, $p < 0.01$]. The bilateral condition proved to be significantly better, or more accurate, than the CI1 condition ($p = 0.016$) and the CI2 condition ($p = 0.002$).

Localization plots for each participant are displayed in Figure 8. In this figure, participants are ordered from best to worst performance in the BICI condition. The first column represents CI1 responses, CI2 responses are shown the middle, and BICI responses are in the last column. Each individual plot displays the sound source location on the horizontal axis by the mean reported location on the vertical axis, both axes reported in degrees azimuth. In these plots, complete accuracy would display all responses along a diagonal line from the lower left corner to the upper right corner. The slopes of fitted lines for individual localization responses for each loudspeaker were compared between the CI1 and BICI conditions using Ordinary Least Squares regression with correction of standard errors for unequal variannce between conditions. P02, P03, and P07-P13 demonstrated a significant improvement in the BICI condition ($p < 0.001$). P15 also exhibited a significant improvement in the BICI condition ($p = 0.0021$). These results revealed 10 of the 15 participants in this study performed significantly better in the BICI condition compared to the CI1 condition.

Demographic Factors

In order to better understand predictive factors in those receiving sequential implants, speech perception and localization performance was correlated with a variety of demographic factors. Demographic factors included in this study consisted of: congenitally deafened vs. non-congenitally deafened, hearing aid history, age at CI1 and CI2, length of deafness in each ear, and time between implant surgeries. Table 4 displays the correlation coefficients and probabilities for these demographic factors.

Participants were separated into two groups based on whether they were congenitally deafened versus non-congenitally deafened. A t-test revealed no significant difference between these two groups. Figure 9 shows the scatter plot demonstrating the relationship bewteen the age at onset of a severe to profound hearing loss in the second ear and speech perception abilties. Results revealed those who declined into the severe to profound hearing loss range at later ages tended to perform worse on BKB Sentences in quiet in the BICI condition.

History of hearing aid use was categorized as continued (n = 9) or discontinued (n = 6) use of amplification in the non-implanted ear after receiving the first implant. A t-test revealed there was no significant difference in performance between these two groups. Figure 10 displays the scatter plot revealing the relationship bewteen age at when the second ear received a hearing aid and speech perception abilties. BICI BKB Sentence scores in quiet were typically higher when amplification devices were fit at a younger age.

Figure 11 displays the statistically significant correlations between age at when the second implant was received and speech perception performance. CNC word scores in quiet tended to decrease as age at implant of the second ear increased, however the result was not significant (r = 0.51, p = 0.52). The same trend was observed in noise however in this case, results were significant (r = 0.66, p = 0.008); scores tended to be higher when the second implant was received earlier compared to those implanted later. Similar correlations and trends were seen for BKB-SIN testing (r = -0.64, p = 0.010) and for HINT in the R-Space (r = -0.51, p = 0.095), indicating better performance (lower SNR values) the earlier the second implant is received.

Significant correlations between length of deafness for the second ear and speech perception abilities are plotted in Figure 12. This figure demonstrates longer periods of deafness before receiving the second implant may result in poorer performance for the CI2 condition for CNC words in quiet (r = -0.522, p = 0.046), CNC words in noise (r = -0.701, p = 0.004), BKB-SIN (r = 0.713, p = 0.003), and lastly for HINT in the R-Space (r = 0.607, p = 0.032).

Figure 13 displays the correlation between the length of CI1 use and speech perception understanding. A signficant correlation was found between length of CI1 use and CNC words in quiet in the CI2 listening condition (r = -0.522, p = 0.027) and for CNC words in noise in the CI2 condition (r = -0.701, p = 0.001).

Figure 14 demonstrates the statistically significant relationships regarding the length of time between the first and second implants and performance in the CI2 condition. Similar to trends observed with age at implant of the second ear and length of deafness, poorer performance was observed when a longer the time interval between implant surgeries was experienced. These relationships were noted for CNC words in quiet (r = -0.575, p = 0.025) and in noise (r = -0.756, p = 0.001), BKB Sentences in quiet (r = -0.467, p = 0.079), and BKB-SIN (r = 0.712, p = 0.003) and HINT in the R-Space (r = 0.638, p = 0.019).

DISCUSSION

The primary purpose of this study was to evaluate speech perception and localization abilities in pediatric sequential bilateral cochlear implant users ranging in age from 5-18 years. Participants in this study received their first implant before age 4 and their second implant before age 12, with at least a three month interval between surgeries.

Results for CNC word testing in quiet revealed a difference between the CI2 and BICI conditions, with the BICI scores being significantly higher. In addition, although it did not reach statistical significance, there was a trend demonstrating the BICI scores were also higher than the CI1 scores. These results support the notion that listening with two ears does enhance speech perception abilities when listening to speech at an average conversational level in a quiet environment. As expected, results for CNC word testing in noise were significantly lower than scores reported in quiet for all three listening conditions. In contrast to the other speech perception measures, both an ear and session effect were exhibited for CNC words in noise. The BICI scores were significantly higher than the CI2 scores as well as CI1 and CI2 scores significantly improving from the first to second test session. Performance was similar between the CI1 and BICI listening conditions for many participants for CNC words in noise.

Results for BKB Sentences in quiet revealed a significant bilateral advantage compared to listening with each CI alone. Because BKB sentences were presented at a softer level (50 dB SPL), these findings indicate listening with two implants compared to one increases one’s ability to understand softer levels of speech.

BKB-SIN and HINT in the R-Space testing allowed for the evaluation of sentence understanding in more real life noisy listening environments. Results for both of these speech perception measures demonstrated significantly lower BICI SNR scores compared to either CI alone. CI1 scores were significantly higher than CI2 scores. Although in this study the second ear did not reach the performance level of the first ear, these findings support the idea that having access to sound in each ear enhances speech understanding in noise. These HINT in the R-Space findings indicate pediatric BICI users in this study are experiencing binaural squelch, a phenomenon that allows better understanding in noise when the speech target and noise are spatially separated.

Localization testing revealed a significant BICI advantage compared to each ear alone. These results suggest two ears are necessary in order to accurately localize a sound source in space. Results varied widely across individuals, with performance ranging from no difference in performance between the three CI listening conditions to obtaining signficant improvement in the BICI condition compared to listening with each implant alone. Ten of the fifteen children demonstrated a significant BICI advantage compared to the CI1 condition. In this study, RMS values ranged from 18.44 – 58.94° (average = 41.16°). The results in this study are in agreement with results found by Greico-Calub et al. (2010), who reported RMS values ranging from 19-56° in pediatric BICI users receiving CI1 at an average of 3.65 years and CI2 at an average of 7.6 years. Van Deun et al. (2010) reported RMS values ranging from 13-63° (average = 38°) in pediatric BICI users, which are similar to those found in this study.

It should be noted speech perception and localization abilities varied widely across children in this study. Factors such as age at implantation at each ear, length of deafness (LOD) in each ear before implantation, time between surgeries, soundfield thresholds, and performance in noise compared to localization performance were examined when looking at individual data in order to better understand performance and outcomes of individuals in this study.

Age at Implantation and Length of Deafness

P01, P02, and P03 had the lowest CI2 scores for testing CNC words in quiet and noise as well as BKB Sentences in quiet. These three participants received their second implants at ages 6.16, 7.87, and 11.40 years of age, which in turn increased the length of deafness in the second ear to 6.16, 4.79, and 8.90 years, respectively. P01 and P03 were also not able complete BKB-SIN and HINT in the R-Space testing in the CI2 condition due to the difficulty of the task. In addition, these three participants received little bilateral benefit compared to the CI1 condition in both quiet and noise. Correlations in this study demonstrated longer LOD periods and increased time intervals between implant surgeries can lead to reduced speech perception abilities in the second ear, which these three children exhibited. The differences noticed in these children between the CI1 and CI2 conditions, in addition lack of BICI benefit, support the notion that receiving the second implant at an older age may reduce the brain's capabilities to centrally combine information presented to each ear. The trend observed for this subset of children is in agreement with studies in the past, which suggest receiving the second implant after the age of 4 years of age hinders the acquisition of speech understanding compared to that of the first ear (Gordon et al., 2009; Asp et al., 2011; Galvin et al., 2008).

In comparison, P14 and P15 were found to have the highest CI2 scores in quiet and in noise. These two participants both received their second implants at ages of 4.69 and 4.50, respectively, which is younger than the three worst performers' ages for their second device. One key difference noted between the two highest performers and three lowest performers is the LOD in the second ear prior to receiving the implant. As previously mentioned, the LOD of the three lowest performers were all above 4.5 years, whereas the LOD in the second ear for P14 and P15 were 3.86 and 2.0 years, respectively. Shorter periods of deafness in the second ear occurs when the second implant is placed at a younger age and/or a progressive hearing loss with successful hearing aid use is present.

Auditory deprivation has been known to play a role in CI user success; however, this study did not find a significant difference between those who continued to use amplification after receiving CI1 versus those who discontinued amplification use. Two of the three lowest performers (P02 and P03) and one of the two highest performers (P15) continued wearing a hearing aid at the second ear after receiving the first implant. Although no difference was found between groups, more research is needed regarding the effects between hearing aid use and implant user success. Because results have been variable regarding hearing aid use prior to implantation, it is still recommended these patients continue amplification use in the non-implanted ear to keep the auditory pathway from becoming dormant and losing function. In addition to keeping the auditory nerve stimulated, wearing a hearing aid in the non-implanted ear may assist in environmental awareness and safety.

Audibility and Speech in Quiet

BKB Sentences presented at 50 dB SPL was utilized as an outcome measure to better understand how softer conversational speech was understood. It is apparent that when comparing scores between the CNC words in quiet and the BKB Sentences in quiet all sentence scores increased to at least 75%, with the exception of P02. This increase in sentence scores, even though the sentences were presented 10 dB below the word tests, is typically seen due to more contextual cues present in sentences compared to what is available in words alone. All children in this current study, with the exception of P02, had BICI sound field thresholds less than 30 dB HL, with many children having thresholds in the 15-20 dB HL range. It is interesting to note P02 was the only child to exhibit thresholds well above 30 dB HL and to demonstrate significantly reduced sentence scores compared to word scores in quiet. This finding is similar to results found in a study conducted by Firszt et al. 2004, which reported lower, or better, sound field thresholds yielded higher word recognition scores in an adult cochlear implant population. Thus, it can be suggested that obtaining better sound field thresholds (in the range of 15-30 dB HL) across the frequency range of 250 – 6000 Hz helps ensure audibility and understanding of soft speech. Having access to these softer components of speech is extremely important for children to develop speech and for incidental learning to occur.

Localization and Speech in Noise

This study is one of few that assessed localization abilities in children with similar testing techniques used in the adult population. For localization testing, the participants had to name a speaker number, among an array of equally spaced 15 loudspeakers, from which they thought the stimuli came from. It seemed that two different response patterns were revealed during localization testing when performing the task in the CI1 or CI2 conditions. One pattern can be viewed in the localization plots for P12. This participant thought the stimuli being presented were always only coming from the two speakers farthest to the right or left when wearing the right CI or left CI alone, respectively. However, in the BICI condition, this participant was able to determine the sound source rather accurately, which is demonstrated by the fairly straight diagonal line in the BICI conditions. A similar pattern emerged for P03.

The other pattern can be viewed in the localization plots for P08. This participant purely guessed speaker numbers in the CI1 and CI2 conditions indicating no real sound source awareness; however, in the BICI condition, P08 was able to determine sound source location rather well. The latter pattern seems to be more common among our study population for CI1 and CI2 conditions, as many other participants demonstrated these response patterns.

BICI conditions yielded RMS values ranging from 18.44 – 58.94° indicting some participants were able to accurately localize a sound source when wearing two implants while others performed similar to when wearing one implant alone. Like other factors affecting CI user success, the advantage gained in the BICI condition was variable across individuals.

In this study, P08, P11, P12, and P13 all received BICI RMS values < 30°. Three of these four participants also demonstrated a bilateral advantage for HINT in the R-Space testing as well. Performance for P11 was the same between the CI1 and BICI conditions for R-Space testing indicating no bilateral benefit was obtained. P08, P12, and P13 all had short time intervals between receiving CI1 and CI2 (0.79, 1.55, and 2.21 years, respectively) and continued use of a hearing aid in the non-implanted ear. These shorter time intervals between implant surgeries and continued use of amplification suggest BICI users obtain the ability to centrally process, combine, and compare information presented to each ear. This idea of a short interval between surgeries and amplification however, did not hold true for P11, who experienced a 5.56 year interval between surgeries and discontinued hearing aid use in the non-implanted ear. Age at implantation does not seem to be a major factor in this BICI localization advantage as age at implantation ranged from 1.27 – 4.72 years for CI1 and 2.06 – 8.40 years for CI2.

P05, P06, and P14 were three participants, whose localization performance was comparable in all three listening conditions, meaning a bilateral advantage was not seen when wearing two implants compared to either implant alone. Although these participants did not demonstrate a BICI advantage on localization testing, all three of them did demonstrate a significant bilateral advantage in R-Space testing. It should be noted that even though a bilateral advantage was seen in these participants for HINT in the R-Space, P05 and P06 were the lowest performers (needed the highest SNR); P01 on the other hand needed an SNR of only 1 dB to understand speech in the noisy listening environment. P05, P06, and P14 had 2.88, 7.82, and 3.47 years between implant surgeries, respectively. These intervals are longer compared to the four individuals who had RMS values in the normal hearing range suggesting that longer intervals between implants may influence BICI localization performance, the organization of the central auditory cortex, and the ability to compare information between ears. In addition, these three participants discontinued amplification in the non-implanted ear after receiving CI1.

Variable performances on localization and speech in noise testing make it hard to predict factors that will influence whether or not a BICI user will exhibit a bilateral advantage. While demographic factors play a role in CI user success, the task being performed by the listener also plays a role in performance outcomes. In addition to demographic factors playing a role in user success, cochlear implant programming and processing need to be considered as well. The speech processors of cochlear implants function independently of each other meaning there is no coordination of auditory input to each ear; because of the independent processing for each implant, a bilateral advantage is not guaranteed in those who receive bilateral cochlear implants. In addition, the fine structure of speech that is important for speech understanding is eliminated in cochlear implant processing strategies.

Overall, results from this study exhibit a significant bilateral advantage in performance on all outcome measures in the BICI condition compared to CI1 or CI2 listening conditions. As in agreement with studies in the past, results on all outcome measures were variable across individuals. Receiving sequential bilateral cochlear implants lends to enhanced speech understanding and/or localization performance in various listening environments for the majority of children in this study with no degradation in performance compared to the CI1 condition for any participant.

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Table 1. Individual Hearing History Information

Participant No.	Age at test	AOHL 1st Ear	AOHL 2nd Ear	AOSPHL 1st Ear	AOSPHL 2nd Ear	Age HA 1st Ear	Age HA 2nd Ear	Etiology
P01	10.23	0	0	0	0	.5	.5	CMV
P02	13.45	2.5	2.5	3.08	3.08	2.75	2.75	EVA
P03	15.98	0	0	2.5	2.5	.5	.5	Familial
P04	9.10	0	0	.92	.92	1	1	Unknown
P05	10.14	0	0	0	0	1.33	1.33	Unknown
P06	13.69	1	1	1.25	1.25	1.58	1.58	Unknown
P07	9.73	0	0	0	0	1.33	1.33	Connexin 26
P08	6.72	0	0	.75	0	1	1	Unknown
P09	6.10	0	1	0	1.17	1.25	1.25	CMV
P10	8.07	0	0	1	1	1.08	1.08	Connexin 26
P11	13.85	0	0	0	0	2.58	2.58	Connexin 26
P12	8.19	0	0	0	0	1.08	1.08	Connexin 26
P13	9.57	0	0	2.5	2.5	2.83	2.83	EVA
P14	10.02	.83	.83	.83	.83	1.	1	Waardenburg
P15	7.97	0	0	2.5	2.5	.5	.5	EVA
Mean	**10.19**	**0.29**	**0.36**	**1.02**	**1.05**	**1.35**	**1.35**	
SD	**2.85**	**0.69**	**0.71**	**1.11**	**1.11**	**0.77**	**0.77**	

Note: AOHL: Age at Onset of Hearing Loss; AOSPHL: Age at Onset of Severe to Profound Hearing Loss; HA: Hearing Aid: CMV: Cytomegalovirus; EVA: Enlarged Vestibular Aqueduct; 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	1.34	6.16	1.34	6.16	8.89	4.07	4.82
P02	3.71	7.87	0.62	4.79	9.75	5.58	4.17
P03	4.43	11.40	1.93	8.90	11.55	4.57	6.97
P04	1.50	4.58	0.58	3.66	7.60	4.52	3.08
P05	2.30	5.18	2.30	5.18	7.84	4.96	2.88
P06	2.28	10.10	1.03	8.85	11.41	3.60	7.82
P07	2.37	3.78	2.37	3.78	7.36	5.94	1.41
P08	1.27	2.06	0.52	2.06	5.45	4.66	0.79
P09	2.73	2.91	2.73	1.74	3.37	3.19	0.18
P10	1.50	2.75	0.50	1.75	6.57	5.32	1.25
P11	2.84	8.40	2.84	8.40	11.01	5.45	5.56
P12	1.74	3.29	1.74	3.29	6.45	4.90	1.55
P13	4.72	6.94	2.22	4.44	4.84	2.63	2.21
P14	1.22	4.69	0.39	3.86	8.79	5.33	3.47
P15	3.85	4.50	1.35	2.00	4.12	3.48	0.65
Mean	**2.52**	**5.64**	**1.50**	**4.59**	**7.67**	**4.55**	**3.12**
SD	**1.17**	**2.79**	**0.87**	**2.50**	**2.59**	**0.97**	**2.34**

Note: CI1: First Implanted Ear; CI2: Second Implanted Ear; LOD: Length of Deafness; LOU: Length of Use

Table 3. Device and Programming Parameters

	INTERNAL		EXTERNAL		Strategy		Pulse Width		Channel Rate/Maxima		Active Electrodes	
P#	**CI1**	**CI2**	**CI1**	**CI2**	**CI1**	**CI2**	**CI1**	**CI2**	**CI1**	**CI2**	**CI1**	**CI2**
P01	N24R	Freedom	Freedom	Freedom	ACE	ACE	25	25	900/12	900/12	22	18
P02	CII	CII	Harmony	Harmony								
P03	N24R	Freedom	Freedom	Freedom	ACE	ACE	25	25;37	900/10	900/10	22	22
P04	N24R	Freedom	Freedom	Freedom	ACE	ACE	25	20	1200/10	1800/10	22	22
P05	N24R	Freedom	N5	N5	ACE	ACE	25	25	1200/12	1200/12	22	22
P06	N24R	Freedom	Freedom	Freedom	ACE	ACE	37	25	900/11	900/11	20	22
P07	N24R	Freedom	N5	N5	ACE	ACE	25	25	900/12	900/12	22	22
P08	Freedom	Freedom	Freedom	Freedom	ACE	ACE	25	25	1200/12	1200/12	21	22
P09	90K1J	90K1J	Harmony	Harmony	HiRes S120	HiRes S120	24.2	25.1	2750	2652	16	16
P10	Freedom	Freedom	N5	N5	ACE	ACE	25	25	1200/12	1200/8	21	21
P11	N24R	N24R	Freedom	Freedom	ACE	ACE	25	25	1200/10	1200/10	22	22
P12	Freedom	Freedom	N5	N5	ACE	ACE	25	37	900/10	900/10	19	20
P13	90K1J	90K1J	Harmony	Harmony	HiRes S120	HiRes S120	20.7	20.7	3228	3228	13	15
P14	N24R	Freedom	Freedom	Freedom	ACE	ACE	25	25	900/12	900/12	22	22
P15	Freedom	Freedom	N5	N5	ACE	ACE	25	25;37	900/10	900/10	20	18

Table 4. Demographic Correlation

Condition	CNC-Q CI2	CNC-Q BICI	CNC-N CI2	BKB-Q CI1	BKB-Q CI2	BKB-Q BICI	BKB-SIN CI2	R-Space CI2	Loc CI2
Age HA 2nd Ear		r = -0.49, p = 0.061		r = -0.5, p = 0.055		r = -.60, **p = 0.019**			r = -0.49, p = 0.073
Age at CI2	r = -0.51, p = 0.52		r = -0.66, **p = 0.008**				r = 0.64, **p = 0.010**	r = 0.51, p = 0.095	
LOD 2nd Ear	r = -0.52, **p = 0.046**		r = -0.7, **p = 0.004**				r = 0.71, **p = 0.003**	r = 0.61, **p = 0.032**	
Length CI1 Use	r = -0.52, **p = 0.027**		r = -0.7, **p = 0.001**		r = -0.34, p = 0.082				
Time betw. Surgeries	r = -0.58, **p = 0.025**		r = -0.76, **p = 0.001**		r = -0.47, p = 0.079		r = 0.71, **p = 0.003**	r = 0.64, **p = 0.019**	
AOSPHL 2nd Ear						r = -0.48, p = 0.074			r = -0.48, p = 0.082

Note: Q: Quiet; N: Noise; Loc: Localization; CI1: 1st cochlear implant; CI2: 2nd cochlear implant; r: correlation coefficient; p: probability value (bolded=signficant); HA: hearing aid; LOD: length of deafness; AOSPHL: Age at Onset of Severe to Profound Hearing Loss.

Figure 1. *Average Group Sound Field Thresholds. CI1 thresholds are indicated by the green triangles, CI2 thresholds are indicated by the blue squares, BICI thresholds are indicated by the purple squares. Error bars = standard deviation.*

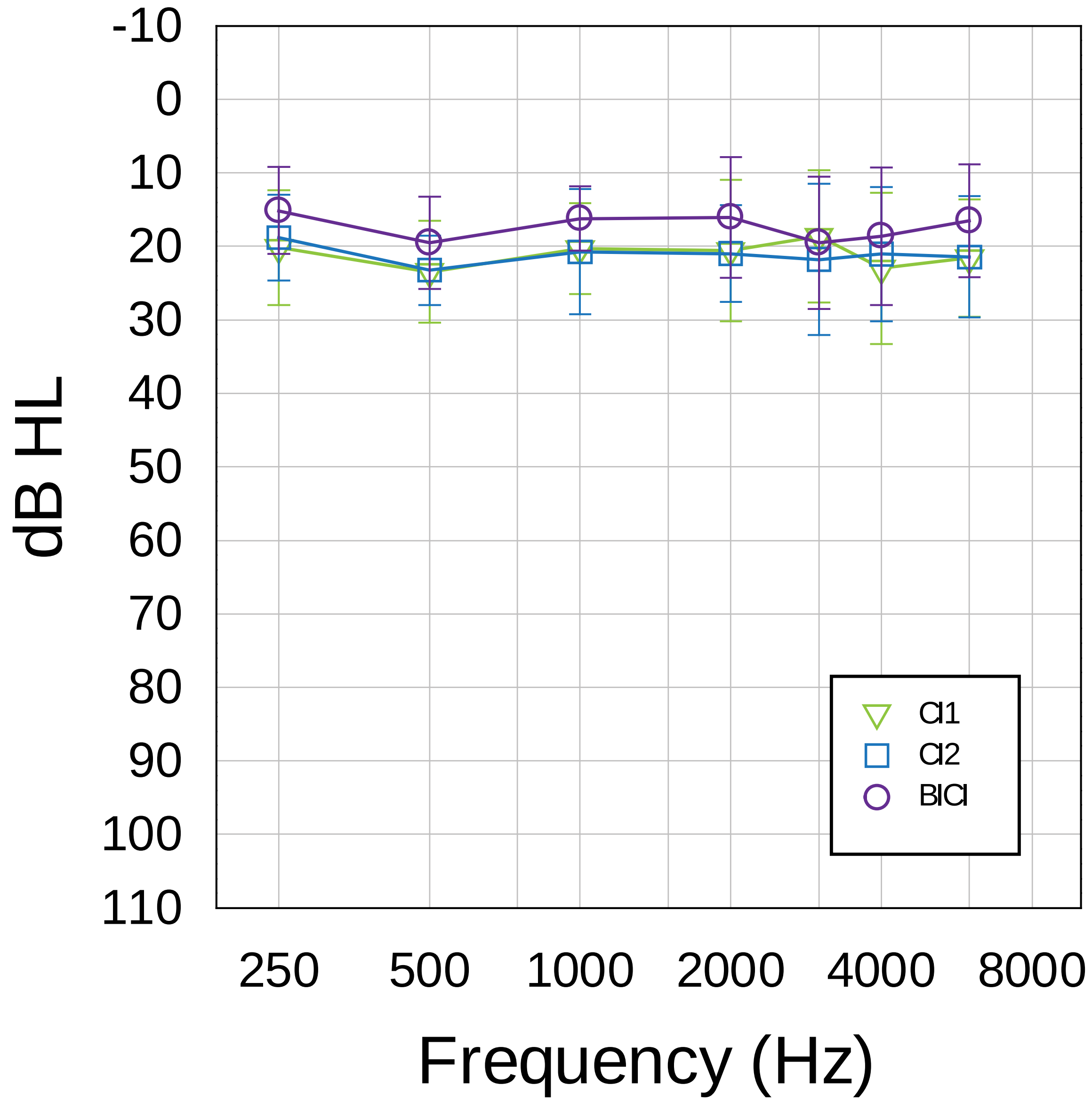


Figure 2. *Average individual and group results for CNC words in quiet presented at 60 dB SPL. Error bars = standard error of the mean (SEM). * p < 0.05. Brackets for individual participant comparisons show significant differences between CI1 and BICI scores at the 0.05 level.*

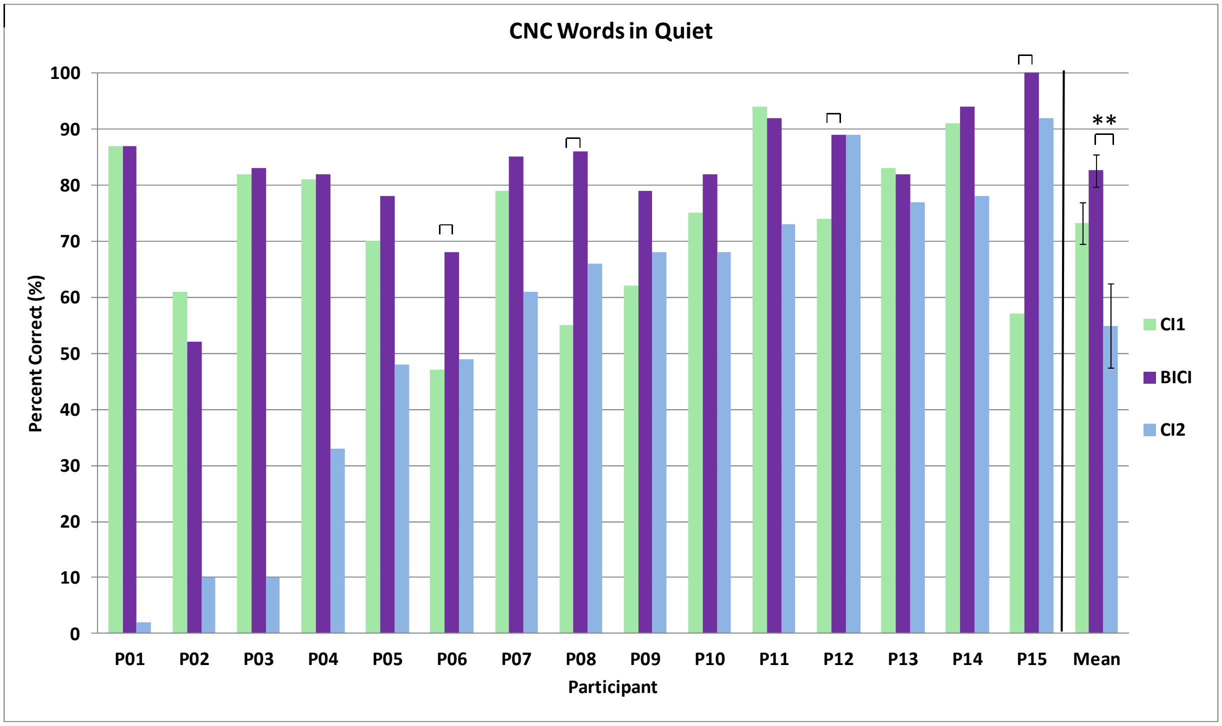


Figure 3. *Average individual and group results for CNC words presented at 60 dB SPL with four-talker babbler at a +8 dB SNR. Error bars = SEM. ** p < 0.01. Brackets for individual participant comparisons show signficant differences between CI1 and BICI conditions at the 0.05 level.*

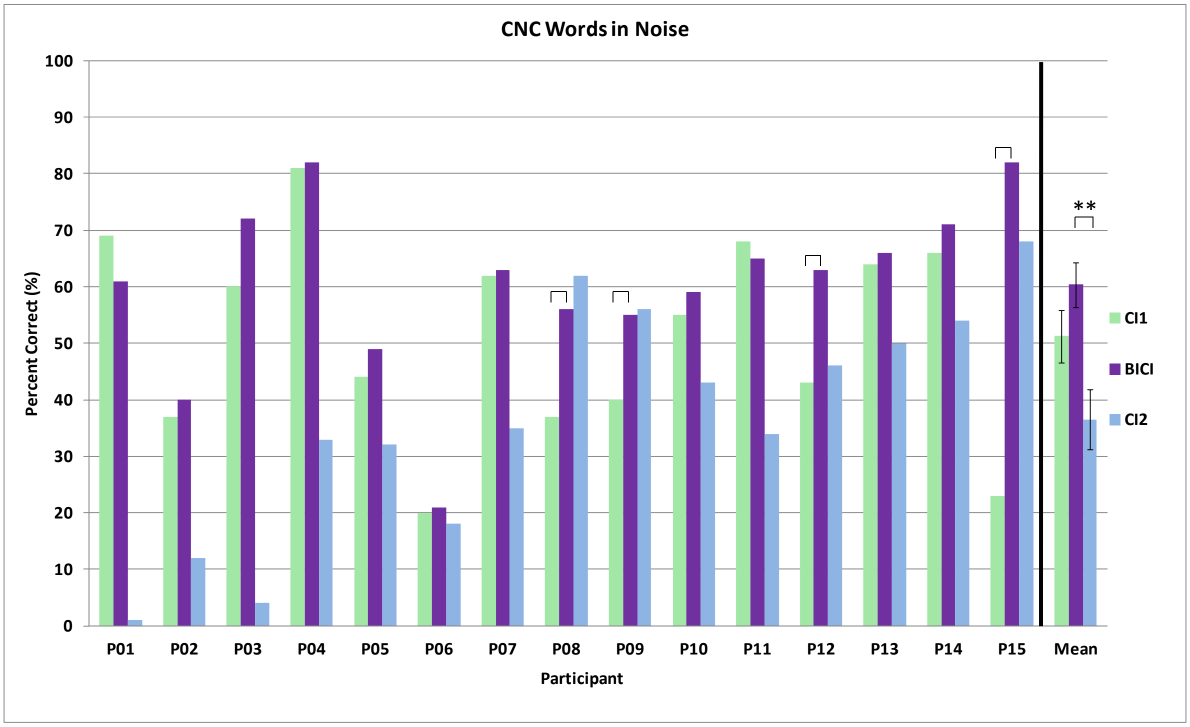


Figure 4*. Average individual and group results for BKB Sentences presented in quiet at 50 dB SPL. Error bars = SEM. * p < 0.05; ** p < 0.01. Brackets for individual participant comparisons indicate signficant differences between CI1 and BICI conditions at the 0.05 level.*

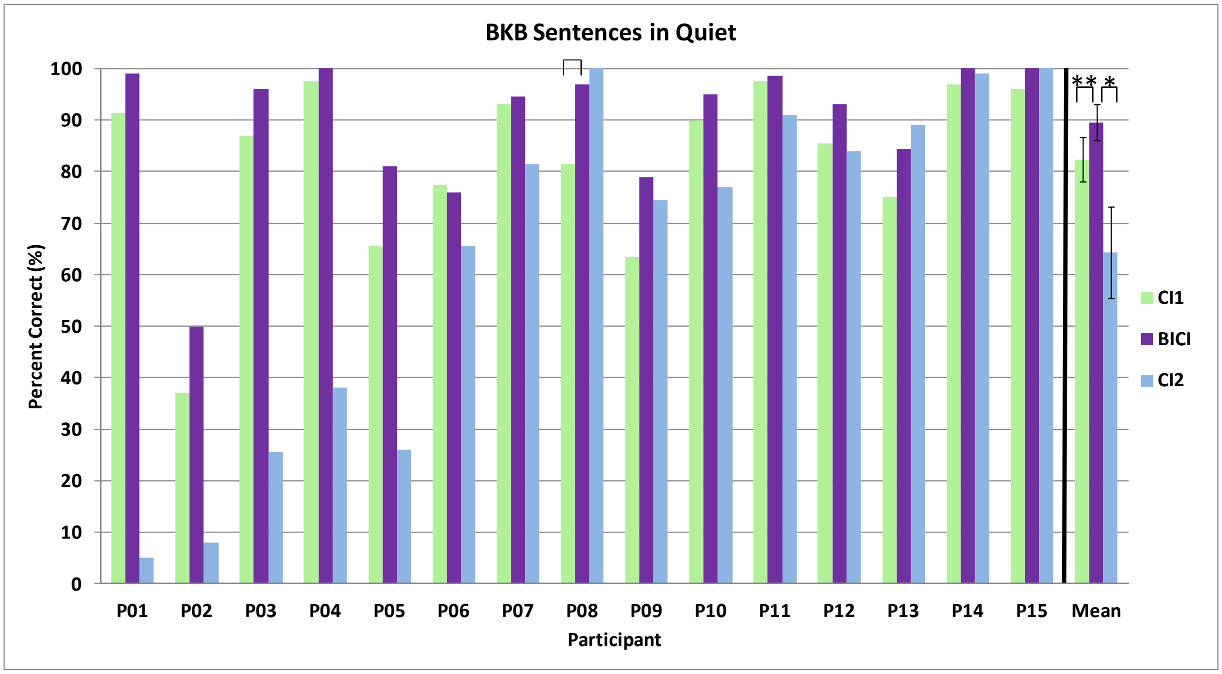


Figure 5. *Average individual and group results for the BKB-SIN. Error bars = SEM. ** p < 0.01. Brackets for individual participant comparisons indicate a significant difference (≥ 3.1 dB) bewteen CI1 and BICI conditions based on the 95% confidence intervals for two list pairs.*

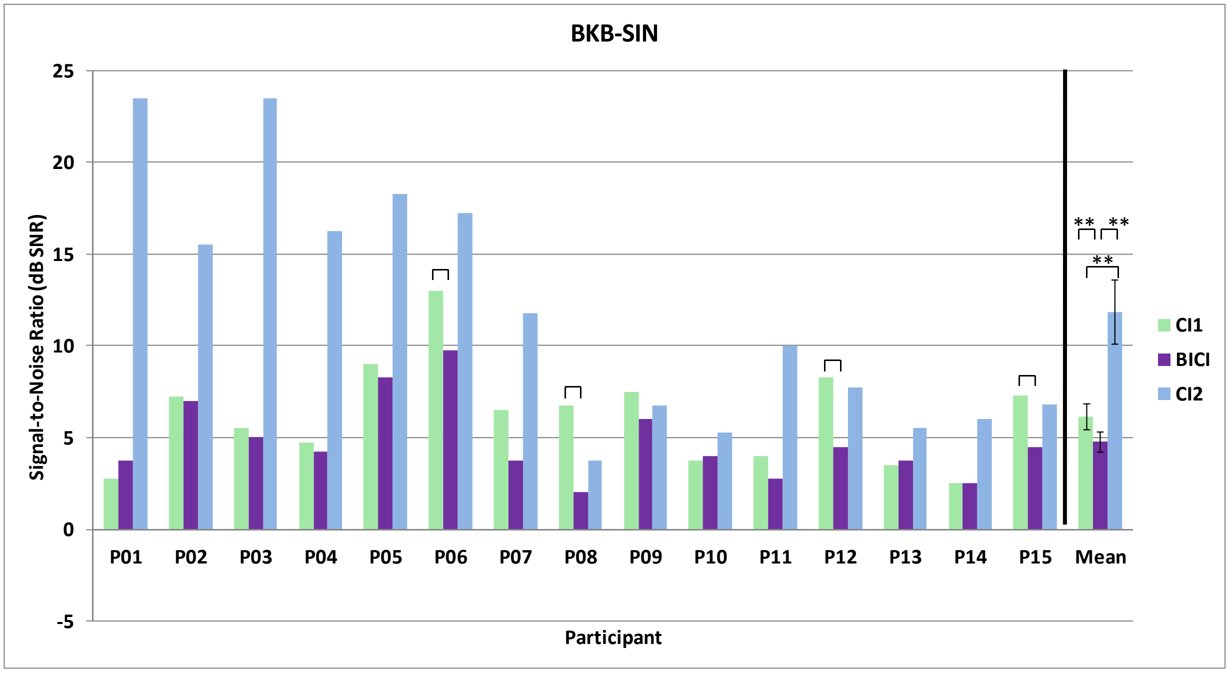


Figure 6. *SNR scores for HINT in the R-Space. Error bars = SEM. ** p < 0.01. Brackets for individual participant comparisons indicate a signficant difference (≥ 1.4 dB) bewteen CI1 and BICI conditions based on the 95% confidence intervals.*

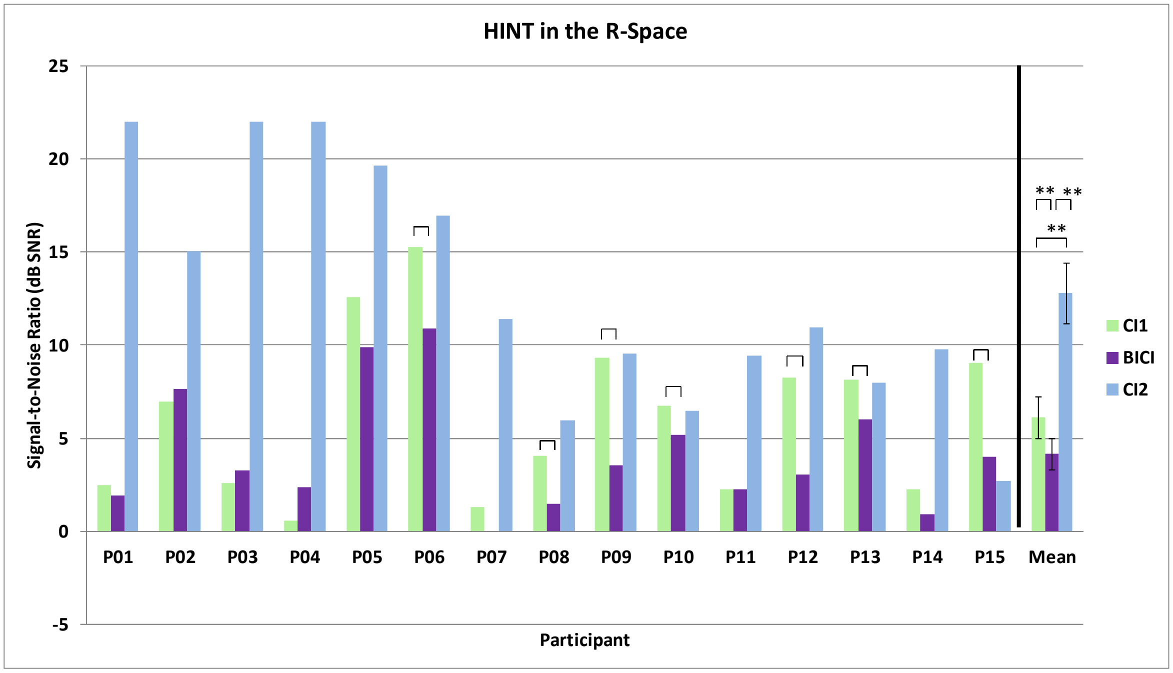


Figure 7. *Individual and group RMS values for localization testing. Error bars = SEM. ** < 0.01. Brackets for individual participant comparisons indicate a significant difference between CI1 and BICI conditions at the 0.001 level, except for P15 (p = 0.0021).*

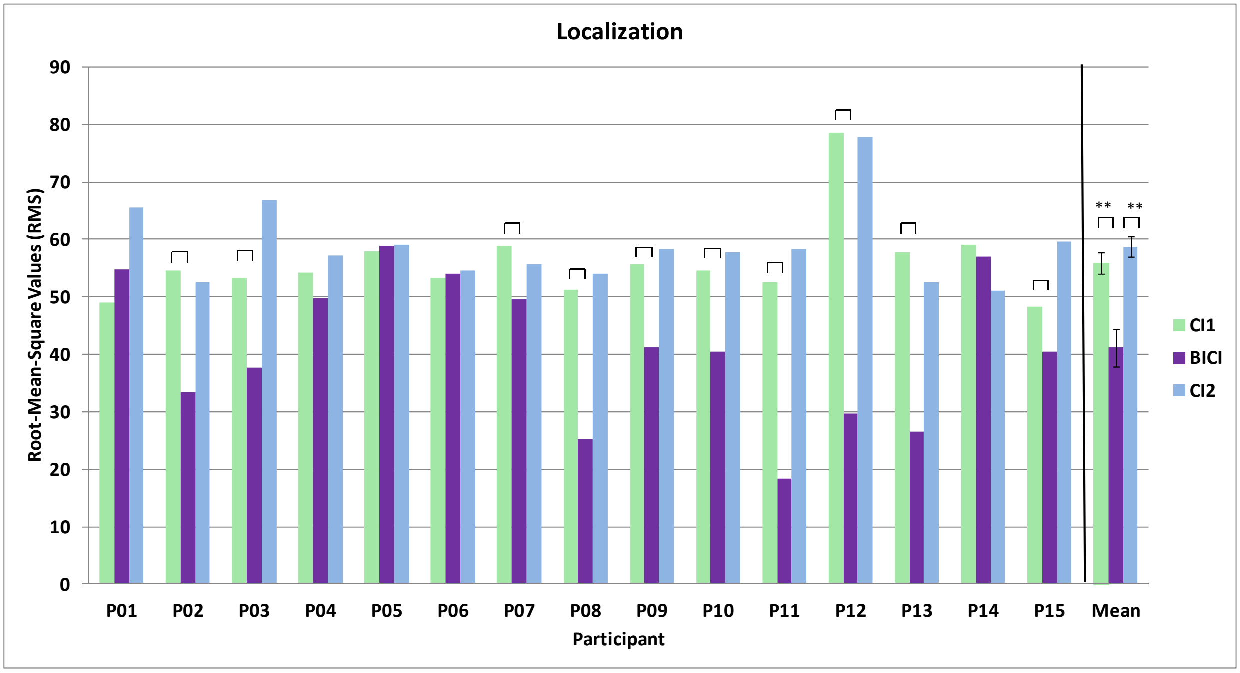
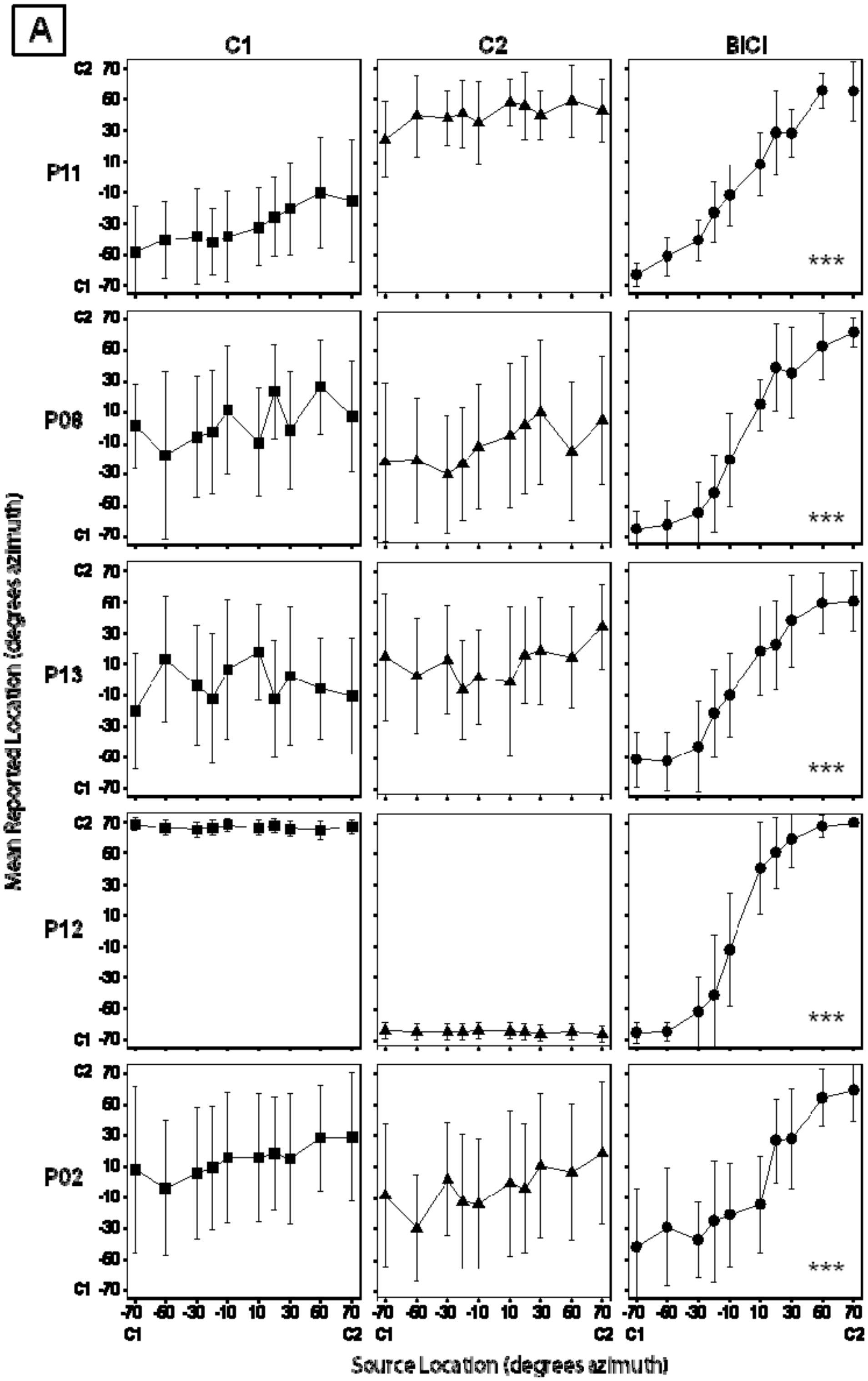
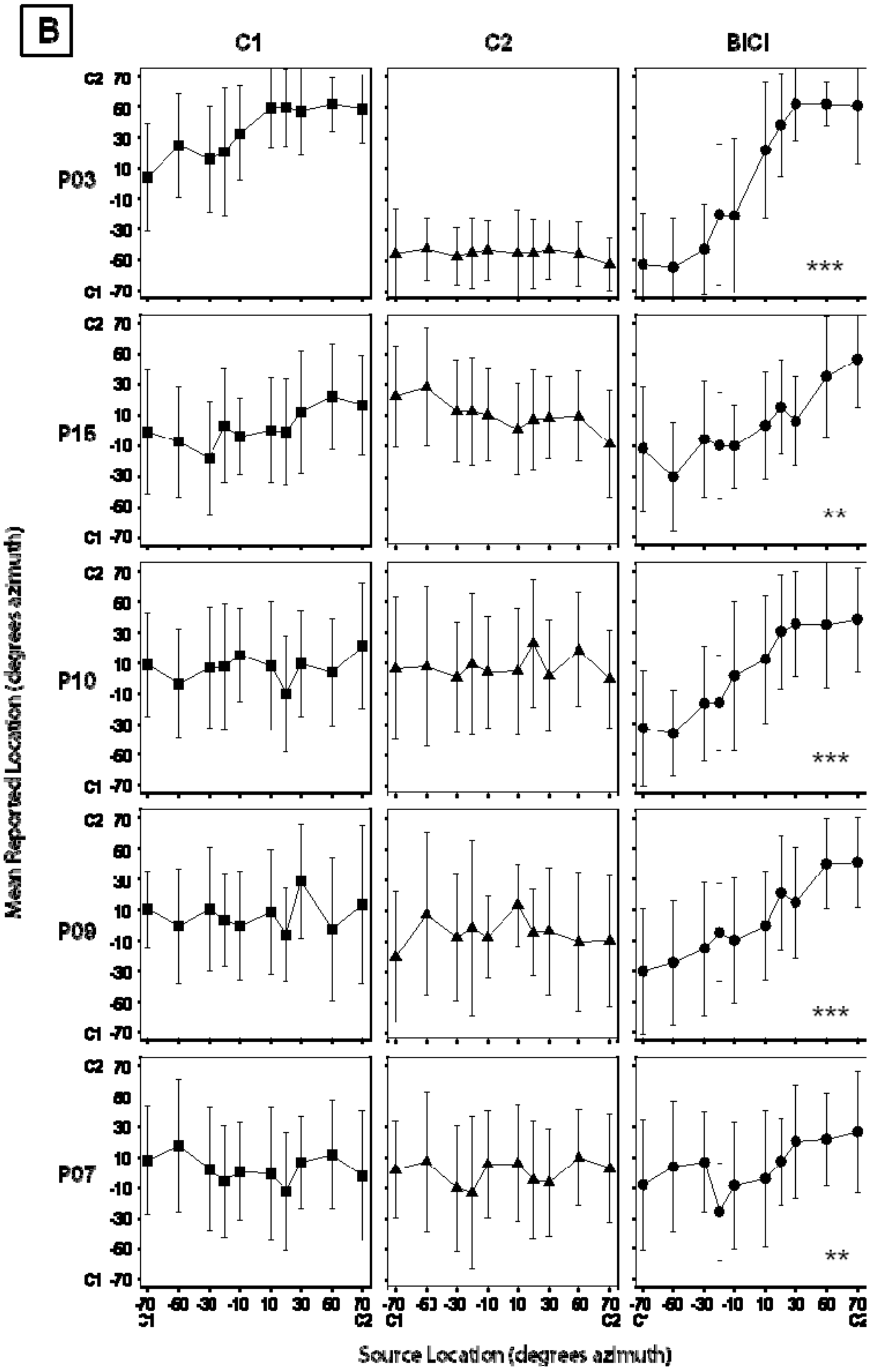


Figure 8*. Individual localization plots (A, B, and C). CI1 responses are in the first column, CI2 responses are in the second column, and BICI responses are in the third column. Participants are ranked in order from best to worst BICI performance.* ** $p < 0.01l$; *** $p < 0.001$.




B
C1
C2
BICI
P03
P15
P10
P09
P07
C2 70
60
30
10
-10
-30
-60
C1 -70
***
**
***
***
**
Mean Reported Location (degrees azimuth)
-70 C1
-60
-30
-10
10
30
60
70 C2
Source Location (degrees azimuth)

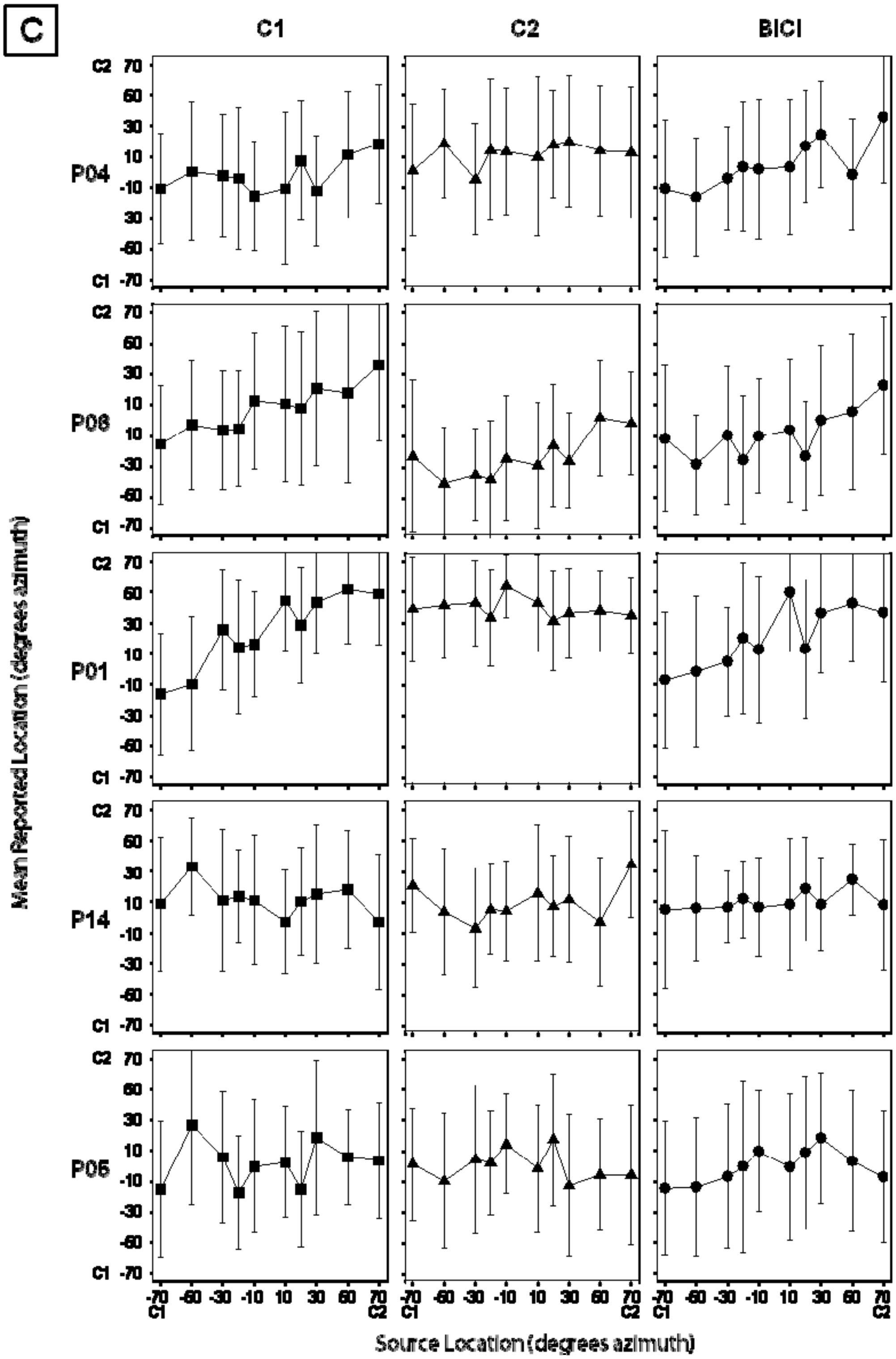

C
C1
C2
BICI
P04
P06
P01
P14
P05
Mean Reported Location (degrees azimuth)
C2 70
60
30
10
-10
30
-60
C1 -70
-70 C1
-60
-30
-10
10
30
60
70 C2
Source Location (degrees azimuth)

***Figure 9**. Scatter plot displays significant correlation bewteen age at onset of severe to prfound hearing loss in the second ear and speech perception abilities. Correlation coefficients (r) and probability (p) values are providied in the figure.*

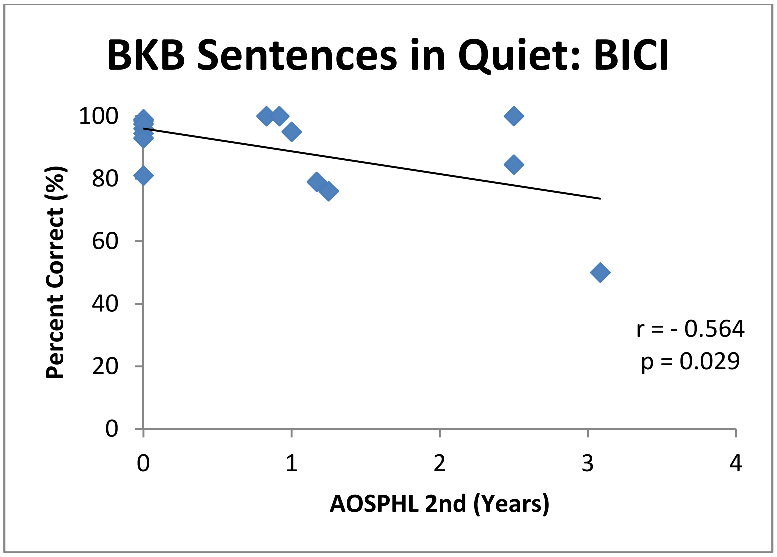


***Figure 10**. Scatter plot displays signficant correlation bewteen age at when hearing aids were fit in the second ear and speech perception abilties. Correlation coefficient (r) and probability (p) values are given in the plot.*

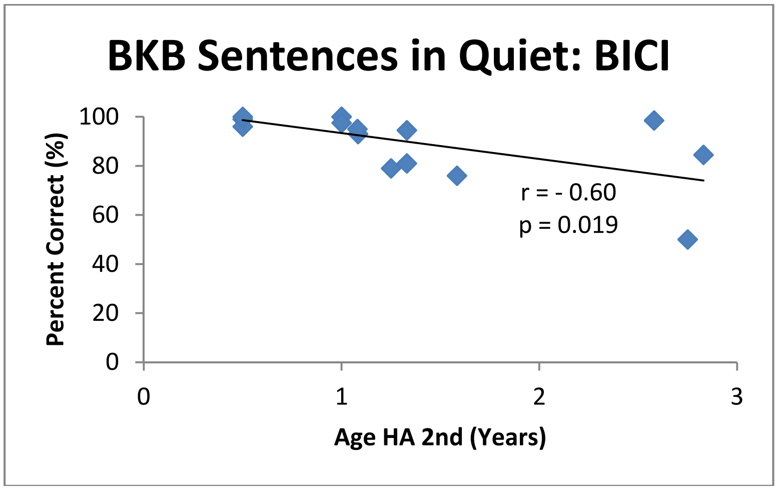


Figure 11. Scatter plots display signficant correlations between age at when CI2 was received and speech perception performance. Correlation coefficients (r) and probabilty values (p) are given in each plot.

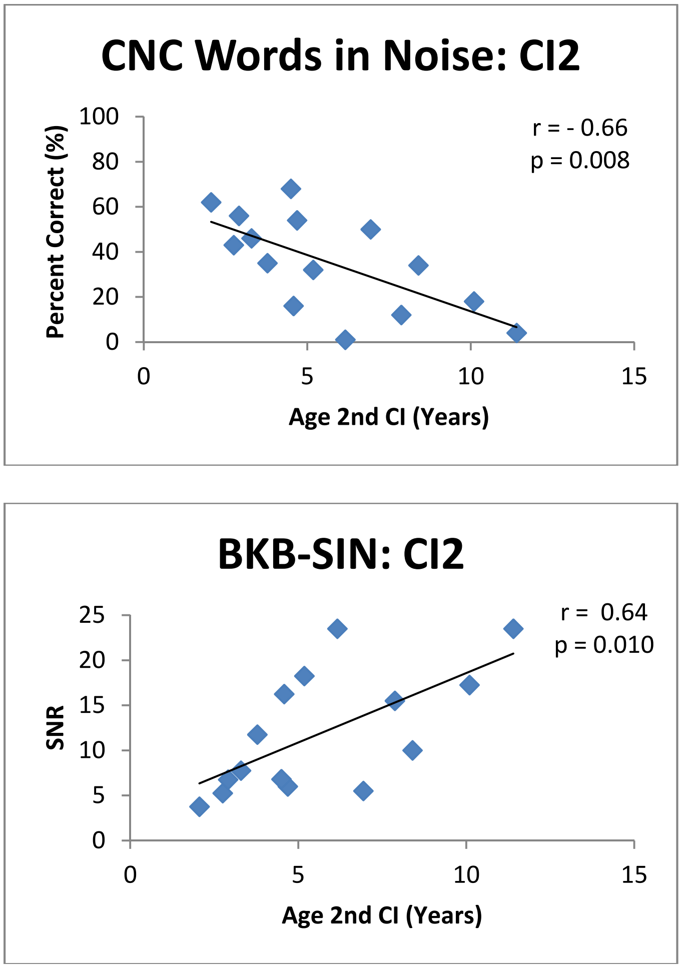
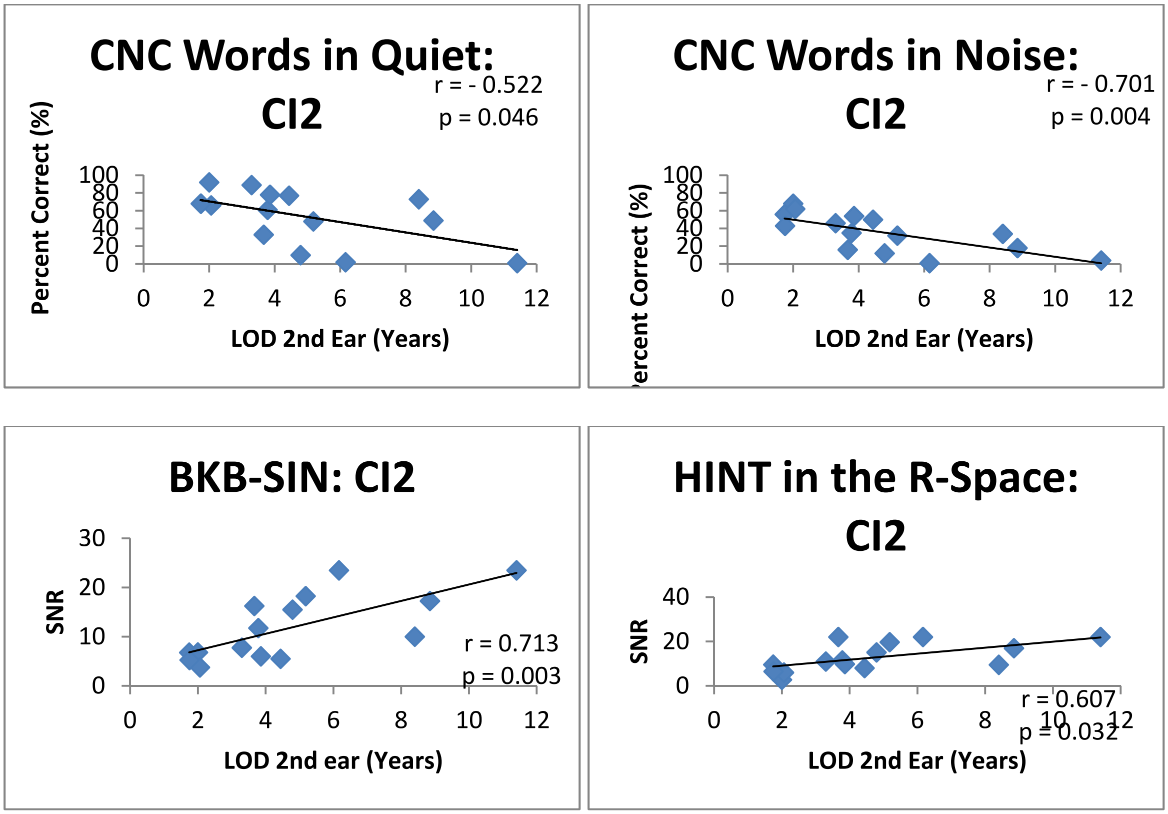


Figure 12. Scatter plots display significant correlations between LOD in the second ear and speech perception abilties. Correlation coefficients (r) and probabilty values (p) are given in each plot.



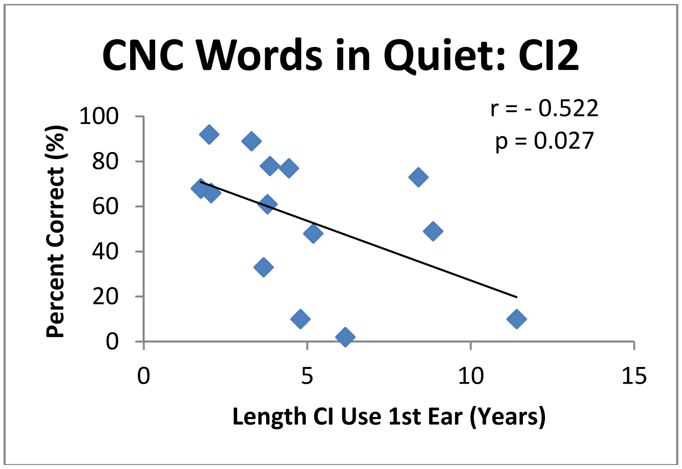
CNC Words in Quiet: CI2

CNC Words in Noise: CI2

BKB-SIN: CI2

HINT in the R-Space: CI2

Figure 13. *Scatter plots show the significant correlations between length of CI1 use and speech perception abilities. Correlation coefficients (r) and probabilty values (p) are given in each plot*



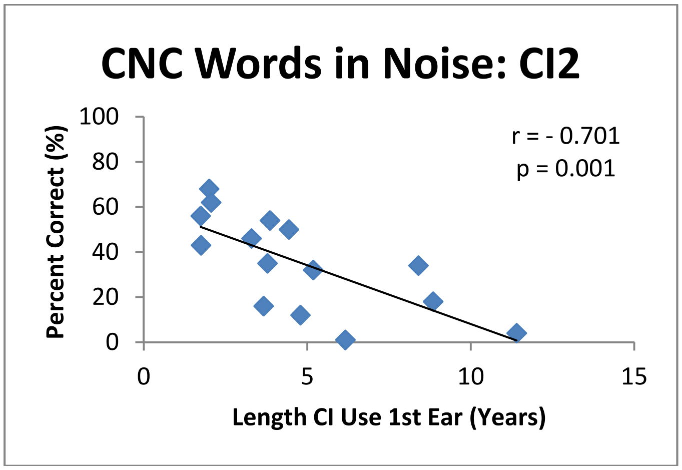


***Figure 14**. Scatter plots display the signficant correlations between the amount of time between surgeries and speech perception outcomes. Correlation coefficients (r) and probabilty values (p) are given in each plot.*