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Effects of combined electric and acoustic hearing on speech perception of a pediatric cochlear implant user

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EFFECTS OF COMBINED ELECTRIC AND ACOUSTIC HEARING ON SPEECH PERCEPTION OF A PEDIATRIC COCHLEAR IMPLANT USER

by

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Approved by:
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ABSTRACT: The primary objective of this study was to document the benefits and possible detriments of combining ipsilateral acoustic hearing in the cochlear implant ear of a patient with preserved low frequency residual hearing post cochlear implantation. The secondary aim was to examine the efficacy of various cochlear implant mapping and hearing aid fitting strategies in relation to electro-acoustic benefits.

ACKNOWLEDGEMENTS

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<u>Introduction</u>

Within the past two decades, there has been a rapid and continuous evolution within the field of cochlear implants (CI), specifically related to the technological advances as well as the surgical procedures used to implant the internal electrode array into the cochlea. Although this procedure was once known to destroy all residual hearing due to the amount of physical trauma during the drilling of the insertion array; improvements in the electrode design, position within the cochlea, and other surgical techniques have minimized the amount of damage. Consequently, individuals undergoing CI surgery are now demonstrating various degrees of residual hearing post-implantation (Balkany, et al., 2006). This was documented as early as 1989 when Boggess and colleagues were able to measure residual hearing within 5 decibels (dB) of pre-operative thresholds in one third of the subjects who received CIs (Boggess, Baker, & Balkany, 1989). Less than 10 years later, Hodges and colleagues were able to demonstrate varied degrees of preserved residual hearing in approximately half of their subjects (Hodges, Schloffman, & Balkany, 1997). Most recently, reports have demonstrated preserved hearing in more than 80% of CI users where post-operative thresholds have remained within 10 to 15 dB of pre-operative thresholds (Gstoettner, et al., 2004; James, et al., 2005).

The preservation of residual hearing is important for several reasons. Criteria for CI candidacy is continuously changing and currently includes individuals with severe-to-profound hearing loss above 1000 Hz, as well as children younger than 12 months of age. Many clinics are considering children with precipitously sloping high frequency hearing loss as potential candidates for CIs. The rational behind these cases is that the cochlear implant may provide high frequency information that can not be obtained with traditional amplification, which is important for detection and discrimination of consonant sounds and may significantly improve speech understanding and production. While bilateral implants are being considered for individuals with profound bilateral hearing loss, the use of hybrid electrode arrays and electro-acoustic stimulation (EAS) is becoming more prevalent for those with residual hearing in the low to mid frequency region. Hybrid, or EAS, refers to the use of a CI and hearing aid at the same ear; it is appropriate for individuals who have preserved residual low frequency hearing post-implantation (Balkany, et al., 2006). This idea was first described by Von Ilberg and colleagues (1999) who were able to demonstrate preserved residual hearing (Von Ilberg, et al., 1999). Later, Gantz and colleagues were able to show the positive effects of EAS on aided pure tone thresholds and speech perceptions abilities (Gantz, Turner, Gfeller, & Lowder, 2005). In order to understand the potential advantages of EAS, it is first necessary to understand the benefits and limitations of electric hearing, alone.

Benefits and Limitations of Electric Stimulation. CIs are able to greatly enhance the speech perception abilities of individuals with severe-to-profound hearing loss. This is accomplished through electric stimulation of the surviving auditory nerve fibers (Kong, Stickney, & Zeng, 2005). Compared to hearing aids, CIs are able to improve listeners' speech understanding abilities due to the increased amount of high frequency information that is delivered to the listener. This is true for both adult and pediatric populations. Within the pediatric population, children with cochlear implants are able to achieve auditory skills that exceed those of their non-implanted peers with profound hearing loss who use hearing aids. This is particularly true with regards higher levels for open set word recognition (Miyamoto, Robbins, Osberger, & Todd,1995).

Although CIs can provide good detection of low frequency sounds, acoustic amplification, as provided by either a normal ear or hearing aids is able to provide more accurate low frequency information as compared to cochlear implants. How does this trade off of frequency information affect the listening abilities of CI users?

One limitation with electric hearing includes significant difficulty understanding speech in the presence of background noise (Ching, van Wanrooy, & Dillon, 2007). This is because low frequency information, which is poorly transmitted through electric stimulation, allows for the separation of voices through the use of fundamental frequency cues, including those relating to voicing and place of manner (Kong, et al., 2005). Another limitation of CIs relates to the perception of the aesthetic qualities of sound, such as pitch perception. This relates to the fact that natural low frequency cues aid in the perception of sound quality and music perception (Ching, et al., 2007). The sound quality of speech relates to the perceived effects of variation in the frequency spectrum and amplitude variations of speech over time. CI users are often unable to appreciate these changes because of the limited amount of pitch and spectral cues that are perceived. In most implant processors, the short-term spectral shapes of acoustic signals are estimated using a bank of band-pass filters. The number of bands that can be used to present electric stimuli to the cochlea is constrained by the number of filter-bands, electrodes, and active channels (Ching, et al., 2007). Due to these limitations, CI users often subjectively report a "mechanical" or "raspy" quality to speech as compared to their experiences with hearing aids. In addition, they also report a depreciation for music (Gantz & Turner, 2003).

Benefits of EAS. A potential benefit of EAS is that the use of a hearing aid may be able to provide low frequency information through the use of residual hearing and acoustic amplification. On their own, hearing aids are not able to provide enough amplification for individuals with severe-to-profound hearing loss; however, they may be able to enhance the speech perception abilities of CI users in cases where low frequency hearing has been preserved post-operatively. The benefits of this combined stimulation are most relevant in the areas of listening in background noise and in the perception of sound quality.

Low frequency cues are able to improve speech understanding in noise due to the additional information that the listener receives regarding the fundamental frequencies of the speaker's voice. With these cues, the listener is able to separate the speaker's voice from the competing signals based on the addition of voice pitch cues (Ching, et al., 2007).

Low frequency cues also provide information which aids in the perception of sound quality. In terms of segmental cues, an ability to hear voice onset times of consonants helps to distinguish between voiced and voiceless phonemes. In terms of suprasegmental cues, variations in pitch convey information relating to stress and intonation patterns, providing listeners with a natural sound quality to speech (Ching, et al., 2007).

Therefore, acoustic amplification may provide important information which can aid in the separation of competing voices and provide important linguistic and perceptional cues. Additionally, because the acoustic features of complex sounds are more degraded in electric stimulation compared to acoustic amplification, combining these two signals would be expected to improve the limitations of either type of stimulation alone (Ching, et al., 2007).

Combining electric stimulation with acoustic hearing is not an entirely new concept. The benefits of traditional bimodal stimulation (CI plus contralateral hearing aid) have been documented over the past 15 years (Armstrong, Pegg, James, & Blamey, 1997; Ching, Psarros, Hill, Dillon, & Incerti, 2001; Chmiel, Clark, Jerger, Jenkins, & Freeman, 1995; Shallop, Arndt, & Turnacliff, 1992). Most notably, benefits include improved speech perception in quiet and in noise, as well as improved localization skills (Ching, et al., 2007; Miyamoto, et al., 1995). This is partially attributed to the addition of head diffraction and redundancy cues. It is also a result of the complementary low and high frequency signals delivered by the two devices. Ching, van Wanrooy, & Dillon (2007) provided a summary of the literature on the effects and differences of bimodal stimulation and bilateral cochlear implantation. One of their studies reported on the effects of bimodal use on a group of adult and pediatric listeners. Within the adult population, approximately 50% showed a binaural advantage within the areas of improved speech perception in quiet and in noise and improved localization as compared to monaural electric stimulation. Within the pediatric group, 62% showed improvements within the areas of speech perception and localization (Ching, et al., 2007).

The concept of combining both electric and acoustic signals in the same ear has been a result of improved surgical techniques leading to preserved post-operative hearing. Although previous research has looked at the need for, and successful maintenance of preserved hearing post-operatively, there is a paucity of research detailing the outcomes of EAS when used in these instances.

As previously mentioned, Von Ilberg et al. (1999) were the first to describe EAS and its effects. They used a single subject design to explore the application of EAS in humans after finding successful outcomes preserving hearing in animal experiments. The participant was an adult female who previously wore bilateral BTE hearing aids due to a severe sensorineural hearing loss. The participant was implanted with a Med-El Combi 40+ CI standard array at the right ear. In the study, speech perception tests were performed in the following ipsilateral conditions: right hearing aid alone, CI alone, and right hearing aid and CI combined. Results were not obtained using the contralateral hearing aid. Post-operative measures included speech perception testing using two sentence identification tests and one monosyllabic word test, all completed in quiet. The results indicated an improvement in speech perception scores in the combined CI and hearing aid condition compared to either device alone. Compared to scores obtained with the CI alone, the patient improved by 4 to 5.5% on the sentence tests and by an additional 5% on the monosyllabic word test. Subjectively, the participant also reported superior sound quality when listening in the EAS condition (Von Ilberg, et al., 1999).

These early results became the catalyst for future studies aiming to identify the effects of EAS. Gantz and Turner (2003) looked at the benefits of EAS with a short, 10 millimeter (mm) experimental electrode array. Six adults with severe high frequency sensorineural hearing loss were implanted with this device and post-operative word and sentence recognition scores were measured. The results indicated a 30% to 40% improvement in word recognition in the EAS bimodal condition (CI and hearing aid at one ear plus hearing aid at the contralateral ear) compared to bilateral acoustic amplification (Gantz & Turner, 2005).

Further attempts to replicate these results and demonstrate additional effects of EAS were made in 2005 by the same group of researchers. In their extended study, Gantz and colleagues (2005) looked at the effects of EAS on 21 participants implanted with the short, experimental device. Additional post-operative measures included word recognition in noise as well as common melody recognition. Long term results revealed significant improvements in word discrimination scores in quiet. On average, participants correctly identified 79% of words on the Consonant Nucleus Consonant (CNC) test. This was compared to scores between 10% and 50% when using binaural amplification. Further findings indicated a 9 dB improvement in signal-to-noise ratio (SNR) for speech perception in noise for word discrimination scores. This was compared to a group of recipients using cochlear implant stimulation alone who were matched for speech recognition in quiet (Gantz, et al., 2005).

In 2005, Kiefer and colleagues studied the benefits of EAS in a group of 11 adults who retained residual low frequency hearing after receiving Med-El Combi 40+ devices. The benefits of EAS were determined by comparing speech perception scores in quiet and in noise; this was done in the CI alone condition and the CI plus ipsilateral hearing aid condition. This test revealed no statistical differences between the two conditions. Speech perception was also tested in noise with speech presented at 70 dB SPL, using a +10 dB SNR. This test revealed significant improvement with the addition of ipsilateral acoustic amplification with an average gain of 23% over electric only stimulation. Individual performances showed improvements of greater than 70% for EAS as compared to CI alone (Kiefer, et al., 2005).

James and colleagues (2006) reported on combined ipsilateral EAS in a group of seven implant recipients with preserved low frequency hearing. The participants were implanted with a full-length electrode array; speech recognition scores were obtained post-operatively in the CI alone condition as well as EAS ipsilateral condition. For words presented at 65 dB SPL, significant improvements were seen for both conditions as compared to scores obtained through binaural amplification. However, the EAS ipsilateral condition showed an additional mean improvement of 12% compared to the CI alone condition. When tested in noise using multitalker babble at a +5 dB SNR, similar results were found. While both conditions revealed significant improvements, an additional improvement of 14% was observed under the EAS condition (James, et al., 2006).

An extension of this study incorporated an additional 9 participants and measured the speech perception abilities of EAS recipients using varying SNRs (Fraysse, et al., 2006). Post-operative results revealed similar findings as those presented by James, et al. (2006). Mean scores for speech perception in quiet indicated an additional 10% advantage for ipsilateral EAS over CI stimulation alone. For speech recognition in noise using a +10 dB SNR, the addition of EAS improved scores by 19% as compared to scores for CI alone. When tested using a +5 dB SNR, the disparity between conditions was increased to a 34% advantage for the EAS condition over CI alone (Fraysse, et al., 2006).

While these studies have reported successful outcomes for adult EAS recipients, there is no data in the literature reporting on the effects of EAS in the pediatric population. This is in part, due to the fact that the use of shorter electrode arrays has not yet been approved for children. As a result, the primary aim of this present study was to document the benefits and possible detriments of combining EAS in a pediatric recipient who received a standard length electrode array and demonstrated preserved low frequency hearing. The following conditions were compared: EAS in the ipsilateral ear to the implant (right CI plus right hearing aid) compared to CI only, EAS in the ipsilateral ear to the implant with acoustic hearing in the contralateral ear (right CI/hearing aid plus left hearing aid) compared to traditional bimodal stimulation (right CI plus left hearing aid). The secondary aim of this study was to examine the efficacy of various cochlear implant mapping and hearing aid fitting strategies in relation to EAS benefits.

Methods

The research protocol and informed consent for this single subject design were reviewed and approved by the Institutional Review Board and the Human Studies Committee at Washington University School of Medicine.

Subject. One female pediatric subject participated in this single subject design. The participant was aged nine years, one month at the beginning of the study.

Audiologic History. The participant's hearing loss is a result of Turner's Syndrome which audiologically, is characterized by a progressive sensorineural hearing loss. The participant was fit bilaterally with behind-the-ear (BTE) hearing aids at approximately three years of age and has received audiologic services since that time. A consistent deterioration in the participant's hearing has been documented and reached the level of severe-to-profound at the right ear and mild to profound at the left ear in February 2007. The decision was made to implant the participant with a Med-El Pulsar ci100 device at the right ear with continual use of a Starkey Destiny 1200 BTE hearing aid at the left ear. Implantation took place in July 2007 when the subject was age 8 years, 8 months; research related testing began five months post-operatively.

Selection Criteria. The selection criteria for this research included measurable residual low frequency hearing following cochlear implantation with a full-length electrode array. Maximum post-operative thresholds were limited to 80 dB HL for 125 to 250 Hz and 90 dB HL at 500 Hz. These values were defined by James et al., (2006) and corresponded to the upper limit of the fitting range of powerful in-the-ear (ITE) instruments as well as the lower limits of vibro-tactile sensations (Fraysse, et al., 2006; James et al., 2006).

Surgical Methods. The participant underwent surgery at a pediatric CI facility where surgical methods are being used to preserve residual hearing. Published accounts in the literature describe the following techniques for preserving hearing during implantation with a full-length electrode array. Low speed drills were used in order to avoid acoustic trauma. In addition, careful placement of the cochleostomy was made anteriorly and inferiorly to the round window in order to avoid damage to the basilar membrane and spiral lamina. A small cochleostomy was also used in order to prevent buckling of the electrode and allow perilymph to escape (Roland, Gstottner, & Adunka, 2005).

Test Equipment

All testing was performed in double or single-walled booths located in a quiet space at each test location. The listener was positioned at 0 degrees azimuth and one meter from the loudspeaker. The FM tones were presented with a Grason-Stadler audiometer (GSI 61).

All speech stimuli were digitized and stored on a desktop computer at each test location. The computer was used to deliver the speech stimuli via an audiometer, amplifier and loudspeaker in the sound field.

Test Materials

Frequency Modulated (FM) Tones. FM stimuli presented at .125, .25, .5, 1, 2, 4, and 6 kHz were produced by the audiometer at each test session. Threshold testing was conducted in the aided and unaided conditions during testing and pre-test phases using conditioned play audiometry.

Consonant Nucleus Consonant (CNC) 50-Word List (Peterson & Lehiste, 1962). The 50-item CNC monosyllabic word lists were selected for measuring open-set word recognition. The words were presented in quiet at 60 dB SPL and in noise at a SNR of +10 dB using multi-talker babble. The participant verbally repeated the words presented in the sound-field.

Bamford-Kowal-Bench Speech in Noise (BKB-SIN) Test (Bench, Kowal, & Bamford, (1979). BKB sentence lists (16 sentences per list pair) recorded in noise were presented in the sound-field. The sentences were presented at 65 dB SPL with SNRs that became progressively more difficult, beginning with a +21 dB SNR and concluding with a –6 dB SNR. The participant verbally repeated the sentences.

Emotion Identification. Three sentences ("It's time to go.", "Give me your hand." and "Take what you want.") spoken by a single female speaker were produced with four different emotions (angry, scared, happy, and sad). Each sentence was produced multiple times. A single-interval, four alternative forced-choice paradigm with a total of 36 trials was used (3 sentences x 4 emotions x 3 tokens). After each sentence was presented, the participant chose one of the four emotions by clicking on one of the 4 labeled pictures of a young female child displaying each emotion.

Emotion Discrimination. The same sentences from the emotion identification task were used for emotion discrimination, a two-interval, two-alternative forced-choice paradigm was used. For this task, two sentences were presented for each trial; the subject indicated whether the emotion conveyed was the same or different in the two sentences. For any given trial, one of the three sentence scripts was used and waveforms were presented having either the same or different emotions. A total of 24 trials were presented. After each trial, the listener chose 'same feeling' or 'different feeling' as her response by clicking on one of the two images corresponding to 'same' and 'different.'

Talker Discrimination. Sentence stimuli from the Indiana Multi-Talker Speech Database (IMTSD) were used to assess talker discrimination. Eight female and eight male speakers were used for all tests. Three types of talker discrimination tests were conducted: a) across gender (male vs. female), b) within female, and c) within male. For all three types of tests, the experiment consisted of a two-interval, two-alternative forced-choice paradigm. In every trial, the sentences differed in the two intervals. The listener responded by clicking on one of two images corresponding to 'same person' or 'different person.'

Across Gender Talker Discrimination. In each trial, the listener had to choose whether two given sentences were spoken by the 'same person' (the same female or the same male talker) or by 'different people' (a male talker and a female talker). A total of 32 trials were presented.

Within Female Talker Discrimination. In each trial, two sentences were presented; the listener was asked to indicate whether the two sentences were spoken by the same female speaker or by two different female speakers. A total of 32 trials were presented.

Within Male Talker Discrimination. In each trial, two sentences were presented; the participant chose whether the two sentences were spoken by the same male speaker or by two different male speakers. A total of 32 trials were presented.

Speaker Localization. This test was used to determine the sound localization abilities of the listeners. The participant heard a single syllable word presented at 60 dB SPL, ±3 dB. The participant was given 100 CNC words for each listening condition. The words were presented from one of 15 speakers arranged in an arc from 70 degrees from the left to 70 degrees to the right. The participant indicated which speaker emitted the word by pointing to the speaker and repeating the number which corresponded to the speaker. During presentation of the words the participant was seated at zero degrees azimuth to speaker number eight with speakers one through seven on her left and speakers nine through 15 on her right. After each presentation she turned and pointed to the perceived sound source. Only 10 speakers were active, those positioned at ±70 degrees, ±50 degrees, ±30 degrees, ±20 degrees, and ±10 degrees. Ten words were presented from each speaker at random. Those positioned at ±60 degrees, ±40 degrees, and 0 degrees were inactive.

Hearing Aid Fitting

The participant was fit with a Phonak Extra 33 ITE hearing aid at the right ear six months post-implantation. The hearing aid was optimized using the AudioScan Verifit system with DSL m[i/o] v5.0 prescribed targets and fine-tuned further for optimal audibility (Cornelisse, Seewald, & Jamieson, 1995). Average values for uncomfortable loudness levels and real ear to couple differences were used according to the participant's age as well as type of transducer used. The hearing aid was adjusted in order to maximally reach the targets for soft, average, and loud conversational speech for the frequencies 250, 500, and 750 Hz. These specific frequencies were targeted due to the amount of residual hearing as well as the potential benefits of acoustic amplification within this low frequency range. The output levels for the high frequencies did not approximate the DSL recommended levels because output and gain were specifically reduced in those areas due to the fact that this information was conveyed through the CI. Adjustments to the hearing aid gain and output using an established prescriptive fitting method was used based on data reported by Vermeire and colleagues (2008) and Ching and colleagues (2007) on the importance of optimizing acoustic amplification in EAS (Ching, et al., 2007; Vermeire, et al., 2008).

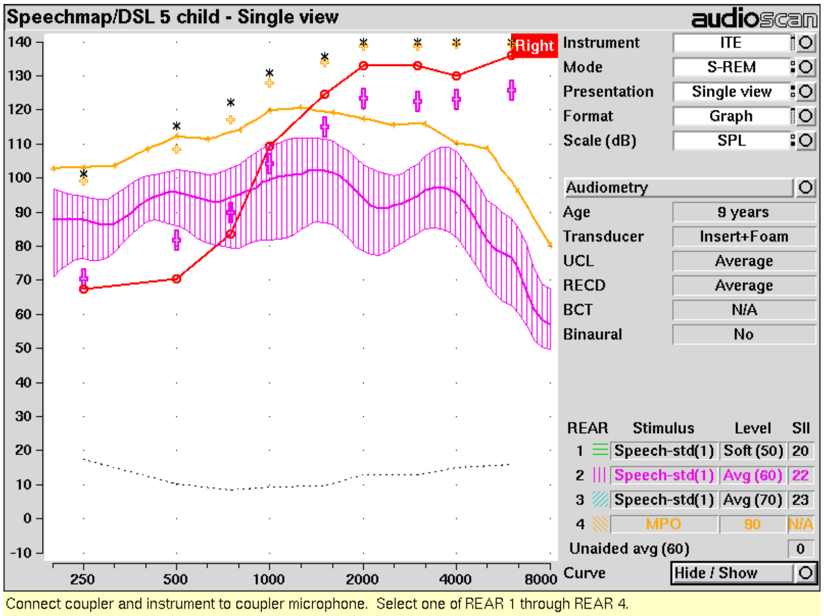


Figure 1. AudioScan Verifit system showing optimized results from 250 to 750 Hz for the Phonak Extra 33 ITE hearing aid.

<u>Speech Processor Programming</u>

Two EAS maps were programmed into the participant's speech processor. Both maps stimulated the same frequency range and had a center frequency of approximately 400 Hz. Stimulation was provided throughout the entire frequency range up until approximately 7000 Hz. The first map had all of the electrodes turned on while the second map had the two most apical electrodes turned off to decrease the overlap between the acoustic and electric signals. This frequency range was restricted compared to the traditional CI only map which started with a center frequency of 253 Hz. These maps were created in order to determine the optimal stimulation range for the cochlear implant while combined with acoustic amplification. In a study looking at the benefits of EAS, Fraysse et al. (2006) found that seven of nine subjects subjectively preferred using a map that did not provide overlapping stimulation between the two devices (Fraysse et al., 2006). In a similar study, Vermeire and colleagues (2008) also found that reducing the overlap between the hearing aid and cochlear implant produced optimal results for participants when listening in noise (Vermeire, et al., 2008). Contrary to these findings, Kiefer, et al. (2005) reported that 10 of 11 participants used an overlapping frequency map based on better results and patient preference. This map stimulated the entire frequency range from 300 Hz to 5500 Hz (Kiefer, et al., 2005). For the treatment phase of the study, the decision was made to use the Vermeire et al. (2008) method of non-overlapping stimulation.

Procedures

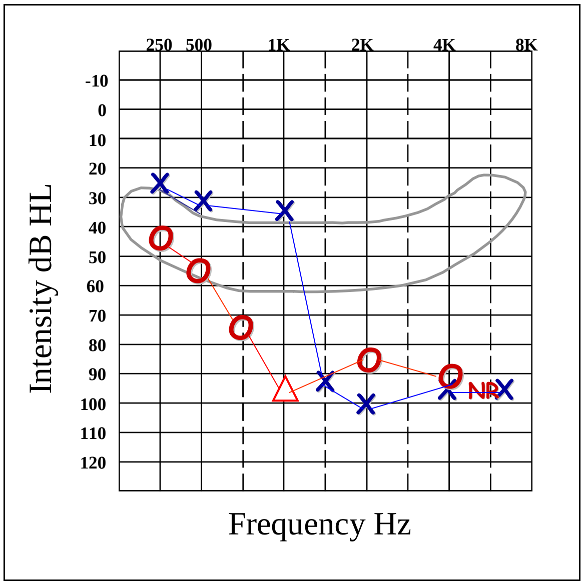
Testing Schedule and Protocol. The tests within the test protocol were presented in a random order; the following four test phases were used: Baseline time 1, Treatment time 1, Baseline time 2, and Treatment time 2. Testing at the Baseline time 1 and time 2 consisted of the test protocol described above in the following conditions: hearing aid only, CI only (with the left ear plugged with the subject's custom earmold) and traditional bimodal (right CI plus left hearing aid). Testing for Treatment phase time 1 and time 2 involved the same test protocol in the following conditions: CI EAS in the ipsilateral ear (right CI/right hearing aid), EAS bimodal condition (right CI/ right hearing aid plus left hearing aid). Note that the hearing aid only condition was conducted only in the Baseline time 1 and time 2 phases and not the Treatment 1 and 2 phases. This was due to the age and attention limitations of the subject and the fact that at the time the study was initiated, performance with the hearing aid appeared to have reached a plateau. Each test phase was conducted over three to four test sessions in order to keep the test sessions under one hour and not fatigue the patient.

The participant received approximately two weeks of rest in between each test phase apart from one exception. After completing Baseline 1, the participant wore her devices in the bimodal EAS configuration for three weeks prior to testing in Treatment 1. In addition, the week preceding the completion of Baseline 1 was used to determine which EAS map provided optimal listening benefits. This was done by switching back and forth between the maps throughout the week as well as through obtaining teacher and participant reports. Speech perception testing was also administered using CNC 50-word lists in quiet at 60 dB SPL. At the end of the week it was determined that map one, which made use of all of the electrodes, would be used for the remainder of the study. This was due to slightly better results found for sound-field thresholds as well as speech perception testing.

Before continuing with the remainder of the testing, the subject wore all three devices for a period of three weeks in order to adapt to the combined stimulation. During this time the subject participated in additional auditory training in order to become better adjusted to the new device configuration.

Results

Pure Tone Thresholds. Pre-operative and post-operative unaided pure tone thresholds for the right ear are shown in Figures 2a) and 2b). These thresholds indicate that the subject retained residual post-operative thresholds from .125 to 1 kHz. Unaided thresholds obtained at the completion of the study indicated that the subject's hearing at that ear had remained stable.



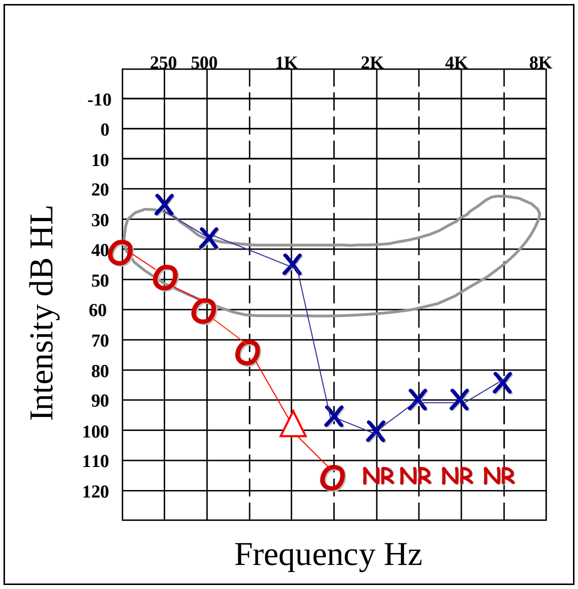


Figure 2(a)

Figure 2(b)

Figures 2(a) and 2(b). (a) Pre-operative unaided pure tone thresholds for the right and left ears obtained approximately fives months prior to implantation. (b) Post-operative thresholds for the right ear obtained approximately fives months preceding implantation.

Figure 3 shows post-operative aided thresholds for the right ear using the CI only as well as the left ear using the BTE hearing aid. The CI was optimized for traditional bimodal use (right CI plus left BTE hearing aid). Figure 4 depicts aided EAS thresholds for the right ear (right CI plus right ITE hearing aid) found in 2 dB steps; aided acoustic only thresholds for the right ear are also shown.

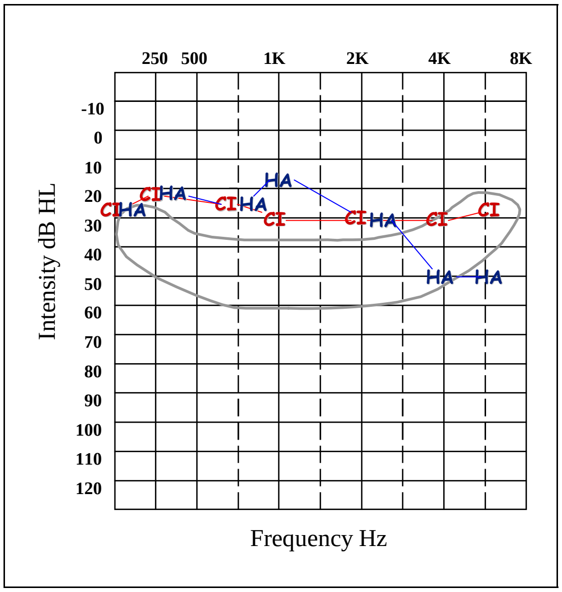


Figure 3. Post-operative aided thresholds for the right ear using the CI only as well as the left ear using the hearing aid.

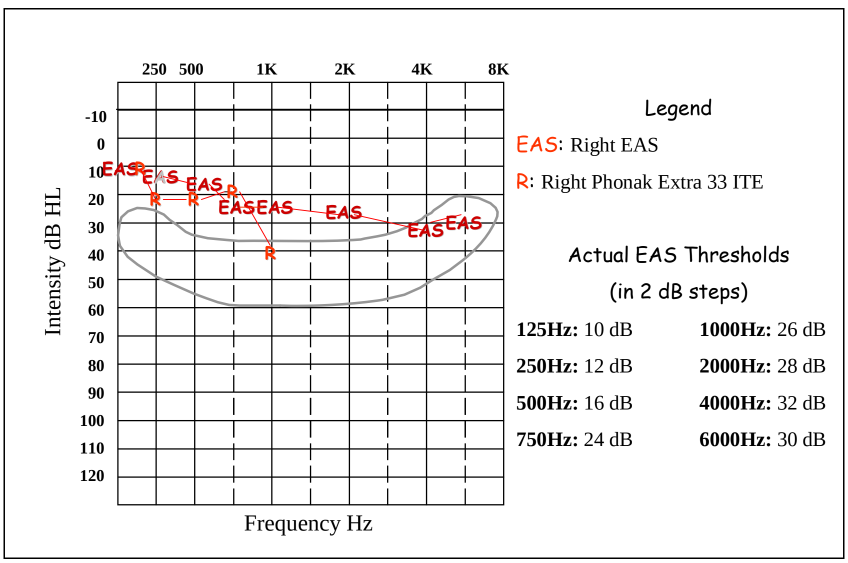


Figure 4. Aided EAS thresholds for the right ear (right CI plus right ITE hearing aid) as well as aided right ear thresholds using the ITE hearing aid.

CNCs in Quiet. Figure 5 shows the number of correctly repeated words for the CNC in Quiet test for each test condition across time. An overall improvement in the percentage of correctly repeated words can be seen. When comparing the averages of each test condition, a bimodal effect can be seen in both the traditional bimodal condition and the EAS bimodal condition the over CI alone and hearing aid alone conditions. The left hearing aid and CI only conditions showed an average of 38% words correct, each. Average scores of 51% and 58% can be seen for the traditional bimodal and EAS bimodal conditions, respectively. This shows that the addition of acoustic amplification in the electrically stimulated ear did not decrease speech understanding abilities of the subject in quiet. Scores comparing the CI only conditions to the CI EAS conditions are shown in Figure 6 with left hearing only scores shown in Figure 7. Similar results were found when comparing performances for the CI only to the CI EAS conditions. Figure 8 shows improvement in scores for both bimodal conditions over time.

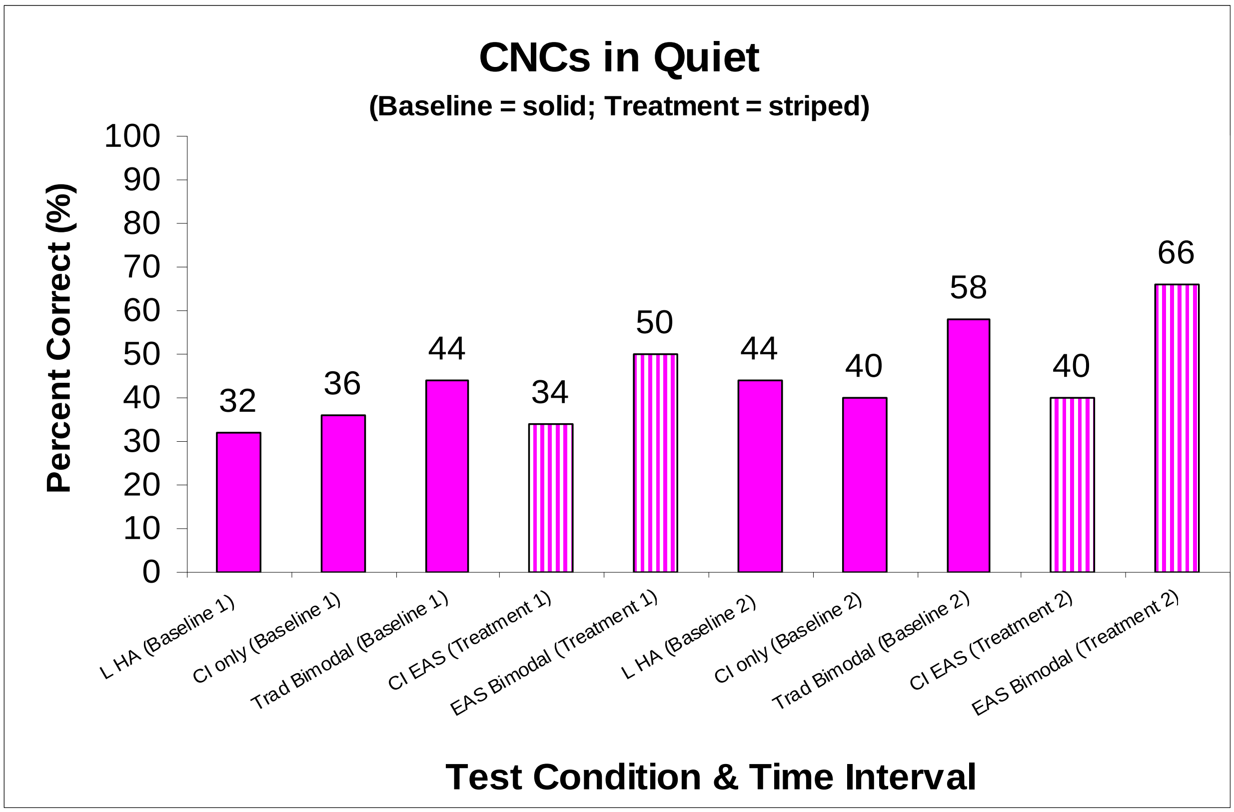


Figure 5. Percentage of correctly repeated words are shown for each test condition and time interval.

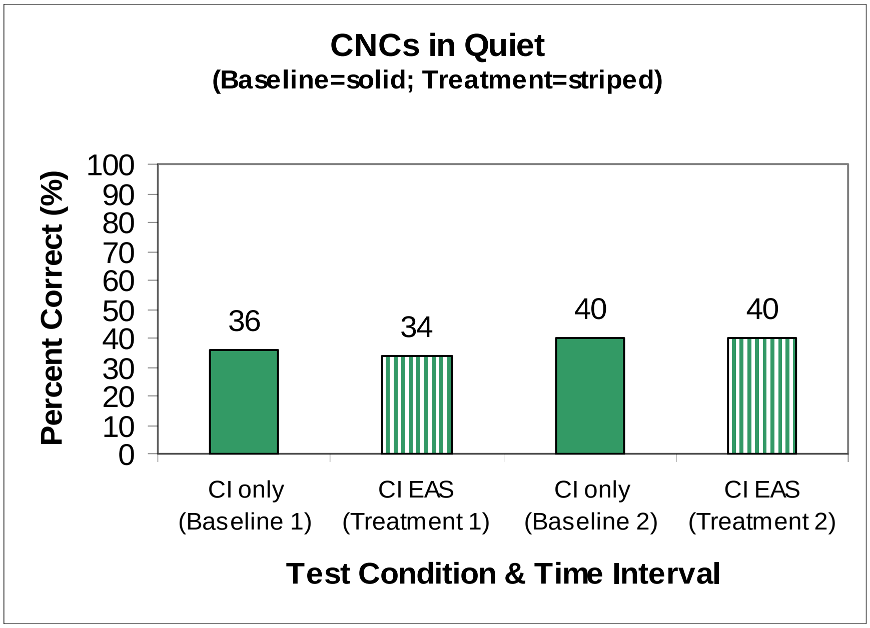


Figure 6. Comparison of correctly repeated words for the CI only conditions and the CI EAS conditions.

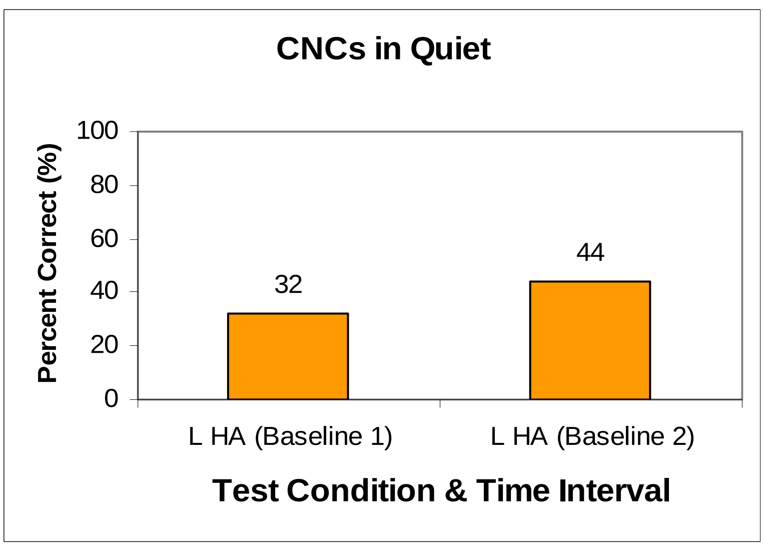


Figure 7. Scores for the left hearing aid only conditions are shown for Baseline 1 and Baseline 2.

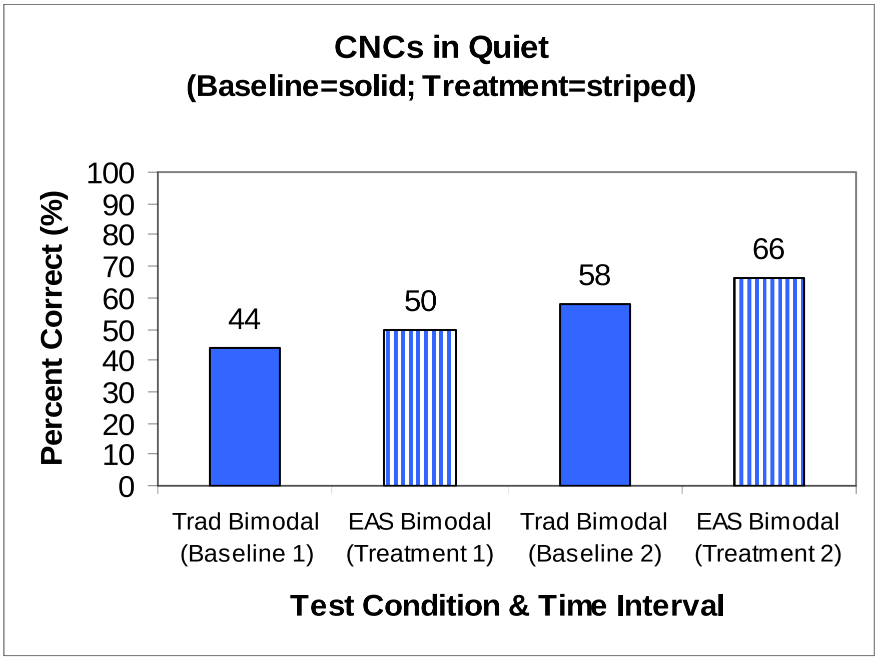


Figure 8. Percentage correct scores for the traditional bimodal and EAS bimodal conditions over time.

CNCs in Noise. Figure 9 shows the percentage of correctly repeated words for the CNC in Noise test for the CI only and CI EAS test conditions. An improvement in scores can be seen over time for the CI only conditions; this suggests that learning was taking place over the test periods. Scores for the CI EAS condition remained stable. Figure 10 shows performances for the left hearing aid only conditions over time. Results initially showed an advantage over CI only scores and showed a learning effect over time. Scores for the CI only and CI EAS conditions reached the level of the left hearing aid by Baseline 2.

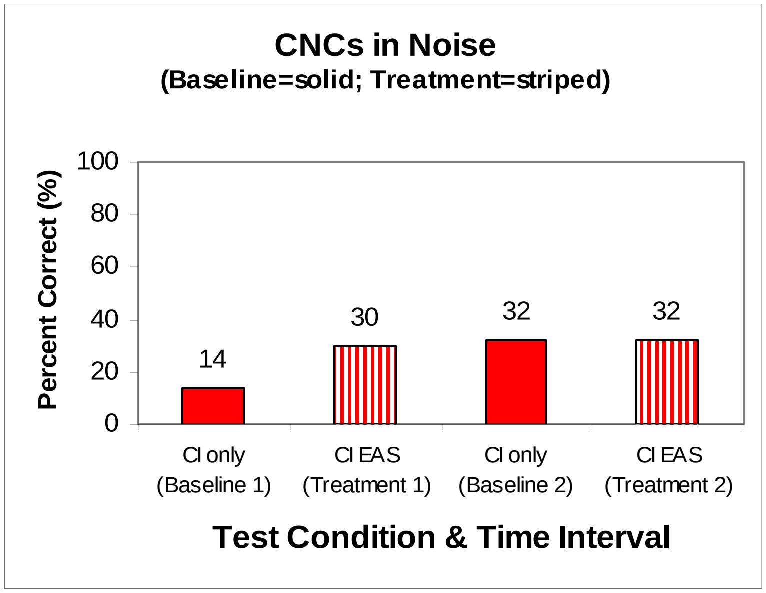


Figure 9. Comparison of correctly repeated words for the CI only conditions and the CI EAS conditions.

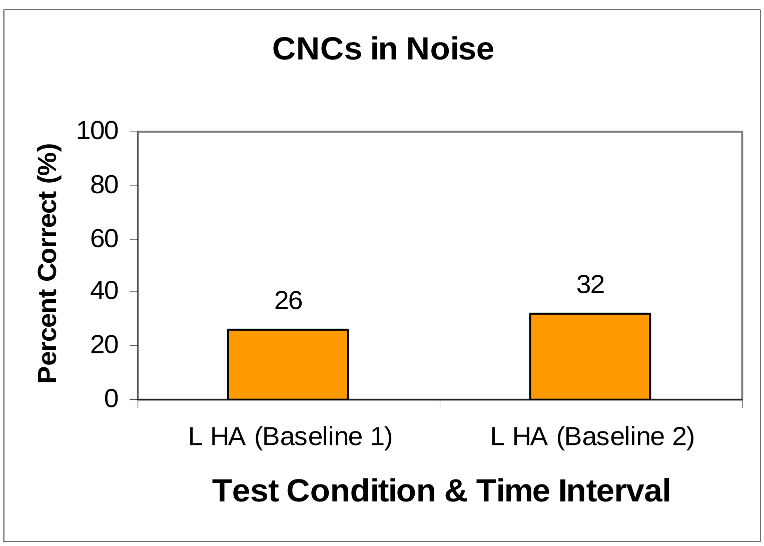


Figure 10. Performance for the left hearing aid condition during Baseline 1 and 2.

Figure 11 compares the traditional bimodal to the EAS bimodal conditions Scores were similar across conditions; surprisingly, scores decreased between Baseline 1 and Baseline 2. Throughout testing for CNCs in Noise, the participant was easily distracted and required continual reminders to stay focused. She had also begun to complain about difficulties listening to noise in her environment at home; this could account for the decrease in performance. It is of interest to note that this decrease was not evident for the left hearing aid only condition or for the CI only and CI EAS conditions. This suggests that the decrease in performance noted for the traditional bimodal and EAS bimodal conditions was not a result of device malfunction.

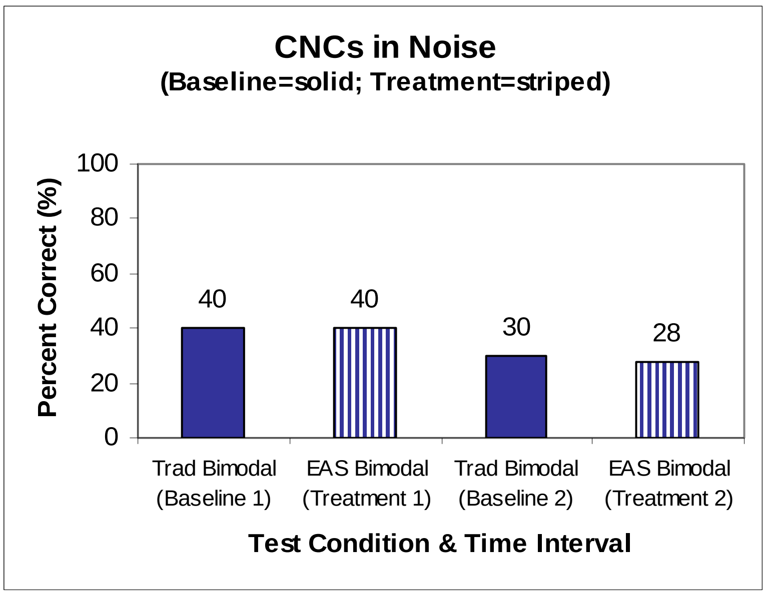


Figure 11. Scores for traditional bimodal and EAS bimodal conditions over time.

BKB-SIN. An improvement in scores could be seen for the CI EAS condition over time while performance for the other conditions remained relatively stable; this suggests that learning was taking place for at least the CI EAS condition. Figure 12 shows the average SNR-50 (dB) values for the CI only and CI EAS conditions. In addition, the CI EAS scores also showed an advantage over the left hearing aid only scores, which showed values of 13.5 dB and 12.5 dB for Baseline 1 and Baseline 2, respectively. Both CI only and left hearing aid conditions remained stable between time intervals. Performance for the left hearing aid only conditions are shown in Figure 13.

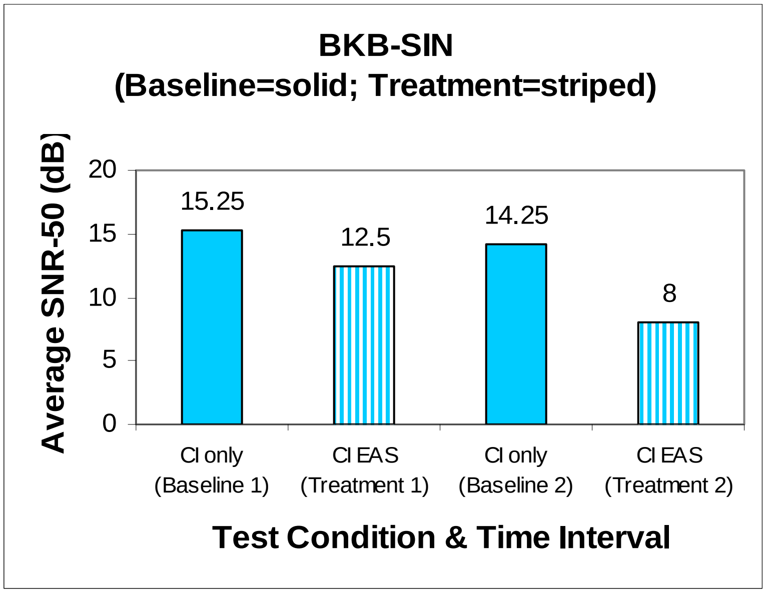


Figure 12. Average SNR-50 (dB) values for CI only and CI EAS conditions for Baseline 1 and Baseline 2.

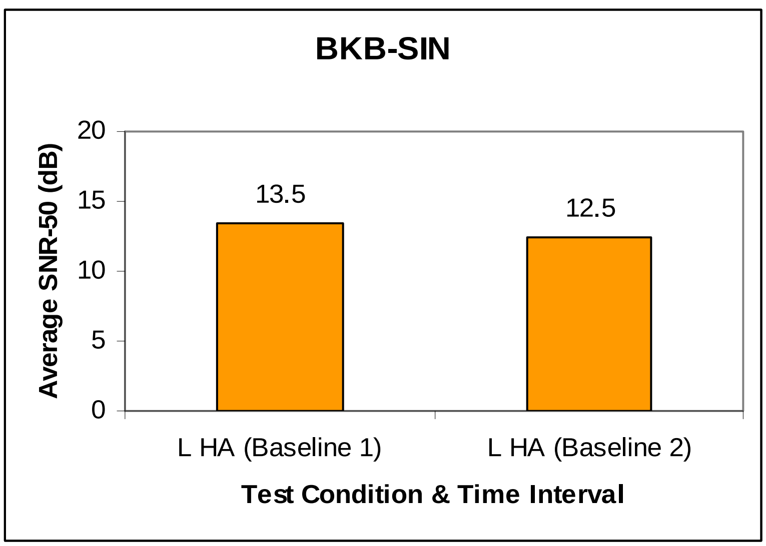


Figure 13. Scores shown for the left hearing aid only condition for Baseline 1 and Baseline 2.

SNR-50 (dB) values for the bimodal conditions are shown in Figure 14. These conditions produced the best results across all conditions and remained stable over time. One exception can be seen for the final CI EAS score. This shows the advantage of bimodal hearing, be it traditional bimodal or EAS bimodal, over stimulation of the CI ear alone.

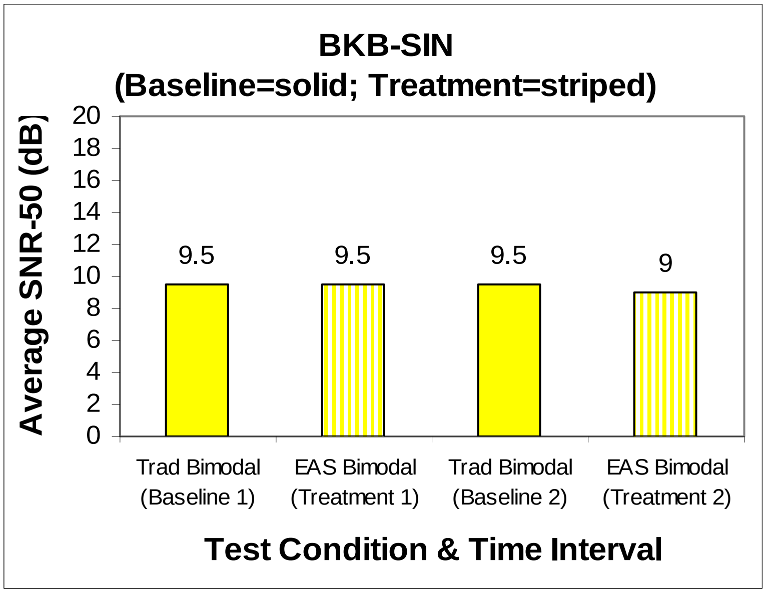


Figure 14. Average SNR-50 (dB) values for both bimodal conditions. All scores remained stable between Time 1 and Time 2.

Speaker Localization. A bimodal advantage can be seen for RMS error scores for the traditional bimodal and EAS bimodal conditions. This is slightly better for the EAS bimodal condition compared to the traditional bimodal condition. Figure 15 shows RMS error values for all of the test conditions over time. Smaller values correspond to better speaker localization abilities; normal listeners obtain RMS error values less than five. All of the conditions showed an improvement in localization over time, except for the traditional bimodal value which showed scores of 26 and 32.5 for Baseline 1 and Baseline 2, respectively. A learning effect can also be seen for the CI only and CI EAS conditions. The left hearing aid showed an advantage over the CI only and CI EAS conditions at Baseline 1; however, at Baseline 2, both CI conditions had reached the score for the left hearing aid condition whereas this condition remained stable over time.

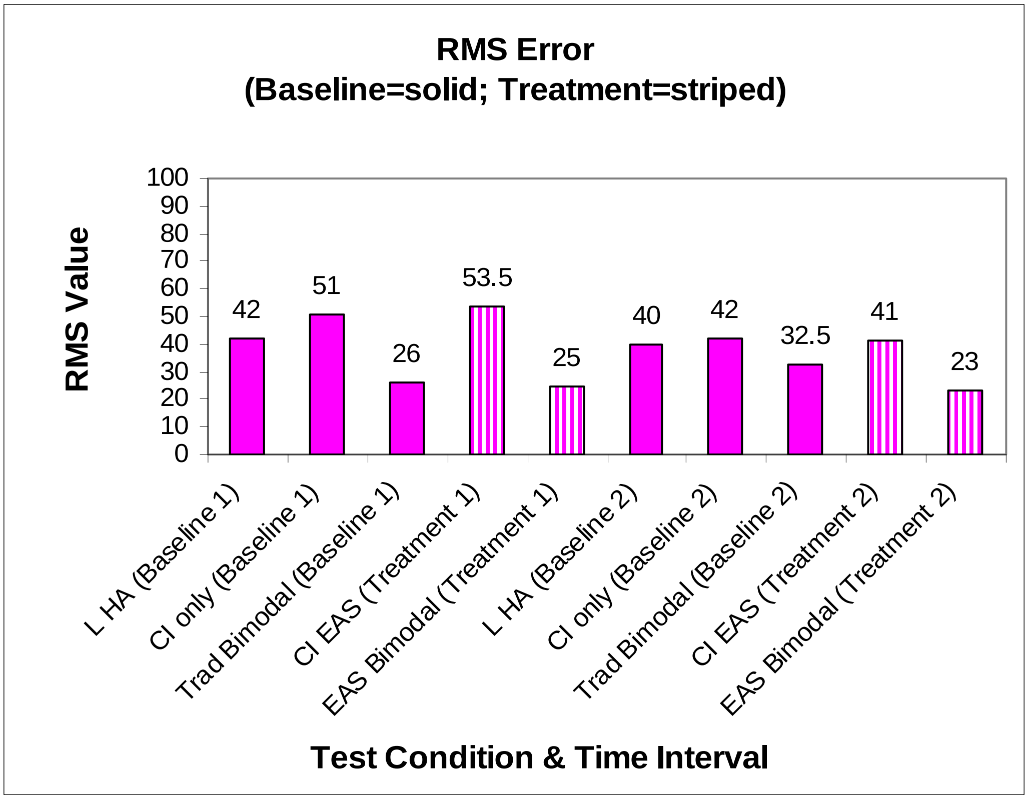


Figure 15. RMS error values for all test conditions for the Baseline and Treatment periods. These values show a bimodal advantage over single sided stimulation, alone.

Emotion Identification. Figure 16 depicts results for the emotion identification task for all test conditions. Scores from Baseline 1 indicate that performance was better for identification compared to discrimination; this is shown in Figure 17. This was of interest to note given that emotion identification should be the more difficult task. With regards to performance for emotion identification, scores for Baseline 1 indicate optimal performance in the left hearing aid only condition. This was to be expected given the reported benefits of acoustic hearing for this type of task. It is of interest to note that a bimodal advantage was not seen under the traditional bimodal condition until Baseline 2; however, this was noticed for both EAS conditions at Treatment 1 and Treatment 2. This demonstrates a bimodal advantage for the EAS bimodal condition during both treatment intervals. A learning effect could be seen for the traditional bimodal condition from Baseline 1 to Baseline 2, showing a bimodal advantage during Baseline 2. The CI only condition also showed a slight improvement over time; however, the left hearing aid only conditions revealed a slight decrease across test periods. Scores for the treatment conditions indicated a bimodal advantage for both the CI EAS and EAS bimodal conditions; performance for these conditions remained stable over time.

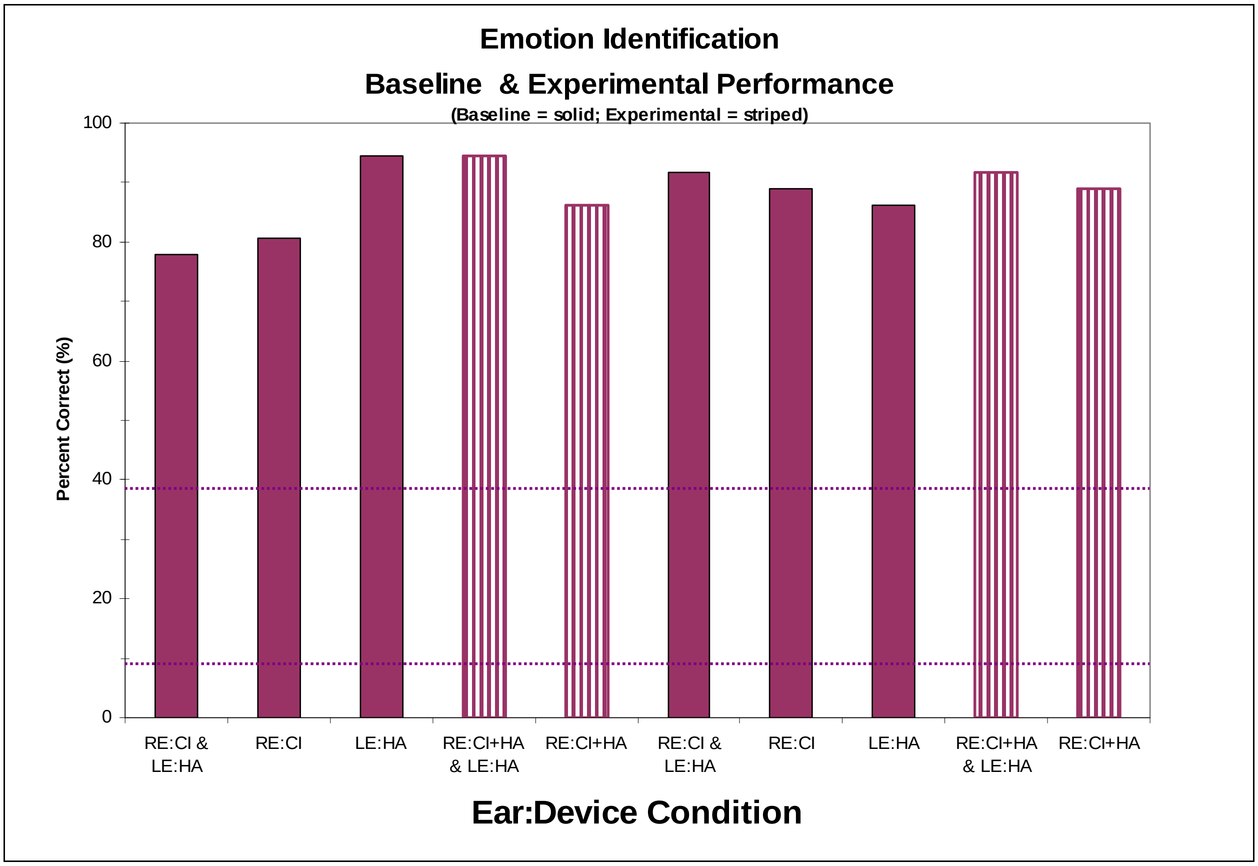


Figure 16. Results are shown for emotion discrimination for all conditions across time. Chance scores are shown as horizontal lines between 13% and 17% correct.

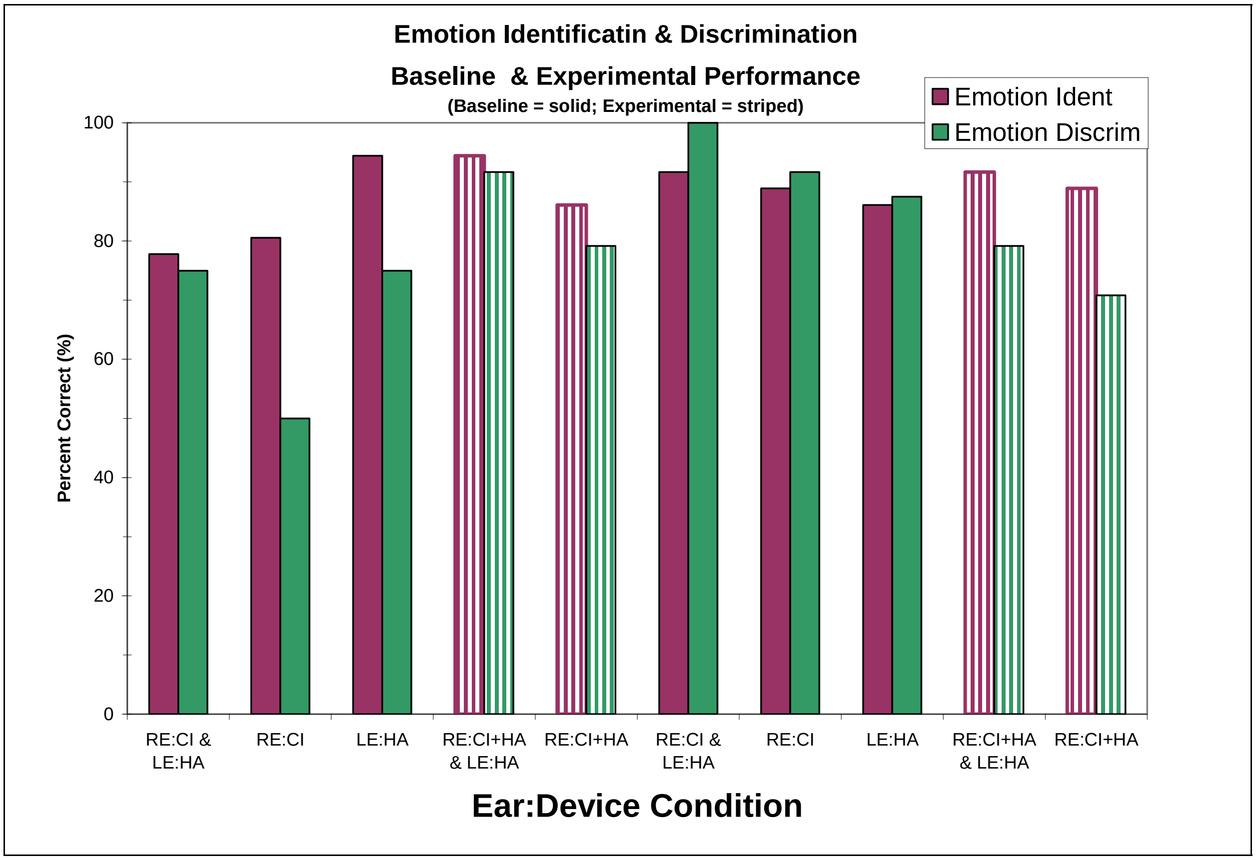


Figure 17. Results showing scores for emotion identification and discrimination.

Emotion Discrimination. Results for the emotion discrimination task are shown in Figure 18. Baseline 1 and Baseline 2 indicate a learning effect for all three baseline conditions: left hearing aid only, right CI only, and traditional bimodal. Initial scores for the CI only condition fell below chance at Baseline 1; however, these scores showed significant improvement at Baseline 2. A bimodal effect could be seen at Treatment 1 for both EAS conditions; this showed improvement over the traditional bimodal score obtained at Baseline 1. A slight decrease in scores could be seen at Treatment 2 for both treatment conditions. Scores for Baseline 2 showed a tendency to be slightly better than those for Treatments 1 and 2.

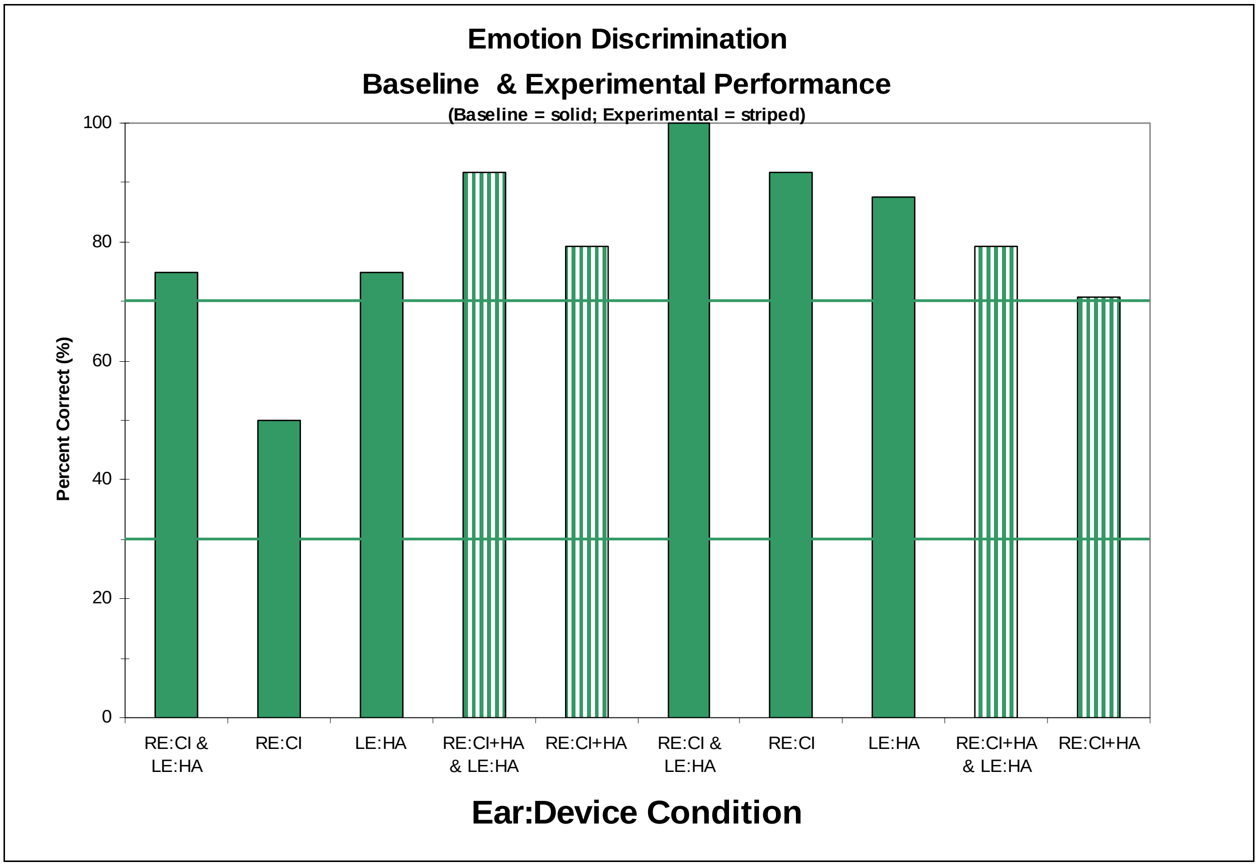
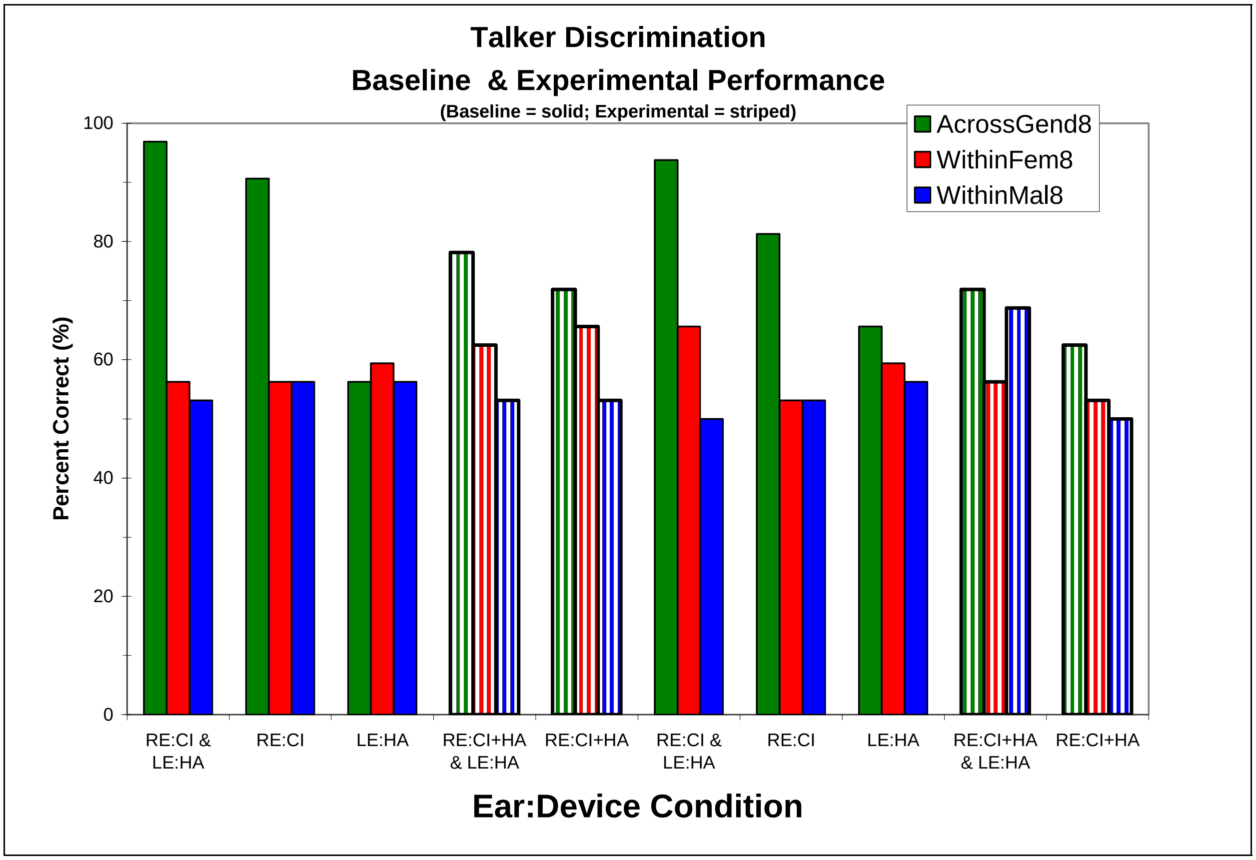


Figure 18. Results are shown for emotion discrimination for all conditions across time. Chance scores are shown as horizontal lines between 30% and 70% correct.

Talker Discrimination. Results for the talker discrimination task are seen in Figure 19. Looking at scores for the across gender task, it can be seen that the participant was able to discriminate between male and female speakers at both Baseline 1 and Baseline 2; however, this is only the case for the two conditions where she is obtaining stimulation from her CI. It is unclear why scores fell below chance for the left hearing aid only condition during Baseline 1 and Baseline 2. These results suggests that ability to discriminate between male and female speakers is directly related to CI stimulation. Scores obtained for the treatment conditions on this task fell slightly above chance; again, it is not clear why these results were obtained.

Performance for the within male speaker task found similar results to those for the within female speaker task. Scores obtained in all test conditions during Treatments I and 2 aswell as

Baseline 2 fell below chance; results from Baseline 1 showed slightly better scores. These results indicate that the participant was unable to discriminate between within gender speakers in either the baseline or treatment conditions.



Talker Discrimination
Baseline & Experimental Performance
(Baseline = solid; Experimental = striped)
AcrossGend8
WithinFem8
WithinMal8
Percent Correct (%)
0
20
40
60
80
100
RE:CI & LE:HA
RE:CI
LE:HA
RE:CI+HA & LE:HA
RE:CI+HA
RE:CI & LE:HA
RE:CI
LE:HA
RE:CI+HA & LE:HA
RE:CI+HA
Ear:Device Condition

Figure 19. Graph showing results for the talker discrimination task. Chance scores are shown as horizontal lines and fall between 34% and 66%.

Discussion

The primary aim of this study was to determine the benefits and possible detriments of combining electric and bilateral acoustic hearing in a pediatric recipient with preserved low frequency hearing. The results from this study indicate that there was no significant decrements seen for the traditional speech and localization measures when performing in both EAS conditions. This suggests that the subject was able to integrate the additional acoustic information provided by the ITE hearing aid in the same ear as the CI. The CNC in Quiet test revealed a bimodal effect for both the traditional bimodal and EAS bimodal conditions. Scores from the CNC in Noise test indicated similar results when comparing CI only scores to CI EAS scores. Comparable results could also be found between the traditional bimodal and EAS bimodal scores. These conditions also showed a drop in the percentage of correctly repeated words between Baseline 1 and 2 and Treatment 1 and 2. In order to help explain these results it is important to note that the subject had more difficulty maintaining attention for the CNC in Noise test; in general, her behavior was more unreliable.

Performance on the BKB-SIN task revealed an improvement in scores for the CI only condition as well as the CI EAS condition over time. Optimal performance was seen for the traditional bimodal and EAS bimodal conditions. Additionally, there appeared to be an advantage for the CI EAS condition compared to the CI alone condition for this measure. With regards to the CNC in Noise test, listening to single words in noise would be expected to be more difficult than listening to sentences in noise, given that the listener can not benefit from the contextual information in the sentence. However, due to this additional information, the BKB-SIN might be a better indicator of how well the subject can listen in everyday situations. Scores from the speaker localization test revealed optimal scores for the traditional bimodal and EAS bimodal conditions.

In general, improvements could be seen across the test battery, excluding the talker discrimination task This could be attributed to both learning effects and possible improvements with the CI given that the participant is in her first year post-implantation. This is of importance because it demonstrates that not only is her performance not deteriorating with the addition of EAS, but it also exhibits continued learning with both types of stimulation.

Anecdotal evidence in support of EAS was reported throughout the test period. The subject reported her preference for listening with EAS bimodal stimulation compared to traditional bimodal stimulation in everyday situations. The subject was also very enthusiastic about returning to the EAS bimodal condition after periods of being in the Baseline conditions. During the time period between Treatment 1 and Baseline 2, the subject reported difficulties understanding with her CI in the presence of background noise. At the completion of the study, the subject was given the choice to return to listening with traditional bimodal stimulation or continue the use of bimodal EAS. The participant emphatically chose to continue listening in the bimodal EAS condition.

The secondary aim of this study was to examine the efficacy of various cochlear implant mapping and hearing aid fitting strategies in relation to EAS benefits. The decision was made to create a speech processor map which did not overlap with the acoustic information provided by the ITE hearing aid. This was based on results from test scores comparing overlapping and non-overlapping maps, teacher and subject reports, and information found in the literature (Fraysse, et al., 2006; Vermeire et al., 2008). Results for the talker discrimination task indicated using an overlapping map may provide a redundancy in low frequency information which may improve speech understanding abilities. Results from that task indicated optimal performance for Baseline 1 and Baseline 2 in the traditional bimodal and CI only conditions with both utilized a map with the full frequency range. It was originally hypothesized that the participant would perform optimally in the conditions where low frequency acoustic cues were being provided; however, this was not the case. Due to the fact that the subject was able to integrate both acoustic amplification and electric stimulation within the same ear, it is possible that the additional information provided by an overlapping map may benefit the subject. It would be of interest to determine the effects of using an overlapping map under EAS conditions in a future study.

There were limitations to this study which resulted from the nature of the research design. No statistical analysis was able to be made given the single subject design. Although learning effects could be seen with the addition of EAS, it is unclear whether these results were statistically significant.

<u>Areas for Future Research</u>

At the time this study was performed, the Food and Drug Administration was in the process of approving a new device by Med-El Corporation for the use of EAS called the Duet®. This device has acoustic amplification characteristics built into the speech processor of the CI. This is beneficial due to the increased synchronization between the acoustic and electric signals as well as better microphone placement. Initial experiments produced by the manufacturer have shown improvements in speech perception understanding when comparing results using the Duet® to combining a CI and hearing aid at the same ear (Med-El Corporation, 2007). It would be of interest to determine any additional benefits that the current subject would obtain from the Duet® compared to the current EAS device configuration.

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