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Spectral resolution and speech understanding in children and young adults with bimodal devices

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SPECTRAL RESOLUTION AND SPEECH UNDERSTANDING IN CHILDREN AND YOUNG ADULTS WITH BIMODAL DEVICES

by

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Abstract: Tests of spectral modulation detection and speech understanding were administered to children and young adults with hearing loss who use bimodal devices (one cochlear implant and one hearing aid at the non-implanted ear). Spectral modulation detection performance increases with participant's age, and better speech recognition scores are associated with better audibility (SII or PTA).

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Abbreviations

BKB-SIN	Bamford-Kowal-Bench Speech-in-Noise Test
CI	Cochlear Implant
CID	Central Institute for the Deaf
CNC	Consonant Nucleus Consonant Words
dB	Decibel
DSL	Desired Sensation Level
FM	Frequency Modulation
HA	Hearing Aid
Hz	Hertz
HRPO	Human Research Protection Office
NIDCD	National Institute on Deafness and Other Communication Disorders
PTA	Pure-tone average
SD	Standard Deviation
SII	Speech Intelligibility Index
SLCH	St. Louis Children's Hospital
SLM	Sound Level Meter
SMD	Spectral Modulation Detection
SNHL	Sensorineural Hearing Loss
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
SREM	Simulated Real-Ear Measures
STM	Spectrotemporal Modulation

Introduction

Understanding and communicating through speech can be difficult for those with severe to profound hearing loss. These skills are usually diminished because of poor audibility and decreased speech clarity (Bernstein et al., 2013), but may have the ability to recover somewhat with the use of high-power hearing aids (HAs) or cochlear implants (CIs). While some individuals benefit from high-power HAs, audibility is generally restricted due to the severity of the loss combined with limitations in gain and output of the HA. In addition, hearing aids rarely restore speech clarity for profound losses, even when the output signal is made loud enough (Bernstein et al., 2013). When HAs are no longer a viable option for assisting with listening and speech understanding, CIs may be recommended. A CI can help restore audibility by sending an electrical signal directly to the auditory nerve, and can help with speech clarity following appropriate programming of the devices and aural rehabilitation or habilitation (National Institute on Deafness and Other Communication Disorders [NIDCD], 2011). However, the spectral information reaching the auditory nerve through a CI is limited and cannot necessarily compare to the natural hearing of those with normal hearing sensitivity (Henry, Turner, & Behrens, 2005).

One way that audiologists measure patient benefit from CIs is by performing speech perception testing in quiet and in noise. During these speech tests, the patient listens to words, sentences, or other speech sounds and is asked to repeat what he or she heard. Curiously, speech recognition ability tends to vary among individual CI users, and can even vary between two ears on bilateral CI users. This variability can be due to length of deafness or length of HA use prior to implantation, to name a few possible causes (Henry & Turner, 2003; Jung et al., 2012; Jones, Won, Drennan, & Rubinstein, 2013). According to some however, not all of the variability in

speech perception abilities in these individuals is fully explained or predicted by these factors (Litvak, Spahr, Saoji, & Fridman, 2007).

When people with normal hearing listen to speech, they can distinguish subtle differences in the spectral shape, or envelope, of each speech sound, which is critical for putting together words and meaning aurally. This discrimination ability comes from the sharp frequency tuning of the normal human auditory system; however, for individuals with sensorineural hearing loss (SNHL), frequency-tuning ability tends to be diminished (Henry et al., 2005). This can cause the spectral cues of speech sounds to blend together, thus decreasing speech clarity.

Recent research suggests that CI users' performance on spectral modulation detection (SMD) and spectral ripple tasks correlates with their speech recognition performance (Henry & Turner, 2003; Henry et al., 2005; Saoji, Litvak, Spahr, & Eddins, 2009; Spahr, Saoji, Litvak, & Dorman, 2011; Anderson, Oxenham, Nelson, & Nelson, 2012). During spectral ripple tasks, participants are asked to discriminate between a broadband noise that is modulated (rippled) in the frequency domain and another such rippled broadband noise with a phase-reversed spectral shape. The spectral ripple discrimination threshold is the highest modulation rate or modulation frequency, measured in cycles/octave, at which the participant can perceive a difference between the rippled noise and its phase-reversed counterpart when the modulation depth remains constant. In an SMD test, threshold is the smallest modulation depth at which the participant can perceive a difference between a noise modulated in the spectral domain and one with no modulation at all, when the modulation rate remains constant (Litvak et al., 2007). Because these two types of spectral discrimination tasks (ripple and modulation detection) and speech understanding rely so heavily on spectral resolution abilities, it is logical to assume that spectral performance abilities and speech recognition scores would be related. The mechanism

underlying this relationship in CI users has been debated. However, recent data (Jones et al., 2013) demonstrate a strong relation between a listener's CI electrode interaction indices and his or her spectral discrimination abilities (as measures by ripple or SMD tasks). Interaction indices were calculated using measured thresholds at which participants detected a test pulse train, either in the presence of a pulse train with the same polarity or with opposite polarity on a nearby electrode. This calculation determined how much interaction existed among pairs of internal CI electrodes, and acted as a direct method of measuring spectral resolution with CI users.

Henry and Turner (2003) were among the first to examine the relationship between spectral resolution, measured by ripple thresholds, and speech perception for individuals with hearing loss, with a particular interest in exploring this relation for electrical hearing through a CI. The participants were eight individuals with normal hearing and twenty-one CI users. Spectral resolution was tested with a spectral ripple paradigm using a four-alternative forced-choice adaptive method, and speech perception was tested in quiet with a vowel identification task. Participants with normal hearing performed the spectral ripple task with a CI simulation, and with an increase in channels in the CI simulation came an increase in spectral resolution abilities. For the CI users, with the number of channels controlled via a research speech-processor, similar improvements with an increasing number of channels was not observed. The results showed that CI users performed more poorly on the test of spectral resolution than did the participants with normal hearing. The results also demonstrated a significant correlation between spectral resolution abilities and speech perception for the CI users. In a similar study, Henry et al. (2005) found that CI users performed more poorly than individuals with normal hearing or with hearing loss on spectral ripple tasks. The investigators also saw a significant correlation between spectral resolution and perception of consonants and vowels for each group of listeners.

The results from both studies indicated a need to develop CI technology to improve the user's ability to resolve spectral differences.

In an effort to learn more about the effects of spectral resolution on speech understanding when listening through a CI, Litvak et al. (2007) created vocoder simulations meant to mimic CI sound processing and neural excitation. Ten young adults with normal hearing participated and completed SMD, vowel identification, and consonant identification tasks with and without vocoder simulation. SMD thresholds were obtained using a two-alternative forced-choice method at spectral modulation frequencies of 0.25 and 0.5 cycles/octave. Litvak et al. (2007) found that their normal hearing participants' average SMD thresholds and speech scores became poorer with the electrode-current-spread parameter in the vocoder simulations, and that the variability among these normal hearing participants compared somewhat to the variability among CI users from an earlier study (Saoji, Litvak, Emadi, & Spahr, 2005). This suggested that neural excitation and spread, whether in a CI user or in a vocoder simulation, influences spectral sensitivity. This spectral-sensitivity variability was also thought to be a main contributor to the variability found in the speech understanding abilities of individuals who use CIs.

Saoji et al. (2009) expanded upon the research done by Litvak et al. (2007) by experimenting with a range of spectral modulation frequencies during SMD testing of the CI participants employed in the previous study (Litvak et al., 2007). Saoji et al. (2009) hypothesized that SMD threshold would have a greater likelihood of being correlated with speech perception scores at higher than lower spectral modulation frequencies. This postulation, based on the idea that speech perception requires the ability to resolve precise spectral details, was not supported by the results. The investigators instead found that thresholds at low modulation frequencies of 0.25 and 0.5 cycles/octave were better predictors of vowel and consonant recognition in quiet

than were thresholds at higher modulation frequencies of 1 and 2 cycles/octave. These results suggested that the CI users depended more on detection of a spectral envelope than fine spectral details, and that envelope detection was related to their detection of speech segments.

Spahr et al. (2011) further investigated the effects of diminished spectral resolution with eleven adult CI users. The investigators intended to learn more about the nature of spectral resolution's effect on speech perception in quiet and noise by changing the noise spectrum in various ways during an SMD task. All SMD tasks required participants to choose the noise that differed from a reference noise in a two-alternative forced-choice adaptive paradigm. However, the target noises of each SMD task varied in terms of spectral modulation frequency and bandwidth of the SMD noise stimuli (1 or 4 octaves). The obtained thresholds were analyzed against scores on a sentence test performed in quiet and with background noise. Spahr et al. (2011) discovered that their CI-user participants' speech scores in quiet were best predicted by the SMD thresholds at modulation frequencies of 0.5 and 1 cycle/octave using the narrowband (1 octave wide) noise, whereas speech scores in noise were best predicted by the SMD thresholds at modulation frequencies of 0.25 and 0.5 cycles/octave using the broadband (4 octave wide) noise. The investigators noted that their small sample size (N=11) might have produced erroneous results, but also maintained that the mechanisms involved in speech understanding in quiet and noise seem to differ.

Anderson et al. (2012) examined adult CI users' performance on spectral ripple, SMD, and speech-related tasks. These investigators hoped to replicate the results found by Litvak et al. (2007) and Saoji et al. (2009) by finding a relationship between spectral resolution and speech perception. Anderson et al. (2012) used the same type of noise stimuli as were utilized by Litvak et al. (2007) and found thresholds for both ripple and SMD tasks for the same group of CI users,

using a three-alternative forced-choice adaptive method. Seven thresholds were found per participant for each of seven modulation rates. Anderson et al. (2012) found that a greater modulation depth (peak-to-valley ratio) was generally needed for higher spectral-ripple frequencies, suggesting that low ripple rate noises were the easiest to identify. The investigators also found a relationship between SMD performance and vowel and sentence recognition abilities, which were measured in a previous study (Anderson, Nelson, Kreft, Nelson, & Oxenham, 2011). Significant correlations were seen between low ripple rate SMD thresholds and both speech measures in quiet, but correlations only approached significance in the presence of background noise. The lack of an observable relationship between the two tasks at higher ripple rates was consistent with previous research (Litvak et al., 2007; Saoji et al., 2009). In addition, the lack of a significant finding with regard to speech in noise performance suggests that spectral resolving powers needed for understanding speech in quiet and in noise are different, as indicated by Spahr et al. (2011).

Similar research by Won, Drennan, and Rubinstein (2007) also indicated a relationship between spectral resolution ability and speech perception in quiet and noise. Spectral ripple thresholds were significantly correlated with both speech reception thresholds in noise and word recognition scores in quiet for a group of CI users. This result differed somewhat from results obtained by Spahr et al. (2012) and Anderson et al. (2013) in that speech scores in quiet and noise were both correlated with the same measure of spectral resolution.

The majority of studies regarding spectral resolution and speech perception for CI users have been performed with adults. Jung et al. (2012) endeavored to study this relationship in children to better understand this population's varied outcomes with speech understanding. A group of eleven 8- to 16-year-old children with CIs were administered a spectral ripple

discrimination test using a three-alternative forced-choice adaptive method. The children's speech perception abilities were also assessed with a consonant-nucleus-consonant (CNC) word test in quiet and a spondee word test in noise. Additionally, the children were given tests of music perception and phase discrimination, two tasks that involve the use of temporal discrimination. Jung et al. (2012) discovered a correlation between spectral resolution and speech perception for these children; this result is consistent with results previously reported for adults (Henry & Turner, 2003; Henry et al., 2005; Saoji et al., 2009; Spahr et al., 2011; Anderson et al., 2012). Jung et al. (2012) also found that their child participants performed similarly to a group of adult CI users on spectral and speech tasks, but performed more poorly on the temporal tasks. The investigators attributed this difference to a lack of complete temporal development in the children, and stated that their spectral resolution abilities were a better predictor of speech performance.

Another study looking at the effects of spectral resolution abilities in children was conducted by Rakita (2012) with twenty children aged 7 to 17 years. All children had hearing within the normal range and completed tests of SMD and sentence understanding in noise. Both the SMD and speech stimuli were processed to simulate listening through a CI, and each test was administered with and without the CI-simulation processing. The results demonstrated a significant correlation between the processed SMD and speech scores; this was consistent with results from previous studies with CI users and normal hearing listeners with CI simulation (Litvak et al., 2007; Won et al., 2007; Saoji et al., 2009; Spahr et al., 2011). The investigator also discovered a significant effect of participant age on SMD performance in the processed and unprocessed conditions, as well as on speech understanding in the unprocessed condition.

In some cases a person with hearing loss may use a CI only at one ear and use a HA at the other ear. A person with this combination of devices, a bimodal user, typically has some usable hearing at the HA ear. The level of hearing may not be enough to understand speech on its own, but may provide the listener with a bimodal advantage when both devices are used together. That is, the listener may be able to combine the natural acoustic signal from the HA with the electrical signal from the CI in a way that is beneficial for speech understanding (Zhang, Spahr, Dorman, & Saoji, 2013). For a group of adult bimodal device users, Zhang et al. (2013) found a relationship between bimodal benefit on speech perception in quiet and in noise, and three different HA-ear measures: low-frequency audiometric threshold, aided speech perception ability, and aided SMD threshold. Test words in quiet and sentences in background noise were used to assess speech perception ability, and SMD thresholds were evaluated using a two-alternative forced-choice method at a spectral modulation frequency of 1 cycle/octave. The researchers discovered that acoustic SMD threshold was the best predictor of bimodal benefit in terms of speech understanding. Unlike audiometric thresholds, acoustic (HA-only) SMD threshold also accounted for much of the variance seen in the speech understanding scores of individuals with similar levels of hearing loss. With their research, Zhang et al. (2013) hoped to shed light on a new way to predict levels of bimodal benefit by assessing spectral resolution performance with acoustic hearing.

An investigation by Golub, Won, Drennan, Worman, and Rubinstein (2012) studied users of hybrid CIs to examine the benefits of having both electric and acoustic hearing in a single ear. Hybrid CIs, devices that stimulate the high-frequency basal area of the cochlea and preserve the low-frequency apical area, are beneficial to individuals with severe to profound high-frequency hearing losses and usable low-frequency hearing. These investigators noted the benefits of

electroacoustic hearing, such as improved speech perception in noise, and hoped to demonstrate that this was due to the spectral resolution allowed by the low-frequency acoustic hearing. Golub et al. (2012) used a three-alternative forced-choice adaptive method to find five hybrid users' spectral ripple thresholds, and tested speech perception by having the participants repeat spondees in the presence of background noise. Their results showed that the hybrid CI users performed better on spectral ripple tasks than a group of typical CI users. They also found no significant difference between hybrid CI users' spectral ripple performance with electroacoustic hearing and with acoustic hearing alone. This suggests that a large portion of spectral resolution ability comes from natural acoustic hearing. These investigators also found a difference between speech-in-noise performance of the hybrid CI and typical CI groups that approached significance.

Because two people with the same hearing loss rarely have the same speech understanding difficulties, Bernstein et al. (2013) attempted to find a better predictor of the speech understanding abilities of those with hearing loss than the Speech Intelligibility Index (SII), a calculated number that is based solely on an individual's audiogram (American National Standards Institute [ANSI], 1997). These investigators used spectrotemporal modulation (STM) detection ability in conjunction with the participants' audiograms for this purpose. The altered broadband noises were modulated in both the spectral and the temporal domains, and a two-alternative forced-choice adaptive procedure was utilized to determine STM sensitivity thresholds. Results from participants with hearing loss were compared to their speech perception scores reported previously (Summers, Makashay, Theodoroff, & Leek, 2013) and to results from a group of participants with normal hearing. The sentences used for the speech test were presented in noise at 92 dB SPL in order to decrease the effects of audibility. In their analysis,

Bernstein et al. (2013) discovered that STM sensitivity, when added to the predictive ability of the SII, accounted for an added 41.3% of the variance in speech understanding.

All of the aforementioned studies have found relationships between spectral resolution and speech perception, which could have implications for patients in the audiology clinic. Using such tests could help clinicians estimate a patient's greatest potential benefit from HAs (Bernstein et al., 2013), and be useful for determining which processing strategies to use for patients with CIs (Henry & Turner, 2003; Won et al., 2007). For bimodal users, this test may be a good way to determine the utility of their acoustic hearing in bimodal speech understanding, or to determine who may or may not benefit more from a second CI (Golub et al., 2012; Zhang et al., 2013). Finally, tests of spectral resolution could be useful tools for the pediatric audiology clinic. The ability to perform these tests, compared to the ability to perform speech tests, is less likely to be influenced by factors such as age, cognitive ability, and primary language used in the home. The fact that tests of spectral resolution are non-linguistic suggests that they would be a good option for use with children (Rakita, 2012; Bernstein et al., 2013). In addition to helping clinicians make more informed decisions about their pediatric patients with hearing loss, these tests could also be more time-efficient than tests of speech perception (Henry & Turner, 2003).

The purpose of the present study is to examine the relationship between spectral resolution and speech understanding in children and young adults with hearing loss, specifically those who use bimodal devices. If a correlation exists, then SMD threshold could be a useful non-linguistic predictor of speech understanding in this population. Learning more about this relationship may help audiologists make more informed decisions regarding device recommendations for their pediatric patients. Drennan, Anderson, Won, and Rubinstein (2014) recently tested a "clinical" version of a spectral ripple test with twenty-eight adult CI users. This

version used similar stimuli to that used by Won, et al. (2007), but presented it with a method of constant stimuli rather than an adaptive method, the latter of which has been used almost exclusively in this line of research. Drennan et al. (2014) found that results from using this method were not significantly different from results obtained using the more traditional (and more time-consuming) method on the same group of participants. The investigators also found that a relationship between the new clinical test and the participants' speech perception scores, as expected. Previously, Won, Clinnard, Kwon, and Drennan (2011) tested spectral ripple sensitivity in CI users with a method of constant stimuli and found similar results. In this Capstone study, a method of constant stimuli is also used, although the stimuli vary in modulation depth and not modulation rate. The stimuli and presentation method are the same as those used by Rakita (2012). It was hypothesized that a significant correlation would be found between the SMD threshold and speech understanding.

A secondary goal is to explore changes in spectral resolution abilities that may occur as a function of age. Rakita (2012) determined that a relationship between age and SMD score did exist in children with normal hearing, both in the CI-simulation condition and the unprocessed stimuli condition. It is important to know whether age has an effect on the SMD threshold in children with hearing loss so that appropriate conclusions can be made about the results of this test for each pediatric patient. It is expected that performance on SMD tasks will improve with the age of the participant. This study was approved by the Washington University School of Medicine Human Research Protection Office (HRPO).

Methods

Participants

Inclusion criteria were:

1) Participants between the ages of 7 years, 0 months and 21 years, 11 months
2) Individual's hearing loss identified before 4 years of age
3) Consistent use of a HA and/or CI since identification of the individual's hearing loss
4) Experience with a CI for 9 months or longer

Children and young adults with significant developmental diagnoses and those who did not fit the inclusion criteria were excluded from the study. Participants were compensated for taking part in the study.

Eight participants (four male, four female) were recruited from Central Institute for the Deaf (CID) in St. Louis and St. Louis Children's Hospital (SLCH) and consented or assented to participation in the study. All participants were bimodal device users and fit the inclusion criteria. The participants ranged from 8.9 to 19.0 years of age (mean: 13.3 years; SD: 3.8) at the time of testing. Demographic data for the participants are shown in Table 1.

Procedure

One test of spectral resolution and two tests of speech understanding were administered. Measures included the Consonant-Nucleus-Consonant (CNC) word test (Peterson & Lehiste, 1962), an SMD test, and the Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) sentence test (Bench, Kowal, & Bamford, 1979; Etymōtic Research, 2005), completed in this order. Each test was completed in three conditions: bimodal, CI-only, and HA-only. Testing was completed within a total of 1.5 to 2 hours for participants who had not had any of these tests done clinically. Some families requested to have the testing done in multiple sessions. For those who had completed some of these tests clinically within six months of participating in the study, those particular tests were not repeated. Results of prior tests were obtained from audiological patient records. For testing completed during the study, test list choice and condition order were

randomized using FreeMat software. Tests were performed in sound booths in the audiology departments at CID and SLCH.

Audiometry. Aided detection thresholds were obtained for participants at the HA ear and the CI ear in order to ensure audibility consistent with proper functioning of each device. Frequency-modulated (FM) tones were presented in the sound field at octave frequencies between 250 and 4000 Hz and at the inter-octave frequency 6000 Hz, as well as at 3000 Hz if the difference between thresholds at 2000 and 4000 Hz was equal to or greater than 20 dB. The participant was seated roughly one meter from the speaker and was asked to respond by raising a hand whenever the tone was heard. Step sizes of 5 dB were used with the modified Hughson-Westlake procedure. Previous unaided audiograms were obtained from the participants' audiologic charts.

Electroacoustic measures. Prior to the study, each participant's HA had been programmed by his or her regular clinician to approximate Desired Sensation Level (DSL v 5.0 [Scollie et al., 2005]) targets across a frequency range of 250 Hz to 6000 Hz. During the study, each HA's output was verified using simulated real-ear measures (SREM) and real-ear-to-coupler-differences (RECDs) when available in the participants' audiologic records. The fitting tool Speechmap was used to measure the HA output levels with soft (50 dB SPL), medium (60 dB SPL), and loud (70-75 dB SPL) inputs. The stimulus utilized was calibrated speech of a male talker, one of the stimuli available in the Speechmap environment (Audioscan, 2012). Electroacoustic measures were completed using an Audioscan Verifit system, and measurements were completed within one month of study enrollment. This verified optimal programming and functioning of each HA. Output Speech Intelligibility Index (SII) at 50 and 60 dB were each calculated automatically during SREM. SII measurements are used to estimate audibility of

different levels of speech, and are sometimes used to predict speech understanding performance (Audioscan, 2012).

CNC word test. Recorded lists were used for CNC testing. All ten CNC lists of 50 words were available for use, and each participant completed one distinct list for each of the three conditions. Words were presented in the sound field at 50 dB SPL with the participant seated roughly one meter from the speaker. The reason for using this soft presentation level was to avoid any ceiling effects in CNC scores. Participants were asked to repeat the recorded words and were encouraged to guess if uncertain. Tests were scored by the percent of words repeated correctly. If a participant was unable to correctly identify the first ten words of a list, the test for that condition was discontinued and the participant received a score of 0%.

SMD test. Spectrally modulated noise recordings were obtained from colleagues at Arizona State University (A. Spahr, personal communication), similar to those used by Eddins and Bero (2007) in a study with normal hearing listeners. These stimuli are the same as those used by Rakita (2012). The stimuli were created by modifying a four-octave wide (~300-5600 Hz) white noise with the application of a desired spectral modulation depth and frequency, and with a random starting phase in the spectral modulayion. Inverse Fourier transform of the noise spectrum produced a waveform with a specified spectral shape, with spectral modulation frequencies of 0.5 or 1.0 cycles/octave and modulation depths of 10, 11, 13, 14, or 16 dB. Reference stimuli, four-octave-wide noises with no spectral modulation, were also provided. Each stimulus was 350 ms in length.

Four sequences of SMD trials were provided. Three of the four SMD sequences were used for testing, and the fourth was used to briefly familiarize the participant with the task. Each sequence was composed of sixty trials, with each trial consisting of three broadband noises (two

reference and one modulated in the spectral domain). The modulated stimulus was randomly placed in the first, second, or third interval of the trial. Each spectral modulation depth was presented ten times per sequence, each spectral modulation frequency presented thirty times, and each depth and frequency combination presented five times. The task represents the method of constant stimuli; thus, each sequence (or list) included the same stimuli presented in different random orders. Lists were presented in the sound field at 65 dB SPL with the participant seated roughly one meter from the speaker. The lists were played from an Apple computer with the program Audacity (Ash, Chinen, Crook, & Ijbulatov, 2010) and routed through a GSI-61 audiometer to a speaker inside a treated sound booth. Sound level of the stimulus was set using the calibration tone for the stimuli and a sound level meter (SLM, A-weighted, fast setting).

After as many as five practice trials, participants began the three-alternative forced-choice task, during which they were asked to select the noise in each trial that sounded "different" by stating their choice or pointing to a sheet labeled "1, 2, 3" (or 1st, 2nd, or 3rd). Participants were encouraged to guess if uncertain. A score of 44% was calculated as the minimum value at which one could have 95% confidence that the participant was performing above the chance level. Tests were scored by calculating the percent correct and the number of errors made for each modulation frequency.

BKB-SIN sentence test. Recorded lists were used for BKB-SIN testing. Only list pairs 9-18, which have been recommended for CI users, were utilized. Each list within a list pair contained eight sentences with three to four keywords per sentence. Sentences and background noise were presented from the same speaker (0° azimuth) in the sound field at 65 dB SPL with the participant seated roughly one meter from the speaker. Sentences were presented with an increasing level of multi-talker babble, starting with a +21 dB signal-to-noise ratio (SNR). For

each consecutive sentence, the SNR decreased by 3 dB. Participants were asked to repeat each sentence to the best of their abilities, and encouraged to guess if uncertain. Tests were scored by calculating the average SNR-50 (SNR for 50% accuracy) for each list pair (BKB-SIN User Manual). If a participant was unable to correctly identify any of the keywords from the first two sentences of any list, testing of that list was discontinued and the participant received an SNR-50 score of 23.5. Lower scores indicate better performance. Each participant completed two list pairs for each of the three listening conditions. The scores from the two list pairs were averaged for data analysis.

Results

All participant data was collected during the study's testing period or was obtained within six months of the test date by the participants' regular clinicians, except for HJB01. Subject HJB01 was scheduled to receive a second CI shortly after enrollment in the study and did not have sufficient time to complete the speech tests. Thus, this participant's CNC scores at 50 dB SPL were obtained outside of six months, but within one year, of study participation. Unfortunately, no prior CNC score at 50 dB SPL in the HA-only condition was available. In addition, electroacoustic measures for the HA of HJB01 were obtained outside one month, but within six months. Another participant, HJB05, misplaced his HA following testing and was not able to have electroacoustic measures conducted at that time. However, electroacoustic measurements from within six months were used for analysis.

Unaided and Aided Audiometric Results

Pure-tone averages (PTAs) for each ear in unaided and aided conditions were calculated by averaging audiometric thresholds at frequencies of 500 Hz, 1000 Hz, and 2000 Hz. In cases where no response was obtained, the threshold was recorded as 120 dB HL, which is beyond the

limits of the equipment. Unaided PTAs for the CI ear ranged from 98.3 dB HL to 120 dB HL (mean: 112.3, SD: 8.4). Unaided PTAs for the HA ear ranged from 63.3 dB HL to 93.3 dB HL (mean: 86.5, SD: 10.5). Aided PTAs for the CI ear ranged from 20.0 dB HL to 30.0 dB HL (mean: 24.8 SD: 4.2). Aided PTAs for the HA ear ranged from 20.0 dB HL to 40.0 dB HL (mean: 33.3, SD: 6.2). Aided low-frequency PTAs were also calculated by averaging audiometric thresholds obtained at 250 Hz, 500 Hz, and 1000 Hz. Aided low-frequency PTAs for the CI ear ranged from 16.7 dB HL to 28.3 dB HL (mean: 24.0, SD: 4.7). Aided low-frequency PTAs for the HA ranged from 20.0 dB HL to 33.3 dB HL (mean: 30.2, SD: 5.0). Unaided and aided audiometric thresholds for the participants are shown in Figures 1-4.

Bimodal Benefits for SMD and Speech Perception

CNC scores for the participants ranged from 18% to 72% correct (mean: 40.8, SD: 19.9) in the CI-only condition, 0% to 50% correct (mean: 20.3, SD: 17.9) in the HA-only condition, and 30% to 78% correct (mean: 52.0, SD: 17.3) in the bimodal condition. Bimodal speech perception benefit was calculated by subtracting each participant's best single-ear score (either HA-only or CI-only) from the bimodal score of the test. For the CNC test, benefit values ranged from -4.0 to 28.0 percentage points (mean: 7.0, SD: 10.5), indicating a trend toward improvement in the bimodal condition. Averages of each participant's BKB-SIN SNR-50 scores from two list pairs ranged from 4.8 dB to 22.8 dB (mean: 11.5, SD: 6.3) in the CI-only condition, 4.8 dB to 23.0 dB (mean: 15.9, SD: 6.3) in the HA-only condition, and 3.3 dB to 15.5 dB (mean: 7.9, SD: 4.7) in the bimodal condition. Bimodal benefit values ranged from -2.5 dB to 1.5 dB (mean: -0.7, SD: 1.3), indicating that SNR-50 scores changed very little in the bimodal condition. SMD scores ranged from 32% to 88% correct (mean: 61.0, SD: 22.2) in the CI-only condition, 35% to 95% correct (mean: 55.0, SD: 22.4) in the HA-only condition, and 30% to

90% correct (mean: 65.9, SD: 23.2) in the bimodal condition. Bimodal benefit values ranged from -25 to 5 percentage points (mean: -4.6, SD: 9.6), indicating that the participants tended to perform more poorly with both devices than with their best single-ear device alone. Scores for the participants can be viewed in Figures 5-7.

Effect of Age

The effect of age on performance for the various tests completed was calculated to address the study's second hypothesis. Data analysis revealed a significant correlation between participant age and SMD percent correct performance in the CI-only condition (r=0.81, p=0.02). A significant negative correlation was also seen in this CI-only condition between age and number of errors made with the 0.5 cycles/octave SMD stimuli (r=-0.84, p=0.009). A negative trend was observed between age and errors made with the 1.0 cycles/octave stimuli in the CI-only condition, but this was not significant (r=-0.66, p=0.08). All other correlations between participants' performance (speech or SMD) and age were not significant (see Figures 8-12). A comparison of the SMD performance by children with normal hearing in the study by Rakita (2012) and in the CI-only condition in the present study is displayed in Figure 9.

A two-tailed unpaired t-test was performed to determine whether or not any significant differences existed between the ages of the participants in the current study and the study performed by Rakita (2012). This analysis revealed the two groups to be statistically similar in age (p=0.59).

Relation between Spectral Resolution (SMD) and Speech Perception

Analysis of data regarding a relation between spectral resolution and speech perception in the bimodal participants revealed one significant correlation between SMD performance and speech performance. This correlation was between number of errors made with the 1.0

cycles/octave stimuli in the HA-only condition and SNR-50 value in the CI-only condition (r=-0.72, p=0.04). This relationship was unexpected due to the measurements being from two different ears. It is possible that, since no other correlations were seen between these variables in the other conditions, this relationship occurred coincidentally.

Relation between SII/PTA and Speech Perception

The effect of audibility, determined with measurements of aided audiometric thresholds from each device and SII calculations from the HA ear, was examined with regard to measurements of speech perception. Aided HA-ear PTA and SII at 50 dB SPL (r=-0.95, p=0.0004) and aided HA-ear PTA and SII at 60 dB SPL (r=-0.87, p=0.005) were highly correlated, suggesting that SII and aided PTA represent roughly equivalent measures of audibility. Analysis of aided PTA revealed a significant positive correlation between aided PTA at the HA ear and SNR-50 for that ear (r=0.77, p=0.02). This correlation indicates that higher (poorer) thresholds were related to higher (poorer) SNR-50 values on the BKB-SIN test. A correlation was also seen between aided PTA at the HA ear and CNC score for that ear (r=-0.70, p=0.052); that is, the lower (better) the aided PTA, the higher the CNC score. This correlation approached significance. The data for PTA are displayed in Figures 13-14.

Analysis of SII from the HA ear also revealed some trends. Significant negative correlations were found between SII at 50 dB SPL and SNR-50 at the HA ear (r =-0.77, p=0.02), as well as between SII at 60 dB SPL and SNR-50 at the HA ear (r=-0.77, p=0.02), indicating that performance on the BKB-SIN test increased with increased audibility in that condition. Relationships that approached significance were also seen between SII at 50 dB SPL and CNC score at the HA ear (r=0.72, p=0.07), and between SII at 60 dB SPL and CNC score at the HA

ear (r=0.71, p=0.07), possibly indicating that performance on the CNC test with the HA increased with increased audibility. The data for SII are displayed in Figures 15-20.

Two significant correlations were seen between SII at 50 dB SPL and bimodal benefit on the CNC test (r=0.73, p=0.04) and between SII at 60 dB SPL and bimodal benefit on the CNC test (r= 0.73, p=0.04). Correlations that approached significance were also seen between aided PTA at the HA ear and bimodal benefit on the CNC test (r=-0.66, p=0.08), and between aided low-frequency PTA at the HA ear and bimodal benefit on the CNC test (r=-0.65, p=0.08). These results indicate that an increase in audibility at the HA ear resulted in an increase in bimodal benefit for the CNC word test.

In the study by Zhang et al. (2013), investigators calculated "normalized acoustic benefit," a percentage value that determines how much bimodal benefit a person gets from the addition of a HA without the influence of ceiling effects. This is calculated by dividing the individual's actual improvement (from CI-only to bimodal) by his or her potential improvement on the task, or by his or her initial CI-only score in cases when bimodal performance decreases. Like the bimodal benefit correlations seen earlier, these "normalized acoustic benefit" values for the CNC test were significantly correlated with SII at 50 dB SPL at the HA ear (r=0.80, p=0.02), SII at 60 dB SPL at the HA ear (r=0.78, p=0.02), aided PTA at the HA ear (r=-0.76, p=0.03), and aided low-frequency PTA at the HA ear (r=-0.74, p=0.04). Data regarding bimodal benefit and normalized acoustic benefit are displayed in Figures 21-25.

Spectral Modulation Frequency

Errors associated with the 0.5 cycles/octave SMD stimuli were analyzed against the errors associated with the 1.0 cycles/octave SMD stimuli for each condition. A one-tailed paired

t-test detected a significant difference between the number of errors for the two stimuli in the bimodal condition (p=0.0003), but not for the other two listening conditions.

Discussion

Rakita (2012) noted that all of her normal hearing participants were able to complete the SMD task above chance level, even at 7 years of age. In the present study, some of these participants with hearing loss performed at chance (<44% correct) for at least one of the conditions. Participant HJB05, the youngest of the group, performed close to the chance level in all listening conditions. Whether this level of performance was due to age, attention, level of hearing loss, or the use of listening devices is unclear. Future research in this area may benefit from taking extra measures to ensure the task is understood and holds the participant's attention. Regardless, it is worth noting that the task was harder for some of these participants than for the participants in the Rakita (2012) study.

Rakita (2012) discovered significant correlations between age and unprocessed BKB-SIN performance, age and unprocessed SMD score, and age and CI-simulation SMD score. A trend between age and CI-simulation BKB-SIN performance that approached significance was also noted. In the Rakita (2012) study, this indicated that with increasing age came increasing performance on speech perception and SMD tasks. In the present study, significant correlations were seen between age and SMD performance (percent correct and errors made with the 0.5 cycles/octave stimuli) in the CI condition. A correlation approaching significance also demonstrated a trend toward decreasing errors with the 1.0 cycles/octave stimuli in the CI-only condition as age increased. These combined results indicate that children are able to perform better on SMD tasks as they grow older, whether they have hearing loss or not. Whether this is due to a better ability to understand the task or to a maturational process in the auditory system is

unknown. In the present study, no relationships were observed between age and SMD in the other listening conditions (HA-only or bimodal). Additionally, no significant relationships were observed between age and any of the speech measures. The results regarding the other two listening conditions (HA-only and bimodal) differ slightly from what was observed by Rakita (2012), despite the similarity of the two participant groups with regard to age. However, those subjects were not administered a HA-simulation or bimodal-simulation version of the SMD test, so a true comparison for these conditions cannot be made. To learn more about the mechanisms involved in SMD and speech processing, further spectral resolution research with young bimodal participants must be completed.

Surprisingly, the anticipated relationship between SMD abilities and speech perception performance was not seen in the data. The one correlation that was seen, between number of errors with the 1.0 cycle/octave stimuli in the HA-only condition and SNR-50 in the CI-only condition was not expected, seems illogical, and is inconsistent with other data. The results also did not support the postulation that SMD performance is correlated with bimodal benefit or normalized acoustic benefit. One would imagine that SMD, which has reportedly been associated with speech perception in the past (Saoji et al., 2009; Spahr et al., 2011; Zhang et al., 2013), would be able to help predict bimodal speech perception benefit, but that was not the case in this study. With more subjects, perhaps the expected relationship between SMD and speech perception would have been observed. To determine whether or not tests of spectral resolution can help predict bimodal children’s speech understanding, more studies with a greater number of bimodal participants need to be conducted.

The data regarding audibility as measured by aided PTA and SII at the HA ear all suggest that audibility is related to speech perception outcomes at that ear. SII measurements for the

participants with hearing loss in the Bernstein et al. (2013) study did account for some of the variance in speech perception scores, but not as much as with the addition of STM detection scores. That study did not report any effects of audibility, likely because the investigators attempted to reduce the effects of audibility by presenting the speech stimuli at a high level of 92 dB SPL. In the present study, audibility appeared to play a role in speech understanding. Although no correlations were seen among aided thresholds and speech perception scores in the CI-only or bimodal conditions, it may be beneficial for future studies to calculate SII in these listening conditions to determine whether or not this measurement can better help predict speech understanding in bimodal device users.

In this study, PTA and SII were also both related to bimodal benefit and normalized acoustic benefit on the CNC test. This seems to make sense because, as discussed earlier, better audibility at the HA ear was related to better speech perception outcomes. It follows that better HA-ear audibility would allow for greater speech perception benefit in the bimodal condition.

The significant difference between SMD errors at the two different spectral modulation frequencies (0.5 and 1.0 cycles/octave) in the bimodal condition suggests that the 0.5 cycles/octave stimuli were easier to distinguish than the 1.0 cycle/octave stimuli. Saoji et al. (2009) found that lower modulation frequency detection, such as for frequencies of 0.25 and 0.5 cycles/octave, was better correlated with speech perception scores than was higher modulation frequency detection. Similarly, Spahr et al. (2011) found that detection of low spectral modulation frequencies applied to a broadband noise was better correlated to speech in noise performance than was detection of higher spectral modulation frequencies. These combined data suggest that future studies of SMD with bimodal children may benefit from using low spectral modulation frequency stimuli to test their participants.

Conclusion

Conducting a study to analyze the relationship between spectral resolution and speech perception in bimodal children was important for several reasons. Firstly, if a relationship were discovered, using SMD or spectral ripple testing could be a useful way of determining which listening devices help patients with hearing loss most, or what programming changes need to be made to an individual's HA or CI. Secondly, previous studies in this realm of research have examined this relationship in CI users, but few have worked with a bimodal population. Oftentimes it is difficult to predict which of these users would benefit from a second CI and which do best with an added HA. Research with this population could assist hearing care professionals in making more appropriate recommendations with regard to amplification options. Thirdly, very few studies have examined spectral resolution performance in children and young adults. The discovery of a reliable, non-linguistic, time-efficient test to predict bimodal speech understanding in this age group would be invaluable to clinicians, especially considering that speech in this often difficult-to-test population can be delayed. This study's main hypothesis was that spectral resolution abilities and speech perception would be correlated, as seen in numerous other studies with adult CI users (Saoji et al., 2009; Spahr et al., 2011; Anderson et al., 2013). However, this was surprisingly not supported by the data. Rather, the data indicated an age effect on SMD performance with the CI alone, and a relationship between aided audibility and word understanding with the HA alone. In addition, measures of audibility were related to bimodal benefit on the CNC word test, whereas SMD performance was not.

Due to the small sample size of eight participants, the results must be interpreted cautiously. Perhaps with a greater number of participants a correlation would have been observed between SMD abilities and speech perception, or between SMD abilities and bimodal benefit.

However, it is worth noting the significant correlation observed between audibility measures and speech perception on the CNC score in the HA condition. This suggests that SII and PTA, tools that audiologists are already familiar with, can help predict speech performance in the clinic, at least in a HA-only condition. Fortunately, SII and PTA, like SMD, can be obtained quickly and without the use of speech or language. Future research focused on the young population of bimodal users should examine this relationship more closely, as well as the effects of age. Future studies should also attempt to include more participants to determine whether or not a relationship exists between spectral resolution and speech understanding in bimodal children, as it appears to in adults with hearing loss.

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Appendix A

Participant Performance of SMD Tasks

	CI			HA			Bimodal		
Subject ID	**SMD Percent Correct**	**Errors at 0.5 c/o**	**Errors at 1.0 c/o**	**SMD Percent Correct**	**Errors at 0.5 c/o**	**Errors at 1.0 c/o**	**SMD Percent Correct**	**Errors at 0.5 c/o**	**Errors at 1.0 c/o**
HJB01	45	17	16	35	18	21	50	12	18
HJB02	85	3	6	77	6	8	78	4	9
HJB03	73	8	8	37	20	18	78	5	8
HJB04	32	21	20	63	11	11	38	17	20
HJB05	38	22	15	35	24	15	30	20	22
HJB06	88	5	2	58	13	12	88	1	6
HJB07	50	15	15	95	0	3	90	1	5
HJB08	77	2	12	40	19	17	75	3	12

Performance on SMD is shown in percent correct scores, errors made with the 0.5 cycles/octave stimuli, and errors made with the 1.0 cycles/octave stimuli in each condition.

Participant Performance on Speech Perception Tests

	CI		HA		Bimodal	
Subject ID	**BKB-SIN SNR-50**	**CNC Percent Correct**	**BKB-SIN SNR-50**	**CNC Percent Correct**	**BKB-SIN SNR-50**	**CNC Percent Correct**
HJB01	5	58	18.3	N/A	4.3	58
HJB02	6.3	56	17.8	0	6.5	64
HJB03	4.8	72	13.0	32	3.3	68
HJB04	15.8	24	4.8	50	4.3	78
HJB05	14	20	23.0	0	15.5	30
HJB06	14.5	36	23.0	14	14.5	42
HJB07	22.8	18	10.3	26	8.3	38
HJB08	9.3	42	16.8	20	6.8	38

Performance is shown for each speech test in each condition. BKB-SIN SNR-50 scores represent an average of scores from two list pairs.

Appendix B

Correlations between SMD Performance and Non-Speech Measures (N=8)

	CI			HA			Bimodal		
	SMD Percent Correct	**Errors at 0.5 c/o**	**Errors at 1.0 c/o**	**SMD Percent Correct**	**Errors at 0.5 c/o**	**Errors at 1.0 c/o**	**SMD Percent Correct**	**Errors at 0.5 c/o**	**Errors at 1.0 c/o**
Age	***r*=0.81*** ***p*=0.02**	***r*=-0.84*** ***p*=0.009**	***r*=-0.66**† ***p*=0.08**	*r*=-0.11 *p*=0.79	*r*=0.52 *p*=0.90	*r*=0.18 *p*=0.67	*r*=0.59 *p*=0.12	*r*=0.05 *p*=0.90	*r*=-0.49 *p*=0.22
SII 50	*r*=-0.47 *p*=0.24	*r*=0.40 *p*=0.33	*r*=0.53 *p*=0.18	*r*=0.18 *p*=0.67	*r*=-0.12 *p*=0.77	*r*=-0.25 *p*=0.55	*r*=-0.42 *p*=0.30	*r*=0.45 *p*=0.26	*r*=0.37 *p*=0.37
SII 60	*r*=-0.51 *p*=0.19	*r*=0.45 *p*=0.26	*r*=0.55 *p*=0.16	*r*=0.27 *p*=0.51	*r*=-0.19 *p*=0.65	*r*=-0.37 *p*=0.36	*r*=-0.36 *p*=0.38	*r*=0.41 *p*=0.32	*r*=0.29 *p*=0.49
PTA CI	*r*=-0.50 *p*=0.21	*r*=0.55 *p*=0.16	*r*=0.57 *p*=0.39	*r*=-0.51 *p*=0.20	*r*=0.44 *p*=0.28	*r*=0.57 *p*=0.14	*r*=-0.49 *p*=0.22	*r*=0.52 *p*=0.19	*r*=0.44 *p*=0.28
PTA HA	*r*=0.26 *p*=0.53	*r*=-0.15 *p*=0.73	*r*=-0.41 *p*=0.32	*r*=-0.24 *p*=0.56	*r*=0.22 *p*=0.60	*r*=0.26 *p*=0.53	*r*=0.26 *p*=0.53	*r*=-0.26 *p*=0.53	*r*=-0.24 *p*=0.56
PTA CI LF	*r*=-0.46 *p*=0.25	*r*=0.54 *p*=0.17	*r*=0.28 *p*=0.51	*r*=-0.41 *p*=0.31	*r*=0.38 *p*=0.35	*r*=0.43 *p*=0.29	*r*=-0.56 *p*=0.15	*r*=0.61 *p*=0.11	*r*=0.48 *p*=0.23
PTA HA LF	*r*=0.25 *p*=0.55	*r*=-0.12 *p*=0.78	*r*=-0.41 *p*=0.31	*r*=-0.22 *p*=0.59	*r*=0.25 *p*=0.56	*r*=0.19 *p*=0.66	*r*=0.36 *p*=0.38	*r*=-0.32 *p*=0.44	*r*=-0.39 *p*=0.34

Age, SII at 50 and 60 dB SPL, PTA, and low-frequency PTA are compared to SMD percent correct scores and errors made with the 0.5 and 1.0 cycles/octave stimuli. Significant correlations and those approaching significance are in bold. The symbol (*) indicates significance at the 0.05 level. The symbol (†) indicates approaching significance.

Correlations between Speech Perception and Non-Speech Measures (N=8)

	CI		**HA**		**Bimodal**		**Bim. Benefit**	
	BKB-SIN SNR-50	**CNC Percent Correct**	**BKB-SIN SNR-50**	**CNC Percent Correct**	**BKB-SIN SNR-50**	**CNC Percent Correct**	**SNR-50 Simple Diff.**	**CNC NAB**
Age	*r*=-0.26 *p*=0.54	*r*=0.29 *p*=0.48	*r*=0.42 *p*=0.30	*r*=-0.22 *p*=0.64	*r*=0.11 *p*=0.79	*r*=-0.24 *p*=0.57	*r*=-0.34 *p*=0.41	*r*=-0.52 *p*=0.19
SII 50	*r*=0.27 *p*=0.52	*r*=-0.31 *p*=0.44	***r*=-0.77* *p*=0.02**	***r*=0.72† *p*=0.07**	*r*=-0.33 *p*=0.42	*r*=0.54 *p*=0.17	*r*=0.004 *p*=0.99	***r*=0.80* *p*=0.02**
SII 60	*r*=0.43 *p*=0.29	*r*=-0.44 *p*=0.28	***r*=-0.77* *p*=0.02**	***r*=0.71† *p*=0.07**	*r*=-0.23 *p*=0.59	*r*=0.39 *p*=0.35	*r*=-0.02 *p*=0.96	***r*=0.78* *p*=0.02**
PTA CI	*r*=-0.31 *p*=0.46	*r*=0.32 *p*=0.44	*r*=-0.25 *p*=0.55	*r*=0.60 *p*=0.16	*r*=-0.38 *p*=0.35	*r*=0.53 *p*=0.18	*r*=0.10 *p*=0.81	*r*=0.13 *p*=0.77
PTA HA	*r*=-0.17 *p*=0.69	*r*=0.21 *p*=0.62	***r*=0.77* *p*=0.02**	***r*=-0.70† *p*=0.052**	*r*=0.43 *p*=0.28	*r*=-0.60 *p*=0.11	*r*=0.13 *p*=0.77	***r*=-0.76* *p*=0.03**
PTA CI LF	*r*=-0.42 *p*=0.30	*r*=0.38 *p*=0.35	*r*=-0.15 *p*=0.72	*r*=0.24 *p*=0.63	*r*=-0.33 *p*=0.42	*r*=0.57 *p*=0.14	*r*=0.38 *p*=0.35	*r*=0.14 *p*=0.74
PTA HA LF	*r*=-0.05 *p*=0.92	*r*=0.20 *p*=0.64	*r*=0.55 *p*=0.15	*r*=-0.42 *p*=0.35	*r*=0.38 *p*=0.35	*r*=-0.56 *p*=0.15	*r*=-0.02 *p*=0.96	***r*=0.74* *p*=0.04**

Age, SII at 50 and 60 dB SPL, PTA, and low-frequency PTA are compared to performance on each speech test. The symbol (*) indicates significance at the 0.05 level. The symbol (†) indicates approaching significance.

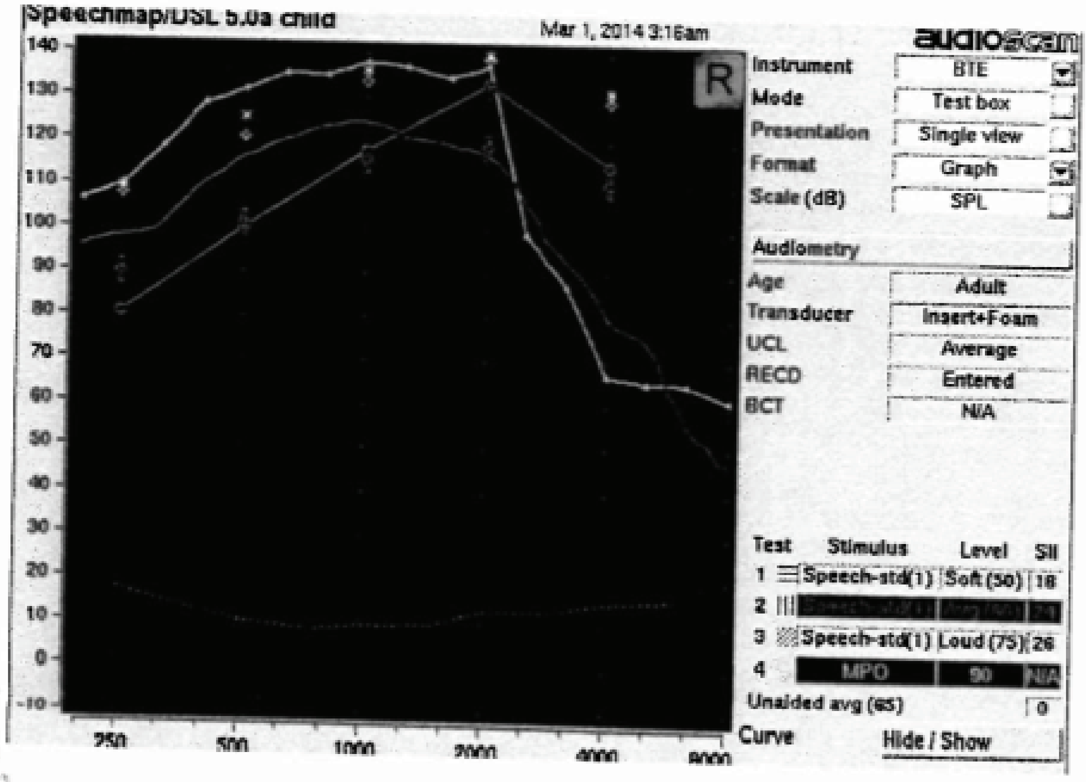
Correlations between SMD Performance and Speech Performance (N=8)

		CI		HA		Bimodal		Bim. Benefit	
		BKB-SIN SNR-50	CNC Percent Correct	BKB-SIN SNR-50	CNC Percent Correct	BKB-SIN SNR-50	CNC Percent Correct	SNR-50 Simple Diff.	CNC NAB
CI	SMD Percent Correct	*r*=-0.37 *p*=0.37	*r*=0.51 *p*=0.20	*r*=0.41 *p*=0.31	*r*=-0.40 *p*=0.38	*r*=0.08 *p*=0.86	*r*=-0.08 *p*=0.86	*r*=-0.19 *p*=0.66	*r*=-0.54 *p*=0.16
	Errors at 0.5 c/o	*r*=0.39 *p*=0.34	*r*=-0.52 *p*=0.19	*r*=-0.28 *p*=0.51	*r*=0.29 *p*=0.52	*r*=0.09 *p*=0.84	*r*=0.04 *p*=0.92	*r*=0.37 *p*=0.36	*r*=0.53 *p*=0.17
	Errors at 1.0 c/o	*r*=0.29 *p*=0.48	*r*=-0.44 *p*=0.28	*r*=-0.56 *p*=0.15	*r*=0.50 *p*=0.25	*r*=-0.30 *p*=0.47	*r*=0.12 *p*=0.77	*r*=-0.10 *p*=0.82	*r*=0.50 *p*=0.21
HA	SMD Percent Correct	*r*=0.62 *p*=0.10	*r*=-0.40 *p*=0.33	*r*=-0.41 *p*=0.31	*r*=0.08 *p*=0.86	*r*=-0.006 *p*=1.00	*r*=0.05 *p*=0.91	*r*=-0.14 *p*=0.74	*r*=0.49 *p*=0.21
	Errors at 0.5 c/o	*r*=-0.52 *p*=0.19	*r*=0.28 *p*=0.51	*r*=0.45 *p*=0.26	*r*=-0.15 *p*=0.75	*r*=0.15 *p*=0.73	*r*=-0.14 *p*=0.74	*r*=0.24 *p*=0.57	*r*=-0.46 *p*=0.25
	Errors at 1.0 c/o	***r*=-0.72* *p*=0.04**	*r*=0.55 *p*=0.16	*r*=0.33 *p*=0.42	*r*=0.01 *p*=0.97	*r*=-0.20 *p*=0.64	*r*=0.09 *p*=0.83	*r*=-0.001 *p*=1.00	*r*=-0.52 *p*=0.19
Bimodal	SMD Percent Correct	*r*=0.07 *p*=0.88	*r*=0.27 *p*=0.52	*r*=0.03 *p*=0.94	*r*=-0.08 *p*=0.86	*r*=-0.06 *p*=0.90	*r*=-0.13 *p*=0.75	*r*=-0.54 *p*=0.17	*r*=-0.38 *p*=0.35
	Errors at 0.5 c/o	*r*=-0.02 *p*=0.97	*r*=-0.29 *p*=0.57	*r*=-0.06 *p*=0.89	*r*=0.09 *p*=0.85	*r*=0.08 *p*=0.84	*r*=0.15 *p*=0.72	*r*=0.59 *p*=0.13	*r*=0.42 *p*=0.30
	Errors at 1.0 c/o	*r*=-0.12 *p*=0.78	*r*=-0.24 *p*=0.57	*r*=-0.003 *p*=0.99	*r*=0.06 *p*=0.88	*r*=-0.12 *p*=0.78	*r*=0.10 *p*=0.81	*r*=0.47 *p*=0.24	*r*=0.32 *p*=0.44

SMD percent correct scores and errors made with the 0.5 and 1.0 cycles/octave stimuli were compared with speech scores and bimodal benefit in each condition. The symbol (*) indicates significance at the 0.05 level.

Appendix C

Speechmap for HJB01



Speechmap/DSL 5.0a child

Mar 1, 2014 3:16am

audioscan

Right	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	109	125		136		140		131	
Entered UCL									
Target1	81	91		106		109		101	
Test 1	88	113	117	115	112	108	83	86	43
Target2	90	101		116		119		111	
Test 2	98	116	122	124	120	117	95	80	60
Target3	92	111		126		129		121	
Test 3	100	118	125	128	125	124	100	85	68
Target4	108	121		134		139		129	
Test 4	110	131	135	138	135	137	90	67	65
SPL threshld	90	100		118		133		115	
Unaided (65)	56	59	55	53	53	56	57	55	46
Entered HL	65	85		105		115		115	
Entered BCT									
nHL to eHL									
HA-2 RECD	1	8	12	12	14	12	4	-2	1
MAP	18	10	9	9	10	13	13	15	18

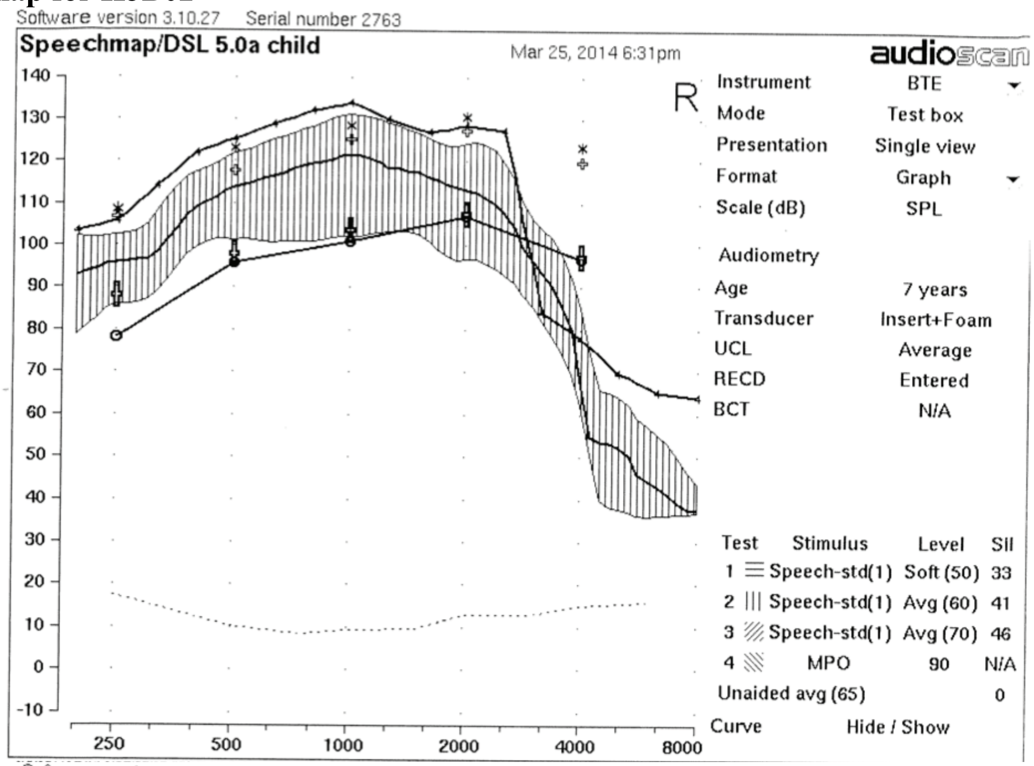
Instrument: BTE
Mode: Test box
Presentation: Single view
Format: Table
Scale (dB): SPL

Audiometry
Age: Adult
Transducer: Insert+Foam
UCL: Average
RECD: Entered
BCT: N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	18
2	Speech-std(1)	Avg (65)	24
3	Speech-std(1)	Loud (75)	26
4	MPO	90	N/A

Unaided avg (65) 0

Speechmap for HJB02



Software version 3.10.27 Serial number 2763

Speechmap/DSL 5.0a child

Mar 25, 2014 6:31pm

audioscan

Right	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	108	123		129		131		123	
Entered UCL									
Target1	80	88		94		97		87	
Test 1	92	109	112	112	112	106	86	61	37
Target2	88	98		104		107		97	
Test 2	96	114	119	121	117	113	96	68	44
Target3	92	106		113		117		107	
Test 3	98	116	121	124	120	117	106	78	55
Target4	107	118		125		127		120	
Test 4	106	125	131	134	128	128	95	78	66
SPL threshld	78	96		101		107		97	
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	65	80		85		90		95	
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	-1	10	15	15	16	11	7	0	3
MAP	18	10	9	9	10	13	13	15	16

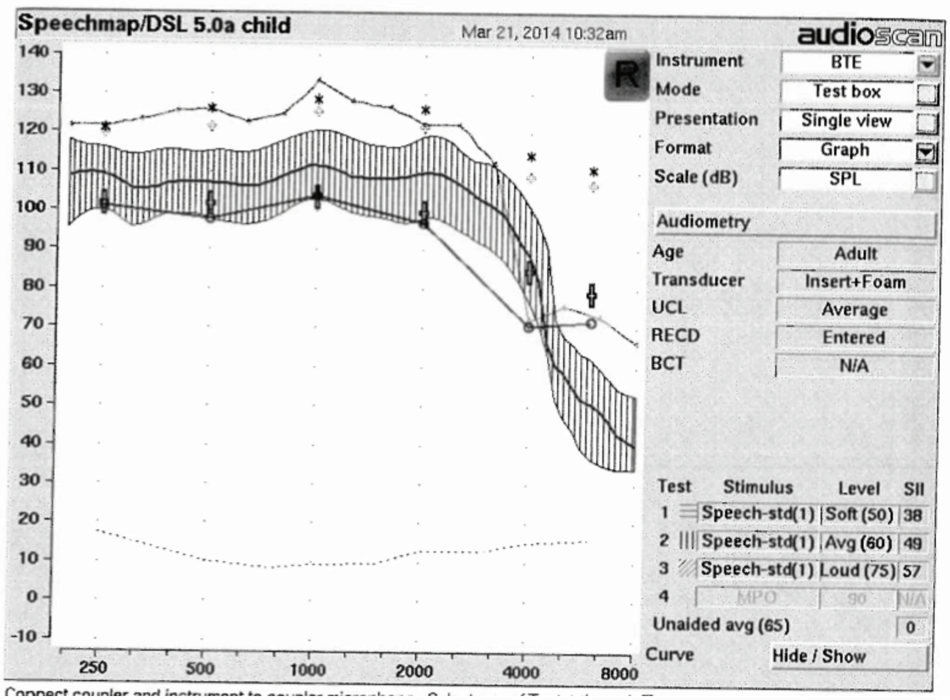
Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL

Audiometry

Age	7 years
Transducer	Insert+Foam
UCL	Average
RECD	Entered
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	33
2	Speech-std(1)	Avg (60)	41
3	Speech-std(1)	Avg (70)	46
4	MPO	90	N/A
Unaided avg (65)			0

Speechmap for HJB03



Speechmap/DSL 5.0a child   Mar 21, 2014 10:32am   audioscan

Right	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	121	126		129		126		114	111
Entered UCL									
Target1	92	92		94		90		75	72
Test 1	103	102	102	106	104	106	93	82	38
Target2	102	102		104		100		85	79
Test 2	109	107	108	112	109	110	102	89	51
Target3	108	112		115		112		94	86
Test 3	109	110	113	117	113	115	113	90	67
Target4	120	122		125		122		109	107
Test 4	122	126	124	133	127	122	115	72	74
SPL threshld	101	98		104		97		71	72
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	90	90		95		85		70	70
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	-3	2	6	8	6	6	3	-1	-1
MAP	18	10	9	9	10	13	13	15	16

Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL

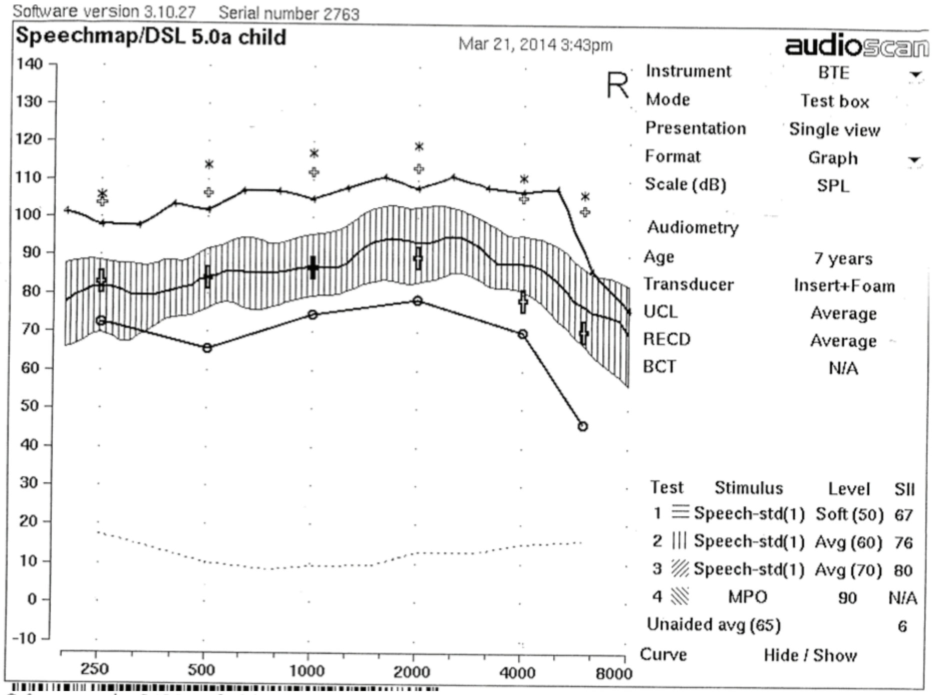
Audiometry

Age	Adult
Transducer	Insert+Foam
UCL	Average
RECD	Entered
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	38
2	Speech-std(1)	Avg (60)	49
3	Speech-std(1)	Loud (75)	57
4	MPO	90	N/A

Unaided avg (65) 0

Speechmap for HJB04



Software version 3.10.27 Serial number 2763

Speechmap/DSL 5.0a child

Mar 21, 2014 3:46pm

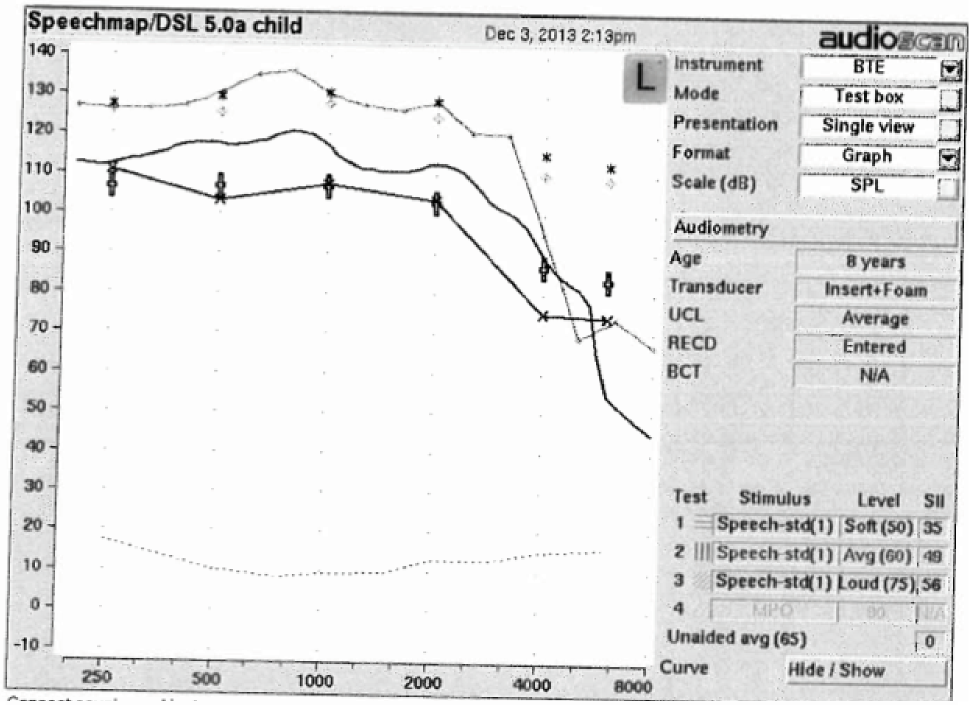
audioscan

Right	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	106	114		117		119		111	106
Entered UCL									
Target1	76	76		77		80		71	65
Test 1	81	78	85	82	88	89	85	82	72
Target2	83	84		87		90		79	71
Test 2	82	84	85	87	94	93	93	88	77
Target3	87	89		92		95		84	77
Test 3	83	88	90	91	98	98	97	93	82
Target4	104	106		112		113		106	102
Test 4	98	102	107	105	110	108	109	107	92
SPL threshld	73	66		75		79		70	46
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	55	55		65		65		55	30
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	3	5	6	9	7	7	8	13	13
MAP	18	10	9	9	10	13	13	15	16

Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL
Audiometry	
Age	7 years
Transducer	Insert+Foam
UCL	Average
RECD	Average
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	67
2	Speech-std(1)	Avg (60)	76
3	Speech-std(1)	Avg (70)	80
4	MPO	90	N/A
Unaided avg (65)			6

Speechmap for HJB05



Speechmap/DSL 5.0a child

Dec 3, 2013 2:13pm

audioscan

Left	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	127	129		131		128		115	113
Entered UCL									
Target1	97	97		97		93		77	75
Test 1	104	112	110	110	104	107	93	81	45
Target2	107	107		107		103		87	84
Test 2	112	118	120	117	111	113	102	90	55
Target3	113	117		119		116		96	90
Test 3	114	120	124	122	117	120	110	98	69
Target4	126	125		128		125		110	109
Test 4	126	131	136	130	127	129	120	95	73
SPL threshld	111	103		108		104		75	74
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	95	90		95		90		75	70
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	2	7	10	12	10	8	3	-2	1
MAP	18	10	9	9	10	13	13	15	16

Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL

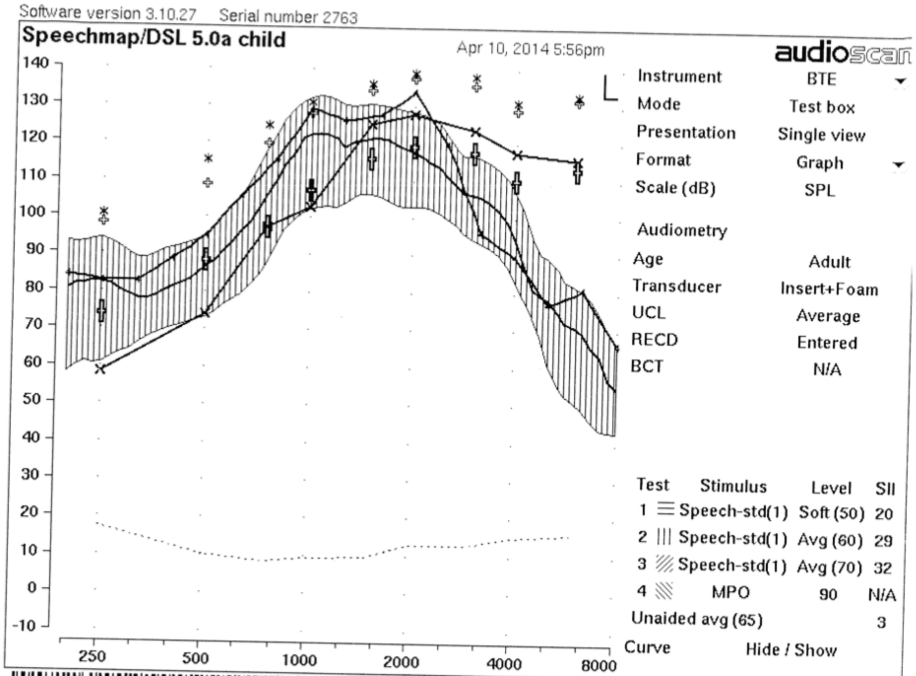
Audiometry

Age	8 years
Transducer	Insert+Foam
UCL	Average
RECD	Entered
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	35
2	Speech-std(1)	Avg (60)	49
3	Speech-std(1)	Loud (75)	56
4	MPO	90	N/A

Unaided avg (65) 0

Speechmap for HJB06



Software version 3.10.27 Serial number 2763

Speechmap/DSL 5.0a child

Apr 10, 2014 5:57pm

audioscan

Left	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	101	115	125	131	136	139	138	131	133
Entered UCL									
Target1	68	79	87	97	106	109	108	100	103
Test 1	71	80	96	112	115	110	97	88	54
Target2	74	88	97	107	116	119	118	110	113
Test 2	82	87	106	122	121	118	106	95	71
Target3	79	93	107	117	126	129	128	120	123
Test 3	85	91	109	124	123	122	112	99	80
Target4	98	109	120	128	134	138	136	129	132
Test 4	83	95	113	129	127	134	102	90	80
SPL threshld	58	74	97	103	125	128	124	118	116
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	40	65	85	90	105	110	115	115	105
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	4	3	10	12	18	12	3	1	8
MAP	18	10	9	9	10	13	13	15	16

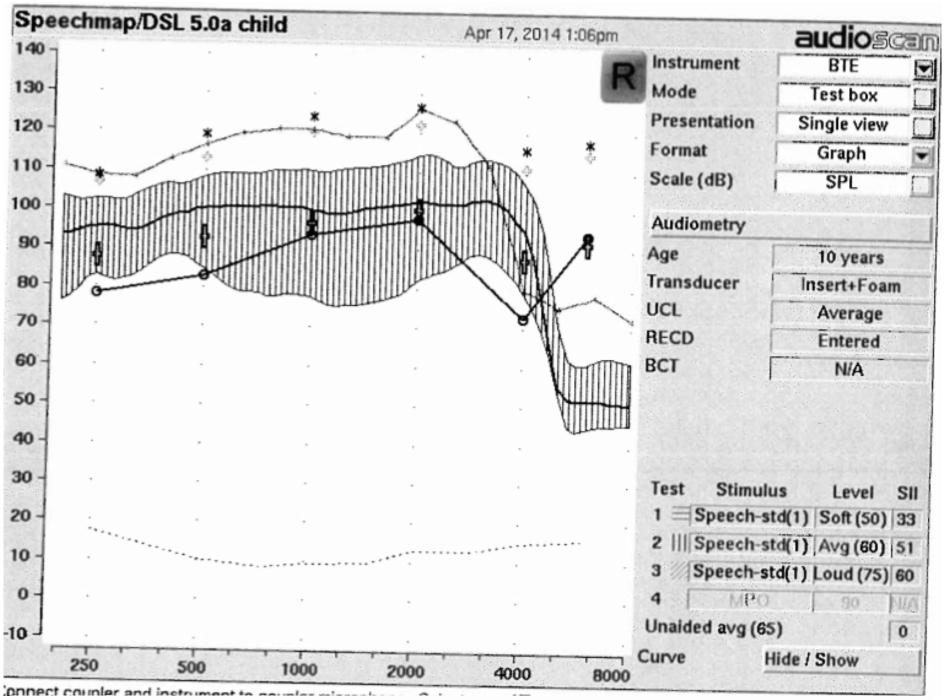
Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL

Audiometry

Age	Adult
Transducer	Insert+Foam
UCL	Average
RECD	Entered
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	20
2	Speech-std(1)	Avg (60)	29
3	Speech-std(1)	Avg (70)	32
4	MPO	90	N/A
Unaided avg (65)			3

Speechmap HJB07



Speechmap/DSL 5.0a child

Apr 17, 2014 1:06pm

audioscan

Right	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	108	119		124		127		116	118
Entered UCL									
Target1	80	83		87		90		78	82
Test 1	88	92	90	88	91	94	91	87	44
Target2	88	93		97		100		88	92
Test 2	95	100	101	100	101	102	103	95	52
Target3	90	100		108		113		97	99
Test 3	99	106	110	110	111	114	115	99	69
Target4	107	113		120		122		111	115
Test 4	108	117	121	121	119	126	115	80	78
SPL threshld	78	83		94		98		73	94
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	60	70		85		80		70	80
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	4	7	8	8	10	12	9	1	11
MAP	18	10	9	9	10	13	13	15	16

Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL

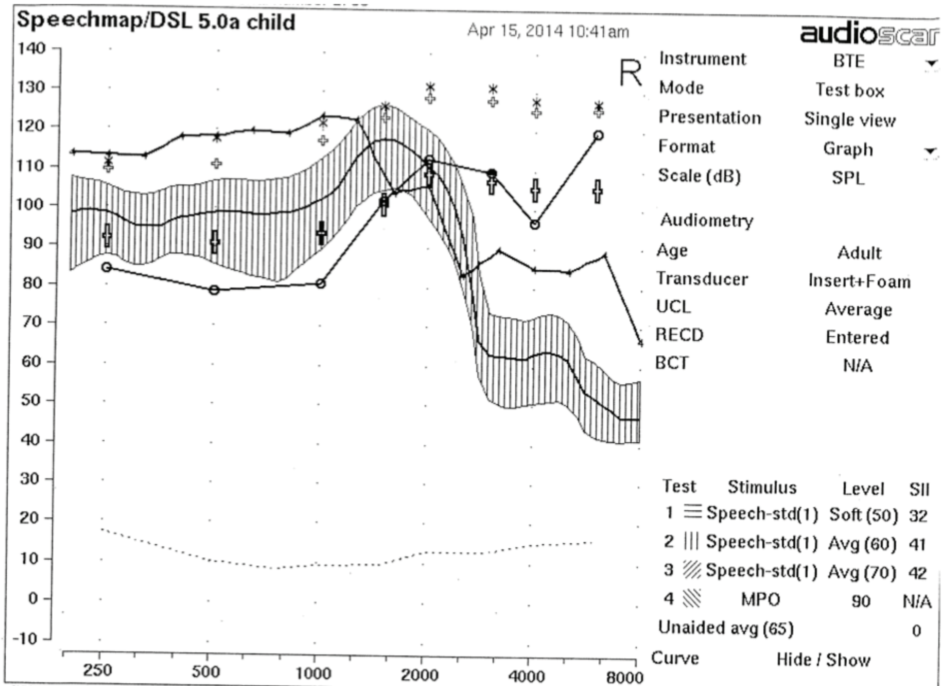
Audiometry

Age	10 years
Transducer	Insert+Foam
UCL	Average
RECD	Entered
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	33
2	Speech-std(1)	Avg (60)	51
3	Speech-std(1)	Loud (75)	60
4	MPO	90	N/A

Unaided avg (65) 0

Speechmap for HJB08



Software version 3.10.27 Serial number 2763

Speechmap/DSL 5.0a child

Apr 15, 2014 10:42am

audioscan

Right	250	500	750	1000	1500	2000	3000	4000	6000
SPL UCL	111	118		122	127	132	131	128	127
Entered UCL									
Target1	82	81		84	91	99	97	95	95
Test 1	90	92	91	93	109	102	52	55	43
Target2	92	91		94	101	109	107	105	105
Test 2	99	99	99	102	118	111	63	63	52
Target3	96	96		101	111	119	117	115	115
Test 3	103	104	104	108	123	118	74	72	58
Target4	110	111		118	123	128	128	125	126
Test 4	113	118	119	124	109	106	88	85	88
SPL threshld	84	79		81	102	113	110	97	120
Unaided (65)	56	59	55	53	53	56	57	55	48
Entered HL	65	70		75	90	100	100	90	110
Entered BCT									
nHL to eHL	30	20	17	15	12	10	7	5	5
HA-2 RECD	5	3	3	5	10	7	4	5	7
MAP	18	10	9	9	10	13	13	15	16

Instrument	BTE
Mode	Test box
Presentation	Single view
Format	Table
Scale (dB)	SPL
Audiometry	
Age	Adult
Transducer	Insert+Foam
UCL	Average
RECD	Entered
BCT	N/A

Test	Stimulus	Level	SII
1	Speech-std(1)	Soft (50)	32
2	Speech-std(1)	Avg (60)	41
3	Speech-std(1)	Avg (70)	42
4	MPO	90	N/A
Unaided avg (65)			0

Tables and Figures

Table 1

Subject ID	Test Age (Years)	CI Ear	Age at Dx of HL (Years)	CI Experience (Years)	CI Device	HA Device
HJB01	12.8	L	3.4	6.6	Harmony	Naida SV UP
HJB02	14.0	L	2.8	6.2	Harmony	Naida III UP
HJB03	12.1	L	1.7	7.0	Freedom	Naida IX UP
HJB04	9.7	L	4.0	1.9	N5	Nios Micro III
HJB05	8.9	R	1.5	6.0	Harmony	Naida DV UP
HJB06	18.7	R	3.8	0.8	N6	Naida SII UP
HJB07	10.8	L	3.9	4.3	N5	Naida SV UP
HJB08	19.0	L	0.3	10.6	N5	Naida III UP

Table 1. Demographic information is shown for each participant. Use of a HA began shortly after diagnosis of hearing loss.

Figure 1

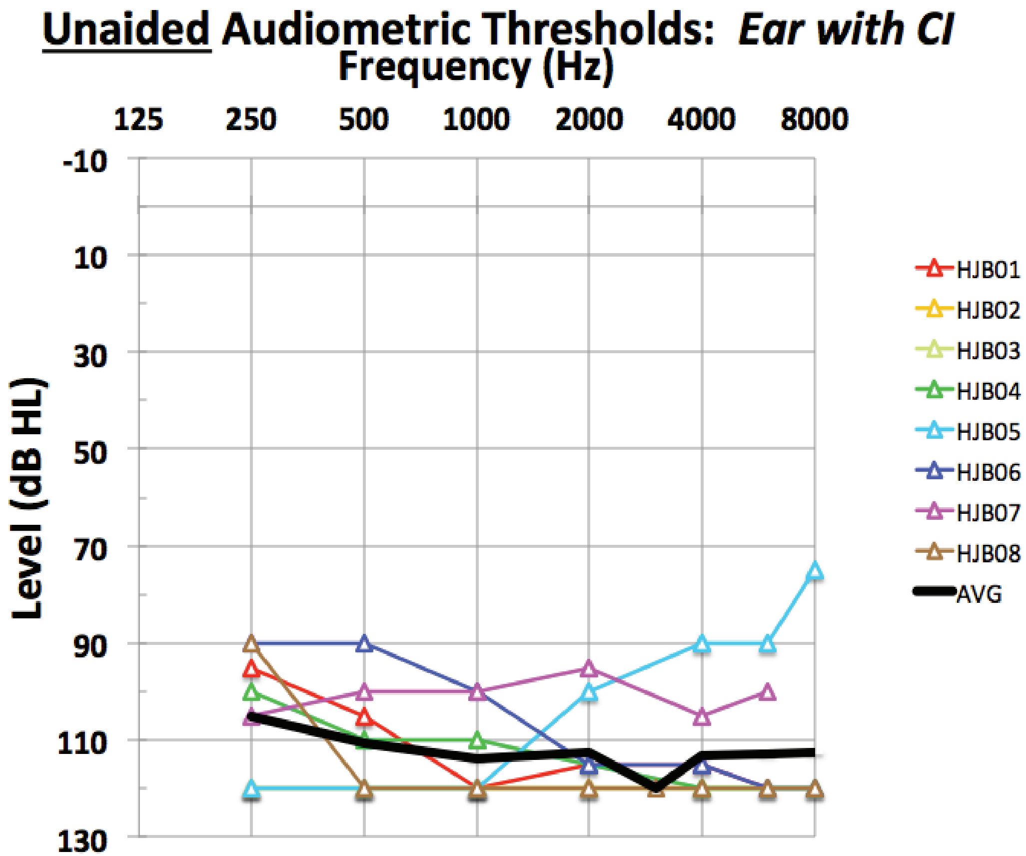


Figure 1. Unaided audiometric thresholds at the CI ear are shown. Symbols represent each participant's thresholds at different frequencies.

Figure 2

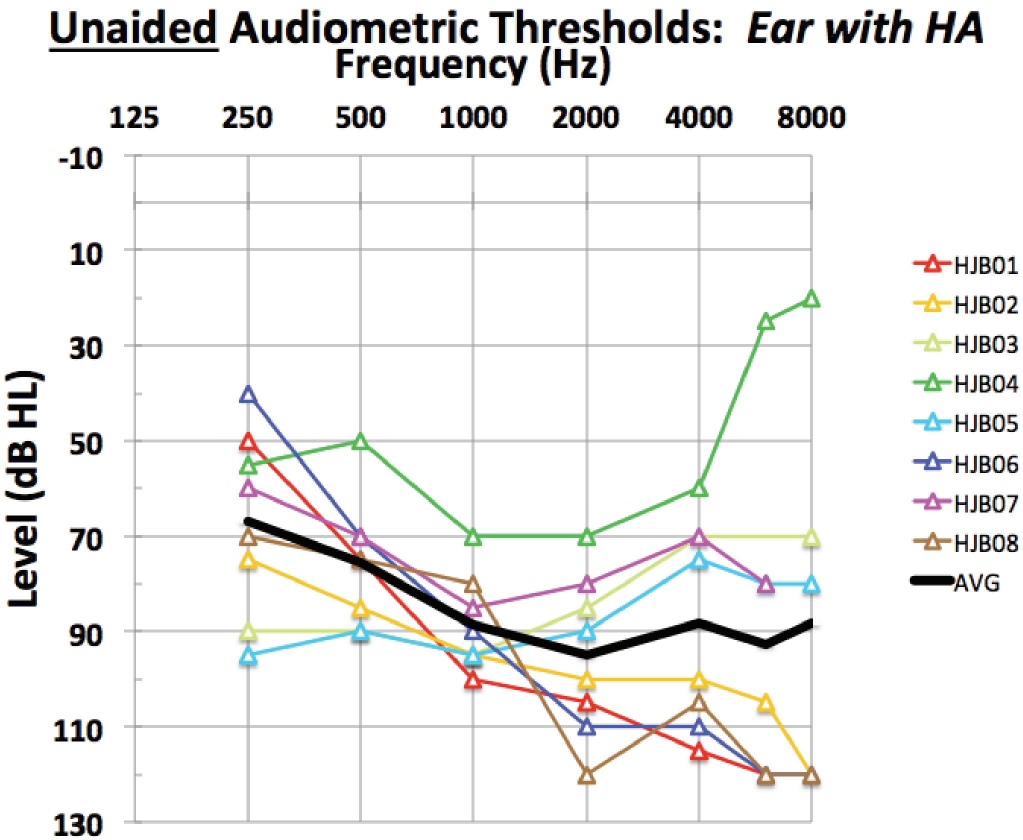


Figure 2. Unaided audiometric thresholds at the HA ear are shown. Symbols represent each participant's thresholds at different frequencies.

Figure 3

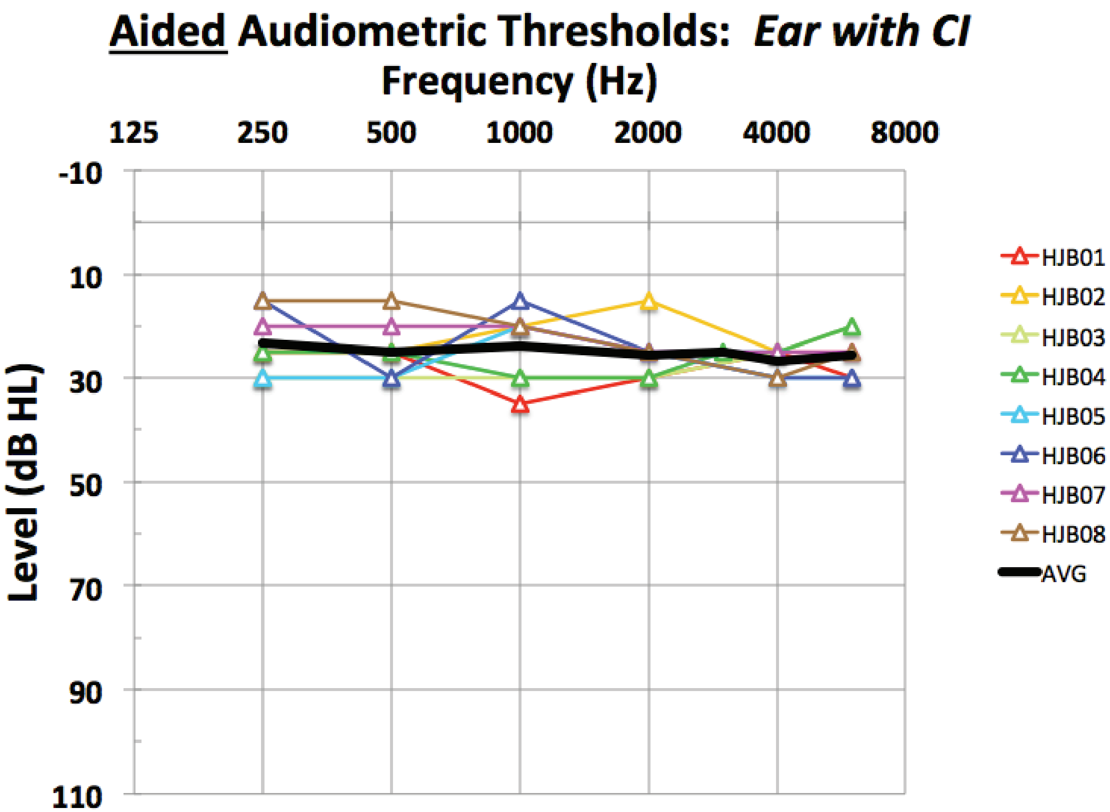


Figure 3. Aided audiometric thresholds at the CI ear are shown. Symbols represent each participant's thresholds at different frequencies.

Figure 4

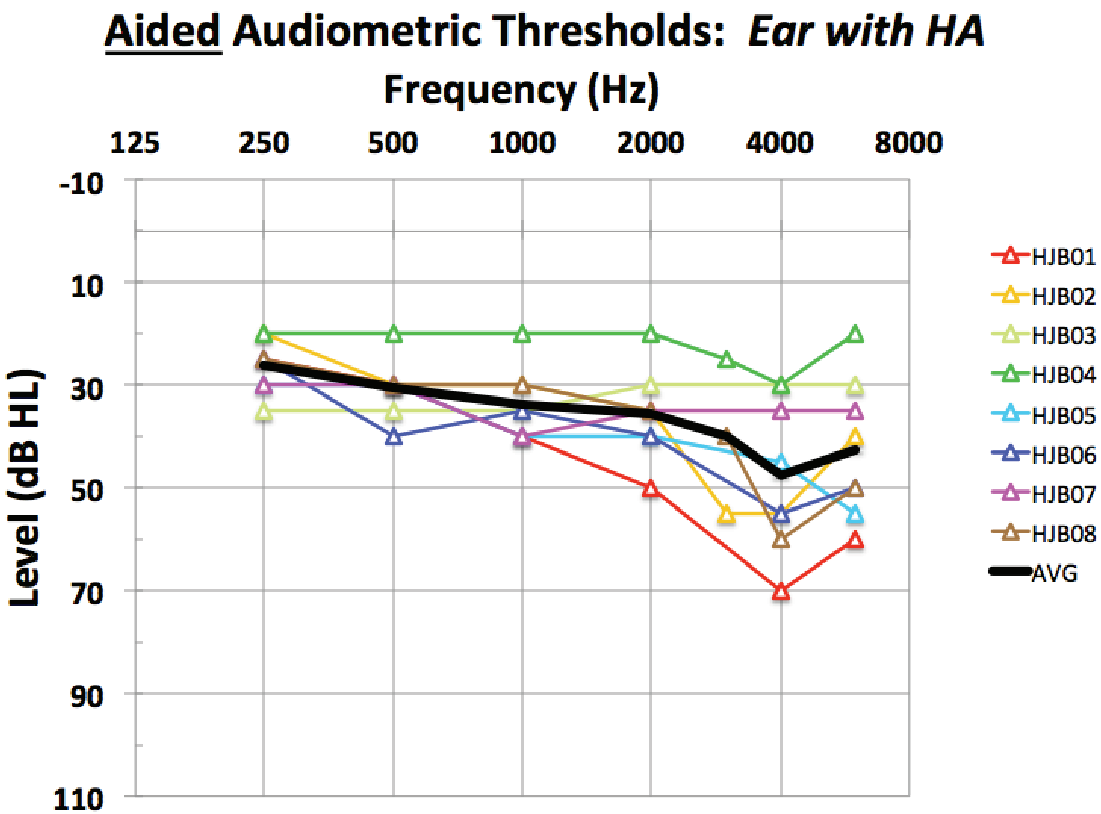


Figure 4. Aided audiometric thresholds at the HA ear are shown. Symbols represent each participant’s thresholds at different frequencies.

Figure 5

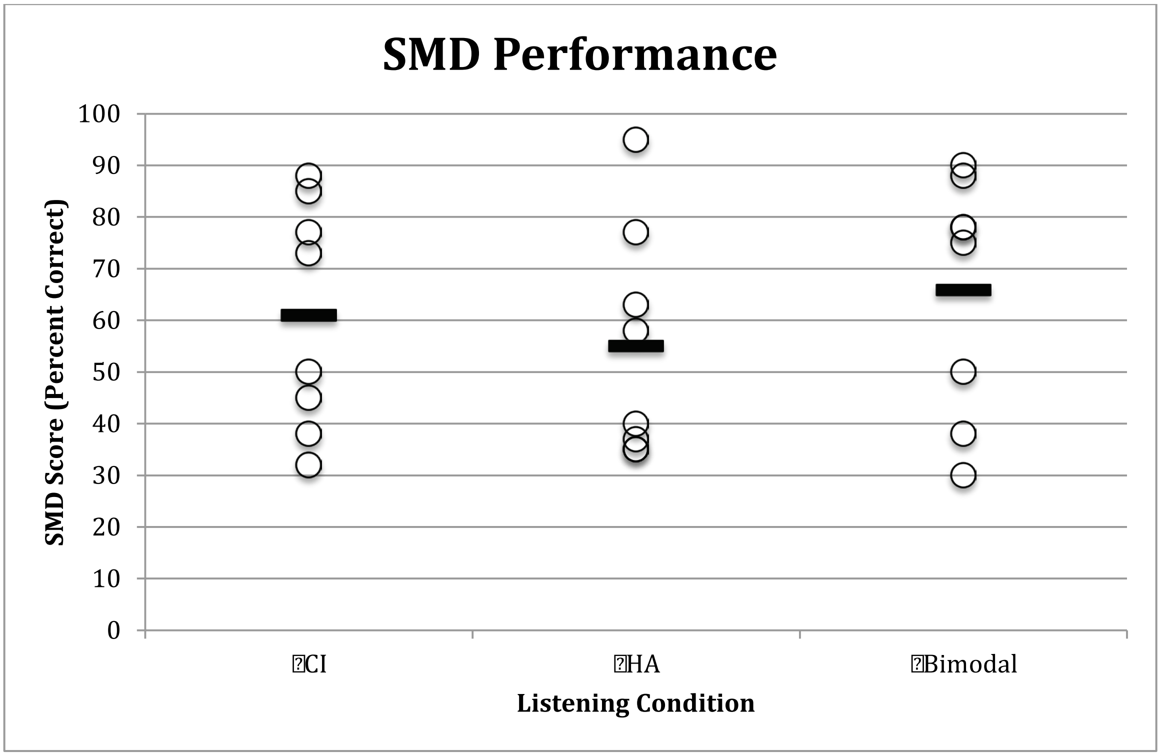


Figure 5. SMD performance for each participant in each condition is represented by an open circle. Average values for each listening condition are represented by horizontal bars.

Figure 6

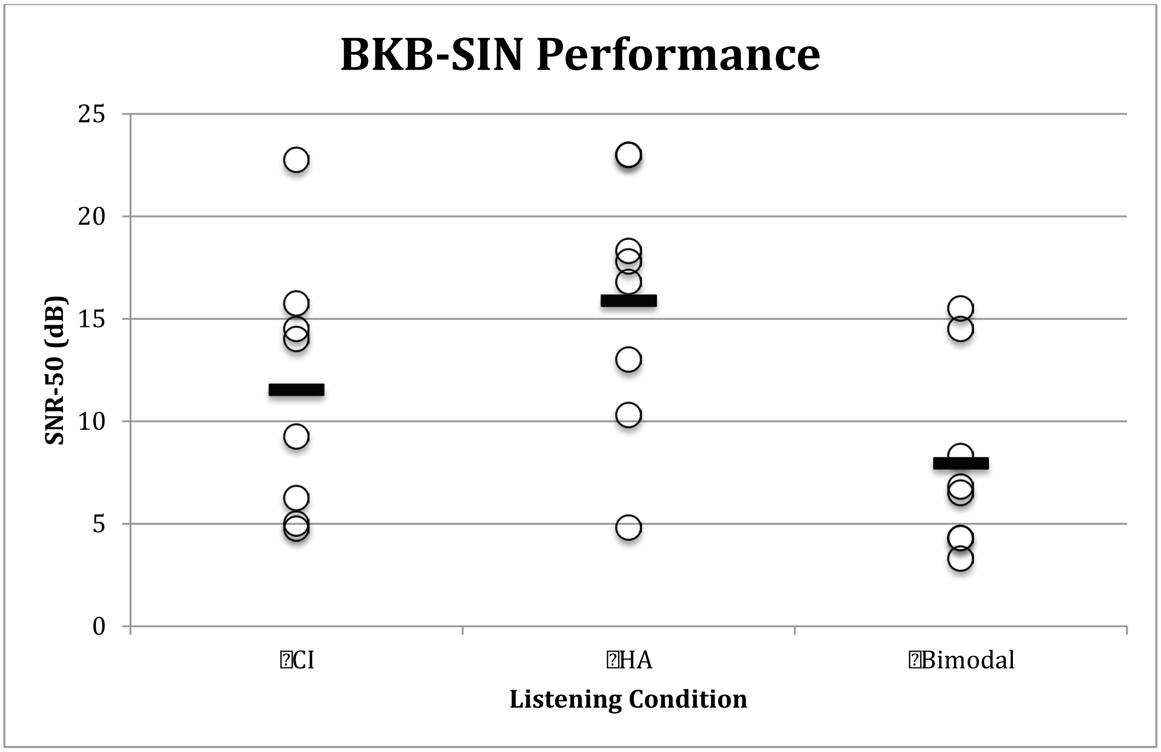


Figure 6. BKB-SIN performance for each participant in each condition is represented by an open circle. Average values for each listening condition are represented by horizontal bars.

Figure 7

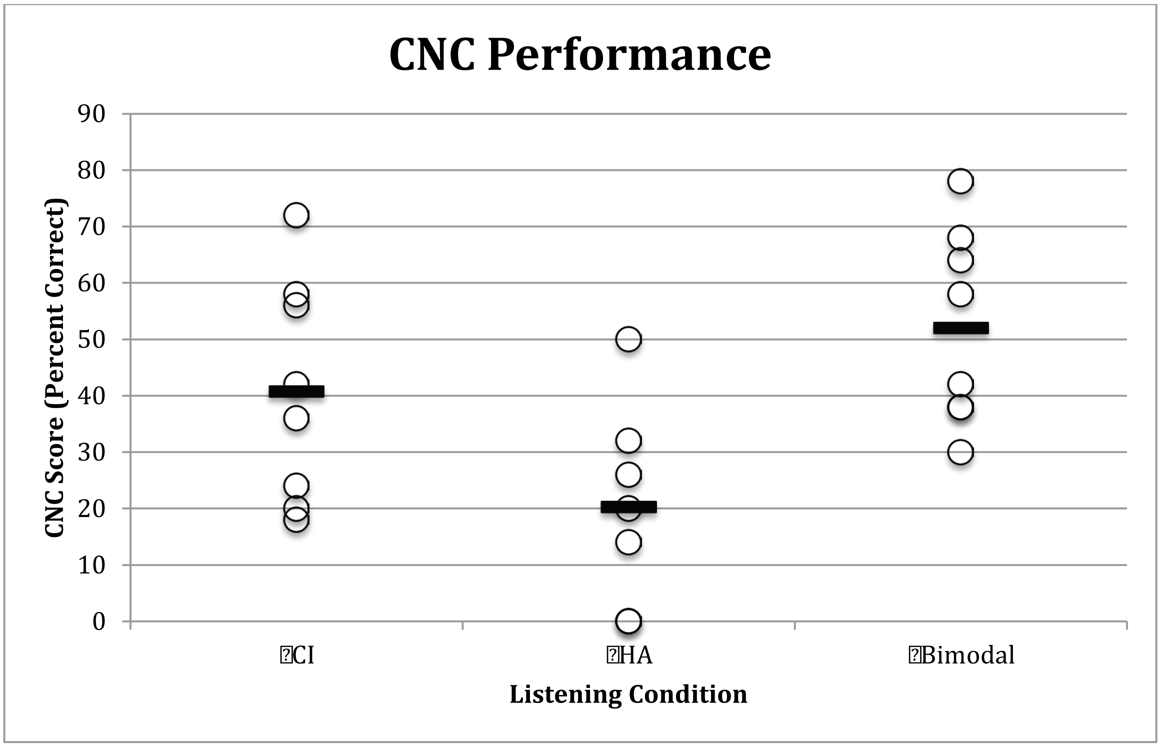


Figure 7. CNC performance for each participant in each condition is represented by an open circle. Average values for each listening condition are represented by horizontal bars.

Figure 8

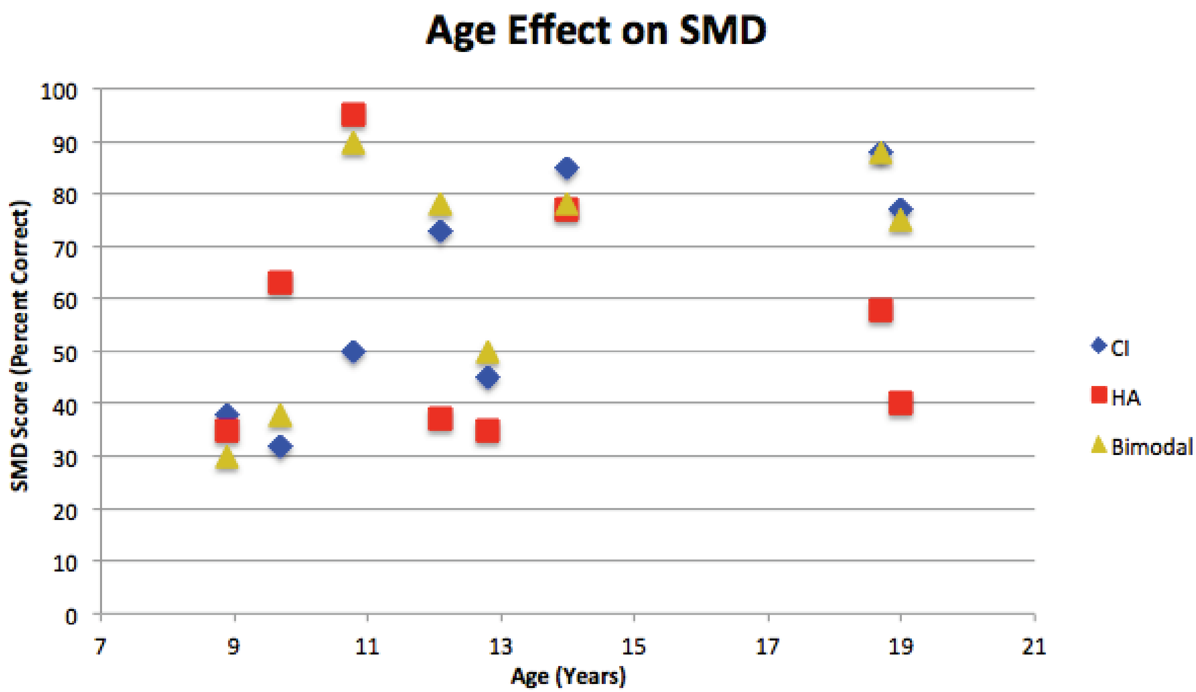


Figure 8. The effect of participant age on SMD performance is shown for the three conditions. A significant correlation is seen in the CI condition (*r*=0.81, *p*=0.02).

Figure 9

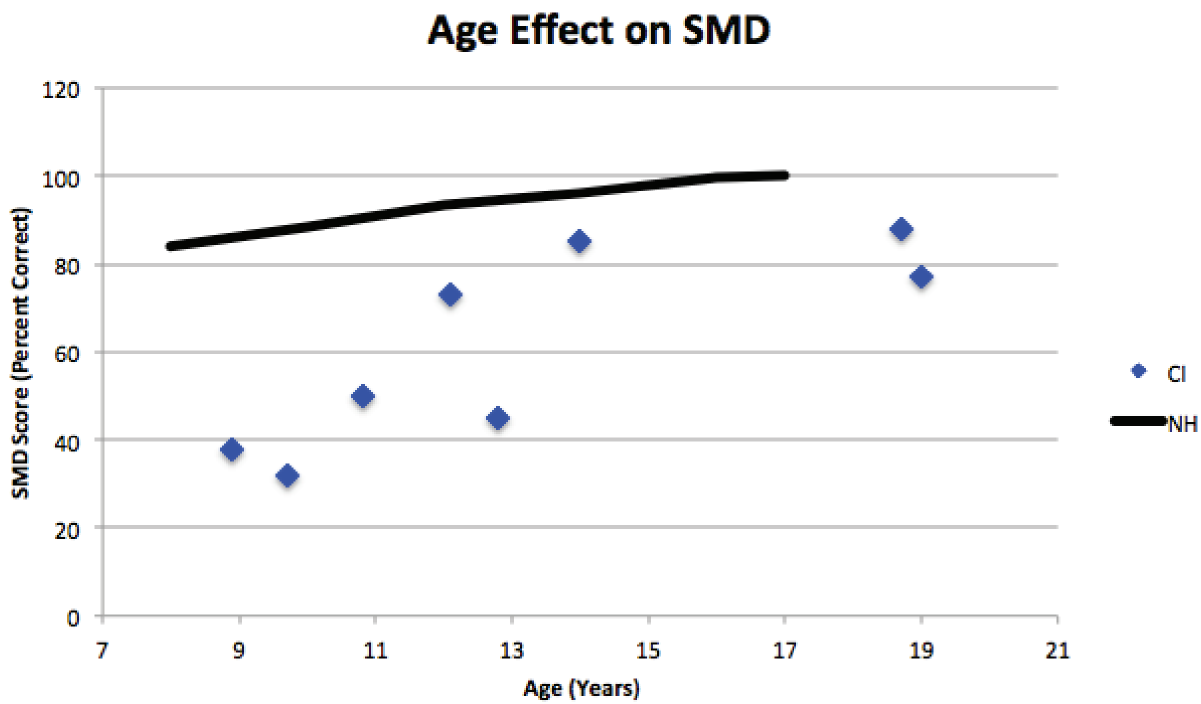


Figure 9. The effect of participant age on SMD performance is shown for the CI-only condition. A significant correlation is seen in this condition (*r*=0.81, *p*=0.02). Average performance by normal hearing (NH) children from Rakita (2012) are displayed, and also demonstrate a positive trend.

Figure 10

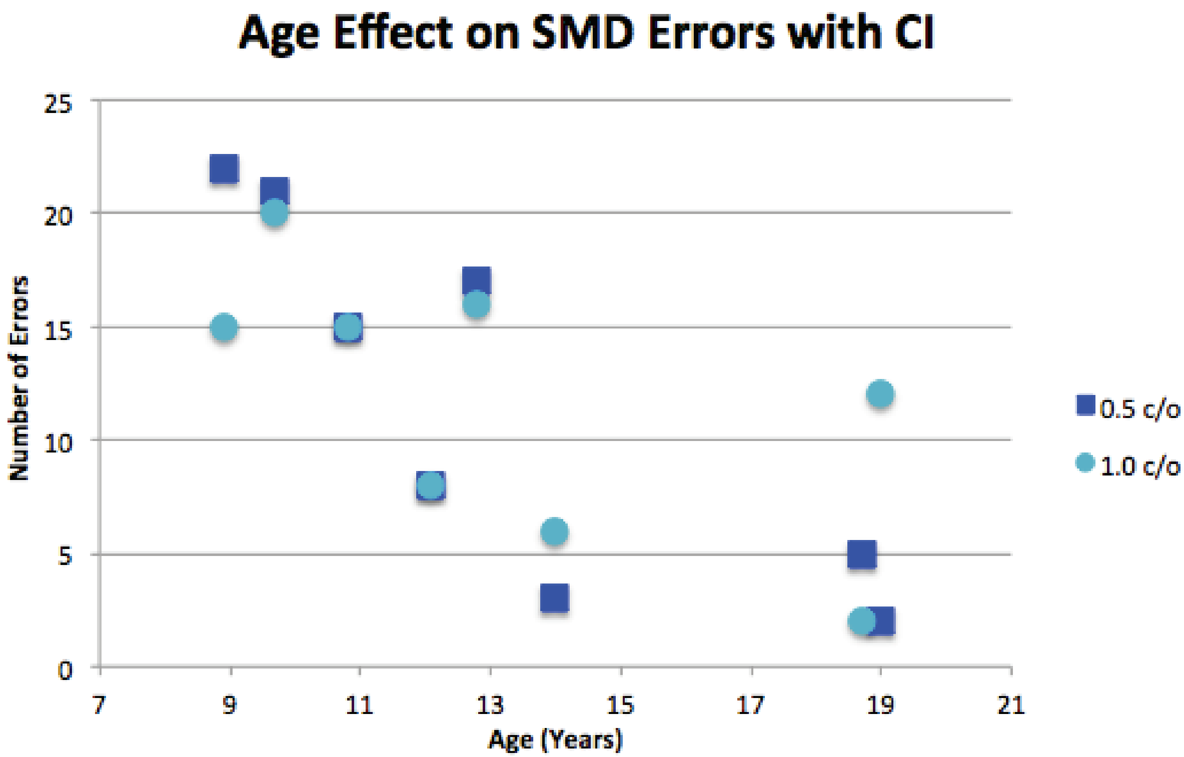


Figure 10. The effect of participant age on SMD performance in terms of errors with the 0.5 and 1.0 cycles/octave stimuli is shown for the CI-only condition. A significant correlation is seen with the 0.5 cycles/octave stimuli (*r*=-0.84, *p*=0.009), and a correlation approaching significance is seen with the 1.0 cyclec/octave stimuli (*r*=-0.66, *p*=0.08).

Figure 11

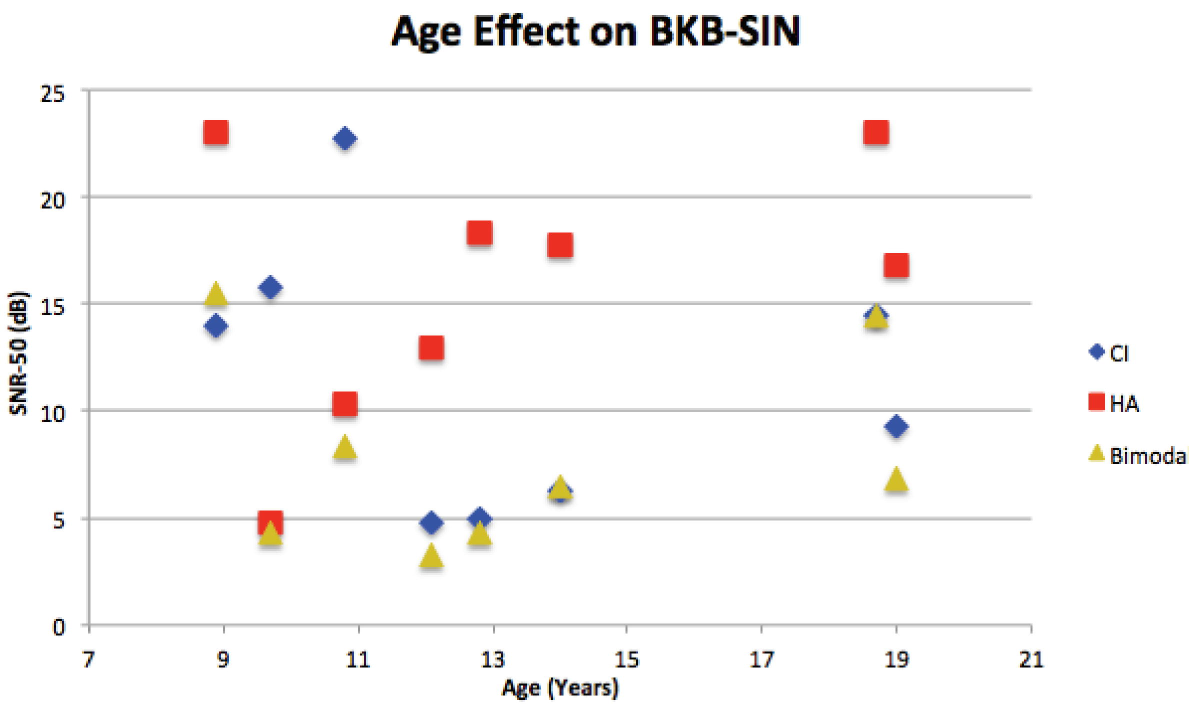


Figure 11. The effect of participant age on BKB-SIN performance is shown for the three conditions. No trends are observed.

Figure 12

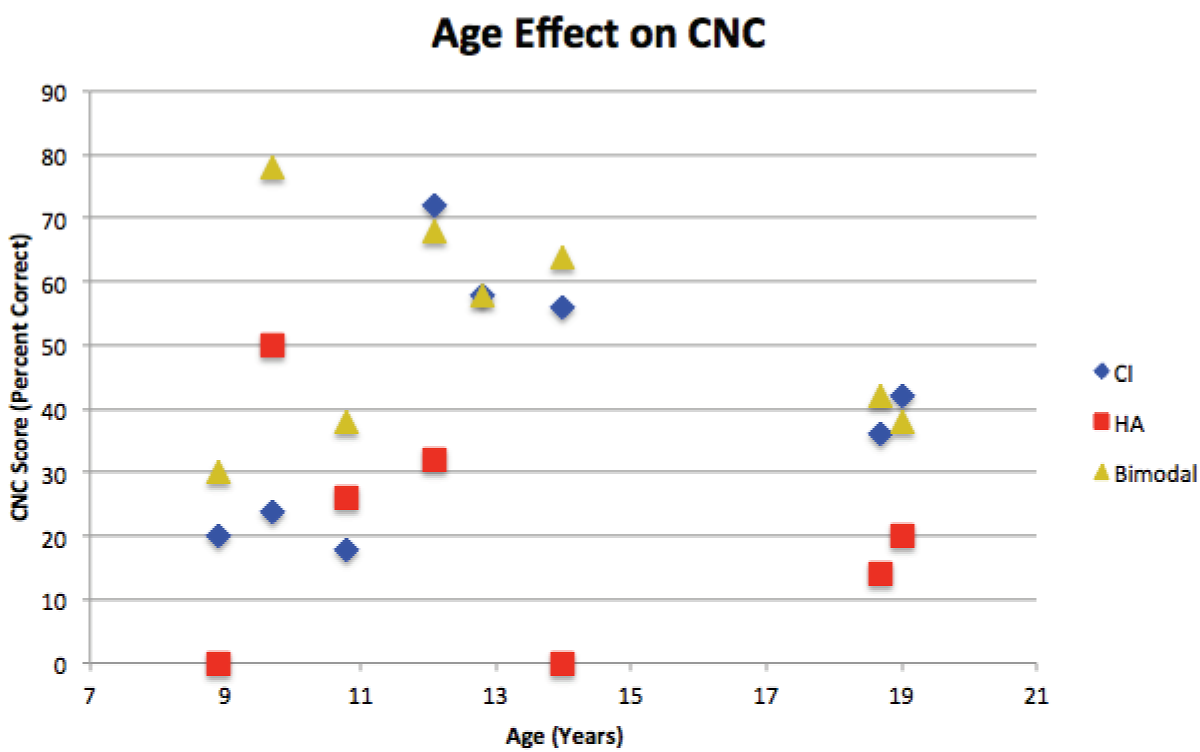


Figure 12. The effect of participant age on CNC performance is shown for the three conditions. No trends are observed.

Figure 13

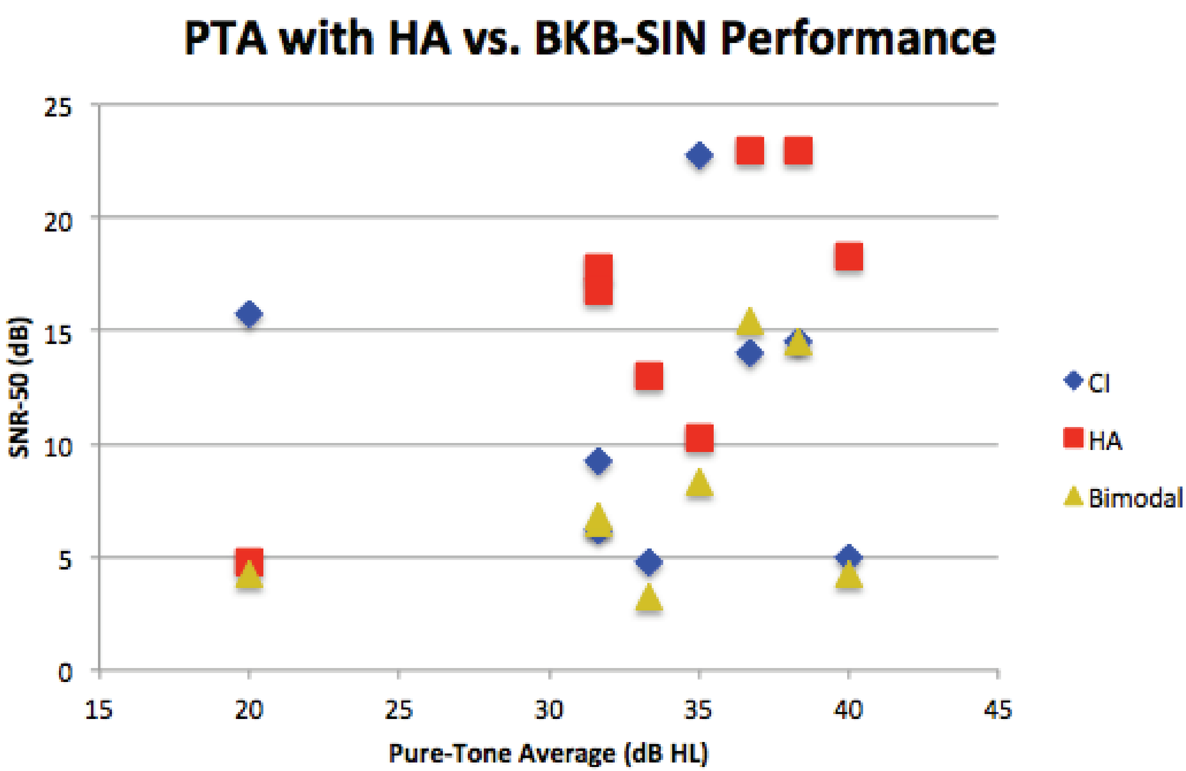


Figure 13. The relationship between PTA with a HA on BKB-SIN performance is shown for the three conditions. A significant correlation is seen in the HA-only condition (r=0.77, p=0.02).

Figure 14

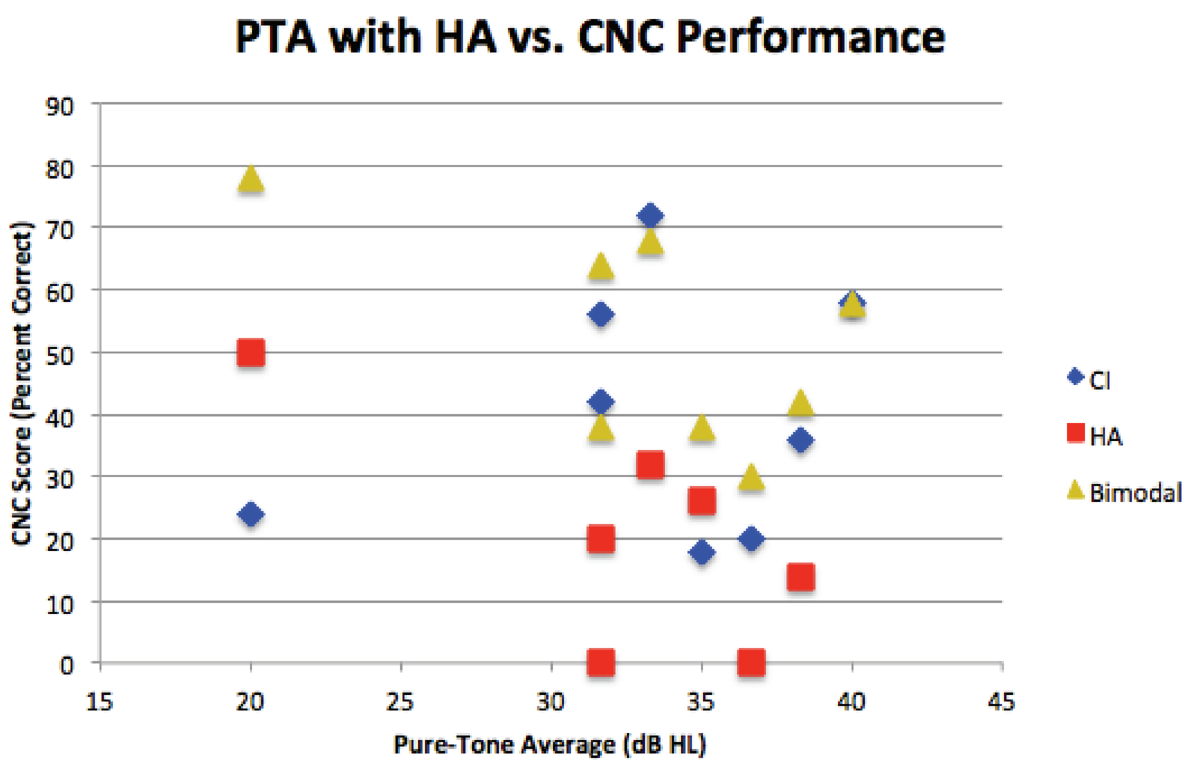


Figure 14. The relationship between PTA with a HA on CNC performance is shown for the three conditions. A correlation approaching significance is seen in the HA-only condition (r=-0.70, p=0.052).

Figure 15

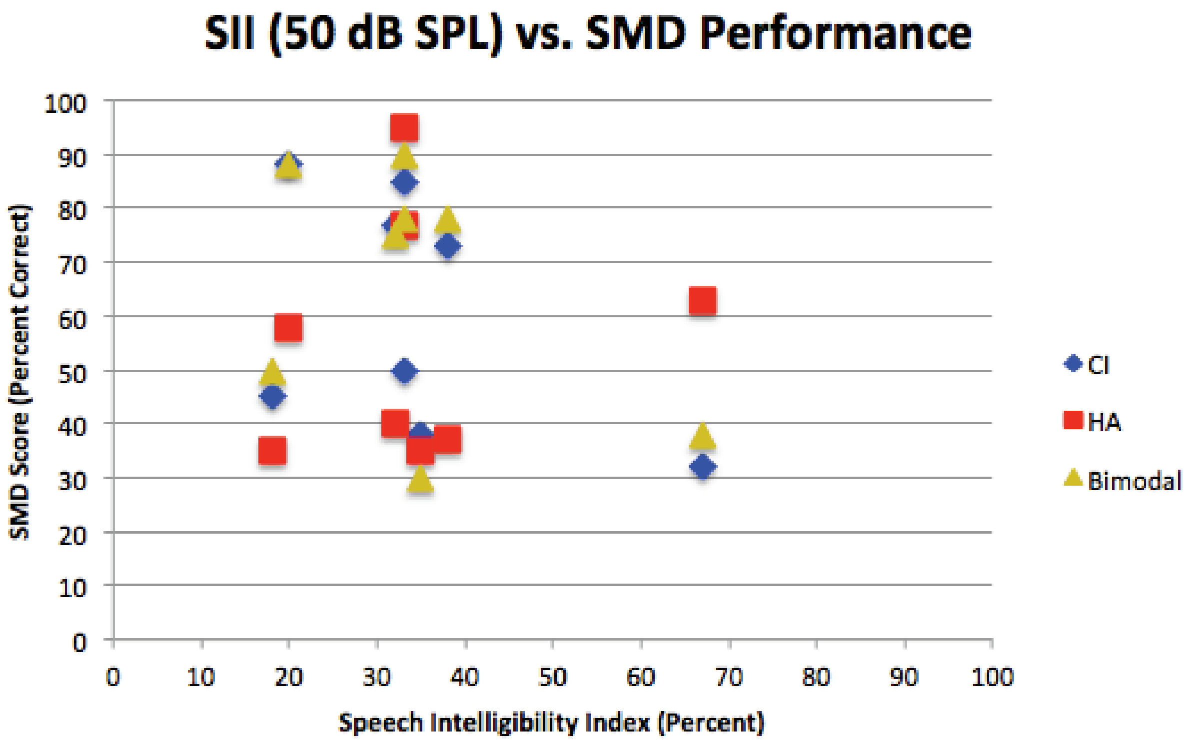


Figure 15. The relationship between SII at 50 dB SPL with a HA on SMD performance is shown for the three conditions. No trends are observed.

Figure 16

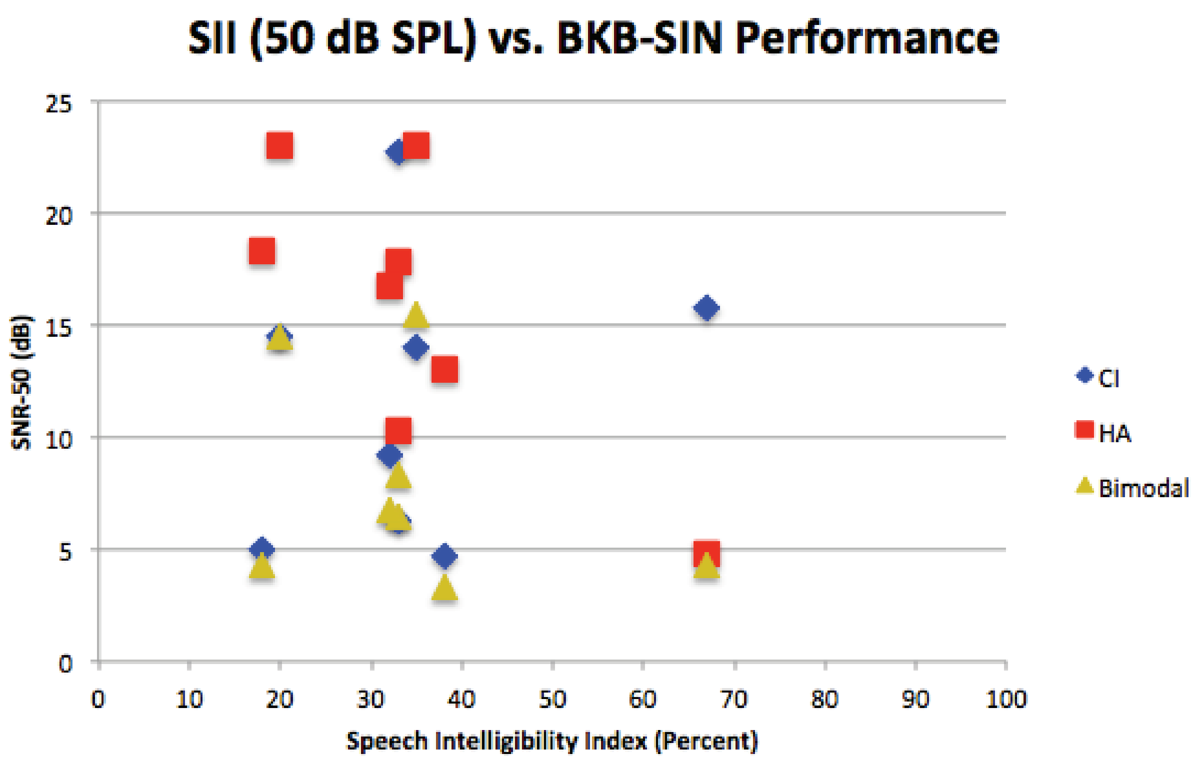


Figure 16. The relationship between SII at 50 dB SPL with a HA on BKB-SIN performance is shown for the three conditions. A significant correlation is seen in the HA-only condition (*r*=-0.77, *p*=0.02).

Figure 17

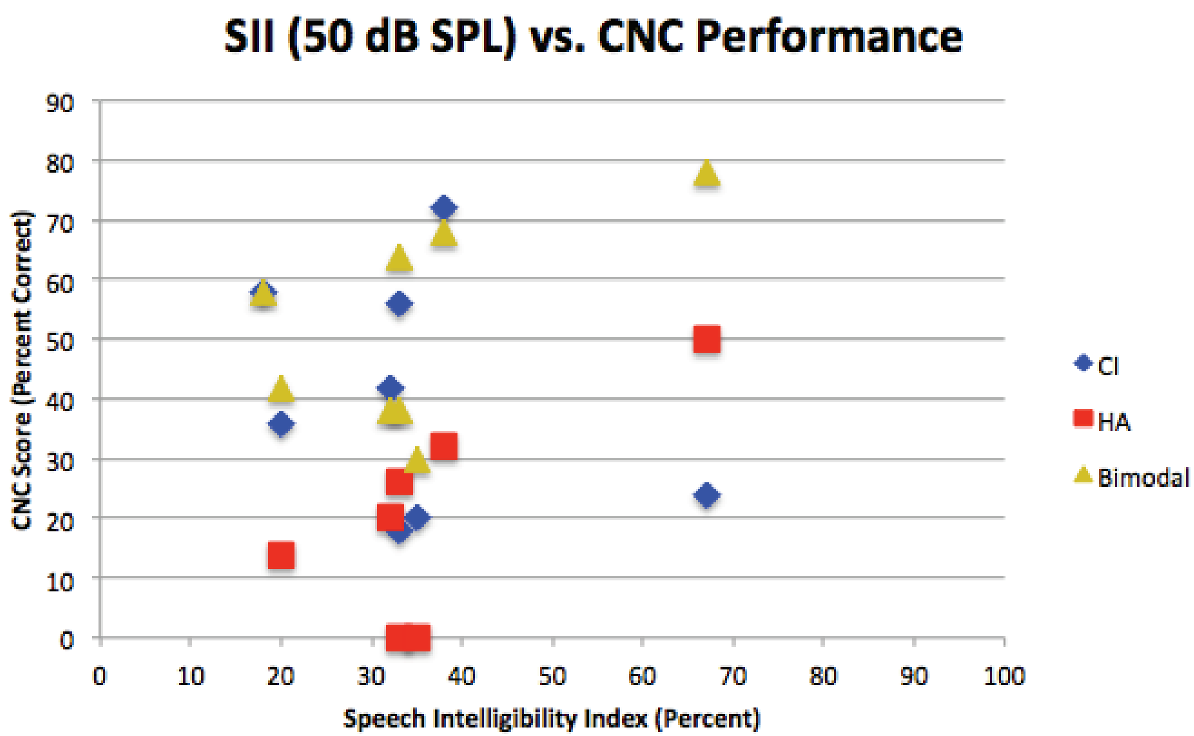


Figure 17. The relationship between SII at 50 dB SPL with a HA on CNC performance is shown for the three conditions. A correlation approaching significance is seen in the HA-only condition (*r*=0.72, *p*=0.07).

Figure 18

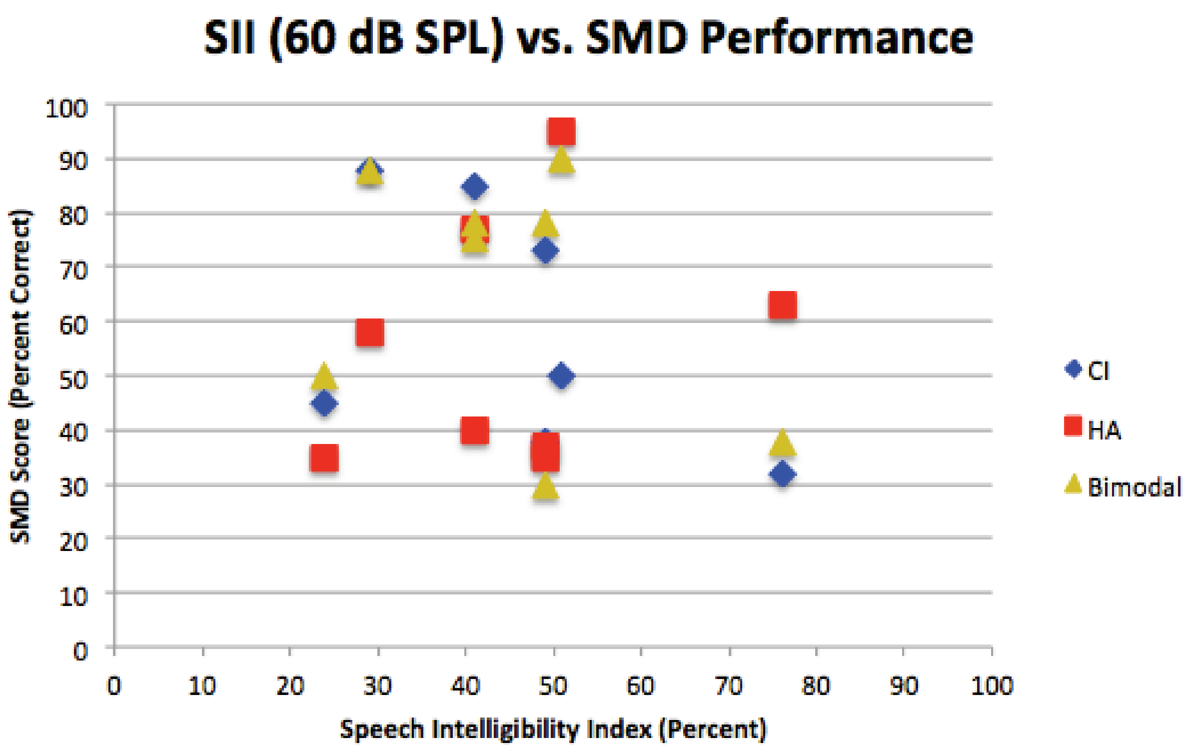


Figure 18. The relationship between SII at 60 dB SPL with a HA on SMD performance is shown for the three conditions. No trends are observed.

Figure 19

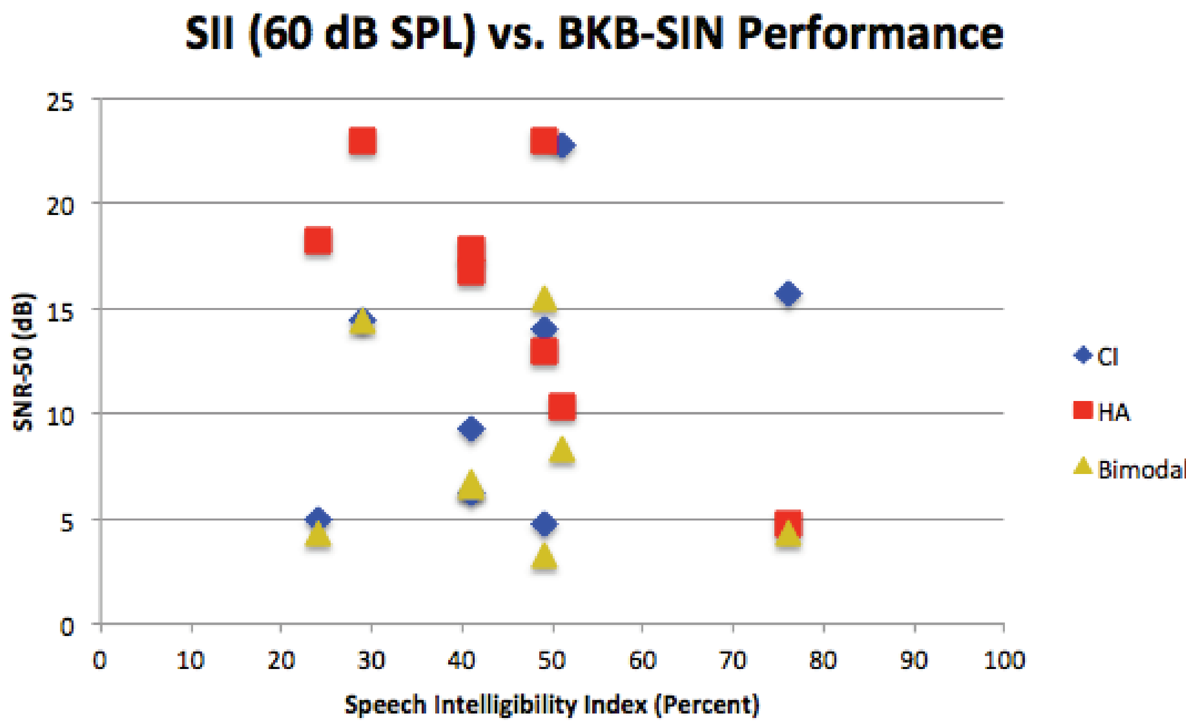


Figure 19. The relationship between SII at 60 dB SPL with a HA on BKB-SIN performance is shown for the three conditions. A significant correlation is seen in the HA-only condition (*r*=-0.77, *p*=0.02).

Figure 20

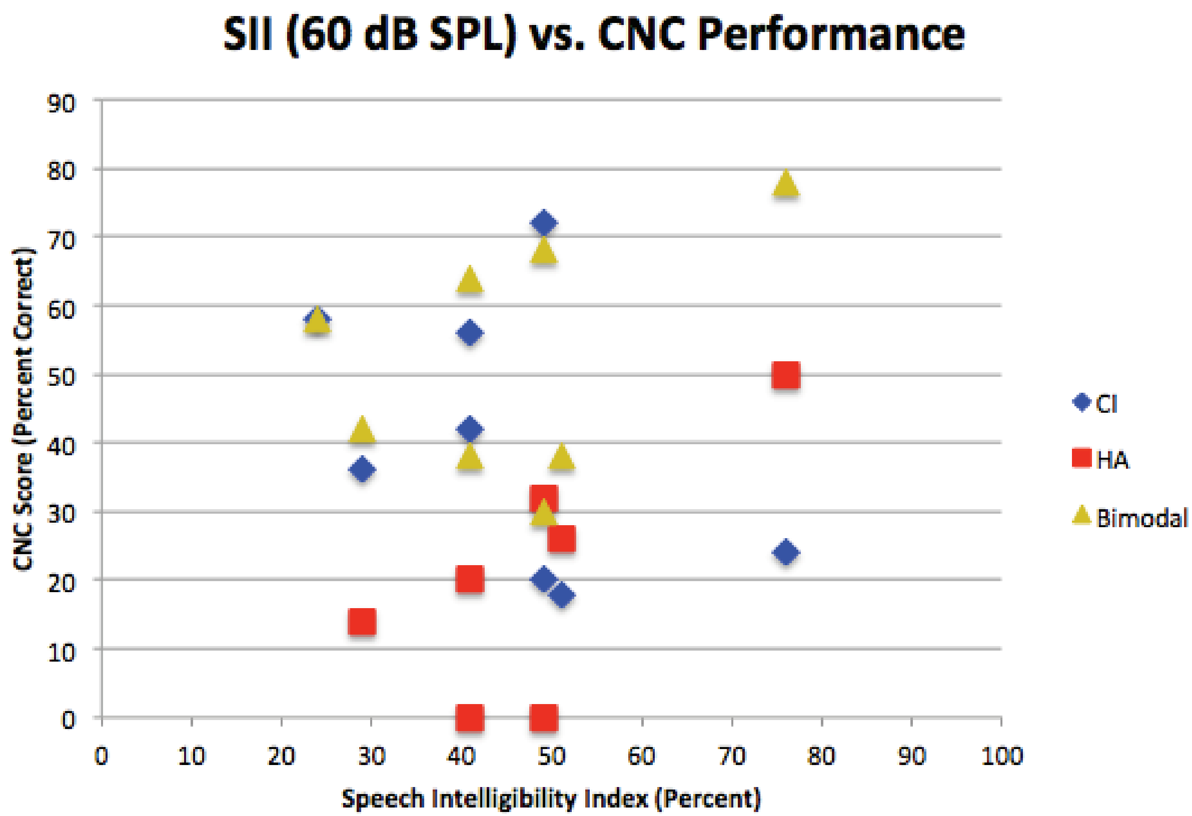


Figure 20. The relationship between SII at 60 dB SPL with a HA on CNC performance is shown for the three conditions. A correlation approaching significance is seen in the HA-only condition (r=0.71, p=0.07).

Figure 21

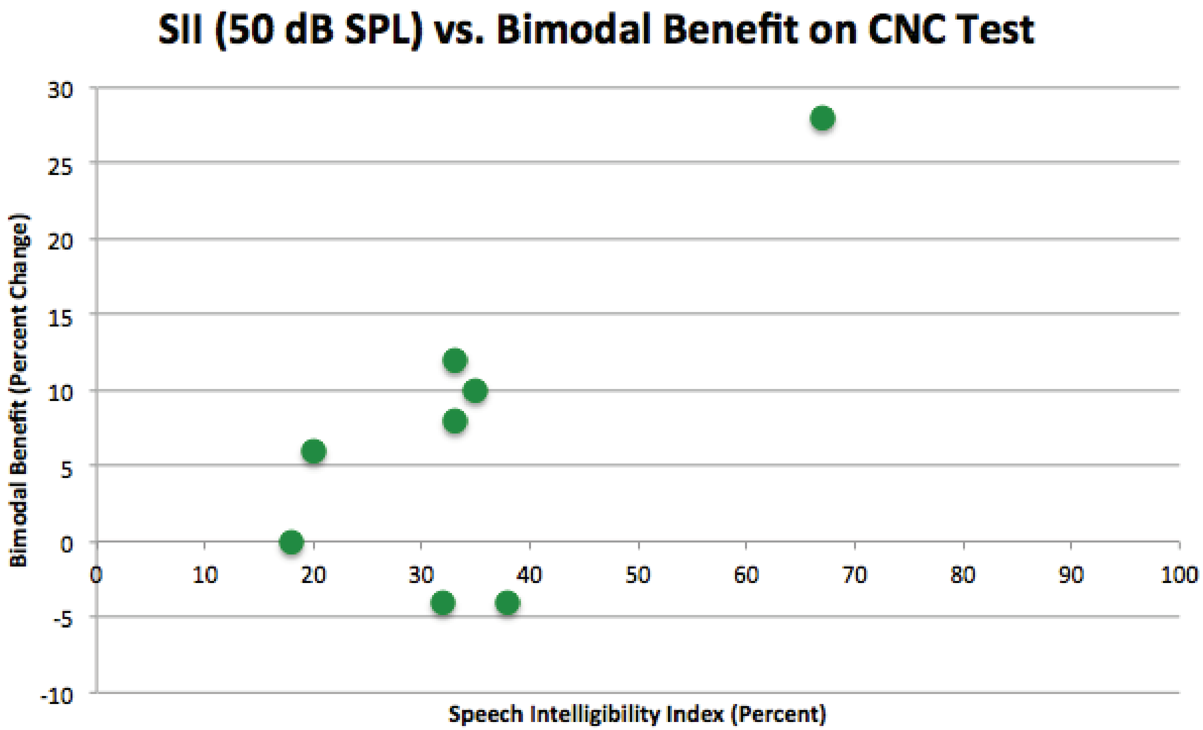


Figure 21. The relationship between SII at 50 dB SPL with a HA on CNC bimodal benefit is shown. A significant correlation is seen (*r*=0.73, *p*=0.04).

Figure 22

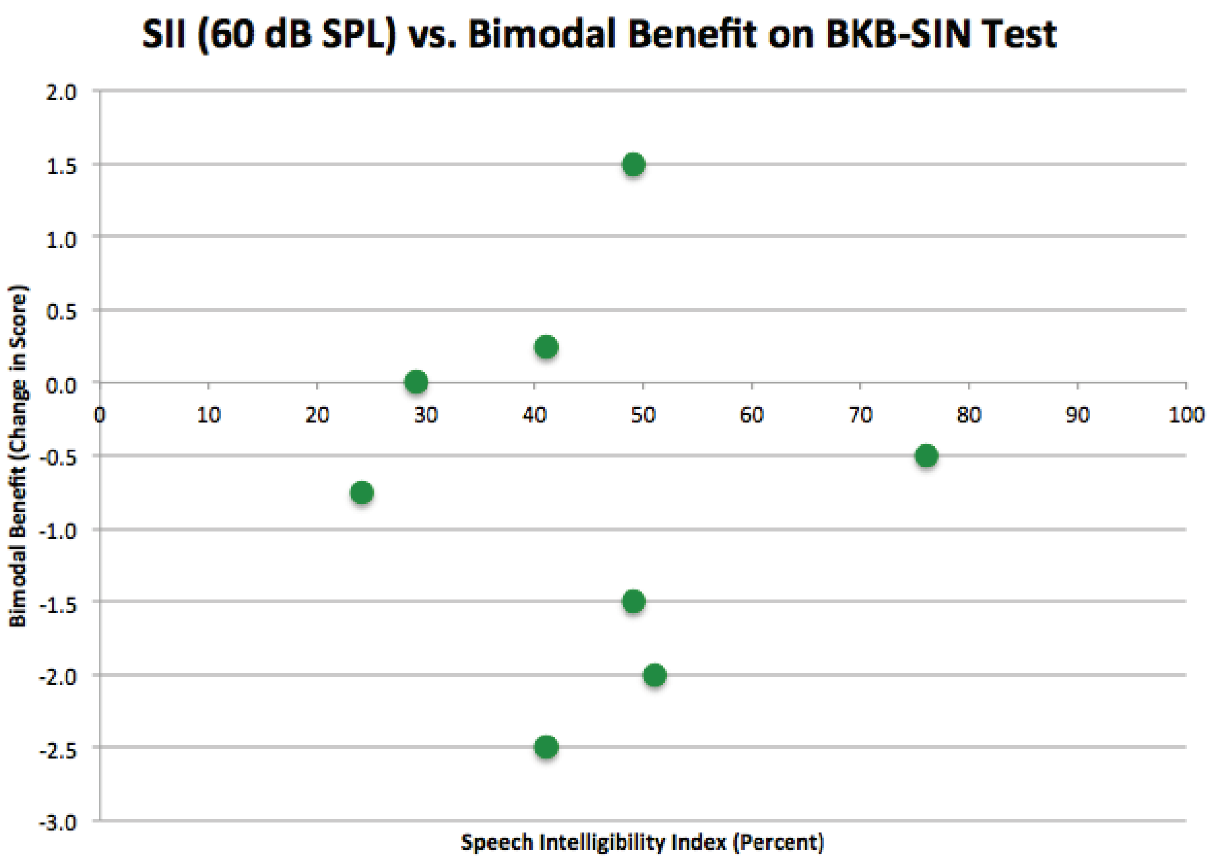


Figure 22. The relationship between SII at 60 dB SPL with a HA on BKB-SIN bimodal benefit is shown. No trend is seen.

Figure 23

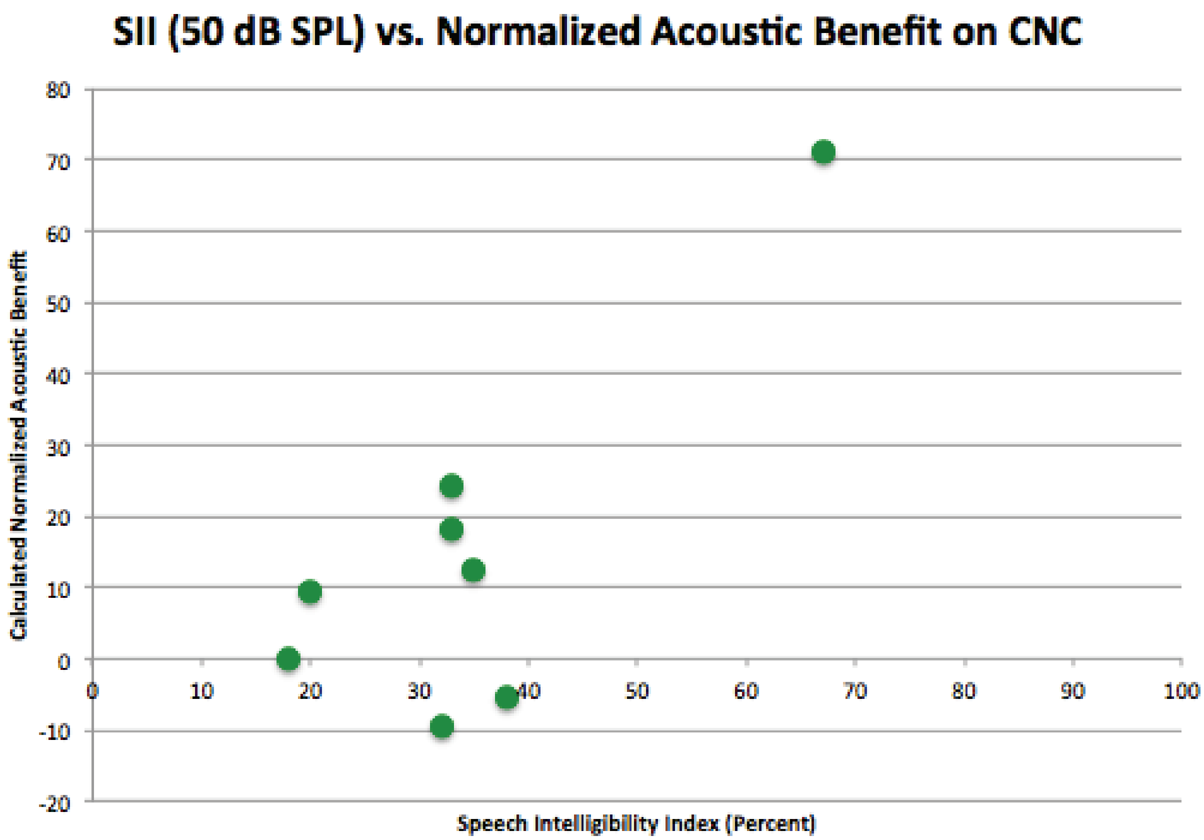


Figure 23. The relationship between SII at 50 dB SPL with a HA on CNC "normalized acoustic benefit" (Zhang, 2013) is shown. A significant correlation is seen (*r*=0.80, *p*=0.02).

Figure 24

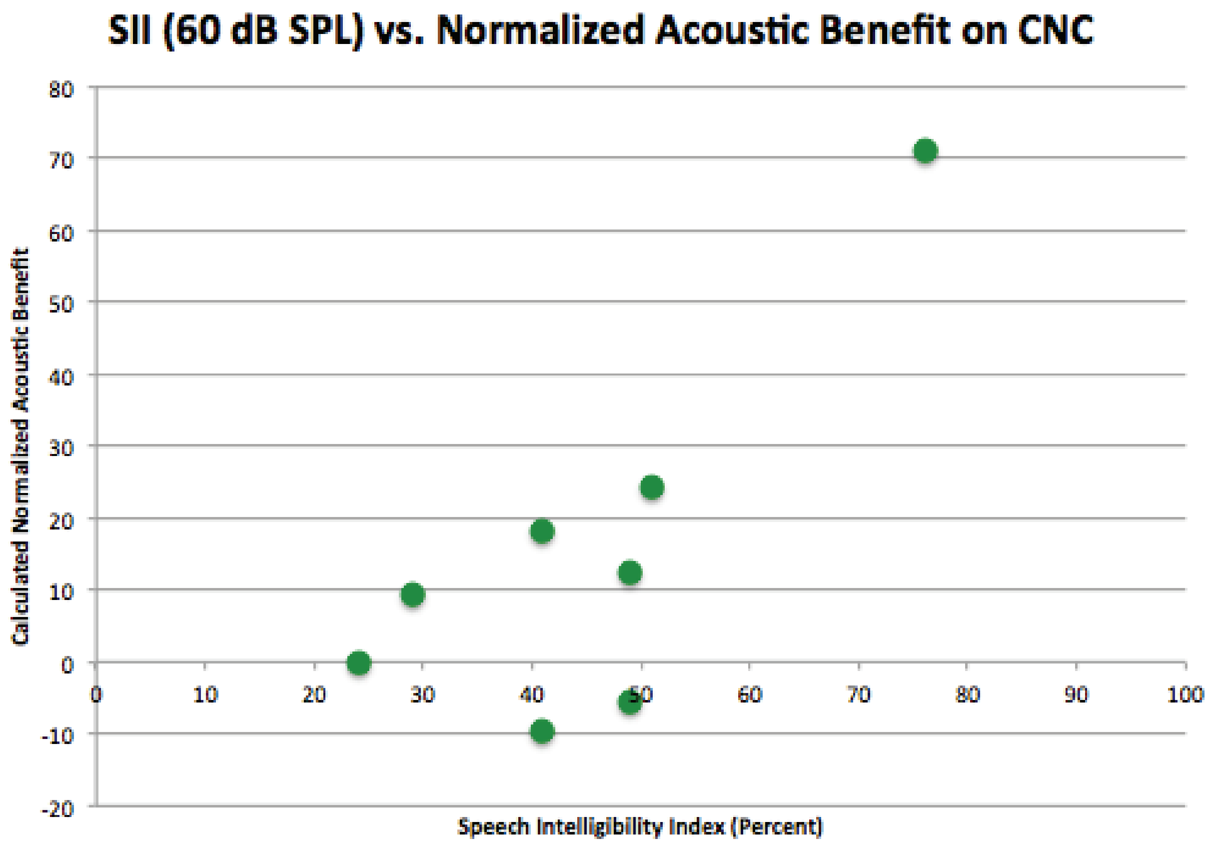


Figure 24. The relationship between SII at 60 dB SPL with a HA on CNC "normalized acoustic benefit" (Zhang, 2013) is shown. A significant correlation is seen (*r*=0.78, *p*=0.02).

Figure 25

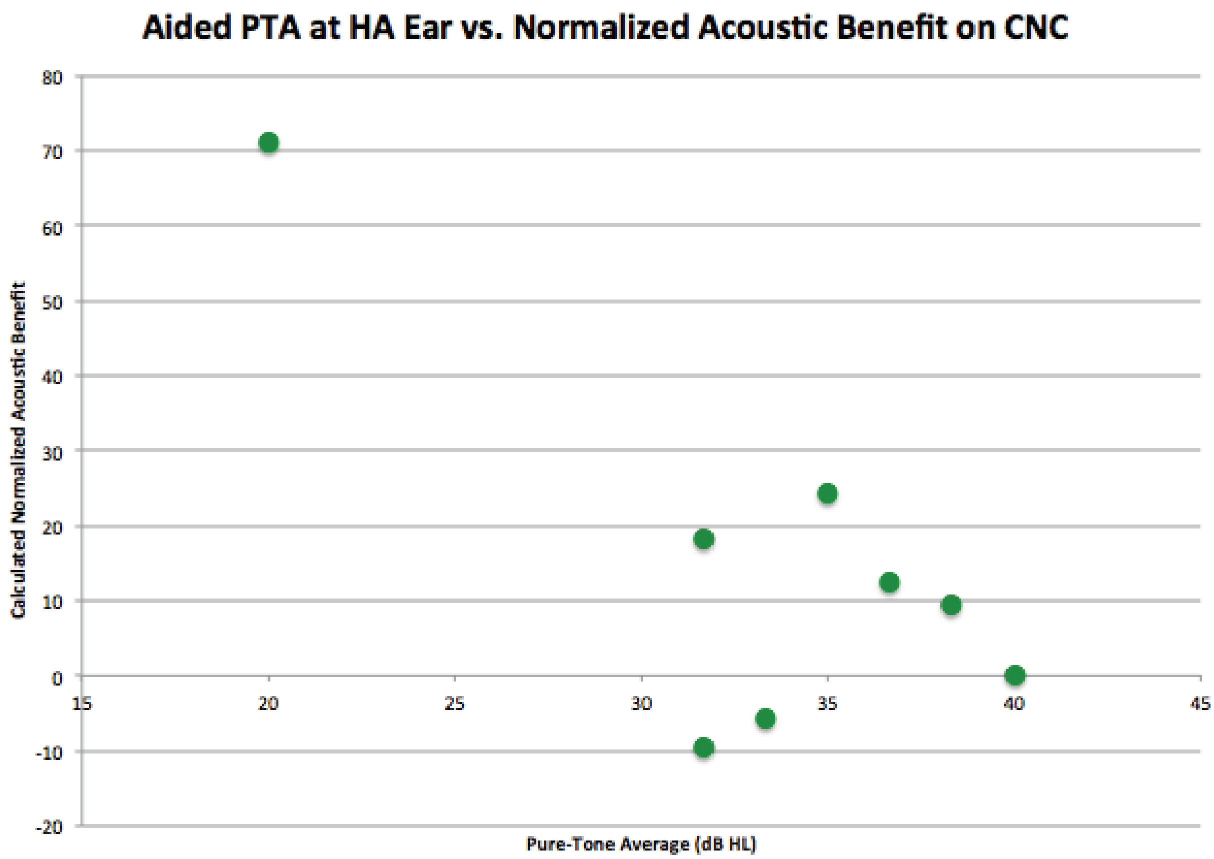


Figure 24. The relationship between aided PTA with a HA on CNC "normalized acoustic benefit" (Zhang, 2013) is shown. A significant correlation is seen (*r*=-0.76, *p*=0.03).