The Value of Two Ears for Sound Source Localization and Speech Understandi

Complex Listening Environments: Two Cochlear Implants vs. Two Partially He

Ears and One Cochlear Implant

by

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ABSTRACT

Two groups of cochlear implant (CI) listeners were tested for sound source localization and for speech recognition in complex listening environments. One group (n=11) wore bilateral CIs and, potentially, had access to interaural level difference (ILD) cues, but not interaural time difference (ITD) cues. The second group (n=12) wore a single CI and had low-frequency acoustic hearing in both the ear contralateral to the CI and in the implanted ear. These 'hearing preservation' listeners, potentially, had access to ITD cues but not to ILD cues. At issue in this dissertation was the value of the two types of information about sound sources, ITDs and ILDs, for localization and for speech perception when speech and noise sources were separated in space. For Experiment 1, normal hearing (NH) listeners and the two groups of CI listeners were tested for sound source localization using a 13 loudspeaker array. For the NH listeners, the mean RMS error for localization was 7 degrees, for the bilateral CI listeners, 20 degrees, and for the hearing preservation listeners, 23 degrees. The scores for the two CI groups did not differ significantly. Thus, both CI groups showed equivalent, but poorer than normal, localization. This outcome using the filtered noise bands for the normal hearing listeners, suggests ILD and ITD cues can support equivalent levels of localization. For Experiment 2, the two groups of CI listeners were tested for speech recognition in noise when the noise sources and targets were spatially separated in a simulated 'restaurant' environment and in two versions of a 'cocktail party' environment. At issue was whether either CI group would show benefits from binaural hearing, i.e., better performance when the noise and targets were separated in space. Neither of the CI groups showed spatial release from masking. However, both groups showed a significant binaural advantage (a combination

of squelch and summation), which also maintained separation of the target and noise, indicating the presence of some binaural processing or 'unmasking' of speech in noise. Finally, localization ability in Experiment 1 was not correlated with binaural advantage in Experiment 2.

DEDICATION

To my mother who has become a victim of Alzheimer’s Disease. She was so enthusiastic, supportive, and proud when I embarked on this journey. Tragically, she is now unable to grasp my accomplishment. Her support was monumental.

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BENEFITS OF BINAURAL HEARING

General Background

Cochlear implants have proven to be a very effective treatment for the restoration of hearing in people with significant hearing loss who receive poor or minimal benefit from hearing aids. It is estimated that 219,000 people worldwide have received a cochlear implant. The FDA estimates that 42,600 adults and 28,400 children have received cochlear implants in the United States (NIDCD 2011). Until relatively recently, a single ear was implanted. The difficulties associated with unilateral hearing are: 1) difficulty understanding on the impaired side when the normal ear receives competing noise, 2) difficulty understanding on the impaired side even when the normal ear receives no competing noise, and 3) difficulty understanding in quiet or noise regardless of location of the source of sound in the azimuth or horizontal plane (Giolas and Wark 1967, Bess and Tharpe 1986). For people with a unilateral cochlear implant, the difficulties would be the same except that the "normal" side would be their implanted side with no usable hearing contralateral to the implant. Just as many hearing impaired people use two hearing aids rather than one, an increasing number of people have been implanted bilaterally, potentially to offset the difficulties of listening with one ear.

Patients with Bilateral CIs

Bilateral implantation has gained momentum as providing superior benefits compared to a single CI. In response to third party payers seeking justification for bilateral CIs, the William House Cochlear Implant Study Group (CISG) reviewed the benefits of bilateral implantation and issued a position statement in 2008, "Bilateral CI is now considered as an accepted medical practice." While the merits of bilateral cochlear implants are not in question, there is a scientific obligation to determine if two really are better than one for all potential candidates.

The benefits for bilateral users are well documented in terms of speech understanding compared to a unilateral implant. For example, Buss et al. (2008) reported an 11% increase in CNC word scores for bilateral users compared to their better unilateral ear. Chang et al. (2010) reported CNC scores for bilateral users of 65% at 24 months post implantation which is approximately 10 percentage points higher than average scores for a unilateral implant. They reported that across studies bilateral scores are 5-20% better than unilateral scores. Additional benefits obtained using two implants include better sound source localization and improved speech understanding both in quiet and in noise, often referred to as benefits of binaural processing (Buss et al., 2008; Dunn et al., 2008; Eapen et al., 2009; Grantham et al., 2007; Litovsky et al., 2006; Ricketts et al., 2006; Tyler, 2006).

Patients with Bilateral Low Frequency Hearing and One CI

A new group of cochlear implant (CI) users has emerged. These patients benefit from hearing preservation surgery and have low frequency (LF) acoustic hearing in the implanted ear as well as LF hearing in the contralateral ear. Both MED-EL Corp. and Cochlear Corp. have clinical trials to preserve hearing and refer to their users as: EAS® for electric and acoustic stimulation in the same ear by MED-EL Corp. and Hybrid, referring to the combined use of electric and acoustic stimulation in the same ear by Cochlear Corp. Others are implanted "off label" to preserve hearing but have not participated in either manufacturer's clinical trials. To simplify for clarity in the remainder of this paper patients who receive both acoustic and electric stimulation in the same ear and continue to use acoustic, low frequency hearing contralateral to the CI will be referred to as 'hearing preservation' patients.

The reported benefits of hearing preservation compared to bilateral (two CIs) and/or bimodal (CI + contralateral HA) benefit are mixed. To date, there is a paucity of research on binaural processing in hearing preservation users. Gifford (2010) has data using R Space™, a surround sound setting using multiple noise sources (Revitt et al., 2007). Speech reception thresholds (SRT) were obtained in R Space™ using the Hearing-in-Noise-Test (Nilsson et al., 1994) sentences adaptively. Results were not significantly different between bilateral and bimodal users which were in contrast to results obtained in traditional testing paradigms. Gifford also tested listeners with hearing preservation. This group showed the greatest benefit. The addition of low frequency hearing from both ears provided a significant improvement of 2.9dB for the hearing preservation group compared to either the bimodal or bilateral groups. Litovsky et al. (2006) showed that a change of 3dB in the signal-to-noise ratio (SNR) resulted in an improvement in understanding of 28%.

Mechanisms Underlying the Benefits of Binaural Hearing

If one looks at the attributes of listening with two ears *vs.* one ear in normal hearing (NH) individuals, benefits of binaural hearing include better understanding in noise, spatial release from masking, and the ability to localize (Hirsh,1948; Licklider, 1948; Hirsh,1950; Koenig,1950; Kock,1950; Cherry,1953; Duralch,1963; Bronkhorst and

Plomp,1988; Yost, Dye, and Sheft,1996; see Bronkhorst, 2000; Middlebrooks and Green, 1991). Other benefits include the head shadow effect, binaural summation or redundancy, and binaural squelch (Durlach & Colburn,1978; Schleich et al., 2004; Middlebrooks and Green,1991; Koenig,1950; Shaw, Newman, & Hirsh,1947).

The head shadow effect is a physical, monaural ear effect and typically is not thought of as a central effect. However the listener must attend to the ear with the better SNR to receive benefit indicating there is a central component. It has also been called the better ear effect. Middlebrooks and Green (1991) found that the head shadow could create as much as a 35dB difference between the two ears when a noise source was presented from the side (90º). Results indicated that the head shadow can provide a great deal of damping and may be very beneficial in noise where one ear is shadowed from the noise and enjoys an improved SNR. Bronkhorst and Plomp (1988) described head shadow based on the angle of the noise presented and the type of noise used. They reported head shadow benefit averaged over five lateral angles of presentation of noise. Head shadow ranged from 8.1dB with free filed noise, 5.5 dB using noise with ILD information, and 4.6dB with noise using ITD information. Litovsky et al. (2006) reported head shadow benefit of approximately 5dB in bilateral CI patients which is less than the 8dB reported for normal hearing listeners with free field noise by Bronkhorst and Plomp (1988).

The binaural summation effect , or binaural redundancy, is the advantage of listening with two ears versus one when the signal is presented diotically. Binaural summation does not require the target to be separated in space from the masker. There is a binaural component, not just a better ear effect. The auditory system is able to have two “looks” at the signal, and therefore, can extract more information than if it receives a single ”look,” assuming the looks are independent (i.e., a maximum gain would be 3dB). Shaw, Newman, and Hirsh (1947) reported that the difference between monaural *vs.* binaural intelligibility for speech is 3dB. Schleich et al. (2004) calculated the summation effect for normal hearing listeners based on the work of Bronkhorst & Plomp,1989; Cox et al.,1981; and MacKeith & Coles,1971. Schleich et al. estimated summation to be in the range of 1.1 – 1.9dB. Litovsky et al. (2006) displayed a figure which estimates that CI listeners had summation effects of approximately 2dB.

Binaural squelch, also known as binaural intelligibility difference or binaural unmasking, is an improvement in speech understanding in noise due to spatial separation of the speech from the noise (Schleich et al., 2004). Understanding is improved when adding in the ear with the poorest SNR, e.g. the ear toward the noise. The importance of binaural squelch is the ability to “unmask” speech in a background of noise. The binaural squelch effect is due to a central processing mechanism and necessitates the processing of interaural time and level differences between the two ears. Senn et al. (2005) contended that “central processing of interaural time and level differences between the two ears is mandatory to take advantage of the binaural squelch effect.” For normal hearing listeners Bronkhorst and Plomp (1988) reported that squelch ranged from 2 – 9 dB depending on the speech materials used. Squelch was lower for monosyllabic words, 1.9 - 3.7dB, medium for SRT, 4 – 7dB, and highest for numbers from a limited set, 5 – 9dB. Schleich et al. (2004) estimated the squelch effect is in the range of 2 – 4.9dB based on the work of Arsenault & Punch,1999; Carhart,1965; and MacKeith & Coles,1971. Litovsky et al. (2006) reported squelch for bilateral CI listeners at close to 2dB.

ILDs and ITDs

Interaural level differences (ILD) and interaural time differences (ITD) are known to provide NH listeners with the ability to localize and are thought to be the underlying mechanisms that provide spatial release from masking. Spatial release improves understanding in noise when the speech and noise are separated in space compared to speech and noise emanating from a single location. ITDs provide an unambiguous cue in the low frequencies (LF) below 800Hz. ILDs are large in the high frequencies (HF) above 1500Hz and very small, less than 5dB, under 500Hz (Blauert,1997). If sounds are filtered eliminating high frequency components (one of the operations in this dissertation), the assumption is that ITD cues are the cues used for sound source localization. Conversely, if low frequency components of a sound are eliminated, then ILD cues would underlie sound source localization.

Differential Access to ILDs and ITDs by Bilateral CI and Hearing Preservation Listeners

Grantham et al. (2007) measured sound source localization abilities to noise stimuli in bilateral MED-EL, Combi 40+ patients. RMS error was calculated for unilateral and bilateral listening. Errors were 30º for bilateral CI listeners, 76º for unilateral CI listeners (chance was 72º), and 7º for normal hearing listeners. In a second experiment, stimuli were filtered to determine the contribution of ILD and ITD cues to sound source localization. The logic was that filtering limits access to cues. As explained previously, low-pass (LP) filtering would force listeners to use ITD cues. High pass (HP) filtering would force listeners to use ILD cues. RMS errors were not provided but adjusted constant error scores of approximately 15º were reported for HP stimuli. When LP information was removed from the stimulus, performance doubled with errors of 29º. The inference is that ITD cues are not available to bilateral CI listeners.

Hearing preservation patients should have access to ITD cues given their bilateral, low frequency, acoustic hearing. Indeed, Gifford et al. (2013) reports hearing preservation listeners are able to resolve ITDs, although not as well as normal hearing listeners. Because hearing preservation listeners have high frequency hearing only in the implanted ear, not in both ears, they should not have access to ILD cues. A study by Dunn et al. (2010) reported that Cochlear Corp., hearing preservation patients could localize with errors similar to those found for bilateral CI patients, estimated at 25 degrees of error. That study did not report the frequency composition of the sound sources used making it difficult to definitively determine which cues were used in sound source localization. However, due to the absence of high frequency hearing in the unimplanted ear, one can infer that only ITD cues were available.

A New Coding Strategy May Allow Access to ITD Cues for Bilateral CI Listeners

As described earlier, nature has provided groups of cochlear implant patients who, in theory, have access to either ITD or ILD cues, but not both. Bilateral CI users appear to use ILD cues for sound source localization but lack access to ITD cues (Grantham et al., 2007). However, access to ITD cues may change given a new speech coding strategy from MED-EL Corporation termed Fine Structure Processing (FSP™). That strategy was not available when Grantham et al., (2007, 2008) measured sound source localization. To date, there have been no reports on whether this strategy can provide ITD cues.

One of the features of FSP™ is to expand the frequency range down to 70Hz to capture the fundamental frequency. FSP™ provides temporal cues, in addition to, envelope cues in the low frequency region of the speech signal.

The standard implementation of CIs is based on continuous interleaved sampling or the CIS strategy (Figure 1). "The CIS strategy filters incoming sounds into bands of frequencies with a bank of bandpass filters (12-22 bands depending on the manufacturer). Envelope variations in the different bands are represented at corresponding electrodes in the cochlea with modulated trains of biphasic electrical pulses. The envelope signals extracted from the bandpass filters are compressed with a nonlinear mapping function prior to the modulation, to map the wide dynamic range of sound into the narrow dynamic range of electrically evoked hearing. The output of each bandpass is directed to a single electrode, with low to high channels assigned to apical to basal electrodes, to mimic… the frequency mapping in the normal cochlea. The pulse trains for the different electrodes are interleaved in time to eliminate channel interaction." (Wilson and Dorman, 2012).

In the early 1990's the Research Triangle Institute created the precursor to what is now MED-EL Corporation's new speech coding strategy, fine structure processing or FSP™. In the early representation of FSP™, fine structure was represented using stimulus pulses at the times of the detected peaks or zero crossings in the output of the bandpass filters on channels with low center frequencies (Wilson and Dorman 2012). At that time it was called a “peak picker/CIS” strategy.

In the standard implementation of cochlear implants, the pulse train is continuous. In the current FSP™ strategy, bursts of pulse packets follow the zero crossing shown in Figure 2. This may better define the intervals in the time domain and possibly provide a better timing cue between ears. The marking of the zero crossings is to cue the auditory system to the rate of incoming low-frequency sounds. In other words, rate is a cue in addition to the place of stimulation being a cue.

One of the goals in this dissertation was to test whether FSP™ does, in fact, allow bilateral CI listeners to access ITD cues for sound source localization.

Aims and Hypotheses

The operating hypotheses of this dissertation were that (i) bilateral CI and hearing preservation listeners would localize using different cues, i.e. bilateral CI listeners would demonstrate access to ILD cues and hearing preservation listeners would demonstrate access to ITD cues, and (ii) hearing preservation listeners would demonstrate binaural processing abilities, particularly for “unmasking” speech in noise due to ITD cues, but that the bilateral CI listeners would not demonstrate benefit from binaural processing due to a lack of ITD cues.

The specific aims of this research were to determine (i) which cue, ITD or ILD, is available to bilateral CI users and hearing preservation users by evaluating sound source localization abilities using filtered noise sources of different spectral content: low-pass

(LP), high-pass (HP), and wideband (WB) stimuli (**Experiment 1)**, (ii) if either group benefits from binaural hearing (**Experiment 2)** and whether access to ITD or ILD cues is more beneficial, (iii) whether bilateral hearing for either group provides greater benefit when the target is not stationary and the signal to noise ratio is poor **(Experiment 3)**, (iv) if preserving hearing in the implanted ear is beneficial for the hearing preservation group **(Experiment 2)**.

SOUND SOURCE LOCALIZATION

Literature Review

Normal Hearing Listeners

John William Strutt, better known as Lord Rayleigh (1907), is credited with the "duplex" theory of localization (see Middlebrooks and Green 1991). Rayleigh calculated when a sound was presented from the side, the listener's head disrupted the path of sound to the far ear. Rayleigh noted this was frequency dependent and the head provided greater shadowing in the higher frequencies resulting in differences in intensity between the two ears, i.e. interaural level differences (ILD). Rayleigh also computed the ILDs in the low frequency region and showed they were negligible. Rayleigh stated "When a pure tone of low pitch is recognized as being on the right or the left, the only alternative to the intensity theory is to suppose that the judgment is founded upon the difference of phases at the two ears." The duplex theory states broadly that spatial information is derived at high frequencies from ILD cues and at low frequencies from ITD cues. Stevens and Newman (1936) also found that sound source localization was frequency dependent. Their results were in good agreement with the duplex theory. Stevens and Newman found that sound source localization errors were greatest at 3000Hz where neither ITD nor ILD cues are beneficial in determining sound source location consistent with the duplex theory.

Lorenzi et al. (1999) evaluated NH listeners and their ability to localize in quiet and in noise. They found sound source localization accuracy was unaffected by noise if the SNR was 0dB or better regardless of whether the noise was presented at 0° or 90º azimuth. In addition, both LF and HF cues were equally affected when noise was presented at 0°; however, LF cues were more susceptible to noise than HF cues when the noise was presented at 90° azimuth. When both LF and HF cues were available and noise was presented at 90°, listeners used HF cues to determine sound source location.

Good and Gilkey (1996) evaluated NH listeners in quiet and in noise. They measured errors in three planes, left/right, up/down, and front/back. They found that sound source localization judgments systematically decreased as the SNR became poorer. They used a broadband click-train signal in quiet and in a broadband noise; the SNR varied from quiet to -10dB SNR. In the median plane, left/right errors were unaffected by noise until the SNR became negative.

Van den Bogaert et al. (2006) tested NH listeners on sound source localization to use as a reference for hearing impaired subjects. Results showed better performance to LF than HF narrow bands of stimuli with average root mean square (RMS) errors of 13.5° and 21.3° respectively. Performance was best to a broadband signal; the RMS error was 6.8°. Van den Bogaert et al. offered an explanation for the improved sound source localization ability in the broadband condition – listeners were able to access both ITD and ILD cues.

Yost et al. (in press) tested 45 NH listeners on sound source localization in the horizontal plane using a 13 loud speaker array. Noise bursts of different spectral content, i.e., low-pass (LP), high-pass (HP) and broadband (BB), were presented randomly from different locations. Yost et al. showed no significant differences between the three conditions. RMS errors were: LP = 6.95º, HP = 6.7º, and BB = 5.98º. Contrary to van den Bogaert et al. (2006),who used narrow-band noise, Yost et al. did not find that NH listeners benefitted from combining ITD and ILD cues for the broadband noise used in their study. Sound source localization was not significantly improved in the broadband condition.

Hearing Impaired Listeners

Hearing aids have been shown to (i) improve sound source localization (Boymans et al., 2008), (ii) depress sound source localization (van den Bogaert et al., 2006) and (iii) have no effect on sound source localization (Kobler and Rosenhall, 2002) for hearing-impaired listeners. These conflicting reports are pertinent to the hearing preservation group who usually wear bilateral hearing aids in addition to their implant.

Boymans et al. (2008) conducted pre- and post- tests on bilateral hearing aid users to determine the benefits of binaural hearing. Prior to being fit with hearing aids (HA), subjects were evaluated under headphones on tests of binaural masking level differences (BMLD), ITD, and speech reception thresholds. Results on the BMLD were significantly poorer for the HI group compared to the NH group although they did report that there was overlap between the NH and HI groups. BMLD scores for NH were 17dB and were poorer,12dB, for the HI. ITD measures were significantly poorer for the HI with ITDs of 211µsec compared to 43µsec for the NH listeners. Absolute sound source localization errors were graphed as a percentage of errors; values were not reported. In the bilateral HA condition errors appeared to be about 32% compared to approximately 50% in the unilaterally aided condition. They reported a weak relationship between bilateral HA benefit on sound source localization and speech reception using spatially separated sources.

An opposing view was raised by van den Bogaert et al. (2006) who reported that hearing aids (HA) may not preserve a user's ability to process binaural cues. They reported advanced digital signal processing introduced distortions in the high frequency region affecting ILD cues. Van den Bogaert et al. reported the problem was mainly due to separate monaural hearing aid systems that may alter compression between ears and introduce different noise reduction algorithms, particularly when using adaptive directional microphones. Van den Bogaert et al. compared sound source localization performance for NH and hearing-impaired (HI) listeners using LF and HF narrow bands of noise and a broadband noise (BBN) -- a telephone ringing. The NH performed better than the HI, and the HI performed better without their HA than they did with their HA. The conclusion drawn was that signal processing in two independently operated HAs does not preserve sound source localization cues. This is reminiscent of reported problems with signal processing for bilateral CI users; each speech processor is fit as a monaural device.

Kobler and Rosenhall (2002) compared unaided, monaural, and bilateral HA performance on speech intelligibility and sound source localization. They used an eight loud speaker array surrounding the patient much like the RSpace™ used in the current study. The speech target moved randomly between all eight loud speakers and noise emitted from the other seven loud speakers. The subjects were required to repeat sentences and identify the location of the speaker delivering the sentence. Results showed improved speech intelligibility with bilateral HAs *vs.* unaided listening, a small but significant improvement with bilateral HAs *vs.* unilateral HA , but no improvement on sound source localization using bilateral HAs compared to unaided results.

Lorenzi et al. (1999) studied effects of hearing loss on sound source localization abilities. Lorenzi et al. reported that HI listeners were affected in the same way as NH listeners - when noise was at the side, sound source localization was poorer than when noise was presented from the front. HI listeners were affected at higher SNR than NH listeners. Overall, HI listeners had poorer sound source localization judgments than NH listeners.

Ching et al. (2005) tested bilateral hearing aid users and found that those with LF thresholds of 65dB or better were able to use timing cues. Sentences were delivered dichotically with a delay of 700 μsec to either ear. Ching et al. reported that bilateral hearing aid users had access to ITD cues because timing information was preserved and transmitted with similar delays to each ear. The HI, however, did not perform as well as NH listeners. Ching et al. reported that an impaired auditory system is still able to take advantage of timing/phase cues to facilitate speech understanding. Ching et al. (2007)

reported that time delays in hearing aids are on average less than 5msec and therefore timing information should be well preserved.

The results from the previous studies on sound source localization in hearing impaired listeners are conflicting on whether they are able to localize sound sources better with or without their HAs. The implications for the hearing preservation group ranged from (i) expected improvement on sound source localization with bilateral HAs, (ii) expected decrease in performance with the use of bilateral HAs, or (iii) no difference in performance with and without bilateral HAs. A pilot study was carried out using bilateral hearing aid users to determine whether or not HAs improved or decreased sound source localization performance. No difference was found between aided and unaided sound source localization to LP stimuli. Based on those results the hypothesis for the hearing preservation listeners was that they would not show any benefit or decrease in performance due to their hearing aids.

Bilateral CI Listeners

As previously stated, there is adequate evidence and agreement that bilateral CI users can localize, although not as well as NH listeners, via access to ILD cues (Grantham et al., 2007; Rickets et al., 2006; Litovsky, 2010; and Dunn et al., 2010). Litovsky (2010) reported that RMS errors averaged between 20 - 30° for bilateral users and 50-60° for unilateral listening. Litovsky reported 5 - 10° of error for normal hearing listeners.

ITD cues are absent or poor and are not available to bilateral CI users wearing their clinical processors. This is primarily due to the signal processing of cochlear implants which discards temporal fine structure information (Ching et al., 2007; Loizou et al., 2009; Litovsky et al., 2004; Francart et al., 2008; and Grantham et al., 2008). Some have suggested that ITD cues are also not available because the processors are not matched or synchronized between ears but are fit as independent processors.

To date, there have been no published reports on MED-EL's new speech coding strategy, FSP™, and the availability of ITD cues for bilateral users. Theoretically, users should have access to interaural timing cues using this strategy since FSP™ adds temporal cues. However, processors are not synchronized between ears making access to ITD cues unlikely.

Hearing Preservation Listeners

To date, Dunn et al. (2010) have the only published report on sound source localization in hearing preservation patients. They tested hearing preservation users with a short 10mm electrode on sound source localization and speech perception in noise. They used 16 everyday sounds such as a baby crying, a child laughing, a glass breaking, and a telephone ringing for sound source localization. However, the frequency responses of the various sounds were not reported so it is not possible to determine whether ITD or ILD cues were available for sound source localization. They reported that preserving hearing in the implanted ear provided significantly better sound source localization abilities compared to bimodal users. RMS errors were calculated for four conditions: combined (bilateral HAs plus CI), EAS (CI plus ipsilateral HA), bimodal (CI plus contralateral HA), and bilateral hearing aids (HA) without the CI. Scores were significantly better in the combined condition than in either condition pairing a CI with a single HA, i.e. the EAS or bimodal conditions. Their results showed equivalent sound source localization abilities when listening in the combined condition and the bilateral hearing aid condition. The addition of the CI did not improve nor did it hinder sound source localization. They did not compare sound source localization for aided and unaided listening. Although actual degrees of error were not reported, average RMS error was estimated from figures and was approximately 25° in the combined and bilateral HA conditions. Dunn et al. claimed that having two ears with similar signal processing in the LF enabled listeners to take advantage of ITD cues and also provided fine structure enabling the listeners to "squelch" information and improve understanding in noise. They reported that ITD and ILD cues were available to this population; however, this claim was not substantiated by the study. Without adequate controls, determination of which cues were available to the hearing preservation population remains unanswered.

Rationale for Experiment One

Experiment I was designed to replicate and extend the work of Grantham et al. (2007) and Dunn et al. (2010) by measuring sound source localization abilities in bilateral FSP™ and hearing preservation listeners.

Dunn et al. (2010) inferred that hearing preservation users were able to take advantage of ITD cues in sound source localization. They reported that the CI used in conjunction with a single HA in either ear yielded on average chance performance. However, when both ears were aided and the CI was activated, RMS errors improved to approximately 25°. They did not report the frequency responses of the stimuli used. This experiment extended that study by using filtered noises to determine which cue, ITD and/or ILD, is available to hearing preservation users. This study further extended the work of Dunn et al. by comparing sound source localization in the unaided and aided conditions to determine whether or not HAs (i) improved, (ii) decreased, or (iii) had no effect on sound source localization.

The purpose of Experiment 1 was to evaluate bilateral FSP™ and hearing preservation users' ability to localize. The goal was to determine: (i) which cues, ITD or ILD, were available to bilateral and hearing preservation users, (ii) if the new coding strategy, FSP™ , provided ITD cues to bilateral CI users, (iii) whether there was a difference in sound source localization between aided and unaided results in the hearing preservation group, and (iv) if adding a CI to the unaided or aided conditions in the hearing preservation group altered sound source localization abilities.

Experiment 1

General Methods

Test environment and stimuli. Testing was conducted in an 11' X 15' sound deadened room. The stimuli were presented from a 13 loudspeaker array with an arc of 180˚in the frontal horizontal plane (Figure 3). There was 15º of separation between loud speakers. To reduce edge effects, stimuli were not presented from loud speakers 1 and 13. Listeners were not notified that these two loud speakers were "dummy" speakers.

Three, 200-msec, filtered (48 dB/octave) white Gaussian noise stimuli of different spectral content were presented in random order. Noise stimuli consisted of:

- low-pass (LP) noise filtered from 125-500Hz

- high-pass (HP) noise filtered from 1500-6000 Hz
- wideband (WB) noise filtered from 125-6000 Hz

Presentation of the stimuli was controlled by Matlab. Four blocks of 33 trials each were presented at 65 dBA. Each stimulus (LP, HP, WB) was presented four times per speaker resulting in 132 presentations (11 speakers X 4 blocks X 3 stimuli). Overall level was randomly roved ±2 dB from presentation to presentation to ensure that the level of the loud speakers was not a cue.

Subjects were seated facing the middle speaker (#7) of the 13 loudspeaker array. Speakers were placed 1.67 meters from the listener's head and were at the level of the listener's pinnae.

Prior to testing, a broadband signal was presented at midline and bilateral FSP™ CI listeners adjusted their volume controls to equate loudness between ears. Perceptual centering of an auditory image refers to the perception we experience when we hear a stereo effect; i.e., a sound that is presented to the two ears is heard in the center of the head. Centering is important because if a sound is heard shifted to one side rather than in the center of the head, then binaural sensitivity to ITD and ILD cues will be reduced (Yost,1974; Yost and Dye,1988).

For hearing preservation listeners, a screening was carried out to ensure audibility for each set of stimuli in the unaided conditions. Adjustments were made to ensure comfortable audibility for each noise source. None of the hearing preservation listeners were able to hear the high-pass stimuli without their CI due to the severity of their high frequency hearing loss. Therefore, the high-pass condition was eliminated for the unaided and aided conditions without the CI but was administered in the unaided and aided conditions using the CI.

A practice trial was provided to ensure (i) understanding of the test protocol and (ii) that the stimuli were audible. Subjects were instructed to look at a red dot on the center speaker (speaker #7) at midline until a stimulus was presented. Subjects were monitored via a webcam to ensure that they looked at the mid line prior to presentation of the stimuli. Each subject identified the speaker of the sound source by pushing a button on a numbered keypad corresponding to the number of the loud speaker. They were instructed to look at the red dot as soon as they pressed the enter button so that they would be looking at midline when the next stimulus was presented. During the practice trial stimuli were played in consecutive order beginning with speaker #2 and stopping at speaker #12. Subjects were able to repeat the practice condition as many times as needed to feel comfortable with the test and using the keypad. Each subject was reinstructed prior to the actual sound source localization test that the sounds would be presented randomly from any speaker and not in order as in the practice test.

Pilot Study 1

Normal hearing listeners – the effect of age. A total of 34 listeners, normal hearing (NH) young listeners and mature listeners with age appropriate hearing, were evaluated on sound source localization ability to determine if age caused changes in sound source localization abilities. Listeners were divided into two groups: younger (n = 22), ages 22-40 years, and older (n = 12), ages 41-70 years. The stimuli were low-pass

(LP), high-pass (HP), and wideband (WB) noise signals. There were no differences for sound source localization based on age for LP or WB stimuli. HP errors were different between groups [t(34) = 2.344, p = .025]. The HP condition was not the condition of interest so that differences between the two groups were not relevant to this study. Mean RMS error in degrees were:

	LP	HP	WB
Young NH listeners	7.80	7.16	6.64
	(sd:1.69)	(sd:1.99)	(sd:2.23)
Mature NH listeners	8.82	9.32	6.51
	(sd:2.47)	(sd:3.58)	(sd:1.03)

NH listeners - a large N study. In order to have a good estimate of variability for sound source localization abilities for NH listeners, 45 young, NH subjects were tested with the LP, HP, and WB stimuli. Mean scores were LP = 6.95º (sd:1.95), HP = 6.7º(sd:2.61), and WB = 5.98º (sd:2.72), (Yost et al., in press). No main effect of filter condition was found for the three measures at a .05 level of significance. Results for the three conditions are plotted in Figure 4. Given that age was not a factor (see Pilot Study 1) for LP or WB stimuli, this large young group became the normative sample for this dissertation.

Pilot Study 2

Bilateral hearing aid users. This study was carried out to determine if hearing aids (HA) altered sound source localization performance for people with bilaterally symmetric hearing loss. This was of interest because most hearing preservation listeners use bilateral hearing aids in addition to their CI.

Eighteen bilateral HA users participated and were evaluated on sound source localization with and without their HA. Nine females and nine males between the ages of 40 – 87 comprised the bilateral HA group. As in Pilot Study 1 the listeners were presented LP, HP, and WB noise stimuli in the sound source localization experiment.

Subjects were recruited from local dispensing practices and wore matched HA, i.e., hearing aids that were the same make and model on both ears. Listeners had ski slope hearing losses that ranged between normal and moderate in the low frequencies and mild to severe in the high frequencies. Hearing losses were similar to the hearing preservation group in the low frequency range but were significantly better in the mid-to-high frequencies. Mean scores for sound source localization (rms errors in degrees) were:

	LP	HP	WB
Unaided	14.99	19.16	15.56
	(sd:8.59)	(sd:8.37)	(sd:9.88)
Aided	16.38	21.04	13.32
	(sd:7.33)	(sd:7.75)	(sd:7.22)

A 2x3 repeated measures analysis of variance (ANOVA) revealed no effect of aided conditions ($p = .776$) but a main effect of stimuli [$F(2,14) = 6.206$, $p = .012$] and no interaction between aided/unaided and stimuli. Post hoc paired samples t tests (2 tailed) revealed that LP and WB were not different ($p=.189$) but HP was significantly poorer than LP [$t(15) = 2.679$, $p =.017$] and WB [$t(15) = 3.59$, $p = .003$]. Consequently, the prediction for the hearing preservation patients was that performance would not be altered based on the use of HAs.

Subjects

Bilateral CI listeners. A total of 16 adult CI users were tested. Eleven used bilateral Opus 2 processors with the FSP™ coding strategy. As noted previously, FSP™ may preserve temporal cues better than non-FSP™ processing strategies. Five subjects used MED-EL's CIS (non-FSP) coding strategy in their signal processors. Poor sound source localization ability using a single processor has previously been established (Grantham et al., 2007, van Hoesel et al., 2002), and therefore, unilateral scores were not obtained. All subjects were tested in the bilateral condition and were not allowed to alter settings during testing. All but two participants had at least one year of CI use. Demographics for bilateral users are shown in Table 1 and include age, gender, age of onset of deafness, etiology, length of CI use per ear, frequency allocation ranges, number of active channels, and number of FSP™ channels. The non-FSP subjects were similar to the subjects that Grantham et al. (2007) tested. These subjects provided a comparison between their study and the outcomes for this dissertation.

Hearing preservation listeners. Twelve adult CI users with hearing preservation in the implanted ear were recruited from centers using the MED-EL or Cochlear devices. Subjects had been, or were, enrolled in MED-EL's EAS clinical trials or Cochlear's Hybrid clinical trials. Two subjects did not participate in either clinical trial but had preserved hearing in the implanted ear. All hearing preservation participants had low frequency hearing in both ears.

Hearing preservation users were evaluated in the following four conditions which were counter-balanced among subjects: (i) unaided, no CI, (ii) unaided plus CI, (iii) bilaterally aided, no CI, and (iv) bilaterally aided plus CI. Eight subjects had symmetrical LF acoustic hearing with differences no greater than 15dB between ears at 250Hz (Figure 5). Five subjects used the MED-EL device and three used the Cochlear device. Four users had asymmetrical LF hearing with differences of 45 - 60dB at 250Hz between ears (Figure 6). Two of the subjects used MED-EL and two used Cochlear devices.

MED-EL processor. The MED-EL Duet processor uses a single, omnidirectional microphone which directs the incoming sound to both the HA and the CI. The HA amplifies LF hearing between 125 - 1000Hz (Helbig et al., 2008) and delivers amplified sound via an earhook to an earmold inserted into the ear canal. The microphone sits on top of the pinna and faces forward.

Cochlear processor. The Cochlear Freedom Hybrid processor uses dual microphones which direct the incoming sound to an in-the-ear HA and the CI. The HA amplifies LF acoustic hearing and delivers sound by connecting the HA to a cable that is connected to the earhook of the processor. The microphones sit on top of the pinna and may be set in an omnidirectional or directional mode.

Hearing aids. All hearing preservation subjects used their own behind-the-ear (BTE) hearing aid in the contralateral ear. Settings on the hearing aids and processors were not changed even if the gain was inadequate or asymmetric between ears. Participants used their everyday settings. All users were tested with a BTE on the contralateral ear except one subject who did not use a hearing aid on either side. That subject did not use hearing aids in either ear due to normal hearing at 250Hz followed by a precipitous drop in hearing. This subject was not tested in the aided conditions. Two subjects had bilateral implants accompanied by bilaterally preserved hearing. Their better CI was used in this research. Demographics for hearing preservation listeners are provided in Table 2. Audiometric thresholds for the symmetrical hearing group are listed in Table 3, and thresholds for the group with asymmetrical hearing loss are listed in Table 4.

All subjects signed informed consents approved by the Arizona State University Institutional Review Board and were compensated for their time.

Results

Root mean square (rms) error in degrees was calculated after Rakerd and Hartman (1986). The D calculation is the overall error of sound source localization and is calculated as: $\mathrm{D(k)} = \sqrt{}[\mathrm{A}^2/M \sum_{i=1}^{M}(ri-k)^2]$. A is the angular separation of the loudspeakers (15º). M is the number of responses, r is the response (1-13) on the i^{th} trial and k is the loudspeaker location (#2 - #12). D is the RMS average of the difference between the location of the source and the location of the response. Chance, or random, error was calculated using a Monte Carlo method of 100 runs of 1000 Monte Carlo trials. The mean chance performance was 73.5˚ with a standard deviation of 3.2˚ for the three noise stimuli. Mean RMS error in degrees for all groups were:

	WB	LP	HP
Normal hearing	5.98 (sd:2.72)	6.95 (sd:1.95)	6.7 (sd:2.61)

Bilateral FSP™ CI	20.32 (sd:6.62)	45.96 (sd:18.65)	19.64 (sd:5.36)
Bilateral non-FSP CI	20.74 (sd:5.71)	37.43 (sd:9.67)	19.44 (sd:3.10)
Hearing preservation$_{symm}$	33.03 (sd:9.05)	23.32 (sd:10.63)	57.77 (sd:22.17)
Hearing preservation$_{asymm}$	49.83 (sd:14.23)	76.48 (sd:20.64)	60.31 (sd:12.27)

Comparisons Between Groups

A mixed design ANOVA with the five groups as the between groups variable and RMS errors for LP, HP, and WB stimuli as the within groups variable. There was a significant main effect of group [$F(4,58) = 106$, $p < .0005$] and a significant interaction between stimuli and groups, [$F(8, 116) = 26.60$, $p < .0005$]. A post hoc Scheffe' test revealed no difference between bilateral FSP™ and non-FSP groups on sound source localization errors ($p= .959$). Post hoc Scheffe' testing revealed a significant difference between all other groups; NH listeners were significantly better than all groups ($p < .0005$). FSP listeners were better localizers than hearing preservation listeners with symmetric hearing, ($p = .04$), and better than hearing preservatric hearing, ($p = .0005$). Non-FSP listeners were better than hearing preservation listeners with symmetric hearing, ($p = .028$), and better than hearing preservation listeners with asymmetric hearing, ($p = .0005$).

Comparison of Stimuli Between Groups

A one way ANOVA was conducted to compare group listening condition on sound source localization abilities to WB , LP, and HP stimuli. There was a main effect of group performance on sound source localization abilities at the $p<.05$ level for the three stimuli, WB: [$F(4,62) = 66.568$, $p. < .001$], LP: [$F(4, 62) = 62.304$, $p. < .001$], and HP: [$F(4, 62) = 81.496$, $p. < .001$]. NH listeners had fewer sound source localization errors to all stimuli than other groups except for the non-FSP listeners in the HP condition, ($p=.088$). Post hoc results are discussed under each stimulus condition.

Wideband stimuli. A post hoc Scheffe' test revealed that bilateral FSP™ and bilateral non-FSP listeners were not significantly different from each other, ($p =1.00$) . Bilateral FSP™ listeners were significantly better at localizing to WB stimuli than the hearing preservation groups, symmetric, ($p =.005$), and asymmetric, ($p < .0005$). Non-FSP were also significantly better than the hearing preservation groups, symmetric, ($p =.029$), and asymmetric, ($p < .0005$). Hearing preservation listeners with symmetric hearing were significantly better than hearing preservation listeners with asymmetric hearing, ($p = .003$).

Low-pass stimuli. Post hoc Scheffe' testing revealed that sound source localization to LP stimuli was not significantly different between FSP™ and non-FSP listeners, ($p = .667$). FSP™ listeners were significantly poorer than hearing preservation listeners with symmetric hearing, ($p = .001$) but significantly better than hearing preservation listeners with asymmetric hearing, ($p < .0005$). Non-FSP listeners were not significantly different from hearing preservation listeners with symmetric hearing, (p =

.231) but were significantly better than hearing preservation listeners with asymmetric hearing, ($p < .0005$). Hearing preservation listeners with symmetric hearing were significantly better than hearing preservation listeners with asymmetric hearing, ($p < .0005$).

High-pass stimuli. Post hoc testing revealed no significant difference between FSP™ and non-FSP™ listeners, ($p = 1.00$). Both groups were significantly better localizers to HP stimuli than the hearing preservation listeners with symmetric, ($p < .0005$), and asymmetric hearing, ($p<.0005$). There was no difference between hearing preservation listeners with symmetric hearing and those with asymmetric hearing, ($p= .993$), when localizing to HP stimuli.

Comparisons Within Groups

A repeated-measures ANOVA was applied to the data for each group using RMS errors as the dependent variables for LP, HP, and WB stimuli. ANOVA determined if the three conditions were significantly different within each group. An alpha level of $p< 0.05$ was used with the Bonferroni correction applied to post-hoc paired-samples t-tests (two-tailed). Table 5 shows the descriptive statistics for each condition for each group.

Normal hearing. The results are shown in Figure 4 and there was no effect of stimulus type for this group.

Bilateral FSP™ listeners. Figure 7 shows the sound source localization errors for each condition. A repeated measures ANOVA [$F(2,20)= 20.408$, $p<.0005$] revealed that the three filtered noise conditions – LP, HP, and WB - were significantly different. Post-hoc paired samples t-tests using the Bonferroni correction indicated that the LP condition was significantly poorer than the HP condition [$t(10) = 5.288$, ($p=.000$)] and the WB condition [t(10) = 4.427 (p=.001)] but that HP and WB were not significantly different [t(10) = .777 (p=.455)]. This was expected since WB incudes HP information and should be comparable to the better of the other two conditions.

Bilateral non-FSP listeners. Figure 8 shows sound source localization errors for each condition. A repeated measures ANOVA, [F(2,8) = 18.719, p = .001], revealed a main effect of stimulus condition. Post hoc paired samples t tests indicated that LP errors were significantly worse than HP errors, [t(4)=4.341, p =.012 and WB errors, [t(4) = 5.336, p = .006]. HP and WB errors were not significantly different, [t(4) = .555, p = .608].

Hearing preservation listeners. Because hearing loss or asymmetry is known to affect sound source localization (Simon 2005), the hearing preservation group was divided into two groups: those with symmetrical LF hearing and those with asymmetries in the LF region, for all statistical analyses.

Hearing preservation with symmetrical hearing. Figure 9 shows sound source localization rms errors for each condition. The everyday listening condition – bilaterally aided plus CI - for the three filtered noise conditions was analyzed using a repeated measures ANOVA. One subject had bilateral CIs and was not tested with a single CI; therefore, those data sets were not included in this analysis. ANOVA showed differences between the three noise conditions, [F(2,12) = 14.87, p=.001]. Post-hoc paired samples t-tests using the Bonferroni correction indicated that the LP condition was significantly better than the HP condition, [t = 4.79 (p=.003)] and was marginally better, [t = 2.40 (p=.053)] than the WB condition. The WB condition was better than the HP condition, [t = 3.213 (p=.018)].

Hearing preservation listeners with asymmetrical hearing loss. Figure 9 shows sound source localization rms errors for the three filtered noise conditions. The everyday listening condition – bilaterally aided plus CI - for the three conditions was analyzed using a repeated measures ANOVA. Mean RMS errors and standard deviations for the four listeners were: LP = 76.48º (sd:20.64), HP = 60.31º (sd: 12.27), and WB = 49.83º (sd:14.23). Results showed no significant differences between the three noise conditions, [F(2,6) = 4.608, p=.061].

The remaining analyses omitted the HP condition since hearing preservation subjects had only one CI and little or no high frequency hearing contralateral to the CI. The HP condition is equivalent to unilateral hearing and, therefore, expected outcomes were that RMS errors for the HP condition would be at chance performance. Additionally, since it has been demonstrated that asymmetrical hearing usually impairs sound source localization abilities, the remainder of the results are from the symmetrical group.

Hearing preservation – effect of HAs. A 2 X 2 (aided *vs.* unaided and LP *vs.* WB) repeated measures ANOVA was calculated to compare aided and unaided results without the CI. Results showed a significance difference for these conditions, [F(3,18)=5.183, p=.009]. Mean RMS errors and standard deviations were: unaided LP = 18.88º (sd:6.0), aided LP = 20.33 (sd: 7.93), unaided WB = 21.36 (sd:12.19), and aided WB = 32.52 (sd:8.86). Paired samples t tests showed no differences between conditions for aided and unaided LP [t = .366 (p = .727)] or between aided and unaided WB [t = 1.71 (p = .138)]. Unlike van den Bogaert et al. (2006) these results did not show that aided responses decreased sound source localization abilities nor did results support the findings of Boymans et al. (2008) that aided responses improved sound source localization abilities. The results from this experiment are in line with Kobler and Rosenhall (2002) who reported that hearing aids made no difference in sound source localization abilities.

Hearing preservation – effect of the CI. A repeated measures ANOVA was used to determine significance between the aided conditions with and without the CI. Significant differences were found between the four conditions: aided LP without CI, aided LP with CI, aided WB without CI, and aided WB with CI, [$F(3, 18) = 3.922$, $p = .026$]. Mean RMS error and standard deviations were: aided LP without the CI = 20.51º (sd:8.15), aided LP with CI = 23.32º (sd:10.63), aided WB without the CI = 30.92º (sd: 8.76), and aided WB with CI = 33.03º (sd: 9.05). Paired samples t-tests showed no difference between aided LP with and without the CI, [$t = 1.134$ ($p = .3$)] and no difference between aided WB with and without the CI,[$t = .542$ ($p = .607$)]. To summarize, the CI does not hinder sound source localization nor does it improve sound source localization scores for the LP or the WB conditions.

Hearing preservation – effect of combining HAs with the CI. The hearing preservation group was adversely affected when using their bilateral hearing aids with their CI which is their normal everyday setting. A paired samples t test showed a significant difference between the unaided and aided WB conditions with the CI, [$t(6) = 2.631$. $p = .039$]. When the CI was combined with the HAs in the WB condition, errors increased by 10º indicating there is an interaction when both devices are used.

Comparisons Between Bilateral CI and Hearing Preservation Listeners with Symmetrical Hearing

An independent t test (2 tailed) was used to compare the WB condition for the bilateral FSP™ listeners and for the hearing preservation listeners. This comparison used their normal everyday settings – bilateral CIs and bilaterally aided plus CI - and provided information regarding whether the two groups had similar abilities for sound source localization. WB was used because it provided the widest range of frequencies, and each group had access to cues specific to their type of hearing within the WB range. Results showed a significant difference, [$t(16) = 2.82$, $p=.012$] between the two groups (Figure 10). RMS errors for the bilateral group were lower (better) than for the hearing preservation group.

An independent t test compared the best condition for each group, i.e. HP for the bilateral FSP™ users and LP in the combined condition for the hearing preservation users. Results were not significantly different, ($t = 1.151$, $p = .266$). These results indicate that the two groups have similar sound source localization abilities despite having access to different cues (Figure 11) . The bilateral listeners were able to localize using ILD cues with the same degree of error that the hearing preservation listeners exhibited when accessing ITD cues for sound source localization.

Discussion

Bilateral CI Listeners. One aim of Experiment 1 was to determine which set of cues, ITD or ILD, were available for bilateral listeners fit with a new coding strategy, FSP™. At issue was whether the new coding strategy provided access to ITD cues. The critical stimulus condition was LP noise because it was assumed that listeners would be forced to use ITD cues for sound source localization.

As shown in Figure 7 most subjects were able to localize to the source of LP stimuli at better than chance levels of performance (Chance = 70º - 77º). The best subject had errors of only 20˚ for LP stimuli which was as good as sound source localization for HP stimuli. Three other bilateral users had errors of 30º, 33º, and 38º. This raised three possibilities: (i) performance was due to the use of ITD cues, (ii) performance was due to head related transfer functions (HRTF), or (iii) performance was due to very small ILD cues in the LF region.

The use of ITD cues. As noted earlier, the FSP™ strategy codes some temporal intervals and, potentially, could provide ITD cues to listeners. Other strategies do not explicitly code these intervals, thus if users fit with CIs that do not code temporal intervals perform as well as FSP listeners, it is not likely that ITD cues are responsible for performance. As shown in Figure 12, FSP listeners and users fit with other devices, tested in a concurrent study, showed similar ranges of performance. This suggested that patients fit with FSP™ are not using ITD cues to localize to LP signals.

HRTF. HRTF is the change in a sound due to the effects of the head, torso, and pinna. One reason that it is highly unlikely that bilateral CI users would be able to make use of HRTFs is that the microphones of the processors sit on top of the pinna and eliminate the combined cues derived from the pinna and the ear canal. Secondly, bilateral CI users generally receive poor spectral representation of the sound by virtue of having a CI. Finally, HRTFs are most sensitive to HF, not LF, which further reduces the probability that HRTFs could account for the better than expected sound source localization to LP stimuli.

Low frequency ILD cues. If FSP™ did not provide timing cues and HRTFs were not available, then the alternative was that usable ILD cues were available in the LP condition. Using KEMAR, signals were measured at the microphone output of the speech processor. As noted in previous reports, small ILDs – less than 5dB - were observed in the low frequency region below 500Hz (Figure 13). These very small ILDs would be further reduced by the 3:1 compression ratio of the automatic gain control on the signal processors and could be compressed further when fit into the limited input dynamic range of the listeners. Although the ILD information available in the LF must have been very minimal, ILDs remain the only viable cue for LP sound source localization.

Hearing Preservation Listeners. A second aim of Experiment 1 was to determine which cues were available to hearing preservation listeners. The critical condition was LP noise because the assumption was that listeners with acoustic hearing would be using ITD cues. The hearing preservation listeners with symmetrical hearing showed errors of 23 degrees suggesting they have access to ITD cues although not with the resolution of NH listeners. It is of interest that the bilateral CI users and the hearing preservation listeners showed similar sound source localization abilities but based, on the one hand, on ILD cues and, on the other hand, on ITD cues.

Neither set of cues was transmitted with fidelity to these listeners -- RMS errors were three times that of NH listeners. Given the previous argument for the bilateral listeners, it's not impossible that this performance was based on ILD cues. However, it seems likely that the listeners would use large magnitude ITD cues rather than the very small ILD cues.

Dunn et al. (2010) also obtained RMS errors of approximately 25º for sound source localization to WB stimuli by hearing preservation listeners. Because the stimuli were WB, listeners potentially had access to both ITD and ILD cues. The LP stimuli in the present experiment eliminated the possibility of using ILD cues for sound source localization and puts the inference of ITD use on firmer ground.

As stated previously, the hearing preservation listeners were separated into two groups: symmetrical (n=8) and asymmetrical (n=4) acoustic hearing loss. Listeners with asymmetrical LF hearing loss showed sound source localization to LP stimuli that was at chance levels (70º - 77º) of performance. It's clear from examining Figure 9 that the patients with asymmetrical hearing loss were much poorer than the patients with symmetrical hearing. One practical consequence is that potential hearing preservation patients should be told that they will localize only if they have symmetrical hearing. An asymmetry in hearing alters ILD cues and potentially ITD cues. The mechanism underlying this is not particularly clear, but fine temporal resolution is known to be impaired in patients with hearing loss (Moore, 2008).

***Adding a CI to bilateral HAs impairs sound source localization*.** When the unaided and aided plus CI in the WB conditions were compared, errors increased by 10º with the addition of bilateral hearing aids. It's of interest that adding a CI to two HAs makes sound source localization poorer since this is the normal everyday wearing setting. This is not surprising because the ILDs have to be greatly altered by having a CI only on one side. This was not reported by Dunn et al. (2010). They compared aided conditions with and without the CI but did not compare unaided and aided conditions with the CI.

Summary

In summary, Figure 11 shows that both bilateral FSP™ listeners and hearing preservation listeners, with symmetrical LF hearing, have the same sound source localization abilities using different cues. The bilateral listeners were able to localize to HP stimuli indicating that they have access to ILD cues. Some bilateral listeners had surprisingly good sound source localization abilities to LP sound sources which appear to be due to very small ILD cues. The hearing preservation listeners with symmetrical hearing were able to localize to LP stimuli indicating that they have access to ITD cues. Two observations were made about the hearing preservation listeners. The first observation was that the group with symmetrical hearing showed a decrease in sound source localization performance to WB stimuli when the CI was combined with bilateral HAs. The magnitude of ILD cues on the CI side, and the lack of ILD cues contralaterally, appear to create an adverse effect for some listeners when determining sound source localization. The second observation was that the group with asymmetric hearing loss were very poor localizers, presumably because they have very reduced access to either cue, ITD or ILD.

SPEECH PERCEPTION IN NOISE

Literature Review

There are many different measures of CI benefit for perceiving speech in noise reported in the literature. The various CI groups, unilateral, bilateral, bimodal, and hearing preservation listeners, have been compared on CNC word scores, various sentence materials in quiet and in noise, adaptive procedures, and different sound source localization measures. Some measures used a direct connection to the CI speech processor, some used head related transfer functions over earphones, while other measures were carried out in a sound field using the speech processor(s) and hearing aid(s) as they are worn normally by the user. Because of different test materials and different test paradigms, comparisons between studies are difficult. Not all research is in agreement as to the mechanism underlying the benefits of bilateral CI users, and there is little published research on the mechanisms that provide hearing preservation users with benefit aside from the synergistic effect of combining acoustic and electric hearing (von Ilberg et al., 1999; Wilson, 2012) and the benefit of voice pitch information (Zhang et al., 2010).

Cochlear implant (CI) studies have shown that both bilateral and bimodal (a CI in one ear and a hearing aid in the contralateral ear) benefits are superior to a single implant alone on various speech perception measures (Buss et al., 2008; Dorman and Gifford, 2010; Dorman et al., 2008; Dunn et al., 2008; Grantham et al., 2007; Litovsky et al., 2006; Luntz et al., 2005; Morera et al., 2005; Ricketts et al., 2006; Tyler 2006; Zhang et al., 2010). Hearing preservation CI users, a relatively new group of implant users, have emerged with well documented benefits in terms of speech intelligibility and music appreciation **(**von Ilberg et al.,1999; Gantz et al., 2009; Kieffer et al., 2005; Gstoettner et al., 2004) but less well documented benefits for availability of binaural hearing. Recently, Dorman and Gifford (2010) published reports on hearing preservation listeners and the benefits of binaural hearing by measuring speech reception thresholds in noise. Reports included CI users who received longer, 20mm, and shorter, 10mm, electrodes.

The interest in comparing the bilateral and hearing preservation groups in listening environments which mimic real life listening situations is that each group has a form of bilateral hearing that is uniquely different. The theoretical question revolves around whether bilateral hearing, either electric or acoustic, provides the benefits associated with binaural or spatial hearing. By necessity, bilateral hearing aid (HA) users will also be discussed since most hearing preservation users wear bilateral HAs.

The Mechanisms for Spatial Release from Masking

In 1948 Hirsh used tones and noise and showed that when the tone was out of phase and the noise was in phase a release from masking occurred. Binaural thresholds were lowest when the tone was out of phase and the noise was in phase at the two ears, particularly at the lower frequencies. The difference was approximately 15dB when a phase difference was introduced compared to both the tone and noise having the same phase. Hirsh reported that both the tone and noise were heard in the middle of the head when they were in phase and were heard at the ears when they were out of phase. Therefore, when the noise was in phase and heard in the middle of the head and the tone was out of phase and heard at the ears it was easier to hear and there was spatial release from masking. When both were heard at the ears or both heard in the middle of the head there was no release from masking.

Licklider (1948) used speech rather than a tone and showed that when the speech was out of phase and the noise remained in phase it was equivalent to doubling the speech power while the noise power remained the same. In other words the binaural masking level difference (BMLD) was greatest when there was a phase difference between the speech and noise. When the speech and noise had different interaural phase relationships they were in effect isolated from each other – e.g. one was heard in the middle of the head and one was heard at the ears – and masking was reduced.

In 1950 Hirsh showed that thresholds of speech intelligibility improved when the speech and noise were separated in space, spatial separation, and were poorer when the speech and noise originated from the same place, coincident in space, or were close together in space. Koenig (1950) demonstrated that a binaural telephone system allowed listeners to "squelch" reverberation and background noise when two separate microphone pick-ups were connected to two separate receivers, one for each ear, compared to a single microphone pick up sent to both ears. With the binaural system listeners were able to understand speech even when the noise levels were very high creating a negative signal to noise ratio (SNR). Kock (1950) showed that when the noise source was picked up by a single microphone and was sent to two earphones, along with the signal, intelligibility was reduced because both the signal and noise were in phase. However, speech intelligibility improved when the noise sources were picked up by two different microphones and sent to the earphones along with the signal. The signal, in phase, sounded like it came from straight ahead while the noise, out of phase, sounded like it came from all around. Although Kock did not report this as interaural phase (time) differences, he noted that the masking level difference, or improved speech in noise, was due to the delay patterns between the two signals (Carhart et al., 1967).

Durlach (1963) proposed the Equalization-Cancellation theory which states that binaural unmasking or binaural interaction is an improvement in a masked signal when presented to two ears. Akeroyd (2006) stated it succinctly: "there is an equalization in level and internal delay of the signals at the two ears, so that a subsequent subtraction of one from the other will cancel as much of the masking noise as possible. There is a resulting gain in target-to-masker ratio over that found at either ear; hence, there is a gain in detectability of the target."

Two ears can improve the intelligibility of understanding in noise for two reasons. One is that there is a head shadow or better ear effect so that masking is attenuated on one side by the shadowing effect of the head. The better listening ear has the benefit of an improved SNR. The second benefit of two ears is the binaural interaction advantage resulting from differences in ITD and ILD for the target and masker when they originate from different places in space. Even with shadowing some noise will be present at both ears. The auditory system is able to calculate the ITDs and effectively cancel or squelch the noise providing greater detectability of the signal (Akeroyd, 2006; Stern, Wang, and Brown 2006).

Bronkhorst and Plomp (1988) reported the binaural intelligibility level difference (BILD), or release from masking, is determined by ITD for low frequencies. The BILD is dependent on squelch. When two maskers on either side of the head are present, a binaural gain is expected and is less affected by head shadow than when using a single masker. They reported that the use of multiple maskers resulted in an increase of unmasking compared to a single masker. The target was heard in the middle of the head while each masker was lateralized to each ear resulting in greater unmasking.

Litovsky (2010) wrote that binaural unmasking results from “interaural decorrelation.” In 1950, in three separate studies, Hirsh, Koenig, and Kock demonstrated this in NH listeners. But it was Cherry (1953) who wrote “how do we recognize what one person is saying when others are speaking at the same time (the ‘cocktail party problem’)?” He was convinced that spatial separation played a large role in our ability to understand speech in such an environment. In a simulated cocktail party environment using up to three different utterances consisting of words, letters, and numbers, Yost, Dye, and Sheft (1996), showed that performance decreased with an increasing number of competing utterances in a condition in which utterances were presented from seven loud speaker locations. They also showed that performance increased as the separation between loudspeakers increased. Utterances were presented from loudspeakers that were separated by one, two, or three loudspeakers. Performance was better when there was a separation of three loudspeakers compared to one or two indicating that spatial separation played a role in performance when three concurrent sources were presented.

Summary on Binaural Benefits

In summary, there have been multiple experiments that show the benefit of, and improvement in, understanding when noise is presented out of phase with the speech to two ears. Reports also demonstrate the improvement in understanding when speech and noise are separated in space, the ‘cocktail party problem’. This can be thought of as the binaural auditory system's ability to squelch the noise resulting in an increase in the gain of the speech.

Bilateral Hearing Aid Users

Festen and Plomp (1986) measured the benefit of bilateral hearing aids (HA), a monaural HA for each ear, and no HAs in noise by obtaining SRTs at the 50% correct level. The subjects were divided into two groups: group one had pure tone averages (PTA) at .5k, 1k, and 2k Hz between 35 and 51dB and group two had PTA between 52 and 66 dB. The residual LF hearing in the two groups is similar to the hearing of the hearing preservation subjects who participated in this research. For group one the SRT improved 4.5dB when the noise was moved from the front to either side. There was no difference in SRT between one *vs.* two HAs. With noise presented to either side unaided SRTs were 2dB lower (better) than for any of the aided conditions, but there were no differences between conditions when noise was presented from the front. For the more impaired group, there were no differences between conditions when noise was presented from the front. When noise was presented ipsilaterally to one HA there was no difference compared to noise presented from the front. Two HAs with noise to either side were approximately 3dB better than with one HA and noise presented to the same side as the HA. For group two the benefit of the second HA was provided by head shadow. Festen and Plomp also measured noise levels at the entrance to the ear canal and at the level of the microphone on the HA sitting on top of the pinna. When speech was presented from the front there was a decrease of 3.3dB when measured at the level of the HA microphone compared to being measured at the entrance to the ear canal. In conditions where speech was presented from the front and noise from the side, the position of the

HA microphone negatively impacted the SNR by 2dB. This is relevant to the hearing preservation listeners as well as the bilateral CI users who both have microphones mounted on top of their pinnae rather than at the ear canal entrance.

In a review by Kasten and Lotterman (1967) of HA microphone placement, they reported on the benefits of head baffle with the signal presented toward the aided ear and the detrimental effects of head shadow with the signal presented away from the aided ear. They presented pure tones across a frequency range from .5k to 4.75k Hz. They reported that the overall output of the HA decreased on the shadowed side as the frequency increased. The greatest shadow effect was found at 60º (this is caused by the 'bright spot' that occurs in the spectral region beyond 1200Hz). They reported that when the microphone was located facing forward there was a decrease in the output of the HA. They also reported on earlier work by Kasten and Tillman in 1964 who found that the head shadow effect for hearing impaired listeners reduced speech intelligibility by up to 29 percentage points. Speech was presented away from the aided ear and compared to speech presented toward the aided ear. During that era, head shadow was reported as a detriment rather than a benefit.

Ahlstrom et al. (2009) studied the benefits received by older hearing impaired (HI) listeners who were aided bilaterally. A specific goal was to determine if they benefitted from spatial separation of speech from noise. The disadvantage that HI listeners had resulted from high frequency(HF) hearing loss and reduced ILD cues. The objective was to restore interaural differences required for spatial listening tasks. They concluded that spatial benefit was greater when aided but only when the speech and noise were spatially separated. They concluded that bilateral hearing aids were able to restore, at least partially, interaural differences but that ILD cues were reduced in some users where audibility could not be restored due to severe HF hearing loss.

Boymans et al. (2008) carried out soundfield tests, post HA fitting, for speech intelligibility using spatially separated sources and sound source localization in the horizontal plane. Speech reception thresholds in noise were measured with the target toward the ipsilateral, monaural HA and competing noise on the contralateral side without a HA. Testing was repeated using bilateral HAs with the second HA toward the side with noise. The bilateral HAs provided a small but significant improvement of .4dB which was reported as binaural processing or squelch. When the target and noise were switched and the noise was toward the monaural HA, the addition of the second HA toward the speech improved thresholds by 3.3dB. This was interpreted as the combined benefit of squelch and head shadow.

Hearing Preservation

Von Ilberg et al. (1999) reported on the first documented patient who used combined electric-acoustic stimulation (EAS) in the same ear. Von Ilberg et al. reported on the ability to preserve hearing in the implanted ear and the synergistic effect of combining acoustic and electric hearing in the same ear. The early reports focused largely on the ability to preserve hearing and the speech scores in the ipsilaterally implanted ear showing improved performance over the CI alone when combining electric and acoustic stimulation.

Gantz et al. (2009) reported on a group of hearing preservation users with improvements for CNC word scores in quiet and SRT on BKB sentences in noise. Only 48% of the patients improved on both measures but 74% improved on at least one of the measures. In a previous report they reported that mean CNC scores in the pre-implant bilaterally aided condition were 35% and improved to 73% at one year post implantation. They also reported that the range of improvement was from 8% to nearly 70%. Gantz et al. (2005) reported mean CNC word scores of approximately 30% in the pre-implant, bilaterally aided condition. In the combined condition of the implant plus bilateral HAs at 6 months mean scores improved to approximately 64%. Gantz et al. also reported that in the best condition the average CNC score was 79% for the Iowa group but did not present the data from all subjects.

Kiefer et al. (2005) reported monosyllabic word scores of 62% in the EAS condition compared to 54% with the CI alone after one year of use. Use of the contralateral ear plus CI resulted in average scores of 67%. On the HSM sentences in noise, CI alone scores were 78% compared to pre-op HA scores of 32%. The EAS condition yielded a mean score of 86%. When sentences were presented in noise, the EAS condition was on average 23% higher than the CI alone condition.

Helbig et al. (2008) reported mean monosyllabic word scores of 64% in the CI only condition which improved to 78% with the addition of aided acoustic hearing in the implanted ear (EAS). For HSM sentences in quiet there was no difference between the CI and EAS conditions due to ceiling effects. However, for sentences in noise, the addition of acoustic hearing to the CI improved scores significantly from 55% to 84% at +10dB SNR and from 26% to 53% at a +5d SNR in the CI *vs.* EAS conditions respectively.

Lorens et al. (2008) compared scores for the CI only, the CI plus ipsilateral acoustic hearing, and combined bilateral acoustic plus the CI conditions for a group of hearing preservation patients on Polish monosyllable word scores using a +10dB SNR. Their results yielded scores of 56%,72% (derived from a figure), and 78% in the respective conditions. Gstoettner et al. (2004) reported word scores for a single patient of 90% for Frieberg monosyllabic words in the EAS mode which were 25% better than the CI only condition and 50% better than the HA only condition. Gstoettner et al. also reported scores on HSM sentences presented at a +10dB SNR which yielded scores of 6%, 39%, and 90% in the HA, CI, and EAS conditions respectively. Other patient performance scores were not reported.

Punte et al. (2010) reported on a bilateral EAS user, i.e. bilateral cochlear implants and bilaterally preserved hearing, with monosyllabic word scores in the first EAS ear using a shorter electrode array, 20mm, of 75% and only 50% in the second implanted EAS ear using a standard electrode array, 31mm. Combined scores were not reported. Punte et al. also reported SRTs obtained in noise. Scores were obtained with speech in front and noise presented from the front, from the left, and from the right. With noise in front, all conditions had SRTs below zero. The right EAS and the bilateral EAS had equivalent scores of approximately -3.3dB indicating that the better ear score carried the bilateral score. In the left EAS condition scores were 1dB worse.

Dorman et al. (2009) compared bimodal patients using a standard CI with good contralateral, LF acoustic hearing, to Hybrid users with a short 10mm electrode and bilaterally preserved acoustic hearing which was similar to the hearing of the bimodal group. CNC word scores differed by 23 percentage points; the bimodal users scored 76% compared to the hearing preservation users who scored 53%. Dorman et al. reported that the addition of the second acoustic ear did not benefit the users. Dorman et al. also reported that the electric only scores with a short electrode array were very poor and probably contributed to the poorer scores.

Dunn et al. (2010) tested nine hearing preservation patients on speech in noise tests obtaining an SNR at 50% correct for a closed set of 12 spondee words. Words were presented from the front and noise comprised of sentences spoken by male and female talkers were presented from the sides at $\pm 54^{\circ}$ or $\pm 38^{\circ}$. Listeners were tested in the combined (bilateral HAs + CI), bimodal (CI + contralateral HA), EAS (CI+ ipsilateral HA), and bilateral HA conditions. As a group, the combined condition provided a significant improvement in performance over the other two CI conditions. They interpreted this as the benefit of being able to access both ITD and ILD cues due to similar signal processing between ears. The listeners were able to squelch the competing background noise due to the presence of temporal fine structure from their bilateral HAs. This report also supported the benefit of preserving hearing in the implanted ear since scores were significantly better in the combined condition *vs.* the bimodal condition.

In a study by Gifford (2010) hearing preservation patients were evaluated in a surround sound setting to determine the benefit of preserving hearing in the implanted ear. SRTs were obtained for sentences in noise. Bimodal scores were on average 3.3dB and improved to 1.2dB when the acoustic hearing in the implanted ear was added.

Bilateral Implants

Although the merits of bilateral implantation are not in question, the literature is conflicted in the belief that bilateral cochlear implant (CI) users benefit from true binaural processing. There are many reports that attest to the benefits obtained using two implants which include better sound source localization and improved speech understanding both in quiet and in noise, often referred to as benefits of binaural processing (Buss et al., 2008; Dunn et al., 2008; Eapen et al., 2009; Grantham et al., 2007; Litovsky et al., 2006; Ricketts et al., 2006; Tyler, 2006).

Loizou et al. (2009) reported that although bilateral implant users benefit from having two implants, they are not able to take advantage of true binaural cues. Results were compared to normal hearing (NH) listeners in a study by Hawley et al. (2004) who showed that performance for NH was significantly better when the masker was informational rather than energetic and when there was spatial separation of the target from the masker.

Energetic and informational masking. Brungart et al. (2006) defined energetic masking as “the loss of detectable target information due to the spectral overlap of the target and masking signals” or more simply “the loss of information caused by an overwhelming masker.” Energetic masking is typically considered peripheral and not central masking. Speech on speech masking is often termed informational masking. There is not a consensus on the definition of informational masking but Freyman et al.

(2004) described informational masking “to be quite broad, encompassing features of masking, or release from masking, that cannot be explained in terms of traditional energetic masking.” Barker et al. (2009) described informational masking as being similar to the target making it difficult to selectively attend to the target. Informational masking is considered to involve the central auditory system and is not just a peripheral phenomenon.

In a previous study, Kidd et al.(1998) found that NH listeners demonstrated greater improvement with increasing separation of the signal from the noise. Kidd et al. also showed that the magnitude of the advantage was greater for informational rather than for energetic masking.

For bilateral CI users, Loizou et al. (2009) showed that the masker stimulus made no difference, speech *vs.* modulated noise, and that separation of the target and masker did not provide spatial release from masking or a binaural advantage. Subjects were tested using HRTFs and a direct connect to the speech processors rather than in a sound field. Loizou reported that although bilateral implant users benefitted from having two implants, they were “less capable of taking advantage of binaural cues for source segregation under conditions of informational masking.” SRTs were calculated using an adaptive technique targeting 50% correct for (i) total advantage, (ii) monaural advantage, and (iii) binaural advantage or binaural interaction. Total advantage, also known as spatial release from masking (SRM), was the difference in scores between the target and masker separated in space compared to the target and masker emanating from the same place in space in the bilateral condition. Monaural advantage was the benefit of listening with one ear with a better signal to noise ratio and was a calculation of head shadow. Binaural advantage was total advantage minus monaural advantage and was thought to assess binaural processing resulting from advantages introduced by spatially separating the target from the noise and listening with two ears *vs*. one ear. No binaural advantage was found for the CI users. They did benefit from two implants largely because of a better SNR to the better side without noise, the head shadow effect or monaural advantage. Bilateral CI users showed no benefit of spatial separation. Loizou et al. concluded that bilateral CI users do not benefit from binaural advantage (not to be confused with bilateral advantage) and attributed the absence of binaural advantage to poor ITD sensitivity, poor spectral resolution, and differences or asymmetries in the binaural auditory pathways.

Loizou et al. also commented that another problem for the bilateral users was that the processors were not synchronized; and therefore, ITD cues were not available. This inability to use ITD cues and the mismatch between processors is also reported by Ching et al. (2004), Litovsky et al. (2006), and Francart et al. (2008). According to Litovsky et al. binaural processing for bilateral CI patients is difficult due to hardware problems, e.g. their speech processors, resulting in 1) two separate microphones which may result in a mismatch in compression between processors and 2) rate of stimulation and the update rate to the processors may be different, fine timing information is not preserved, and therefore, the auditory system cannot take advantage of binaural cues. This lack of synchronization has also been reported for bilateral hearing aid users as well and is reportedly due to differences in noise reduction algorithms and compression between hearing aids (van den Bogaert et al., 2006).

In opposition to Loizou et al. there are reports in the literature that support bilateral CI users ability to use binaural cues. Rickets et al. (2006) reported that bilateral CI users are able to benefit from binaural cues. Using both an adaptive and a fixed SNR with multiple noise sources their results showed statistical significance of 3.3dB or 10% for bilateral CIs compared to the better ear performance. They reported benefit was due to squelch and summation in uncorrelated noise with the speech spatially segregated from the noise. Eapen et al. (2009) reported that median squelch effects improved from 8% to 18% and that summation increased from 8% to 11.5% at one year and at four years in bilateral CI listeners. They reported this indicated that bilateral users can make use of interaural difference cues attributed to binaural processing.

Schleich et al. (2004) reported binaural benefits for bilateral CI listeners. They calculated SRT thresholds for Oldenburg Sentences in noise. Noise was presented from the left, right, or front and speech was always presented from the front. Head shadow was the difference between SRTs for noise ipsilateral to the implant minus noise contralateral to the implant. Binaural squelch was the difference in SRTs when listening with both implants and noise to the lateral side minus the SRT with the implant contralateral to the noise. Binaural squelch reflects the benefit from separation of the signal from the noise. Summation was the difference between bilateral input and monaural input with speech and noise in front. Summation is the benefit of listening with two ears to identical signals. They reported significant binaural effects of 6.8dB for head shadow, .9dB for squelch, and 2.1dB for summation.

Chan et al. (2008) reported that bilateral CI users benefit from SRM. Chan et al. measured thresholds using the HINT sentences with noise presented from the left, right, and front. They reported on head shadow, binaural squelch, and binaural summation effects. Head shadow was the largest effect, 5dB, calculated by subtracting SRT thresholds in the monaural ipsilateral noise condition from the monaural contralateral noise condition. When noise was presented to the right ear, the left ear was shadowed and the difference in the right and left ear thresholds was the calculated head shadow effect. Binaural squelch which they reported as SRM, was calculated by taking the difference between bilateral and monaural thresholds in the noise left and noise right conditions - e.g. a binaural threshold for noise to the left ear is the effect of binaural SRM, or binaural squelch, for the right ear. The monaural threshold for the right ear with noise to the left is the head shadow effect for the right ear and was subtracted from the binaural threshold. Binaural squelch was approximately 2dB. Summation was calculated by taking the difference of the monaural noise-front condition from the bilateral noise-front condition. The summation effect was 1dB.

Muller et al. (2004) reported on bilateral CI benefits in percent correct on sentences in noise. They found that bilateral scores were 20.4 percentage points higher compared to the unilateral scores with the ear away from the noise reflecting the benefit of head shadow effects. When scores for the ear toward the noise were compared to bilateral scores a difference of 10.7 percentage points was obtained reflecting the benefit obtained from binaural squelch. They also measured summation effects on monosyllabic words in quiet. The summation effect was 18.7 percentage points higher in the bilateral listening condition compared to the better ear condition. They concluded that bilateral CI users appear to benefit from each of the three effects, head shadow, binaural squelch, and summation, that contribute to binaural advantage in NH listeners.

Laszig et al. (2004) reported significant head shadow effects on two different sentence tests. They also reported on a small but significant binaural squelch effect of 8% for sentences in noise. Their subjects were tested at six months after activation. Eapen et al. (2009) suggested that binaural squelch effects may be larger if CI users are given more time to develop binaural processing.

Litovsky et al. (2012) reported on bilateral adult CI users and the benefits provided by bilateral listening. SRTs were measured establishing the SNR that provided speech intelligibility of 50% correct on BKB sentences. They reported that the primary benefit was due to the better ear, or head shadow effect, which resulted in a 5.5dB benefit. The squelch benefit was 2dB and summation was 2.5dB. They reported that bilateral CI users were able to unmask speech in noise but also reported that they were unable to access binaural cues with clinic processors.

Summary

The assumption is that the ability to localize and gain a spatial release from masking are intertwined. Binaural squelch is based on the ability of a central mechanism to process interaural cues between the two ears. Binaural squelch is the basis for unmasking when a target and noise are separated in space. In theory, spatial release from masking and binaural squelch are the same concept: the unmasking of speech in noise using a binaural mechanism. In the literature these two concepts are usually treated as two different parameters and are measured differently. SRM is measured using two ears with speech and noise coincident in space compared to speech and noise spatially separated. Binaural advantage, or binaural squelch, compares one ear to two ears when speech and noise are spatially separated. Both measures depend on interaural cues but

Loizou et al. (2009) used binaural advantage as the determining factor for measuring binaural processing.

There is a discrepancy in published reports on bilateral CI users' ability to benefit from spatial release from masking or to access squelch. On one hand, Ricketts et al. (2006), Chan et al. (2008), Schleich et al. (2004), and Muller et al. (2004) reported that bilateral CI users are able to access binaural cues. On the other hand, Loizou et al. (2009) and Litovsky et al. (2012) reported that bilateral users are not able to access true binaural cues. Reports on binaural and/or spatial hearing in the newer hearing preservation group are very limited. Therefore, further research is warranted in this area for both groups of CI users.

Definitions for Binaural Hearing

To assist the reader with the various terms related to binaural hearing, the terms, listening conditions, and calculations to determine benefit are listed.

Spatial Release from Masking	Bilateral CI Combined hearing preservation	A comparison between speech and noise collocated in space *vs.* speech and noise separated in space
Binaural Advantage (Squelch + Summation)	Bilateral *vs.* better CI Combined *vs.* bimodal	A comparison between the better ear *vs.* two ears when speech and noise are separated in space – adding back the poorer ear
Summation	Bilateral *vs.* better CI Combined *vs.* EAS	The difference between one ear vs. two ears when speech and noise are collocated in space – presented from the front

Mimicking a Real Life Environment

A new test paradigm, R SPACE™, provides a "virtual real world" listening environment and was used in the current study to compare the benefits of bilateral CI and hearing preservation CI listeners. R SPACE™ was developed to target specific goals which included: 1) the simulated environment should sound real, and 2) the simulated environment should allow the hearing mechanism to perform in the lab as it does in the real world (Revit, 2007). R SPACE™ was designed to test various hearing aid microphones in a more real world atmosphere. It creates the illusion of listening in a large restaurant due to the recording procedure.

The R Space™ set up consists of eight speakers placed circularly around the subject seated directly in the center. The speakers are 2 feet from the subject at ear level and are 45° apart. The speakers are numbered with speaker 1 directly in front of the subject and the right speaker adjacent to 1 is 2, then 3, going around to speaker 8 adjacent to speaker 1 on the left (Figure 14). The recording system for the noise presented in the RSpace™ environment consisted of 8 directional microphones placed 45 degrees apart facing out 2 feet from the center. The microphones picked up sounds in all directions in the horizontal plane. Lou Malnati's restaurant noise was used and the restaurant sounds were recorded on 8 separate tracks of a digital recording system. The playback system consisted of eight loudspeakers which play back the original recordings of the 8 microphones. The playback allows the continued path to the center, i.e. the subject's head, of the original recordings. The result is a "virtual" restaurant environment mimicking a real life listening situation that can be used in a sound booth.

Dorman and Gifford (2010) presented data using RSpace™ for unilateral, bilateral, bimodal, and hearing preservation CI listeners. Speech reception thresholds (SRT) were obtained in RSpace™ using HINT sentences adaptively. Results were not significantly different between bilateral users and bimodal users which are in contrast to results obtained in traditional testing paradigms. In the R Space™ environment the bimodal group did not outperform the bilateral group. Put another way, the bilateral users performed as well as the bimodal users. They also tested CI users with hearing preservation. This group showed the greatest benefit of all. The addition of LF hearing from both ears provided a significant improvement of 2.9dB for the hearing preservation group compared to either the bimodal or bilateral groups. Theoretically, each dB of improvement in the SNR can result in an 8 - 15% improvement in speech recognition (Plomp and Mimpen, 1979; Nilsson et al., 1994; Litovsky et al., 2006).

Speech Understanding in R Space™

Rationale for Experiment 2

This experiment was designed to compare speech intelligibility in two different real life environments using RSpace™ to determine if bilateral FSP™ and/or hearing preservation listeners benefit from binaural hearing (**aim two**).The traditional testing paradigm used to assess speech understanding in a clinical environment does not provide a dynamic listening environment (i.e., situations in which a target sound changes location) which all of us encounter in daily life. Current testing typically presents speech and noise from a single loud speaker in front of the listener. Such a test paradigm may show summation effects but it cannot show other benefits of binaural hearing that include spatial release from masking and squelch. Litovsky et al. (2004) stated that the effect of separating speech from noise is a strong measure of binaural benefit. In this experiment, speech and noise were separated in order to evaluate binaural benefit. This experiment also addressed **aim 4**: does preserving hearing provide added benefit for the hearing preservation group.

A unique feature in this experiment was the almost complete elimination of head shadow as a benefit. In RSpace™, noise emanated from all eight loudspeakers and in Cocktail Party maskers were presented on both sides. In both test paradigms neither ear was able to benefit from the shadow cast by the head from the noise. Therefore, all calculations are different from those reported in the literature. The calculation of SRM is the comparison of bilateral scores for speech and noise presented coincident in space *vs.* bilateral scores for speech and noise spatially separated. Binaural advantage, or squelch, is a calculation of the better ear *vs.* two ears when speech and noise are spatially separated. Both are determinants for accessing binaural hearing.

As stated previously, adding a second implant improves speech intelligibility but true binaural benefit remains debatable. The benefit of having bilateral acoustic hearing in conjunction with a CI (e.g. hearing preservation listeners) in terms of binaural hearing has not been the focus of most reports. Dunn et al. (2010) claimed that hearing preservation users have the ability to access binaural squelch based on the presence of ITD and ILD cues. That study lacked proper controls to determine the presence of interaural cues (e.g. filtering the stimuli). Their claim that hearing preservation patients were able to take advantage of binaural cues has not been fully substantiated and warrants further research.

In a very recent study, Gifford et al. (2013) reported on the benefits of preserving hearing in the implanted ear. Gifford et al. found small, but significant improvements of 1.7 - 2.1dB when measuring SRTs in noise and 6 – 10 percentage points of improvement when calculating scores for the combined *vs.* bimodal conditions.

Experiment 2

Introduction

The purpose of Experiment 2 was to determine if either group, bilateral FSP™ or hearing preservation listeners, (i) benefitted from binaural hearing in complex listening environments and (ii) if preserving hearing in the implanted ear was beneficial for the hearing preservation group. The operating hypothesis was that hearing preservation listeners would demonstrate binaural processing abilities due to access to ITD cues, but the bilateral CI listeners would not benefit from binaural processing due to their lack of ITD cues.

Two different speech tests were administered. The first experiment (**Part A**) used the AZ Bio sentence test (Spahr and Dorman, 2004; Spahr et al., 2012) presented in diffuse or energetic noise and is referred to as RSPace™. The second experiment (**Part B**) used the BabyBio sentence test (Spahr and Dorman, unpublished) presented against informational masking. It is referred to as the Cocktail Party.

The Test Battery

Part A: RSpace™

Speech stimuli. The AZ Bio Sentences developed in the Arizona State University Cochlear Implant Research Laboratory were used as the speech stimulus. Thirty-three lists comprised of 20 sentences per list with equal intelligibility varied in length from 4-12 words. All lists consisted of two male and two female talkers using normal conversational speaking rates. Sentences were presented with an inter-stimulus interval of 5 seconds. No list was presented more than once for a single subject. Two lists for a total of 40 sentences were presented and averaged for each listening condition. Sentences were presented at 60dB SPL in the separated and unseparated conditions.

***Noise stimuli*.** The original Lou Manalti's restaurant noise was used as RSpace™ was originally designed. This created a virtual restaurant setting, due to the recording procedure, using different noise sources in each loudspeaker. When sitting in the center of RSpace™ the perception is that of sitting in a noisy restaurant. The restaurant noise is considered diffuse or energetic masking (see definition on page 70).

Condition 1 – unseparated. AZ Bio Sentences and restaurant noise were presented from a single loud speaker at 0° azimuth (front). The uncorrelated restaurant noise from all eight tracks was combined onto a single track and presented continuously from this loudspeaker. This was referred to as the unseparated condition.

***Condition 2 – separated*.** AZ Bio sentences were presented from a single loud speaker at 0° azimuth in a background of eight spatially separated maskers. The uncorrelated, restaurant noise emanated continuously from all eight speakers including the speaker presenting the sentences. This was referred to as the separated condition. Condition 2 was a slightly different experimental situation for spatial separation of speech and noise than the more common approach in which the signal is presented from one loudspeaker in front and the noise is presented from a loudspeaker to the side (i.e., the loudspeaker containing the speech signal does not contain a masker). This experimental set up mimicked listening in a place like a noisy restaurant. The implication for this is discussed in the results section.

Test environment. Testing was conducted in a sound treated double walled booth using R Space™. Patients were seated in the middle of RSpace™ in a stationary chair with a straight back to maintain the position of their head in the center.

Calibration. All speakers were calibrated to within .5dB of each other. The MiniSPL, an omnidirectional microphone, was placed in the center of R Space. The Minilyzer ML1 by Neutrik Test Instrument was used to determine the SPL of pink noise generated by the sequence editor in the R Space software. Pink noise was used only for calibration; adjustments were made in 1dB steps to each speaker using potentiometers on the QSC Professional Amplifier to equalize the level from each speaker.

Pilot Study 1

Normal hearing listeners. It was necessary to determine how NH listeners would perform in the RSpace™ environment to use as a reference prior to testing CI listeners. Nine undergraduate students with normal hearing were evaluated in RSpace™ and in the Cocktail Party setting to determine if they benefitted from SRM and from binaural advantage. Participants were compensated for their time.

Testing was designed to measure SRM and binaural advantage in the unseparated and separated conditions. An SNR was obtained for the monaural ear with the contralateral ear plugged and muffed in the unseparated condition, i.e., speech and noise presented together from the front loudspeaker. The SNR was adjusted to obtain a 50% correct response on the AZ Bio sentences in RSpace™. Right and left ears were alternated between participants for monaural listening. The same SNR was used for all conditions: monaural unseparated, monaural separated, binaural unseparated, and binaural separated. The same procedure was used for the Baby Bio sentences in the Cocktail Party.

Methods

Subjects. The same bilateral FSP™ and hearing preservation users from Experiment 1 (sound source localization) participated in Experiment 2.

Bilateral FSP™ listeners. Eleven adult, bilateral MED-EL CI listeners using FSP™ were evaluated in three conditions: poorer CI, better CI, and bilateral CI. Prior to testing in RSpace™, AZBio sentences in quiet and in noise at SNR of +10dB and +5dB were obtained in a traditional setting using a single loud speaker to determine their better CI ear. CNC word scores were also obtained in quiet and at +10dB SNR. Subjects used their processors set to their everyday settings. No reprogramming was done. Changes were made to volume settings by the users to equate loudness between ears.

Hearing preservation listeners. Twelve adult, hearing preservation listeners were evaluated in the following five conditions: (i) CI only with acoustic hearing plugged and muffed, (ii) combined: bilateral HA* + a single CI, (iii) bimodal: contralateral HA + CI with ipsilateral acoustic hearing plugged and muffed, (iv) EAS: ipsilateral HA + CI with contralateral acoustic hearing plugged and muffed, and (v) bilateral HAs without their CI. Each condition is referred to as CI, combined, bimodal, EAS, and HA. CNC word scores were obtained in quiet in a traditional setting using a single loud speaker prior to testing in RSpace™. Subjects used their own HAs and processors set to their everyday settings. No changes were made to their HAs or processor maps.

*One subject did not use hearing aids in either ear due to normal thresholds at 250Hz. All other subjects used bilateral HAs.

Procedure. Subjects were seated in the middle of RSpace™ and instructed not to turn their head but to look straight ahead. The better CI ear for the bilateral group was used and the EAS condition for the hearing preservation group was used to determine the SNR necessary to achieve 50% understanding in RSpace™. Since unilateral scores were compared to bilateral scores for the bilateral CI listeners, justification for using the EAS ($E+A_{ipsi}$) rather than the bimodal ($E+A_{contra}$) mode was to maintain a unilateral/bilateral hearing comparison for the hearing preservation users. Sentences and noise were presented from the front speaker and the noise was raised or lowered adaptively until the subject understood approximately 50%. A complete list of sentences was administered and a score was calculated. If a score was not in the range of 50% the level of noise was adjusted and another list was presented. This placed all subjects at approximately the same starting level and allowed for a comparison between conditions for each group as well as a comparison between groups. For several of the hearing preservation listeners SNR had to be adjusted to a more difficult level to prevent ceiling effects in the combined condition. If this was necessary the SNR was set to obtain scores in the combined condition to between 60-80%.

Speech intelligibility scores were calculated for the unseparated and separated conditions maintaining the same SNR for all conditions for each subject. There were three conditions for the bilateral group and five conditions for the hearing preservation group. Listeners were instructed to repeat back any portion of the sentence they understood. A percent correct score was calculated based on the number of words in a list correctly identified.

Part B: Cocktail Party

Target speech stimuli. The BabyBio Sentences were used as the speech stimulus and consisted of a single female talker using a normal conversational speaking rate. Sentences were presented with an inter-stimulus interval of 5 seconds. Sixteen lists comprised of 20 sentences per list varied in length from 3 - 11 words. No list was presented more than once for a single subject. If additional lists were needed the lists with very poor scores were reused. One list was presented for each listening condition. Sentences were presented at 0º (front) at 60dB SPL (1) coincident in space with the maskers in the unseparated condition, and (2) spatially separated from the maskers, presented at ±90, in the separated condition.

Masker stimuli. IEEE sentences (1969) spoken by two different male talkers were used to produce informational masking. The same 10 sentences from List 1 were looped and offset in time. Male talkers were used as maskers to differentiate the maskers from the target when both emanated from the front speaker (0º azimuth) in the unseparated condition. In other words, if the target and maskers were of the same gender it would be difficult, if not impossible, to know which talker to listen to. Speech on speech masking is often termed informational masking (see definition on page 70).

Condition 1 – unseparated. A female talker (target) and both male talkers (maskers) were presented from a single loud speaker at 0° azimuth.

Condition 2 – separated. A female talker (target) was presented from a single loud speaker at 0° azimuth. The male talkers (maskers) were presented from loudspeakers at +90º and -90º, one on each side of the listener. In this condition, unlike in RSpace™, there was true separation of the speech from the maskers because masking was never presented from the front loud speaker in the separated condition.

Procedure. The procedure was identical to the procedure for RSpace™ except that the target and maskers were different. An SNR was established using the better ear from the bilateral group and the EAS or combined condition from the hearing preservation group. All of the listening conditions were the same as in RSpace™: three for bilateral FSP™ and five for hearing preservation listeners. Additionally, only three of the loud speakers were used instead of eight.

The procedure was explained to each subject and was approved by the Arizona State University Institutional Review Board (IRB) for the Protection of Human Subjects. All subjects signed an informed consent prior to testing and were compensated for their time.

Results

Descriptive statistics for all groups in RSpace™ and Cocktail Party are listed in Tables 6 and 7. The following is a list of the terms and definitions for binaural hearing presented with results in percent correct for each group.

Spatial Release from Masking	Bilateral CI Combined (CI + bilateral acoustic)	A comparison between speech and noise collocated in space *vs.* speech and noise separated in space	**RSpace Results** NH = -5 Bilateral= -10 Combined= 0	**Cocktail Party Results** NH = 23 Bilateral = 6.5 Combined = 4.7

Binaural Advantage	Bilateral *vs.* better CI Combined *vs.* bimodal	A comparison between one ear *vs.* two ears when speech and noise are separated in space	NH = 15 Bilateral = 10 Combined = 11	NH = 38 Bilateral = 18 Combined = 19
Summation	Bilateral *vs.* better CI Combined *vs.* EAS	The difference between one ear vs. two ears when speech and noise are collocated in space – presented from the front	NH = 11 Bilateral = 11 Combined = 20	NH = 14 Bilateral = 14 Combined = 13

Comparison Between Groups

A one way ANOVA was conducted to compare the three groups, NH, bilateral CI, and hearing preservation listeners, on speech understanding abilities for SRM, binaural advantage, and summation. There was a main effect of group performance at the $p<.05$ level for SRM : [$F(2,31) = 15.557$, $p. < .0005$], and binaural advantage: [$F(2,31) = 6.680$, $p. = .004$]. There was no difference between the three groups for summation: [$F(2,31) = .061$, $p = .941$]. The bilateral and hearing preservation listeners performed as well as the NH listeners for summation. Post hoc Scheffe tests revealed that there was a significant difference between NH and the bilateral and hearing preservation listeners for the conditions of SRM and binaural advantage. NH listeners performed better than the bilateral CI and hearing preservation groups on measures of SRM, $p < .0005$. NH listeners also outperformed the bilateral listeners, $p = .011$, and hearing preservation listeners, p = .012, on binaural advantage. There was no difference in performance for either SRM or binaural advantage between the two CI groups, SRM: p = .861, and binaural advantage: p = .994.

Normal Hearing Listeners

Spatial release from masking. The NH listeners were evaluated to use as a reference for the CI listeners. NH listeners performed differently in RSpace™ than in the Cocktail Party. Spatial release from masking (SRM) was calculated by subtracting the percent correct scores in the bilateral unseparated condition from the percent correct scores in the bilateral separated condition (after Hawley et al., 2004).

NH listeners did not benefit from SRM in the RSpace™ environment. Averaged group scores were -5% (sd:4.92). In RSpace™ there was not a separation of speech and noise since the noise was also presented from the front speaker with the target. Based on the literature there should not have been a spatial release from masking since the target and masker were not spatially separated.

The NH listeners exhibited large improvements for SRM of 23% (sd:7.7) in the Cocktail Party setting (Figure 15) where the speech target was separated by 90 degrees from the two speech maskers.

Aside from an incomplete separation of speech from noise in RSpace™ there were two other major differences which may have played a role in performance. First, the diffuse restaurant noise in RSpace™ was energetic masking. In the Cocktail Party setting, the male maskers provided informational masking. Hawley et al. (2004) demonstrated greater SRM for informational masking than for energetic masking in NH listeners. Second, an added benefit in the Cocktail Party may be attributed to gender differences between the target and the maskers. Festen and Plomp (1990) found that a male voice was more susceptible to masking than a female voice for NH listeners. Festen and Plomp also found that SRTs were lower (better) in modulated noise compared to steady state noise and even better when the masker was a competing voice. This did not hold true for hearing impaired (HI) listeners who did not show benefit when the masker was changed from steady state to modulated or competing voice; all conditions were roughly the same. The HI also did not show improved understanding for a female voice largely due to HF hearing loss making the female voice less robust.

Yost (in press) noted that when a target is located in a different place from a masker the target may be more easily localized, and therefore, it is more easily attended to by a listener. At the same time, a listener may more easily ignore the masker. The ability to attend to and ignore the different sound sources becomes more difficult when both are co-located in space.

Binaural advantage. In both settings NH listeners had a large binaural advantage calculated by subtracting percent correct scores in the monaural separated condition from the bilateral separated condition. Binaural advantage is a calculation of squelch, the ability to unmask speech from noise when the speech and noise are separated in space. It also captures summation effects due to the diotic input from the target. The binaural advantage benefit in RSpace™ was 15% (sd:7.75) and in the Cocktail Party it was 38% (sd:17.1) (Figure 16). Based on the literature, it was expected that the Cocktail Party would allow greater binaural benefit due to 1) spatially separating the target from the noise and 2) using informational masking rather than energetic masking.

Summation effects. NH listeners also demonstrated significant summation effects of 8% (sd:10) in RSpace™ and 14% (sd:6.96) in Cocktail Party (Figure 17). Summation, or binaural redundancy, is the difference between the bilateral and better ear scores when speech and noise are collocated in space, i.e. presented from a single loudspeaker in front. In Cocktail Party NH listeners showed the same summation effects as both of the CI groups.

Bilateral FSP Listeners

Traditional testing using a single loudspeaker. CNC word scores were significantly different for poorer ear, better ear, and bilateral listening measured by a repeated measures ANOVA [$F(2,20) = 8.781$, $p = .002$]. Paired samples t tests showed that bilateral scores were significantly better than the poorer ear, $t(10) = 3.317$, $p = .008$ but were not different from the better ear, $t(10) = 1.985$, $p = .075$. ANOVA revealed that AZ Bio sentences presented in the traditional setting at +10, [$F(2,20) =17.407$, $p < .0005$] and at +5, [$F(2,20) =27.063$, $p < .0005$] showed significant differences between the poorer, better, and bilateral listening conditions. Paired samples t tests showed that the +10 condition showed that the bilateral condition was better than the poorer ear [$t(10) = 5.761$, $p = .000$] but was not different from the better ear [$t(10) = 2.137$, $p = .058$]. In the +5 condition the bilateral condition was better than the better ear [$t(10) =2.728$, $p = .021$] and the better ear was better than the poorer ear [$t(10) = 5.209$, $p = .000$]. CNC word scores and AZ Bio sentences using a +10dB SNR are not always sensitive tests for discerning bilateral benefit.

Binaural hearing. Effects in the Cocktail Party were larger than in RSpace™ just as for NH listeners. A repeated measures ANOVA showed differences between bilateral

CI and the better CI ear in the Cocktail Party, [F (3,30) = 17.224, p < .0005]. Post hoc paired samples t tests using the Bonferroni correction showed a small, but significant, SRM, [t(10) = 3.11, p = .005] **(aim 2)**, a significant binaural advantage, [t(10) = 5.451, p < .0005] **(aim 2)**, and a significant summation effect, [t(10) = 5.344, p < .0005]. In the Cocktail Party setting, the bilateral listeners benefitted from all of the binaural effects: SRM 6.46% (sd:5.93) (Figure 21), binaural advantage 18.19% (sd: 11.06) (Figure 22), and summation 13.79% (sd:8.58) (Figure 23). However, due to the results from the One Way ANOVA (see above) which demonstrated no significant difference between the bilateral and hearing preservation groups on SRM, the significance from the repeated measures AVOVA should be disregarded and a more realistic and conservative interpretation of the statistics indicate that the bilateral listeners did not benefit from SRM. They did, however, show a significant benefit for binaural advantage.

Hearing Preservation Listeners

Traditional testing using a single loudspeaker. A repeated measures ANOVA [F(2,22) = .461, p = .637] revealed no significant difference on CNC word scores between the conditions of combined, bimodal, and EAS listening. The CNC word test is not a sensitive measure to determine the benefit of preserving the acoustic hearing in the implanted ear.

Binaural hearing. The hearing preservation group did not show SRM in RSpace™, - 0.13% (Figure 24). Due to the results for the NH listeners this was expected. They did show binaural advantage (Figure 25) and summation (Figure 26) of 14.15% (sd:13.64) and 18.5% (sd:12.54) respectively.

In the Cocktail Party a repeated measures ANOVA showed differences between the separated and unseparated conditions for the combined, bimodal, and EAS conditions, [$F(5,55) = 4.591$, $p = .001$]. Post hoc paired samples t tests using the Bonferroni correction showed that the combined separated and combined unseparated conditions were not significantly different, [$t(11) = 1.646$, $p = .128$] indicating there was no benefit from SRM **(aim 2)** (Figure 27). The group as a whole showed SRM of 4.75% (sd:10). When just the subjects with symmetrical hearing were used to determine SRM benefit, a paired samples t test failed to reach significance, [$t(7) = 1.458$, $p = .188$].

However, in the Cocktail Party, the hearing preservation group did show a significant binaural advantage of 16.62% (sd:13.08) calculated by subtracting the bimodal scores in the separated condition from the combined scores in the separated condition. They benefitted significantly from squelch [$t(11) = 3.876$, $p = .003$] which requires binaural processing **(aim 2)** shown in Figure 28. The binaural advantage showed the benefit of preserving hearing in the implanted ear with scores improving 17% with the addition of the acoustic hearing in the implanted ear **(aim 4).**

There was also a significant summation effect of 12.63% (sd:14.91) (Figure 29) [$t(11) = 2.934$, $p = .014$]. Summation was calculated by taking the difference of the combined and the EAS conditions when speech and noise were presented from the front.

Discussion

Loizou et al. (2009) reported that bilateral CI users are not able to take advantage of true binaural processing. They reported this was due to the absence of ITD which are thought to be the underlying mechanism used by NH listeners for SRM. The Loizou et al. study used Cochlear Corp. listeners who did not have access to the FSP™ algorithm.

Those bilateral listeners were also tested using HRTFs and a direct connect to the processors.

Bilateral FSP listeners and binaural benefits. In the current study, the bilateral group demonstrated significant benefits of binaural processing consisting of binaural advantage, 18%, and summation, 14%, in Cocktail Party. They did not, however, demonstrate spatial release from masking. Loizou et al. stated that the calculation of SRM is thought to be derived from the combined benefits of head shadow and binaural advantage. That study showed that all of the benefit was due to the better ear effect or the head shadow benefit. In the current study head shadow benefit was eliminated by using maskers on both sides of the listener.

The value for the FSP™ listeners may be partly due to the Fine Structure Processing which MED-EL designed to provide some temporal fine structure information in the low frequency region. The FSP™ processing algorithm provides low frequency information down to 70Hz which has not previously been available to CI users. Li and Loizou (2008) suggested that "glimpsing" " (a low frequency SNR advantage for speech relative to fluctuating noise) provides an account of enhancing a speech signal relative to noise in the frequency region below 500Hz. Perhaps the FSP™ users are receiving better voice pitch information allowing access to low frequency landmarks that lead to syllable markers and word boundaries which reduce the number of contenders in a lexicon (Zhang et al. 2010).

The bilateral FSP™ listeners showed that they do obtain binaural benefits, and yet, Experiment 1 showed that they do not have access to ITD cues, the theoretical basis for unmasking speech in noise. However, they do have access to ILD cues. Wilson and

Dorman (2008) suggested that bilateral implants may provide users with additional effective channels helping to fill the “gaps” of frequency representation. The ILD cues should provide bilateral CI listeners with an enhancement of the speech target relative to the noise. For binaural advantage, two ears may provide “two looks” compared to listening with a single ear alone. The equalization cancellation theory suggests that listening with two ears provides the listener the ability to cancel or squelch the noise relative to the speech which is then enhanced.

Bilateral FSP™ listeners: Two ears are better than one. Bilateral listeners performed significantly better when listening with two ears than with their better ear alone. This test paradigm did not allow for a calculation of head shadow effects which are generally the largest benefit for bilateral CI listeners. It should be noted that the head shadow effect should have been greatly reduced or eliminated since noise was provided to both CI ears, and there was not a head shadow benefit from the noise.

The results for SRM are in line with the report by Loizou et al. (2009) who reported that the CI listeners did not show spatial release from masking. However, Loizou et al. also reported no binaural advantage and considered the binaural advantage as the strongest indication of binaural processing. They concluded that CI listeners did not benefit from “true” binaural processing because they did not show a benefit when comparing bilateral benefit to one ear. They reported that the better ear effect, or head shadow, provided the majority of the contribution and therefore, “bilateral users are less capable of taking advantage of binaural cues, in particular, under conditions of informational masking.” They also stated that, unlike NH listeners who had a greater release from masking when informational maskers were used, bilateral CI users did not benefit when the masking was informational rather than energetic. They suggested that performance using informational maskers may have reflected an inability to take advantage of directional cues. Results from the current study are in disagreement with this view and showed a significant binaural benefit without head shadow and benefit was obtained using informational maskers.

This study concluded that bilateral CI listeners are able to benefit from "true" binaural cues based on their significant benefit from binaural advantage. In addition, their ability to localize using ILD cues indicate that they are able to take advantage of directional cues. This strengthens the argument for their ability to benefit from binaural processing **(aim 2)**.

Accounting for outcome differences in the Loizou et al. study and the current research. There are several differences between the current study and the one carried out by Loizou et al. (2009). The important question is why the outcomes differed. On the one hand, Loizou et al. reported that bilateral CI users did not have access to true binaural benefit. On the other hand, the current research studies demonstrated that bilateral CI users do have access to true binaural processing.

In the Loizou et al. study, the target was a male and the maskers were female. The reverse was true in the current research. Festen and Plomp (1990) reported that male voices are more susceptible to masking by a female voice than female voices are for male maskers in NH listeners. They showed that the long term spectrum of the female voice was approximately 10dB greater than the male voice between 3k and 6kHz. An earlier study reported in Licklider and Miller (1951) reported a slightly different long term speech spectrum. They showed differences between male and female talkers of only 2-

5dB beginning at approximately 4500HZ. If the male target was more easily masked in the Loizou et al. study or the female voice was more easily understood in the present study, that is a potential account for the differences in outcomes. The long term speech spectrum in the current study revealed more energy in the female target than the male maskers in the frequency range between 3000 – 5000Hz. The range of increased energy for the female voice was between 2-10dB.

Another difference between studies was the lack of head shadow in the current study compared to the availability of head shadow in the Loizou et al. study. In that study head shadow was calculated and subtracted from results for spatial release from masking. However, that calculation may be questionable since SRM is the difference between speech and noise collocated in space *vs.* speech and noise separated in space when listening with two ears. After the calculation for SRM, head shadow was subtracted to eliminate the better ear effect. In theory, one could argue that a double subtraction was made, which would decrease any benefit obtained.

Loizou et al. reported no differences for the bilateral CI listeners when using energetic masking (modulated speech noise) *vs.* informational masking (sentences spoken by a female). However, they reported that NH listeners had larger benefits when the masking was informational and the target and masker were separated in space. In the current study, there was a large difference between the use of energetic masking in RSpace *vs.* informational masking in Cocktail Party. Binaural advantage was nearly double for bilateral CI listeners when informational masking was used compared to energetic masking, 18% vs. 10%. NH listeners showed an even larger advantage, 38% vs. 15%.

One must also wonder if the use of HRTFs and a direct connect to the speech processors has an effect on outcomes compared to testing in a soundfield. Loizou et al. used HRTFs but the current study used the speech processors as they are worn in every day listening and testing was conducted in a soundfield.

Placement of the maskers was different between studies. The Loizou et al. study placed maskers at -30, 60, and 90 degrees. The current study placed maskers at +90 and -90 degrees. Bronkhorst and Plomp (1988) reported that when two maskers are placed on either side of the head, a binaural gain (in the target) is expected and is less affected by head shadow. Durlach’s Equalization Cancellation theory (1963) suggests that binaural processing enables cancellation of the maskers, due to squelch, which results in a gain of the target-to-masker ratio compared to a better ear.

Perhaps the combination of differences between studies is larger than any one single difference. However, using a female voice which is more robust in the high frequency region than a male voice and having maskers on both sides creating an increase in the target-to-masker ratio may be the best account of the outcome differences between studies. In the current study, the bilateral listeners displayed binaural processing and appear to have benefitted from a gain in the target by squelching the maskers. The gain in the target may have increased further due to the use of a female voice.

Hearing preservation listeners and lack of SRM. One of the operating hypotheses for this dissertation was that hearing preservation listeners would demonstrate binaural processing abilities, particularly for spatial release from masking due to the presence of ITD cues. In contrast to the hypothesis, the hearing preservation group did not show benefit from SRM. Although those with symmetrical hearing have sound source localization capabilities to low-pass noise indicating that they have access to ITD cues, their sound source localization errors were not within the range of NH listeners.

Two reasons for absent SRM should be addressed. One cause of an inability to benefit from SRM may be an impaired processing of temporal fine structure. Moore (2008) reported that people with hearing loss have greater difficulty listening in the dips of a fluctuating background noise, such as the Cocktail Party, due to poor processing of temporal fine structure (TFS) cues. Moore also reported that people with ski slope hearing losses and normal LF hearing may also have deficits in processing TFS. Another probable cause of reduced benefit for SRM may be lack of HF information in the non-implanted ear. The hearing preservation group did not have HF diotic input for speech understanding which would theoretically decrease summation effects for the HF and increase the effect of the masker on the side without the CI. This is supported by Bronkhorst and Plomp (1988) who reported that the information contained in the high frequencies (for speech understanding) is of importance when calculating the squelch effect. In other words, if access to the high frequencies is eliminated on one side, as it is for the hearing preservation listeners, the effect on performance would be deleterious.

Benefits of preserving hearing – Binaural advantage and summation effects. The hearing preservation group did show significant benefits of binaural advantage and summation in Cocktail Party. The large benefits of binaural advantage demonstrated the value of preserving hearing in the implanted ear (**aim 4**). Seventeen percentage points were gained by adding in the acoustic hearing in the implanted ear compared to the bimodal condition.

Hearing preservation listeners benefitted from binaural processing due to symmetrical LF hearing. Their ability to unmask speech in noise when the two sources are separated in space must be due to ITD cues allowing the auditory system to centrally squelch or cancel more of the masking, which in turn, allows enhancement of the speech target. Despite their hearing loss they must be able to process some temporal fine structure cues. TFS provides F0 and some harmonic information enabling them to “hear out” or glimpse the target from the noise, as well as, to squelch the noise.

Binaural advantage and sound source localization. The test for binaural advantage, rather than SRM, may be a better indication of the binaural processing which bilateral CI and hearing preservation users access. It is the measure which determined the benefit of two CIs compared to the better ear, as well as the benefit of preserving hearing in the implanted ear of the hearing preservation listeners. It may be thought of as the test of functional improvement. Both groups had significant binaural advantage but also were two times poorer than the NH listeners. This compares nicely to the sound source localization results. Both groups were able to localize well using different cues – the bilateral CI listeners demonstrated that they had access to ILD cues, and the hearing preservation listeners demonstrated that they had access to ITD cues. Both groups showed RMS errors on sound source localization that were two to three times poorer than NH listeners. The results of binaural advantage are more in line with the results of sound source localization. Both cues individually, ITD and ILD, support sound source localization and binaural advantage. Taken together, sound source localization and binaural advantage support binaural processing for both groups.

Summary

These results indicate that bilateral CI and hearing preservation listeners have access to binaural cues and benefit from binaural hearing (Figure 30). Although the bilateral listeners do not have access to ITD cues, they appear to be able to rely on ILD cues for binaural advantage. The hearing preservation listeners do have access to ITD cues but appear to be penalized by the lack of HF information on the unimplanted side for SRM. They do, however, show benefits for binaural advantage that are equivalent to the bilateral listeners.

Correlations were run to determine if there was a relationship between high-pass RMS sound source localization errors and binaural advantage for the bilateral listeners and between low-pass RMS sound source localization errors and binaural advantage for hearing preservation listeners. The correlation for the bilateral group was not significant, r = -.095, n = 11, p = .781, two tails. A correlation for the hearing preservation group with symmetrical hearing also failed to show significance, r = -.254, n = 8, p =.544, two tails.

These results are in agreement with those reported by Tyler et al. 2006 who also found no correlation between sound source localization and squelch or binaural advantage. They reported a correlation of r = .25. They offered no reason for this lack of correlation except to say that better tests are needed to measure binaural processing.

Results differ from those reported by Litovsky et al. (2009). They reported that there were positive correlations for SRTs in babble presented from the front, right, and left, and sound source localization with an *r* value of .5 when speech was presented from the front and *r* = .6 when speech was presented from either side. However, they go on to say that there is limited data on comparing outcomes and relationships between speech intelligibility in noise and sound source localization.

The lack of correlation between sound source localization and binaural advantage warrants further investigation. Although both measure a form of spatial hearing, sound source localization is obtained in quiet while unmasking necessitates testing in noise. Perhaps noise has a greater effect than is evident from a comparison between the two measures. In addition, little is known about the central processing of ILD cues which the bilateral listeners appear to rely on for sound source localization, as well as, for binaural advantage.

Speech Understanding Using a Roving Target with Multiple Spatially Separated Noise Sources

Rationale for Experiment 3

Experiment 3 was designed to determine if a dynamic test paradigm with a roving target in a background of multiple spatially separated maskers captured more accurately 1) the benefit of a second implant compared to the better ear implant and 2) the benefit of a second acoustic ear, e.g. the benefit of preserving hearing in the implanted ear, compared to the bimodal condition.

A roving target was used to more closely mimic daily life encounters that CI users engage in particularly when they are in a group setting. It was also designed with the reported need for new assessments (Noble et al., 2006; Tyler, 2006) to determine the benefit of binaural hearing that depends on dynamic listening such as a moving target. The questions were: 1) does bilateral hearing (electric or acoustic) provide greater benefit when the target is not stationary and the signal to noise ratio is poor (**aim 3**) and 2) does preserving hearing in the implanted ear add additional benefit to the hearing preservation group in difficult listening environments (**aim 4**).

Noble et al. (2006) looked at binaural benefit for hearing aid users. Noble et al. stated that the benefit of bilateral hearing aids is not in the domain of speech understanding in noise but "it is in domains of dynamic spatial hearing (distance, movement), rapidly switching and divided attention, and listening effort, that two aids do their work. Two aids deliver more effectively at the basic level of function (direction, distance, movement), and remove the need for strategic positioning and re-positioning; two aids may also support higher order functionalities through improvements in binaural processing." Noble et al. went on to say that it is difficult to show the benefits of bilateral hearing aid fittings because "researchers have been looking in the wrong (or, at least, in too limited a set of) places to discover where the benefits of bilateral hearing aid fittings are to be found."

In a later paper, Noble et al. (2008) compared three groups of CI users: unilateral, bilateral, and bimodal. Noble used the Speech, Spatial, and Quality of Hearing Scale (SSQ) which was designed to cover a range of hearing abilities including some hearing functions that rely on binaural listening. The SSQ was designed to demonstrate the usefulness of two hearing aids versus one and, therefore, was considered appropriate to use with bilateral implant users. Comparing between groups, the bilateral CI users had the highest ratings on all of the subscales. Noble et al. reported that bimodal users were no different from unilateral CI users on any of the subscales. The bilateral CI users had lower disability and less social restriction compared to unilateral CI users. Bilateral users had significantly greater ratings than unilateral CIs on the subscales of sound source localization, distance and movement, and listening effort. Bilateral users had greater self-perceived benefit than the bimodal users on distance and movement, and listening effort. They looked at the correlation between CNC words and the SSQ and found that the Qualities subscales were more correlated and the spatial subscales were less correlated. In other words, there was a gulf between self-report and performance on speech perception measures as we test traditionally with speech and noise coincident in space. As stated previously, Noble et al. contended that it is the “dynamic spatial hearing (distance, movement), rapidly switching and divided attention, and listening effort” that makes a difference in the use of one versus two devices. CNC words and sentences in quiet do not tax the spatial function of the hearing mechanism; there is no movement of the target or switching or dividing of attention due to location of the target which is stationary, and there is no background noise.

Noble et al. (2006) results were based on self-reports. Noble et al. stated that performance measures are needed that capture a dynamic listening environment. Tyler (2006) supported the concept of binaural processing in bilateral users but stated that “new tests are needed to more accurately examine the potential benefit of two implants.” There is a need to test CI users with more dynamic test paradigms rather than traditional static arrangements to determine functional benefit. Determining benefit is necessary in order to provide potential CI users and hearing health care providers with the necessary information to make an informed decision regarding expected outcomes. It is also necessary to be able to provide objective information to insurance companies as the demands for bilateral implantation and more liberal candidacy requirements are being proffered.

If listening effort was eased by a second implant as Noble et al. (2008) reported, it was theorized that using a roving target rather than a stationary target would be a more sensitive measure than traditional measures using a single loud speaker placed in front of the listener. It might also be a more sensitive measure than the previous experiment where the target was fixed but the listening environment was more life-like. By combining the real life listening environment used in Experiment 2 and a roving target, the hypothesis was that it would show increased benefit of having a second ear whether a listener had bilateral CIs or bilateral acoustic hearing paired with a CI, and it would better capture the binaural effects of head shadow, squelch, and summation. In addition, a roving or non-stationary target places more of an attentional demand on the listener which is often encountered in everyday life. Yost et al. (1996) reported that the "cocktail party effect" involves selective attention. It is the ability to selectively attend to a particular target that Noble et al. (2006) described as the benefits of binaural processing for dynamic spatial hearing – being able to switch or divide attention when the target moves or changes.

There is a discrepancy between anecdotal reports of bilateral/binaural benefit and what we have been able to measure in the laboratory or clinic. Some bilateral users have reported that it is easier to determine location of a sound source and therefore follow a conversation because they are not searching for the speaker. Particularly if they are more reliant on lipreading, they are not spending time to find the talker and losing the beginning of a conversation. Other bilateral patients have reported that the benefit of the second implant is a quality of life (QOL) issue. The burden of listening with one ear is eased when listening with two ears.

The purpose of Experiment 3 was to parse out whether either group benefitted more by having a second ear in a real world environment using a non-stationary target in a noisy environment. This is more of a “real life” phenomenon such as sitting in a restaurant at a circular table or listening in an environment surrounded by other people talking, such as in a cocktail party, and trying to follow conversations that switch between speakers and their location.

Experiment 3

Test Battery

Two different speech tests were administered. The methods were the same as in Experiment 2, Part A except that (i) TIMIT sentence materials (Lamel et al., 1986) replaced the AZ Bio sentences and (ii) the target was not fixed but roved randomly between three loud speakers at 0º, 90º, and -90º. The second test was the same as Experiment 2, Part B except that (i) the target Baby Bio sentences were not fixed but roved randomly between five loud speakers at 0º, 45º, 90º, -45 º, and -90º, and (ii) the background noise consisted of the diffuse restaurant noise from Part A.

Part A: Roving TIMIT

Speech stimuli. The TIMIT sentences were used as the speech stimulus. Thirty lists of 20 sentences per list with equal intelligibility (Dorman et al., 2005) were randomly assigned to groups of three lists per group for a total of 10 groups of 60 sentences per group. The sentences were spoken by four different talkers, two male and two female, with different regional accents and different speaking rates to replicate various dialects found across the United States. Not all sentences were grammatically correct or complete sentences and all were low in context. Sentences were presented with an inter-stimulus interval of 5 seconds and were presented at 60dB SPL. Sentences were scored as percent correct words per sentence. Three scores resulted based on location of presentation with a score from the front (0 º), the right(+ 90º) and the left (-90º). Each score was based on a list of 20 sentences.

Masker stimulus. Lou Manalti's restaurant noise from Experiment 2, Part A was presented from all eight loud speakers in R Space™ including the loud speaker presenting the target.

Methods

Subjects. Ten bilateral listeners and 10 hearing preservation listeners from Experiments 1 and 2 participated in Experiment 3, part A, using the TIMIT sentences. The test was too difficult for one listener, one subject was too tired to participate, and time was an issue for another listener. All subjects from Experiments 1 and 2 participated in part B, the Roving Cocktail.

Procedure. The target sentences were presented randomly at 60dB SPL from three loud speaker locations 0º, + 90°, - 90°. A target sentence was presented from each loud speaker a total of 20 times per condition. An SNR was established using a single list of 20 sentences presented from the front loudspeaker for the better ear from the bilateral group and the $E+A_{ipsi}$ for the hearing preservation listeners. The listening conditions for the bilateral group were: better ear, poorer ear, and bilateral. For the hearing preservation group the listening conditions were: EAS ($E+A_{ipsi}$), bimodal ($E+A_{contra}$), and combined (bilateral acoustic hearing + CI).

Results

Bilateral FSP™ listeners. This was a new test paradigm and, consequently, some of the binaural calculations were not derived using traditional calculations. In Roving TIMIT there was theoretically no head shadow from noise since noise was always presented all around eliminating the protective shadow from noise to one CI. In order to show that head shadow (HS) did not contribute to overall performance in the bilateral listening condition, HS was calculated. Scores for the target presented away from the better ear – e.g. toward the poorer CI – were subtracted from scores when the target was presented toward the better ear. The gain in understanding from head shadow was 6% (Figure 31). A paired samples t test showed the HS effect was not significant [$t(9) = 1.393$, $p = .197$] indicating there was no HS benefit in the bilateral condition. In this paradigm, HS was very small because both CIs were exposed to noise. Using a more traditional approach for calculating head shadow, the better ear alone was used and scores for the target presented on the contralateral side of the better ear were subtracted from scores when the target was presented toward the better ear. Head shadow was 40%. The same calculation was made for the poorer ear and was 44%. This large benefit of HS for the better ear did not provide enhanced performance compared to the bilateral condition.

Binaural advantage was calculated using the averages of the scores when the target roved between 0º, +90º, and -90º in the bilateral and better ear conditions. In this calculation, binaural advantage must be considered to be a combination of HS, squelch, and summation and resulted in a significant advantage of 16% in the bilateral condition compared to the better ear condition (Figure 32) [$t(9) = 7.15$, $p = .000$]. Summation effects were calculated using only the target presented to the front. Better ear scores were subtracted from bilateral scores and yielded a significant summation effect of 16% (Figure 33) [$t(9) = 4.129$, $p = .003$].

Effect of the Opus 2 earhook on speech scores. During TIMIT testing, several subjects had poorer scores with the target to the front than to the side. The Opus 2 processor has an earhook that acts as a wind shield by covering the microphone from the front. The vent on the earhook is on the side causing sound from the front to be baffled. This led to a small study where the earhook was eliminated and testing was repeated with the earhook off. Targets were presented at 0º. The Tempo+ earhook was used to maintain the position of the processor on the ear without covering the microphone. For one subject, scores for the target in front improved 17% with the earhook removed. Two other subjects participated in this project. Their scores with a roving target from the front did not improve; however, all three subjects commented on how much clearer and crisper speech sounded with the earhook removed. The first subject returned for testing approximately one year later and the same experiment was carried out. His scores improved 13.5% compared to having the earhook on. This indicated good replication. Unfortunately, the other two subjects were not tested with the target fixed. A fourth subject with bilateral CIs and bilateral acoustic hearing was tested with the target fixed in front. Scores did not improve with the earhook removed but the participant commented that it sounded richer/fuller with the earhook removed.

Hearing preservation listeners. Head shadow was calculated using the combined (bilateral hearing aids + CI) listening condition with the target presented toward the CI side and contralaterally to, or away from, the CI side. In this calculation, listeners still had aided acoustic hearing bilaterally picking up noise from both sides. In effect, head shadow benefit was reduced for noise because noise was presented to both acoustic hearing ears. However, the CI benefitted from HS and the CI provided most of the understanding. The HS effect was statistically significant, $t(9) = 2.899$, $p = .018$, and provided increased understanding of 15.5% (Figure 34) when the target was presented to the CI side. When the symmetrical subjects were used and asymmetrical subjects were eliminated, HS benefit increased to 21%. Using the CI alone condition, with both acoustic ears plugged and muffed, a much larger HS benefit of 39% was obtained. This is similar to the HS benefit for the bilateral group's better ear.

Binaural advantage was also calculated using the average of the scores from the three roving positions, 0º, 90º, and -90º, in the combined and bimodal conditions (Figure 35). Scores in the bimodal condition were subtracted from the combined condition. A small, but significant binaural advantage of 7% was found [$t(9) = 2.296$, $p = .047$]. Summation was calculated using scores obtained when the target was presented from the front (Figure 36). The difference between the combined and EAS conditions yielded summation effects that were not significant, $t(8) = 1.472$, $p = .179$. As mentioned previously, the hearing preservation group does not have bilateral, HF information to sum for understanding. They are at a disadvantage because both ears are picking up noise but only one ear, the CI ear, is able to be used for the majority of understanding speech. The CI ear is at a disadvantage when the target is presented toward the opposite ear.

Part B: **Roving Cocktail**

Target speech stimuli. The BabyBio Sentences from Experiment 2, Part B were used as the speech stimuli. Target sentences were presented in the frontal horizontal plane and were roved randomly between speakers at 0º, 45º, 90º, -45º, and -90º.

Masker stimulus. The noise consisted of the diffuse restaurant noise described under Experiment 2, Part A. The restaurant noise emanated from all eight loud speakers, including the target loud speaker, creating a virtual restaurant setting.

Procedure. The target sentences were presented randomly at 60dB SPL from five different speaker locations between ±90°, e.g. speakers 1,2,3,7, or 8 (Figure 14). A target sentence was presented from each speaker a total of four times per condition. An SNR was established using the better ear from the bilateral group and the EAS for the hearing preservation listeners. The SNR had to be recalculated for some of the hearing preservation subjects to avoid ceiling effects in the combined condition. The combined condition was then used to determine the SNR for performance between 60 - 80% correct. The listening conditions for the bilateral group were: better ear, poorer ear, and bilateral. For the hearing preservation group the listening conditions were: EAS, bimodal, combined, CI only, and bilateral HAs.

Results

Bilateral FSP™ listeners. Bilateral CI users showed significant benefit from adding the 2nd (poorer) CI on the Roving Cocktail test. Bilateral scores shown in Figure 37 were 28 percentage points higher than the better ear alone. A repeated measures ANOVA revealed a significant difference between the better ear, poorer ear, and bilateral listening conditions [$F(2,20) = 74.103$, $p < .0005$]. A paired samples t test showed that bilateral listening was significantly better than the better ear alone [$t(10) = 8.843$, $p < .0005$]. The benefit was largely due to the head shadow effect since either CI always had a more favorable SNR to the target. However, squelch and summation also contributed to the benefit which was evident in the Cocktail Party setting using a fixed target.

Hearing preservation listeners. The hearing preservation group gained 13 percentage points in the combined condition compared to the bimodal condition (Figure 38). A gain of 21% was obtained in the combined condition over the EAS condition. When comparing the CI only scores for the hearing preservation group to the EAS, bimodal, and combined conditions, scores improved by 18% in the EAS condition, 26% in the bimodal condition, and 39% in the combined condition. The benefit of adding acoustic hearing to the CI scores is evident in all three acoustic plus CI conditions. A repeated measures ANOVA revealed that the five conditions were significantly different [$F(4,44) = 35.161$, $p < 0005$]. Paired samples t tests showed no difference between the bilateral HAs and the CI scores [$t(11) = 1.324$, $p = .212$]. The combined condition was significantly better than the bimodal condition, [$t(11) = 4.974$, $p < .0005$] and the EAS condition [t(11) =6.145, p < 0005].The bimodal condition was significantly better than the EAS condition [t(11)= 2.412, p = .035]. All three conditions adding acoustic to electric hearing, EAS [t(11) =3.738, p = .003], bimodal [t(11) = 4.841, p = .001], and combined [t(11) = 6.165, p < .0005], were significantly better than the CI alone condition.

Benefit of preserving hearing. These results showed the benefit of adding acoustic hearing to electric hearing, and more importantly, the benefit of preserving hearing in the implanted ear. This benefit is largely due to squelch; by adding in the ipsilateral acoustic ear, scores improved in the combined condition over the bimodal condition by 13 percentage points. Summation and head shadow also contributed to the improved results in the combined condition.

Summary for roving tests (results in percent correct)

	Binaural Advantage	Summation
Roving TIMIT		
Bilateral FSP™	16	16
Hearing preservation	7	9
Roving Cocktail		
Bilateral FSP™	28	CNE*
Hearing preservation	13	CNE*

*could not evaluate in this condition

Discussion

A roving target is more realistic and a more demanding task than a stationary target. The Roving TIMIT and Roving Cocktail tests showed clearly the benefit obtained by having two implants compared to one. With electrical stimulation on both sides, the benefit from two implants was sizable resulting in a more favorable SNR, despite which side the target was on, and the possibility of better frequency representation with two implants compared to one.

Bilateral FSP™ listeners. On the Roving TIMIT test, two CIs were 16 percentage points better than the better ear alone for both binaural advantage and summation. During the TIMIT test, the problem of baffling sound from the front with the earhook on the Opus 2 processor became apparent and warrants further research. A follow up study has been planned to determine if scores improve with elimination of the earhook when evaluating other Opus 2 users.

On the Roving Cocktail test, scores of improved listening in the bilateral condition compared to their better ear alone were on average 28 percentage points higher. The range of binaural advantage was 13 - 52%. The Roving Cocktail test provided a significant improvement of 10 percentage points in the bilateral condition when compared to the Cocktail Party with a stationary target in the separated condition [$t(10) = 4.034$, $p = .002$]. It should be noted that in Roving Cocktail the noise emanated from all speakers, including the speaker for the target, unlike in the Cocktail Party. The masker noise from the two experiments was also different. The restaurant noise used in Roving Cocktail is considered energetic rather than informational.

Hearing preservation listeners. The Roving TIMIT test did not show benefits as large as those obtained in the Roving Cocktail Party for the hearing preservation group.

Roving TIMIT showed a small, but significant, binaural advantage of seven percentage points. Summation effects of nine percentage points were not significant.

The Roving Cocktail test displayed the benefits obtained from preserving hearing in the implanted ear. Combined scores were 13 percentage points better than the bimodal condition, 21 percentage points better than the EAS condition, and were 39 percentage points higher than in the CI alone condition. The hearing preservation group had the benefit of squelch from their bilateral acoustic hearing but benefitted very little from summation effects in the HF with only one CI. However, the absence of summation indicates the true benefit of squelch afforded to the hearing preservation group.

When the combined condition from the Roving Cocktail was compared to the combined condition in the Cocktail Party using a fixed target, there was no significant difference between the two tests, $t(11) = 1.46$, $p = .172$. The hearing preservation group did not show increased benefit using a roving target like the bilateral group demonstrated, but they also did not show a decrease in performance. The lack of benefit is most likely due to the absence of HF hearing when the target is on the non-implanted side making understanding more difficult due to the deficiency of HF information.

CONCLUSIONS

Two conclusions are readily apparent from this research. First, having bilateral hearing in both ears, either electric or acoustic, is beneficial for sound source localization and for listening in complex noisy environments. Second, using more sensitive tests with spatial separation of speech from noise showed benefits obtained by adding a second implant or preserving hearing in the implanted ear that less sensitive tests do not show.

CNC word scores were not a sensitive measure to determine whether the combined condition was better than the EAS or bimodal conditions (Figure 39). Neither CNC nor AZ Bio in Quiet or at +10dB SNR were sensitive enough to determine whether bilateral CI scores were significantly different than better ear scores (Figure 40). Traditional testing at a +5dB SNR did provide a separation of bilateral *vs.* better ear scores. These tests which are presented from a single speaker in front are generally not sensitive enough to show bilateral benefit or benefit for preserving hearing because i) only a single speaker in front is used, (ii) speech and noise are not spatially separated which is necessary to show any binaural (not bilateral) benefit, and (iii) it is difficult to show greater benefit than the better ear alone. Only when speech and noise are spatially separated can unmasking or binaural advantage be evaluated and demonstrated.

Outcomes from Experiment 1: Sound source localization

The outcomes of this research showed that having the same hearing in both ears provided bilateral CI and hearing preservation listeners with some of the same binaural benefits known to NH listeners. The outcomes from Experiment 1 indicated the value of bilateral hearing, either bilateral electric or symmetrical acoustic hearing, for sound source localization abilities. The ability to localize using either ITD or ILD cues can be an important aid to CI listeners. Both bilateral and hearing preservation listeners with symmetrical hearing were able to localize equally using different cues.

Bilateral CI listeners demonstrated good, but not normal, sound source localization abilities to high-pass stimuli indicating access to ILD cues. Sound source localization to low-pass targets indicated that hearing preservation listeners had good, but not normal, access to ITD cues as long as the acoustic hearing is symmetrical. There was a clear difference in sound source localization between those with symmetrical and asymmetrical hearing. Those with asymmetrical hearing showed poor or close to chance performance (70-77º) on sound source localization compared to those with symmetrical hearing.

Outcomes from Experiments 2 and 3: Binaural Benefits

The outcomes from Experiments 2 and 3 showed advantages for both the bilateral and hearing preservation groups. Unlike in traditional testing using a single loud speaker in front, the important benefits of binaural hearing can only be demonstrated using multiple loud speakers with the speech target and maskers separated in space.

Bilateral implant users have some clear advantages over listeners with a single CI. They demonstrated the ability to "unmask" speech from noise in difficult listening environments using multiple spatially separated maskers **(aim 2)**. The Cocktail Party and Roving Cocktail tests were the most sensitive to the binaural benefits of bilateral CI listeners. Bilateral CI listeners showed the binaural processing available to NH listeners which include binaural advantage, summation, squelch, and head shadow. They did not, however, show benefit from SRM as it was measured for bilateral listening when comparing the separation of speech and noise to the unseparated condition. Unlike in a previous study by Loizou et al. (2009), the outcomes for bilateral FSP™ users showed that they did have access to binaural processing by benefitting from binaural advantage, a combination of squelch and summation, in RSpace and in the Cocktail Party setting. The bilateral listeners demonstrated access to binaural processing without having access to ITD cues. ILD cues appear to enable bilateral CI listeners to "unmask" speech presented in noise. It is doubtful that the FSP™ strategy is the basis for their ability to use binaural processing cues. In an ongoing, concurrent study using AB and Cochlear CI devices, the bilateral CI users had a significant binaural advantage of 17 percentage points, [$t(25) = 6.736$, $p < .0005$].

The advantage for the hearing preservation listeners was the benefit of preserving hearing in the implanted ear **(aim 4).** Although the hearing preservation listeners did not show benefit from SRM, they did exhibit significant binaural advantage, a combination of squelch and summation. Most notably they exhibited the benefit of being able to squelch background noise and, therefore, improve speech understanding when the target and maskers were not co-located in space. The Cocktail Party was the most sensitive test for showing the attributes of preserving hearing in the implanted ear. The results point to the benefit of preserving hearing rather than having access to acoustic hearing in only one ear. The results also underlie the necessity of not just preserving hearing but to maintain as much symmetry as possible. This is an important message for surgeons as they counsel their patients.

The Cocktail Party and the Roving Cocktail tests are excellent tools which can be used to provide surgeons, clinicians, potential CI candidates, and insurance companies with expected outcomes and benefits for bilateral implantation as opposed to having a single implant. These tests also indicate that hearing preservation listeners perform significantly better in the combined listening condition than in the bimodal condition underscoring the benefits of preserving hearing.

Future Directions

Future studies need to compare informational and energetic masking for CI users. Loizou et al. (2009) found no difference in performance regardless of masker type. In the current study, the bilateral listeners in the Cocktail Party, which used informational masking, benefitted from a significant binaural advantage.

One question that arose from this study was whether or not having a female target and male maskers had any influence, either positive or negative, on performance. The problem with using the same gender for the target and masker is that it may not be possible to determine which target to listen to when all are presented in front from the same loud speaker. A future study should determine whether changing the target to a male and using female maskers has any influence on outcomes.

The outcomes for the hearing preservation group showed a clear benefit to preserving hearing in the implanted ear. Although previous studies (von Ilberg et al., 1999; Gantz et al., 2009; Dorman et al., 2009; Zhang et al., 2010; Dunn et al., 2010) have shown significant benefits of adding an acoustic ear to an electric ear in terms of speech understanding, previous studies have not shown the merits of binaural processing by preserving hearing. The Cocktail Party showed a clear benefit (i) for preserving hearing and (ii) for binaural advantage when the speech and noise are separated in space. However, three loud speakers rather than one are needed to show the availability of binaural processing. Test paradigms in the clinics need to use multiple loud speakers for their standard test protocol. Future studies need to expand the number of hearing preservation listeners to determine if a larger number of subjects strengthens the results found in the current research.

For hearing preservation listeners nothing is known about whether or not having matched hearing aids for both ears would improve performance for sound source localization or enable better binaural processing in difficult listening environments. A future study should explore whether matched hearing aids make a difference in performance for this group.

Over 20 years ago Festen and Plomp (1990) reported on the deleterious effects of having a microphone above the pinna. Another study that needs to be done is to move the microphone from on top of the pinna to a place in or near the concha such as the T-mic® used by Advanced Bionics. Gifford and Levitt (2010) showed a 4.4dB improvement for SRTs in noise when using the T-mic as opposed to the BTE microphone on the processor. Hardware issues seem to take extremely long times to change but the CI companies need to look to the progress made by the hearing aid companies to improve their products.

The improved scores on the TIMIT test for one subject with the Opus 2 earhook removed warrants further research. If the perception is that speech sounds clearer without the earhook and that scores improve, this is a design issue which MED-EL could easily fix without great cost. Further research is underway to determine if removal of the baffling effect from the earhook on the Opus 2 improves performance.

In a concurrent study, testing on bilateral CI users from all three manufacturers showed some interesting results for the LP, HP, and WB sound source localization conditions. In Figure 41, the bilateral MED-EL users, both FSP™ and non-FSP, show fewer errors and less variability in all three conditions, but especially for WB and HP conditions, compared to users with Advanced Bionics (AB) and Cochlear Corporation (CC). Perhaps the AGC in the MED-EL processor provides some additional cues or at least does not deliver increased distortion when engaged. It is possible that the independent AGC for each ear engages at different times depending upon where the sound is and/or whether AGC is engaged on both ears. That might present a very small ITD cue to the user. In Wilson and Dorman (2012), they reported measuring short ITDs of 25µsec using independent, non-synchronized CIS processors. A future study should determine why the MED-EL listeners fared better in the WB and HP conditions compared to other devices and whether or not this might be attributed to AGC in the MED-EL processor. Perhaps the signal processing in the MED-EL device does not deliver as much distortion when the AGC engages. The deleterious placement of the microphone above the pinna does not appear to have an adverse effect for the MED-EL users compared to the other two companies. In particular, the MED-EL users show fewer errors and less variability compared to the AB users, all of whom used the T-mic. It should be noted that the CI listeners between manufacturers were not matched on any parameter but were simply tested as they presented for various research projects. Still, the results are striking and deserve additional research.

Quality of life (QOL) issues can be difficult to measure objectively but are an important aspect of a user's perception in relation to performance. More studies are needed that objectively measure QOL. One such study might measure reaction time to determine ease of listening, a QOL issue, with two *vs.* one cochlear implant for bilateral listeners or the combined condition relative to the bimodal condition for the hearing preservation group. A measure such as this could provide strong, objective evidence for the benefits of bilateral CIs or hearing preservation as insurance companies elect to continue to cover CI benefits.

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Table 1

Demographic information for 11 bilateral MED-EL FSP™ and five non-FSP listeners

Subject	Age	Gender	Age HL onset (years)	Years of CI Use RE/LE	Device RE/LE	# Active channels RE/LE	Etiology of Deafness
S2*	41	M	37	2	Sonata	8/9	Bacterial infection
S3	32	F	14	2/2	Sonata Medium	9/10	Viral infection
S4*	79	M	19	1	Sonata	9/10	Hereditary
S6*	53	F	20	8	Combi 40+	9/10	Unknown
S7	59	M	25	1/2	Sonata	11/10	Head Trauma
S9	77	F	20	6/2	Combi 40+/ Sonata	12/12	Unknown
S10	65	F	30	7/1	Combi 40+/ Sonata	9/9	Unknown
S11	43	M	42	.6/.5	Sonata	12/12	Head Trauma
S13	50	F	3	5/8	Pulsar/ Combi 40+	12/11	Hereditary
S14	66	M	38	.8/.7	Sonata	11/11	Unknown
S15	60	M		2.5/1.9	Sonata	7/10	Unknown
NonFSP*	50	F	29	9	Combi 40+	12/12	Unknown
NonFSP	50	F	3	5/9	Pulsar/ Combi 40+	10/11	Hereditary
NonFSP	59	M	39	1.5/1	Sonata	7/10	Unknown
NonFSP	39	F	2	8/5	Combi 40+/ Pulsar	12/11	Hereditary
NonFSP	39	F	14	1/3	Pulsar/ Sonata	12/12	Unknown

*Simultaneous implantation

Table 2

Demographic information for 12 hearing preservation users. ME = MED-EL. CC = Cochlear Corp. * hearing preservation, not EAS or Hybrid

Sub	Age	Gender	Age HL onset (in years)	Processor/ HA	Years of CI Use	CI Ear/ Device	Strategy	# Active Channels	Frequency Allocation in Hz	Etiology of Deafness
S17	68	M	27	Tempo+Duet/ Widex	5	L/MED-EL Pulsar EAS	CIS	10	500-8500	Unknown
S18	67	M	21	Tempo+Duet/ Phonak	1	R/ ME Sonata EAS Flex	CIS	10	500-8500	Noise Exposure
S19	39	F	14	Tempo+Duet/ Tempo+Duet	1	R/ ME Pulsar EAS Flex	CIS	12	300-8500	Unknown
S20	79	M	40	Freedom/ Phonak	2	R/CA Hybrid L24	MP12	20	1188-7938	Hereditary
S21	55	F	40	Freedom/ Phonak	2	R/CA Hybrid L24	MP12	20	1188-7938	Unknown
S22	70	M	42	Freedom/ Widex	1.6	L/CA Hybrid L24	MP12	20	1188-7938	Hereditary
S23*	64	M	20	Opus 2 Duet/ Danalogics	6	L/ME Pulsar Medium	FSP	10	690-8500	Hereditary
S25*	69	F	47	Opus 2/ Phonak	1	R/ ME Sonata Flex	FSP	10	100-8000	Hereditary
S26	47	F	32	Freedom/ Phonak	3	R/CA Hybrid L24	MP12	20	1188-7938	Unknown
S27*	35	M	5	Opus 2/ Unaided	2	L/ ME Sonata Medium	FSP	11	332-7500	Unknown
S28	50	F	32	Freedom/ Phonak	3	R/CA Hybrid L24	MP12	20	1188-7938	Hereditary
S29	62	F	52	Tempo+Duet/ Phonak	2	L/ ME Sonata EAS Flex	CIS	12	500-8500	Viral Infection

Table 3

Thresholds in dB by frequency (Hz) for each hearing preservation subject with symmetrical acoustic hearing. Thresholds are listed for the implanted ear/unimplanted ear. NR = no response at equipment limits >120dB

Subject	**125Hz**	**.25kHz**	**.5kHz**	**.75Hz**	**1kHz**	**2kHz**	**4kHz**
2	40/45	50/40	65/50	70/60	80/70	100/75	NR/85
3	40/35	50/35	65/45	80/55	90/60	NR/NR	NR/NR
4	10/30	30/40	80/70	85/85	90/80	105/90	NR/NR
5	30/35	20/20	50/30	65/50	70/55	110/90	115/100
6	30/30	30/25	50/30	65/50	85/65	120/115	120/120
11	15/15	15/15	60/65	85/90	95/100	NR/NR	NR/NR
12	5/0	10/5	40/30	90/70	100/100	NR/110	NR/NR
13	35/20	40/25	55/40	70/45	80/60	100/100	105/90

Table 4

Thresholds in dB by frequency (Hz) for each hearing preservation subject with asymmetrical acoustic hearing. Thresholds are listed for the implanted ear/unimplanted ear. NR = no response at equipment limits >120dB

Subject	**125Hz**	**.25kHz**	**.5kHz**	**.75Hz**	**1kHz**	**2kHz**	**4kHz**
7	50/10	55/10	75/10	90/30	115/50	115/105	115/110
8	65/20	80/20	80/35	110/35	NR/55	NR/95	NR/NR
9	50/25	70/20	80/45	95/70	95/80	115/105	NR/115
10	70/10	60/10	85/15	110/35	NR/60	NR/85	NR/85

Table 5

Mean RMS errors for sound source localization and standard deviations(SD) for the different groups. Hearing preservation errors are in the bilaterally aided plus CI condition. NH = normal hearing, HI = hearing impaired, LP=low pass, HP=high pass, WB=wideband, Hrg Pres symm = Hearing preservation with symmetrical hearing, asymm = asymmetrical.

RMS errors	**NH**	**HI unaided**	**HI aided**	**Hrg Pres symm**	**Hrg Pres asymm**	**Bilateral CI**
LP Mean	6.95	14.69	15.70	23.32	76.48	45.96
SD	1.95	8.30	7.17	10.63	20.64	18.65
HP Mean	6.7	19.16	22.19	57.77	60.31	19.64
SD	2.61	8.37	8.88	22.17	12.27	5.36
WB Mean	5.98	15.53	12.90	33.03	49.83	20.32
SD	2.72	9.57	6.94	9.05	14.23	6.62

Table 6

Means and standard deviations (sd) for SRM, binaural advantage, and summation for all groups in RSpace. Hearing Pres = hearing preservation, Symm = symmetrical acoustic hearing, all = symm + asymmetrical hearing.

RSpace™	**NH**	**Bilateral**	**Hearing Pres symm**	**Hearing Pres all**
SRM Mean	-5	-10.15	0.64	-.13
SD	4.92	12.28	10.99	8.57
Bin Adv Mean	14.73	9.6	14.62	10.96
SD	7.75	6.82	12.48	11.81
Summation Mean	11	11.17	23.69	20.41
SD	12.75	8.1	13.84	12.16

Table 7

Means and standard deviations (sd) for SRM, binaural advantage, and summation for all groups in Cocktail Party

Cocktail Party	**NH**	**Bilateral**	**Hearing Pres symm**	**Hearing Pres all**
SRM Mean	23	6.46	4.70	4.72
SD	7.7	5.93	9.12	9.59
Bin Adv Mean	38	18.19	20.08	18.84
SD	17.1	11.06	11.73	11.93
Summation Mean	14	13.79	11.41	12.63
SD	6.69	8.58	10.34	8.43

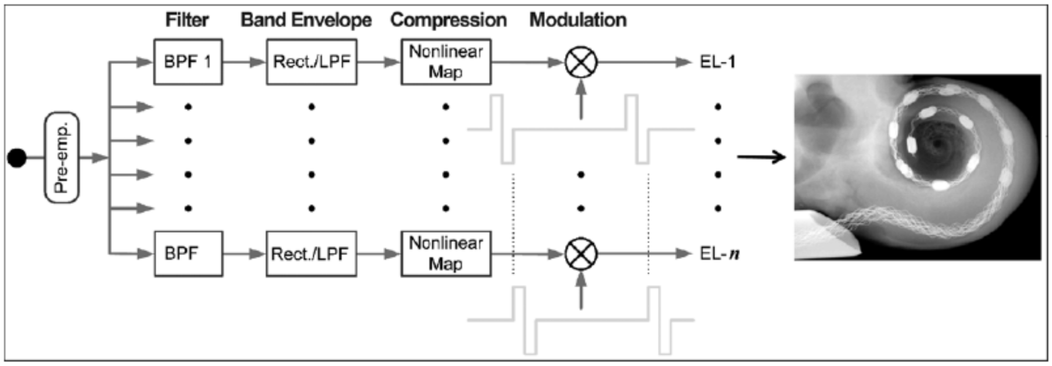

Figure 1. Implementation of the signal processing on the CIS strategy.
(From Wilson and Dorman 2008).

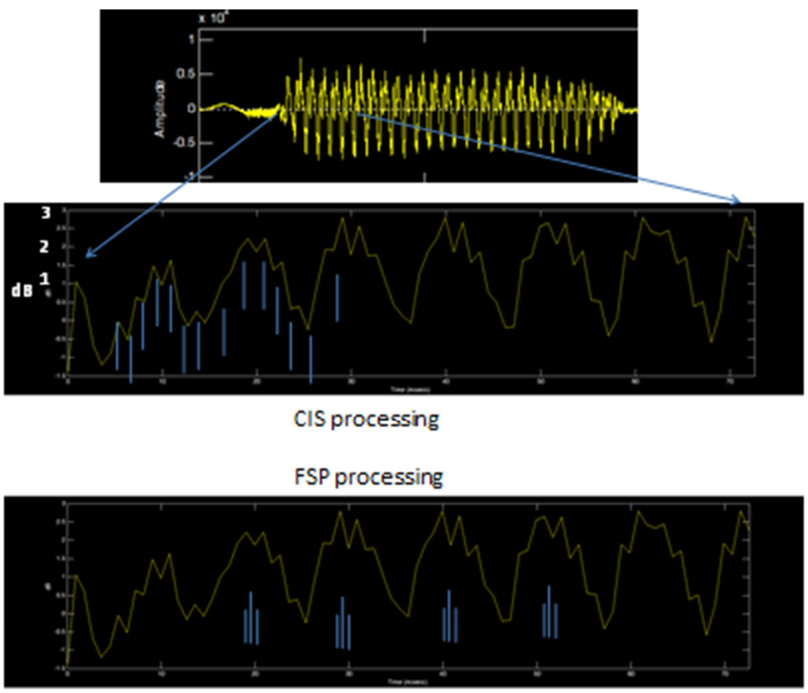

Figure 2. FSP™ uses rate cues represented by blue pulse packets to provide temporal information (bottom panel). CIS uses a continuous pulse train (middle panel).

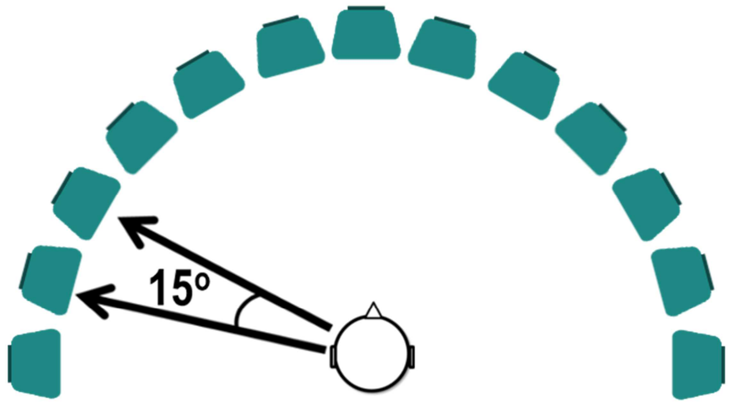

Figure 3. Loud speaker array spanning 180˚ in the horizontal plane. Speakers are spaced 15º apart.

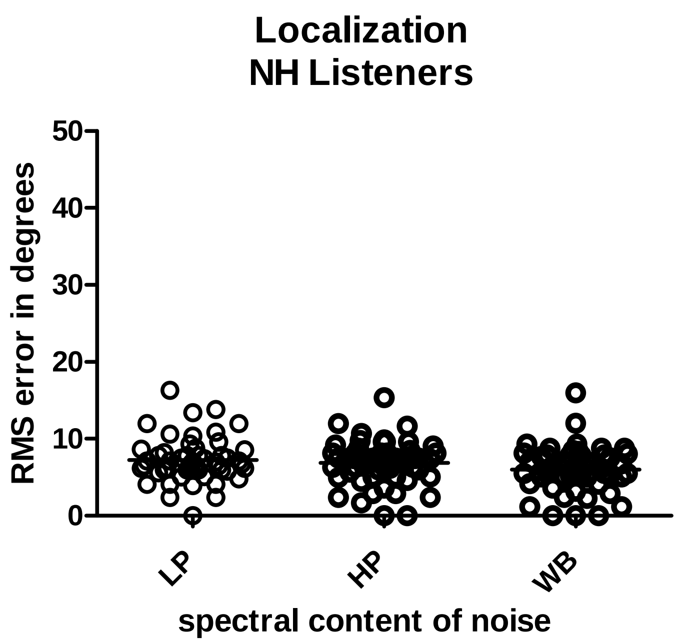

Figure 4. RMS errors for NH listeners to LP, HP, and WB stimuli.

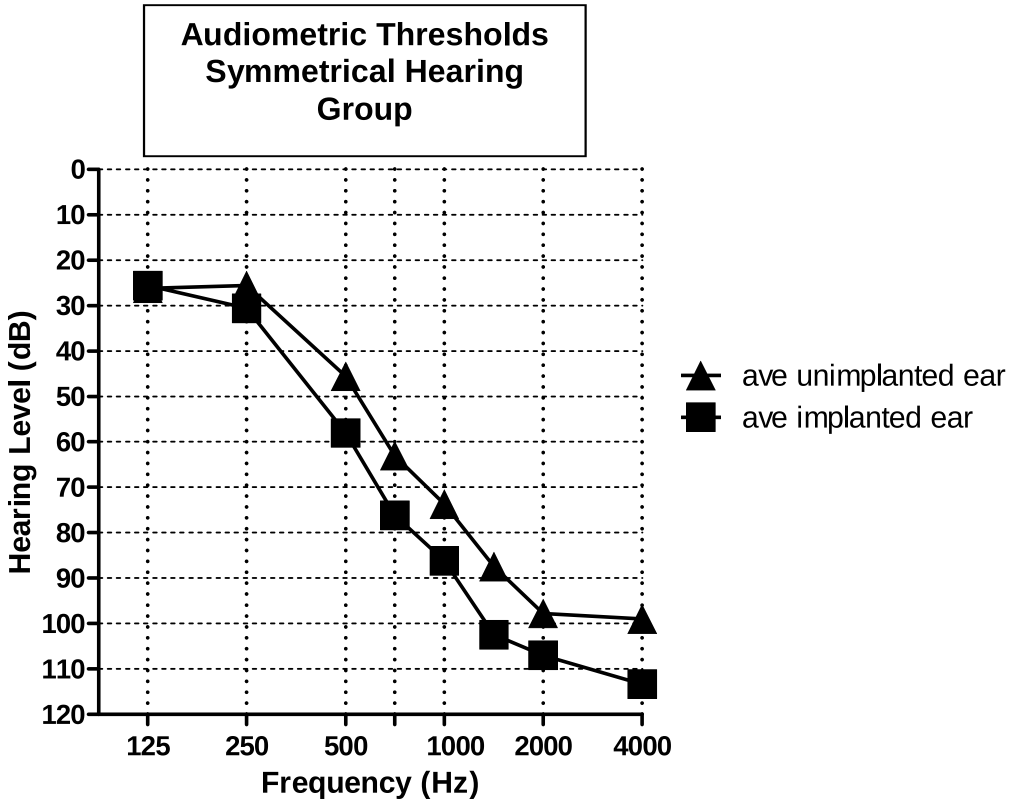

Figure 5. Mean audiometric thresholds for the hearing preservation group with symmetrical, low frequency hearing.

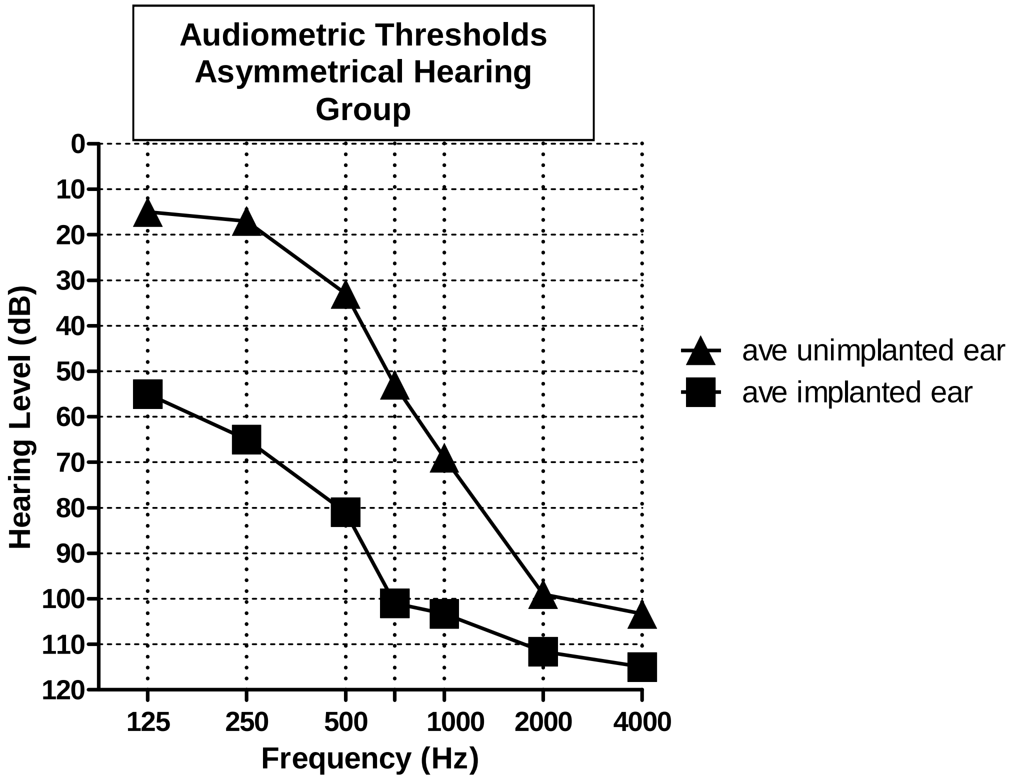

Figure 6. Mean audiometric thresholds for the hearing preservation group with asymmetrical, low frequency hearing.

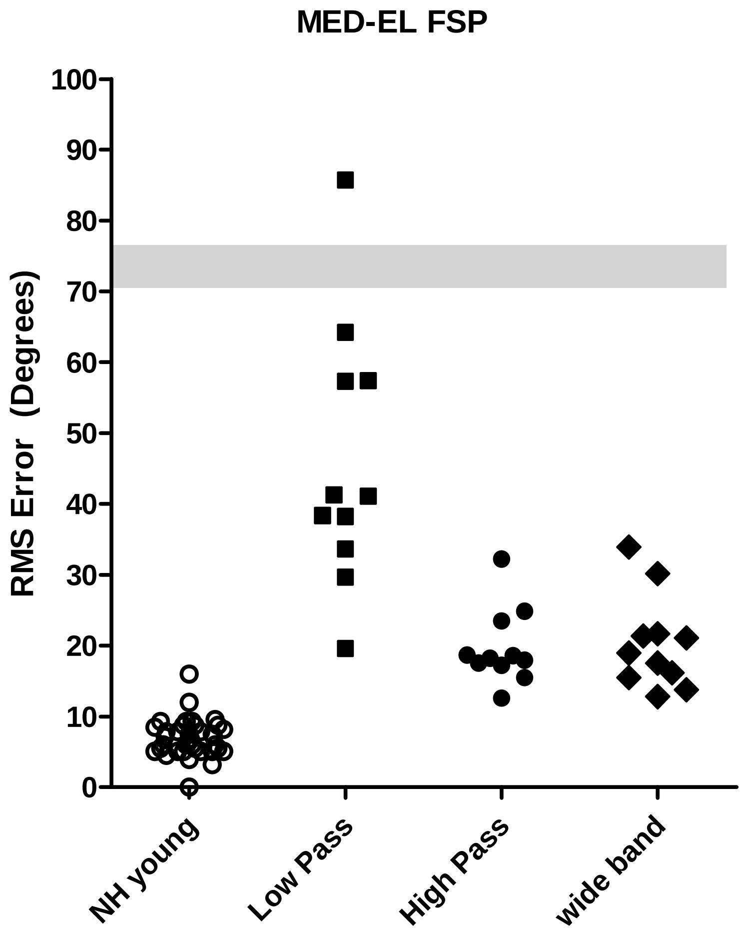

Figure 7. RMS errors to LP, HP, and WB stimuli for bilateral FSP™ listeners. RMS errors are plotted as a function of spectral stimuli. NH listener errors to LP stimuli are plotted on the far left.

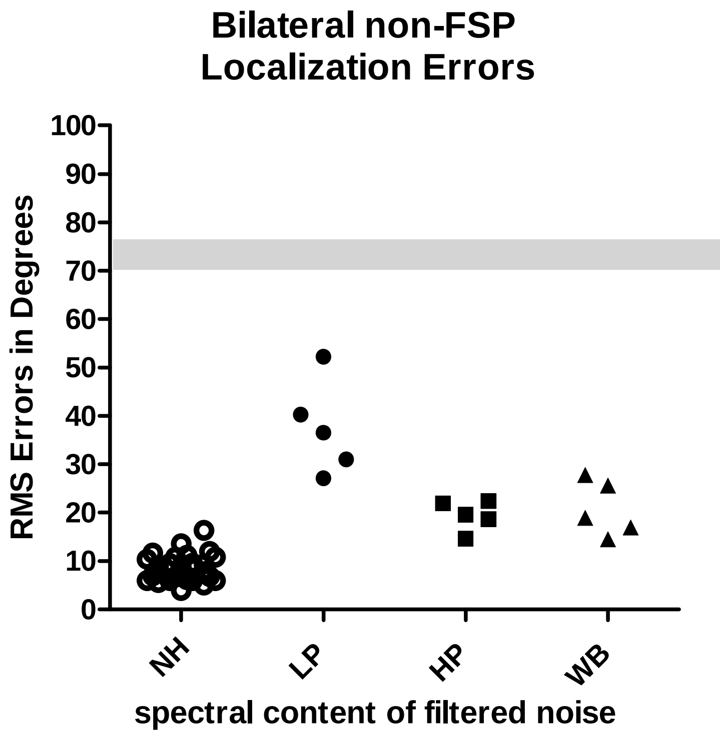

Figure 8. RMS errors for bilateral non-FSP listeners. RMS errors are plotted as a function of spectral stimuli. NH listener errors to LP stimuli are plotted on the far left.

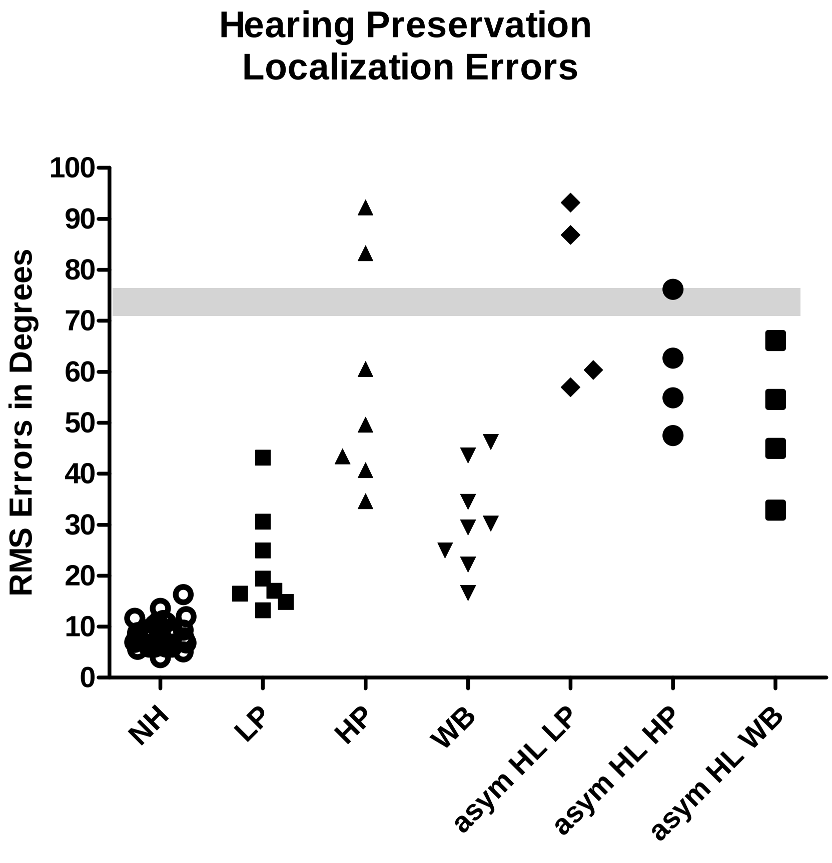

Figure 9. Localization errors as a function of spectral content for the symmetrical and asymmetrical (asym) hearing preservation listeners in the combined condition. NH errors to LP stimuli are plotted as open circles on the far left.

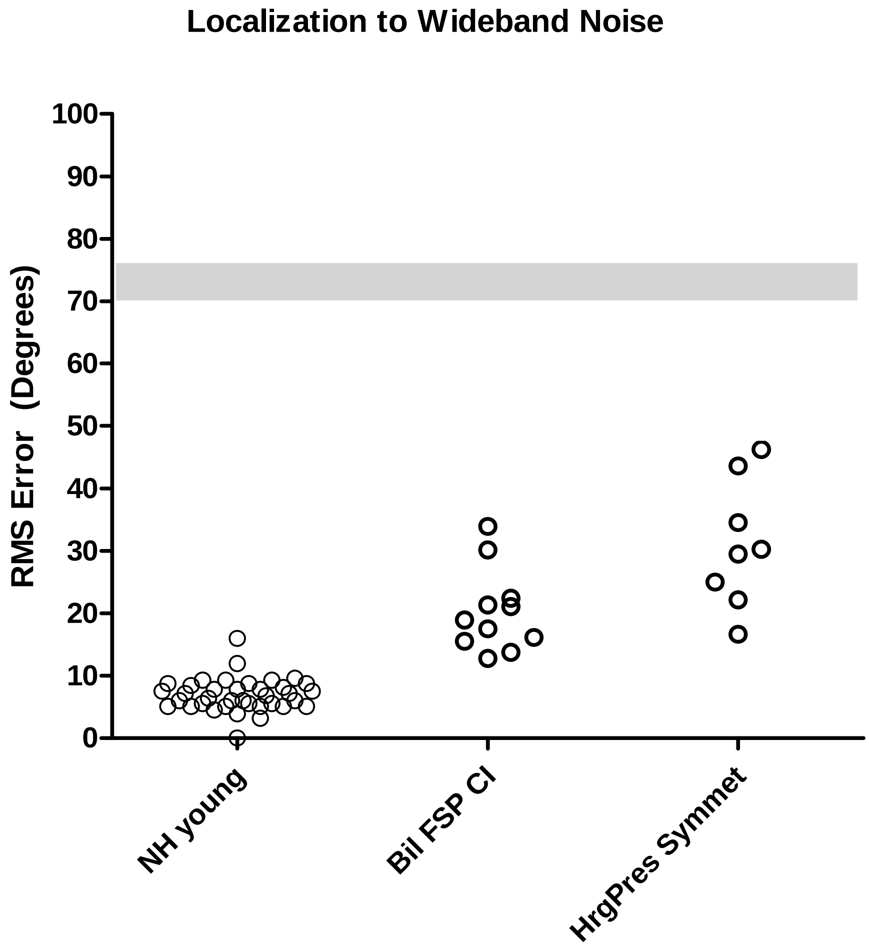

Figure 10. Localization errors for bilateral FSP™ and hearing preservation listeners to WB stimuli. WB errors are plotted for NH listeners on the left.

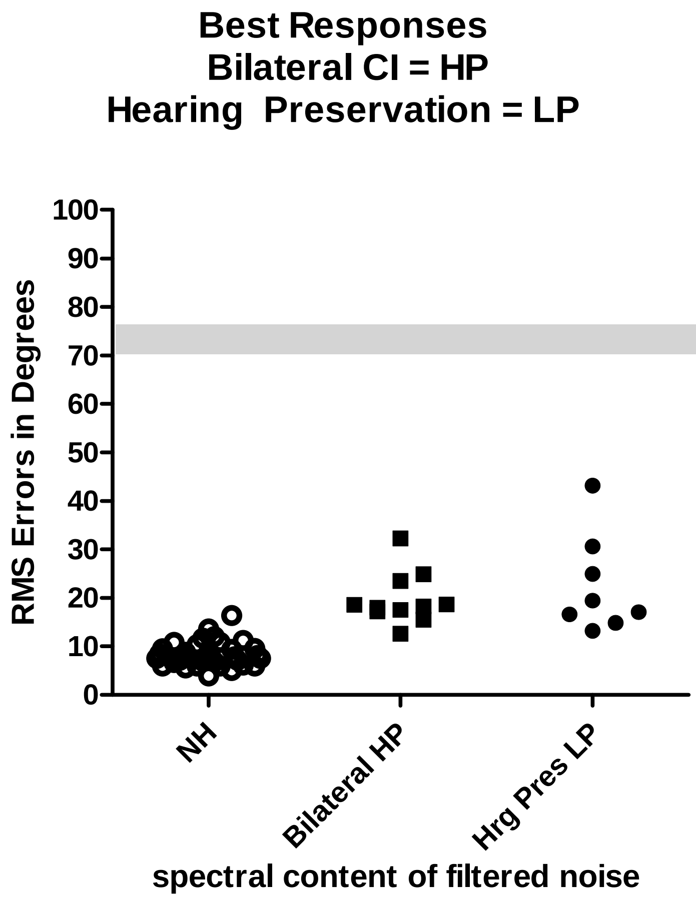

Figure 11. RMS errors plotted as a function of the best condition for bilateral CI (high-pass) and for hearing preservation (low-pass) listeners.

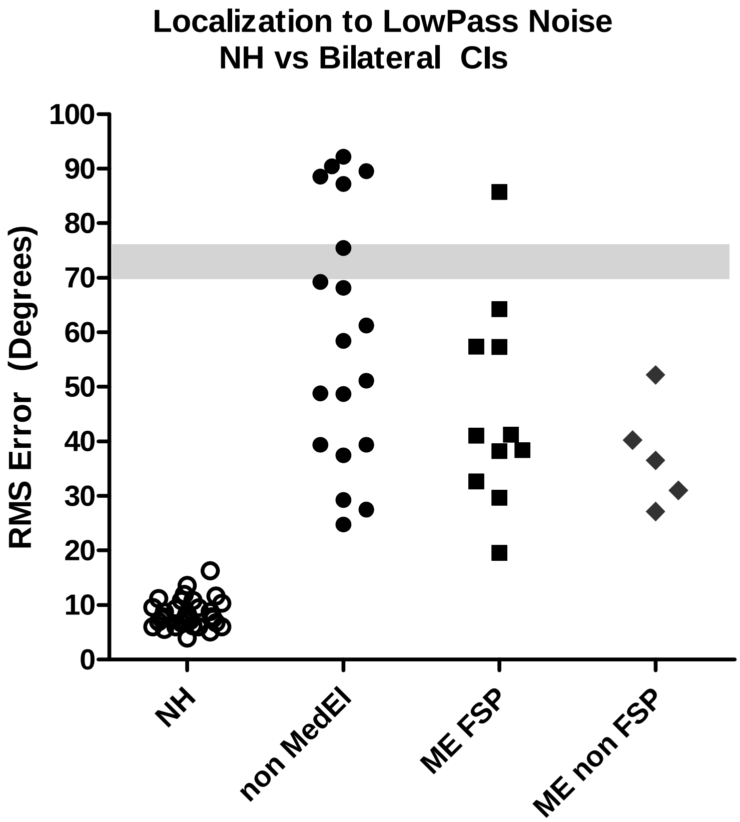

Figure 12. Low-pass RMS errors plotted for NH, non-MED-EL, MED-EL FSP™, and MED-EL non-FSP™ bilateral CI users.

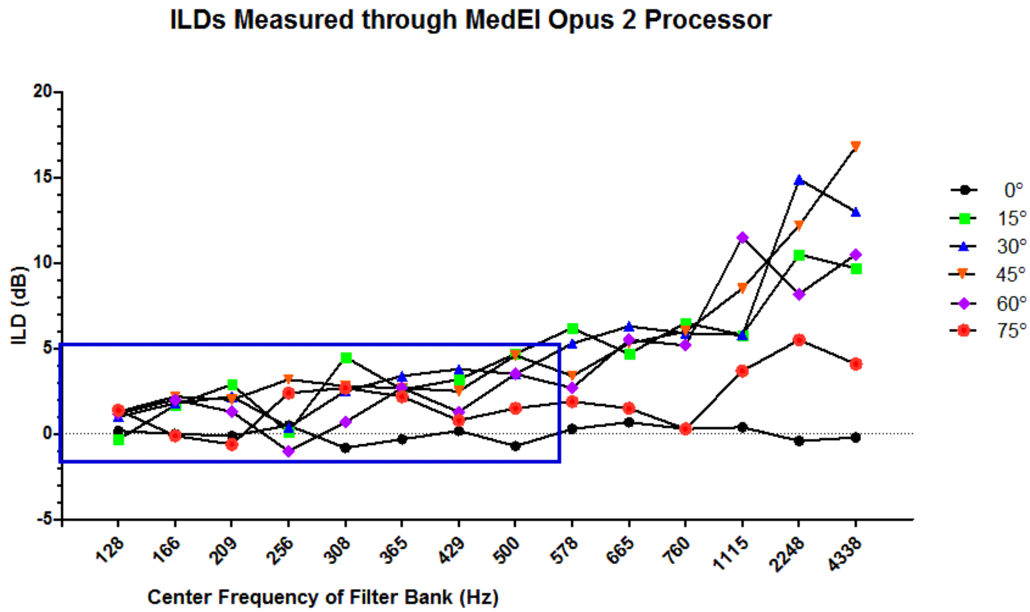

Figure 13. ILDs as a function of the center frequencies of the filter banks in the Opus 2 processor. The blue box denotes the ILDs below 500Hz.

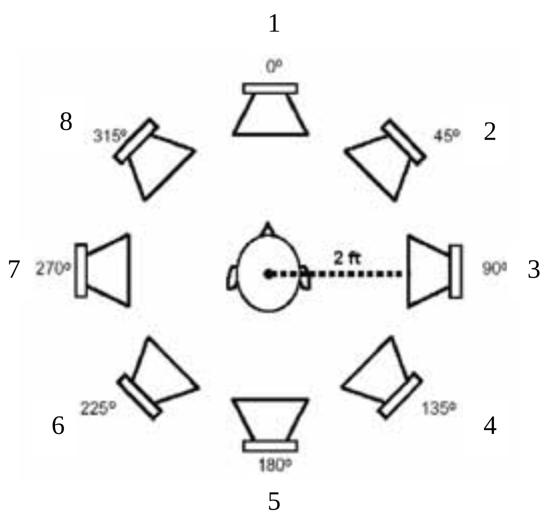

Figure 14. Configuration of loud speakers in RSpace™. Speakers are numbered 1 – 8.

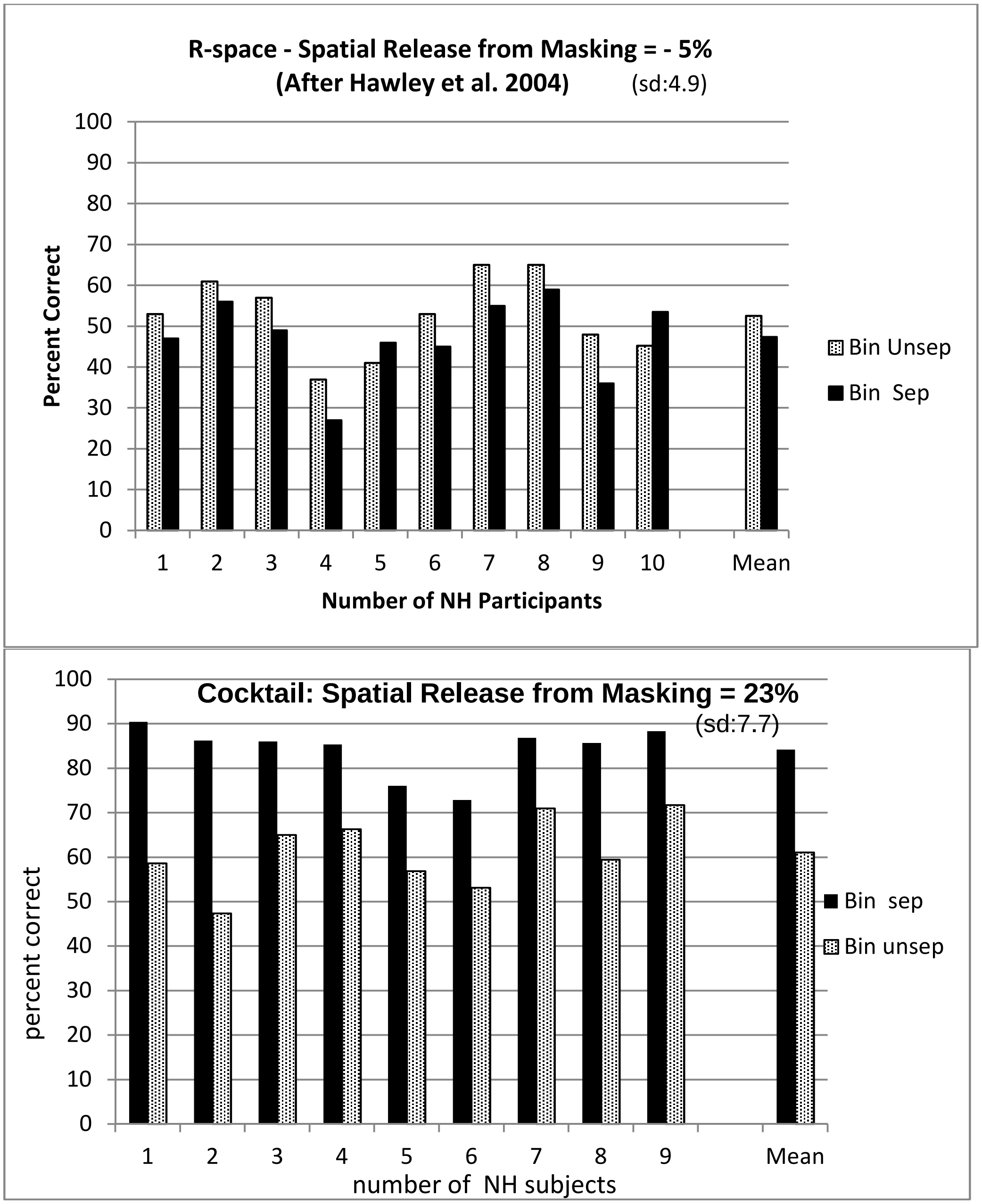

Figure 15. SRM, in percent correct, for NH listeners in RSpace and Cocktail Party.

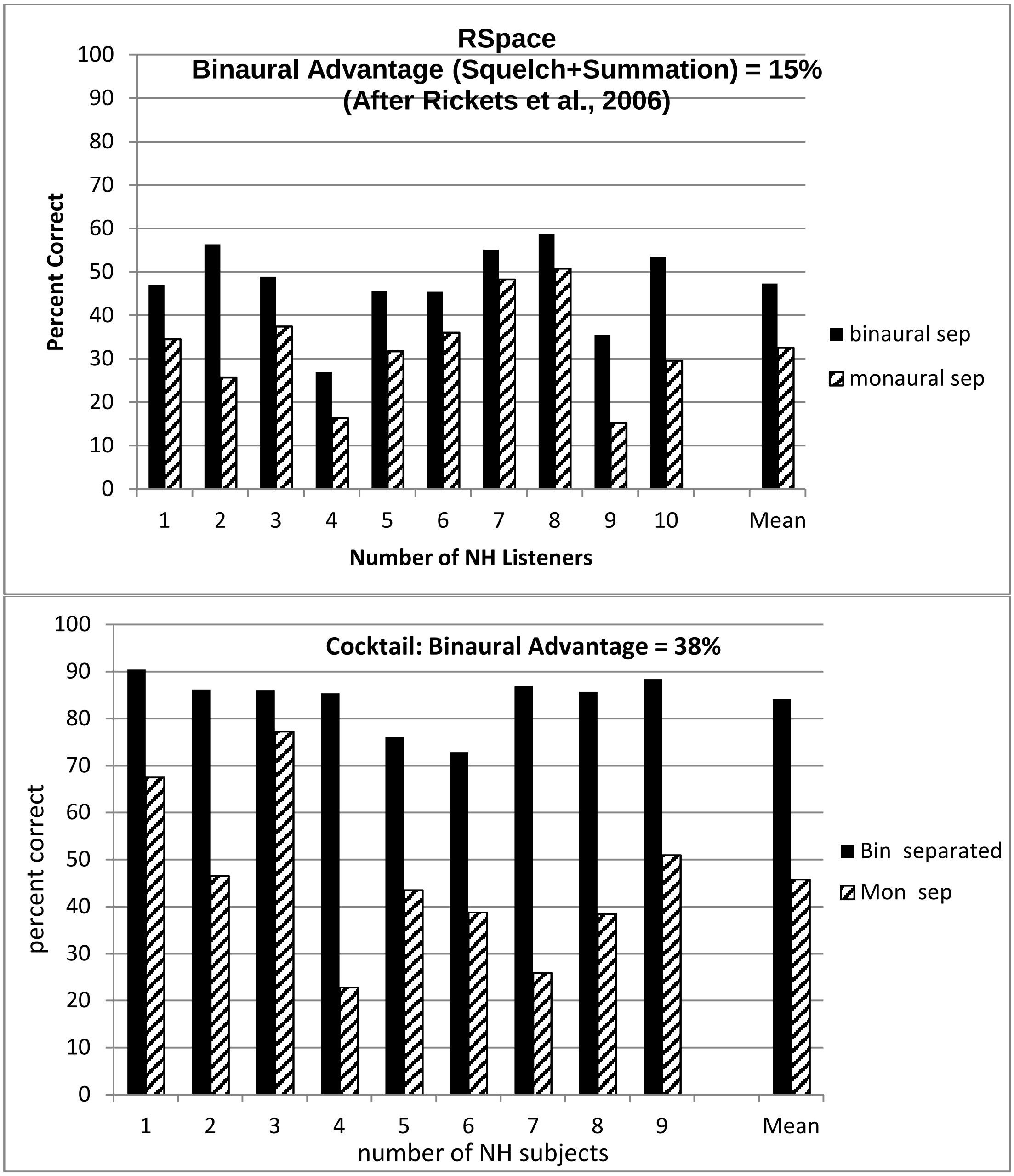

Figure 16. Binaural advantage, in percent correct, for NH listeners in RSpace and Cocktail Party.

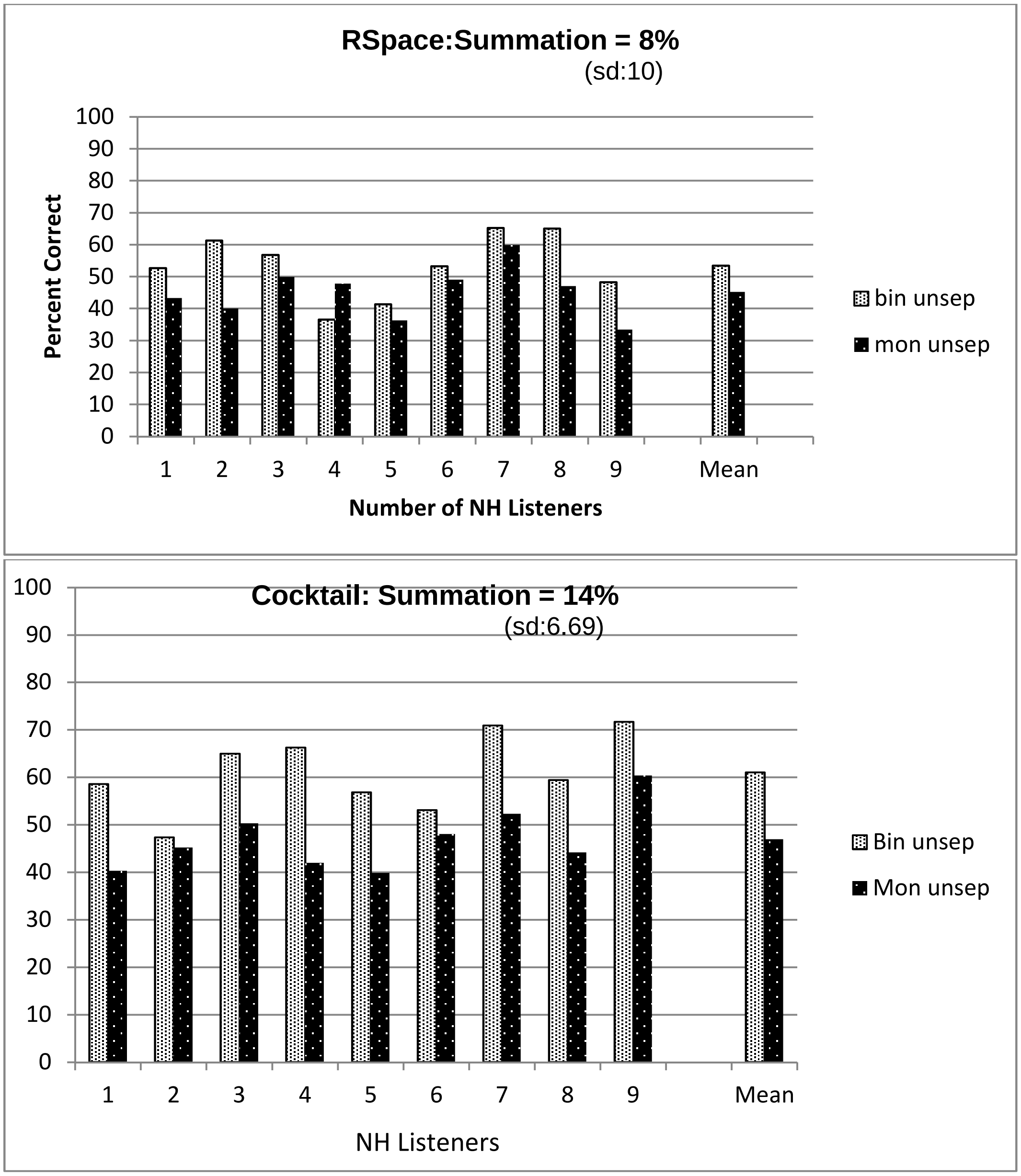

Figure 17. Summation, in percent correct, for NH listeners in RSpace and Cocktail Party.

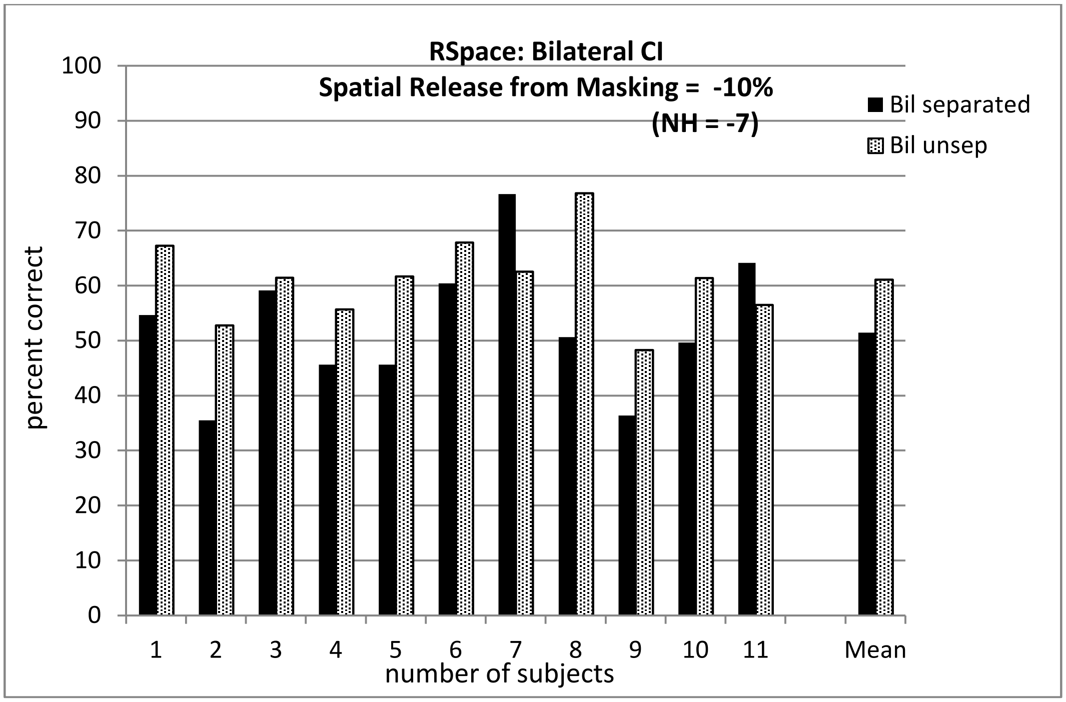

Figure 18. Spatial release from masking, in percent correct, for bilateral listeners in RSpace.

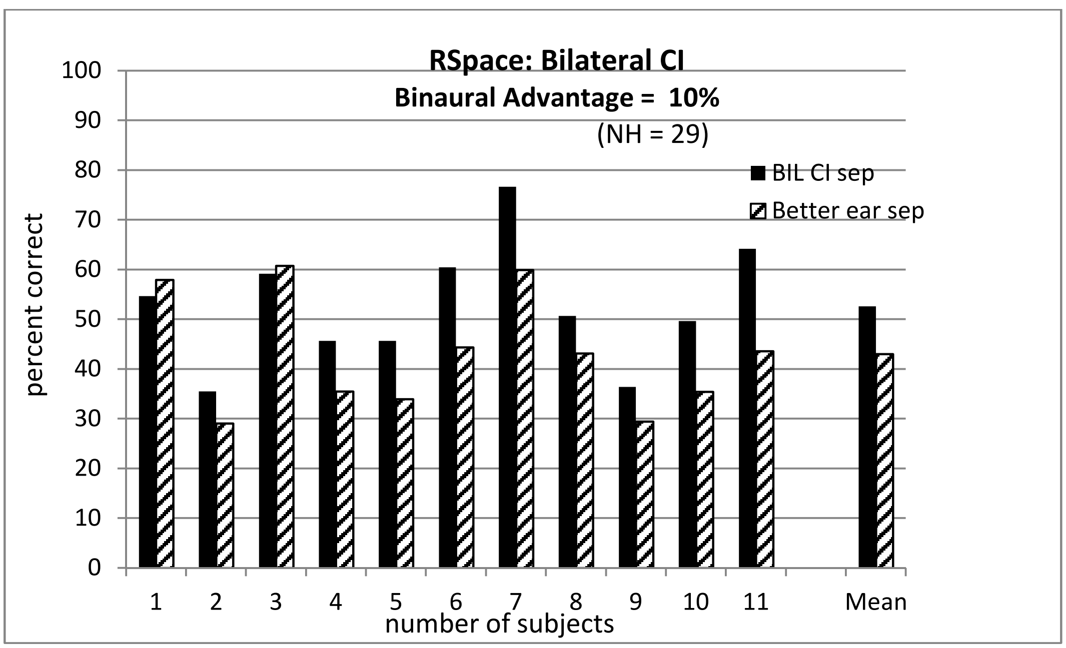

Figure 19. Binaural advantage, in percent correct, for bilateral listeners in RSpace.

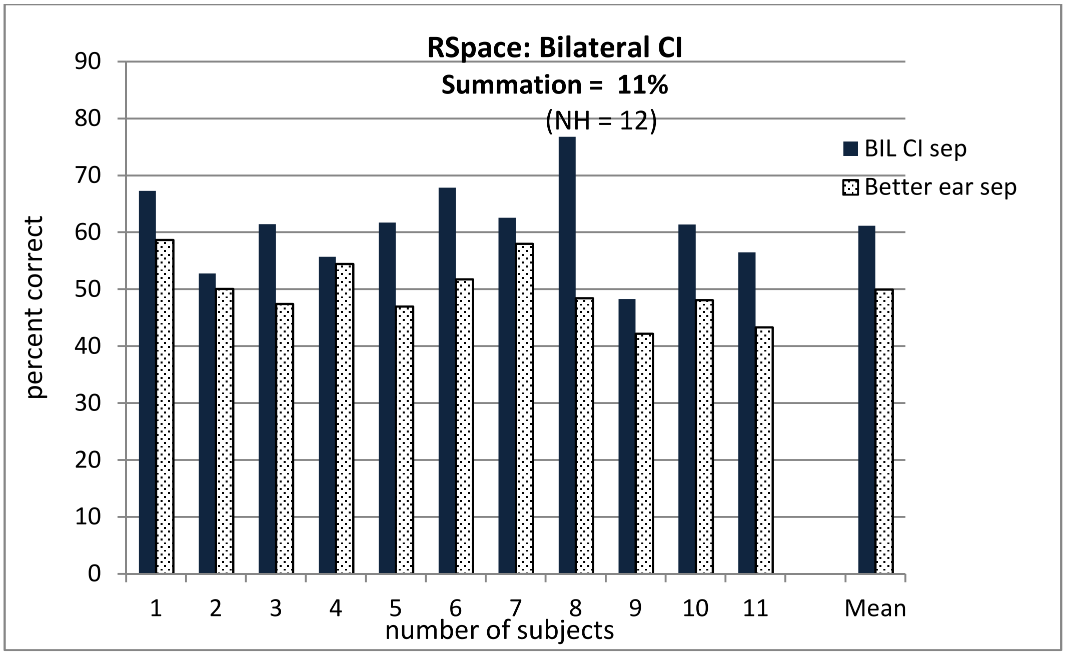

Figure 20. Summation, in percent correct, for bilateral listeners in RSpace.

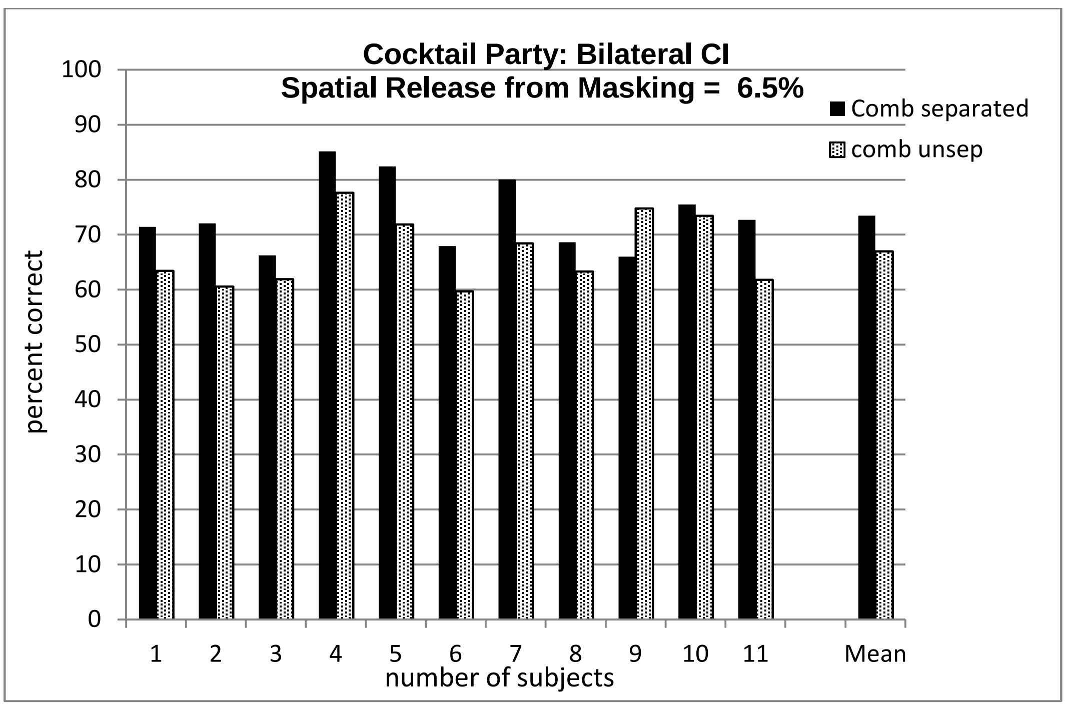

Figure 21. SRM, in percent correct, for bilateral listeners in the Cocktail Party environment.

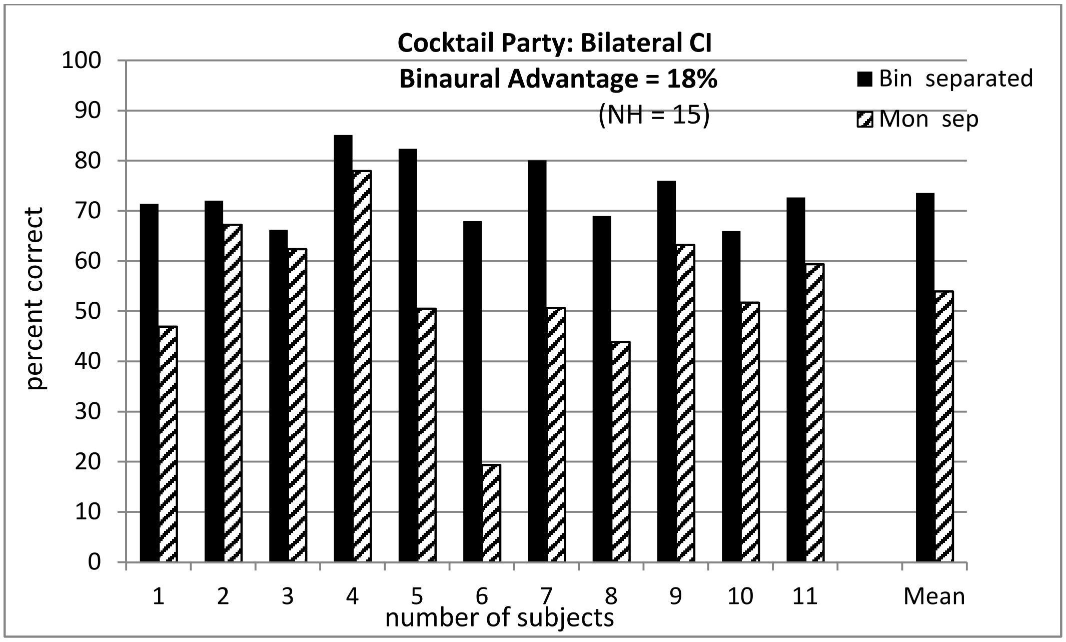

Figure 22. Binaural advantage, in percent correct, for bilateral listeners in the Cocktail Party environment.

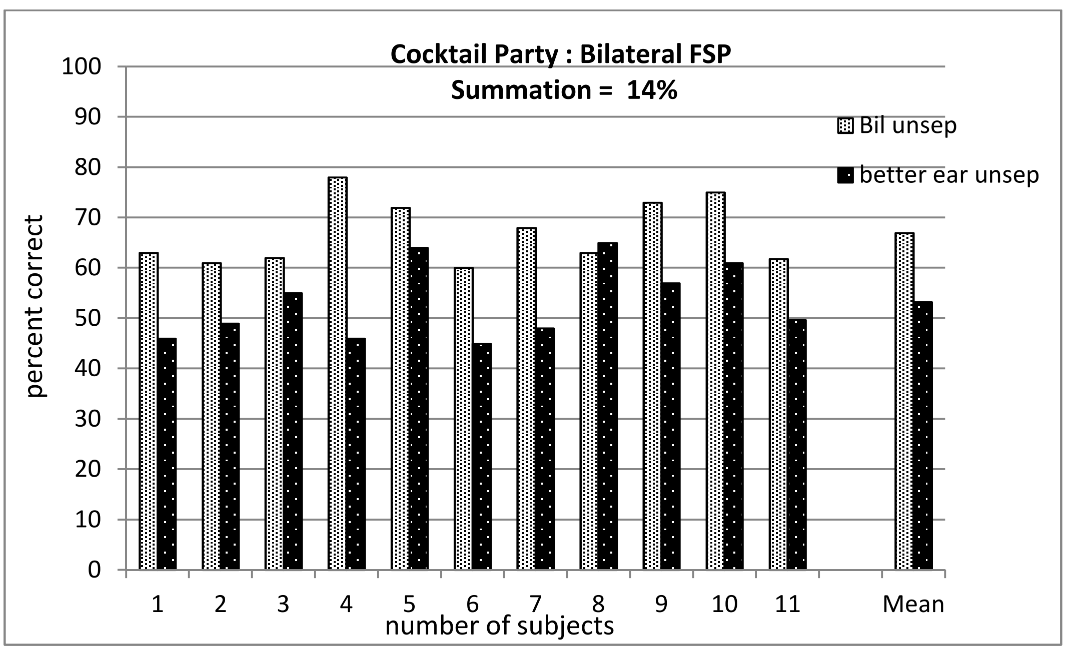

Figure 23. Summation, in percent correct, for bilateral listeners in the Cocktail Party environment.

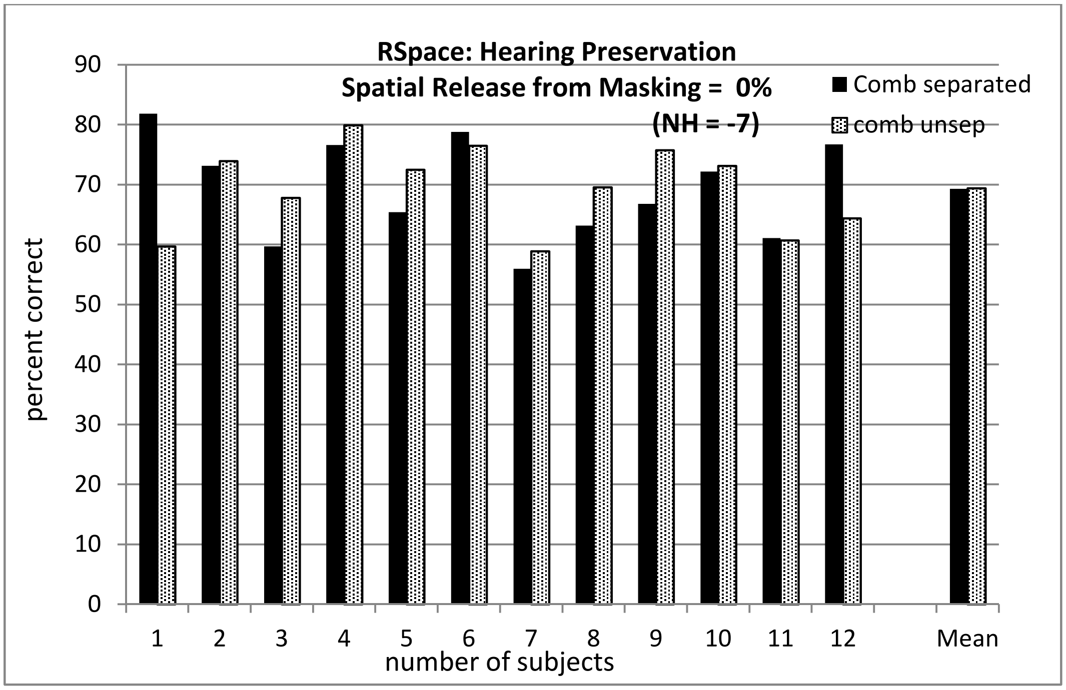

Figure 24. SRM, in percent correct, in RSpace for the hearing preservation listeners.

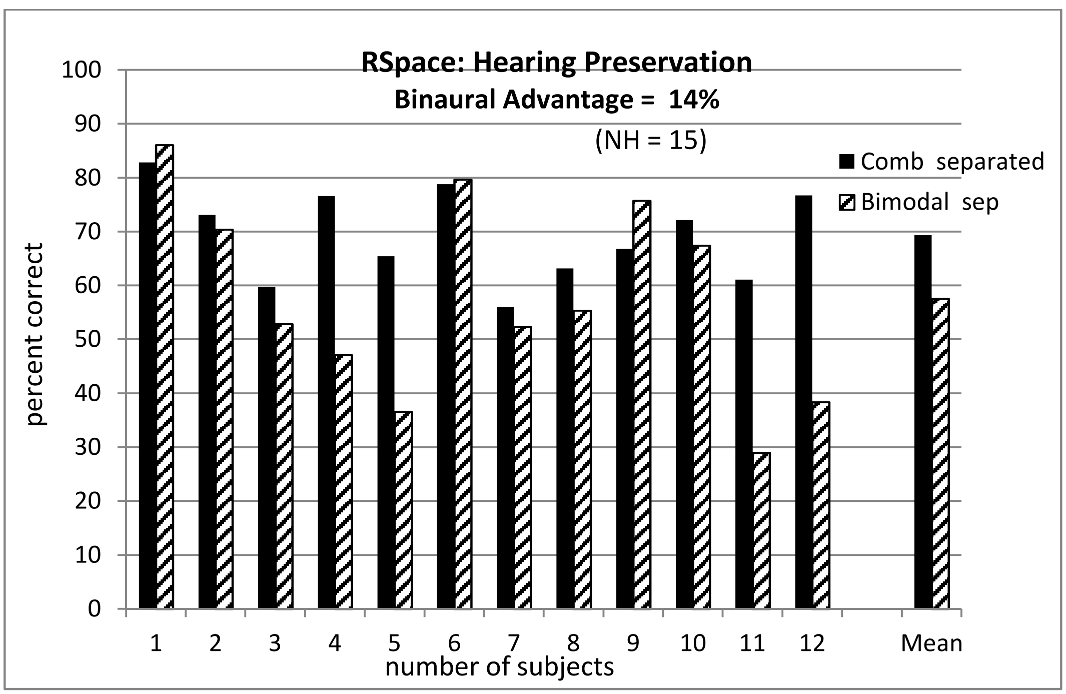

Figure 25. Binaural advantage, in percent correct, in RSpace for the hearing preservation group.

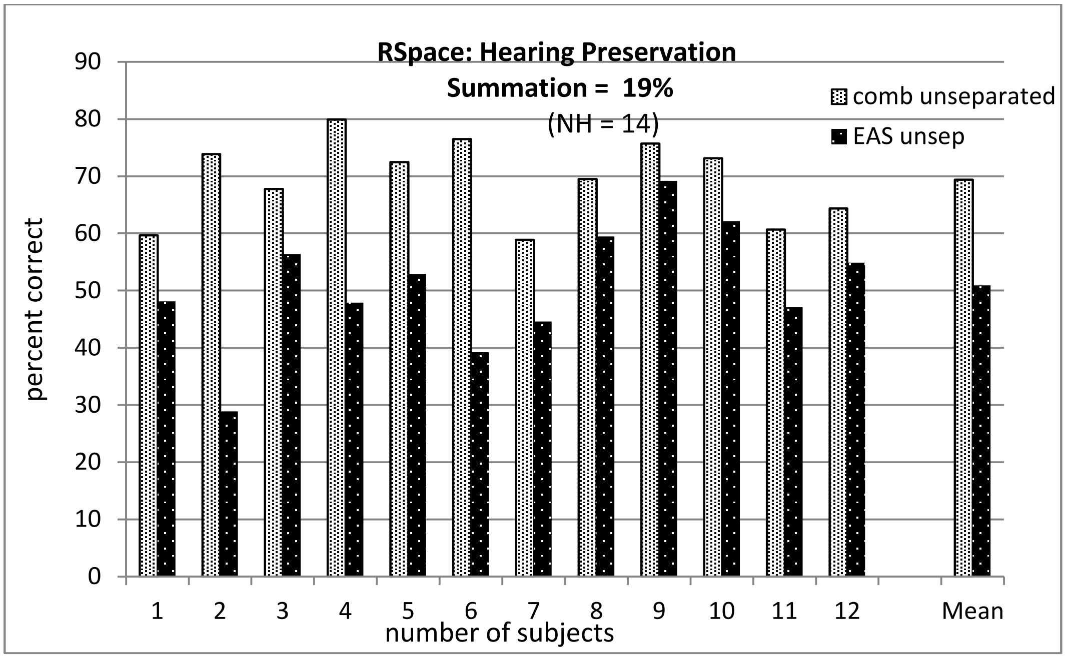

Figure 26. Summation, in percent correct, in RSpace for the hearing preservation group.

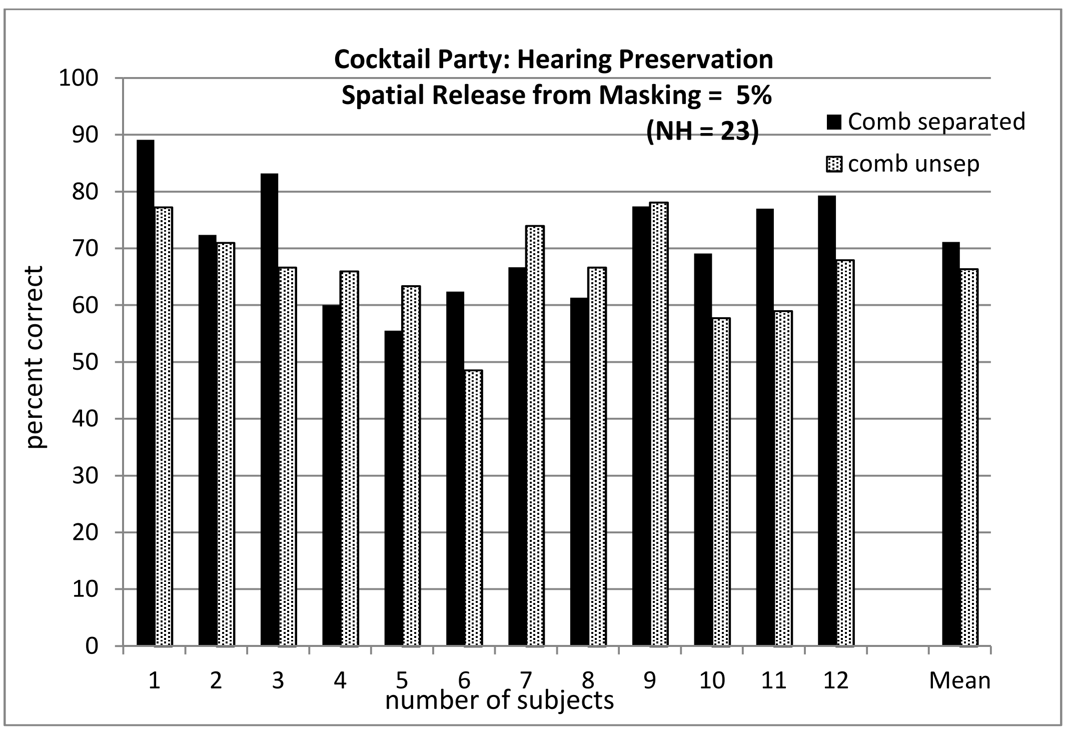

Figure 27. SRM, in percent correct, for the hearing preservation listeners in Cocktail Party.

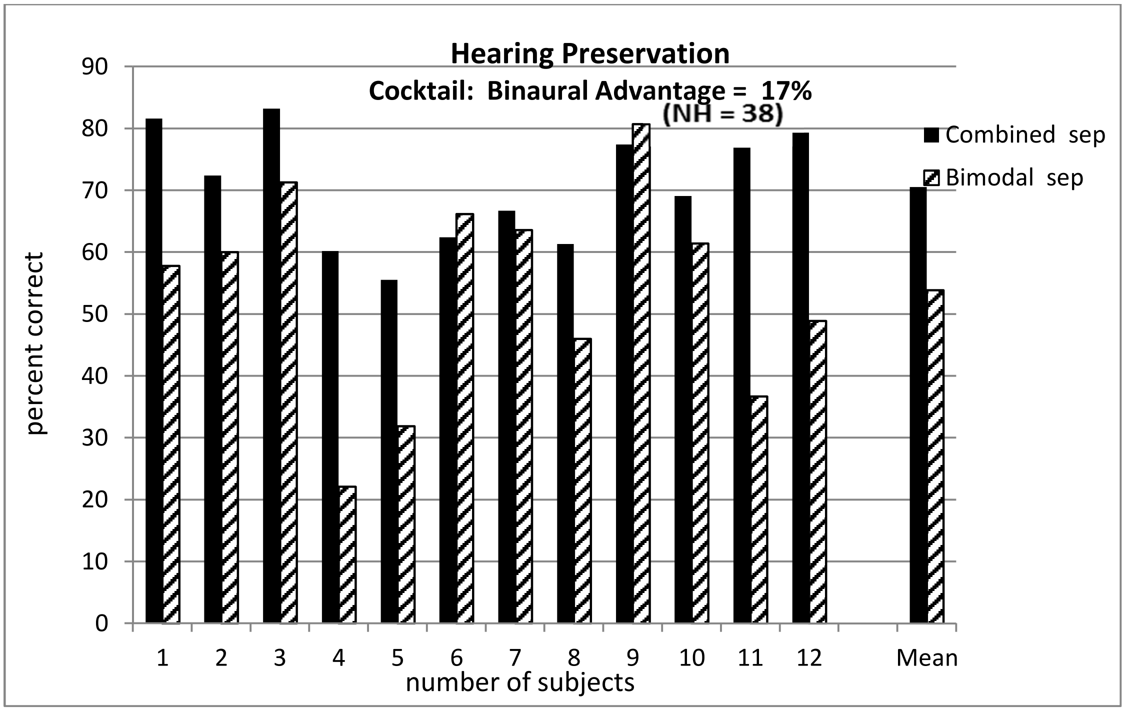

Figure 28. Binaural advantage, or squelch, in percent correct, in the Cocktail Party for hearing preservation listeners.

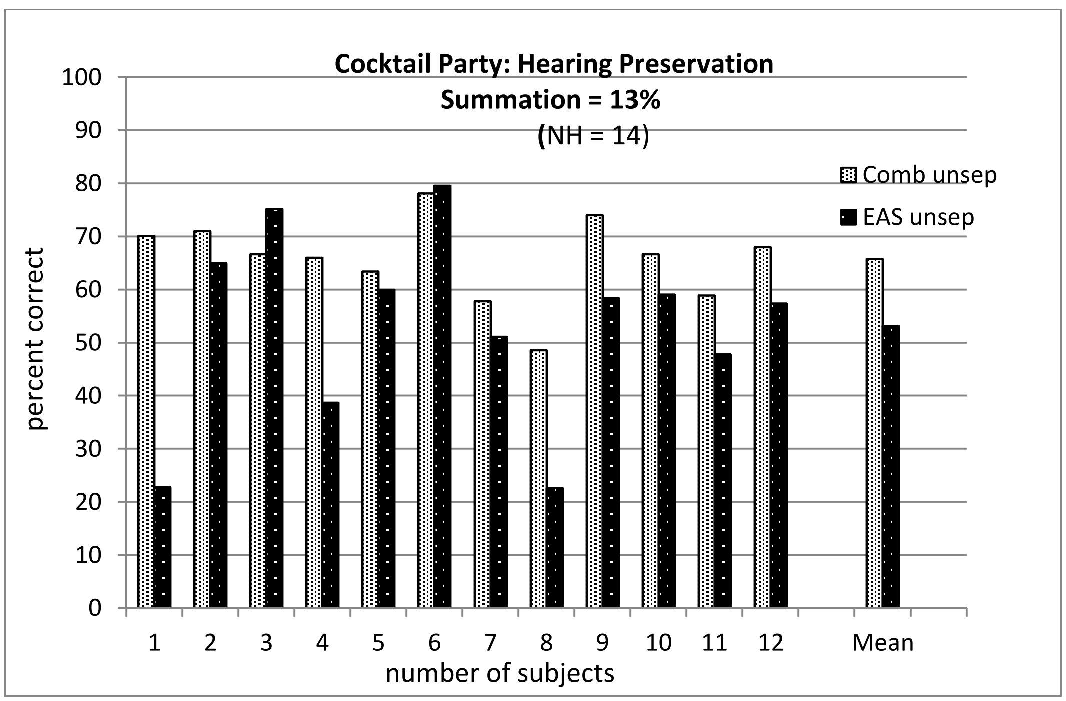

Figure 29. Summation, in percent correct, in the Cocktail Party for hearing preservation listeners.

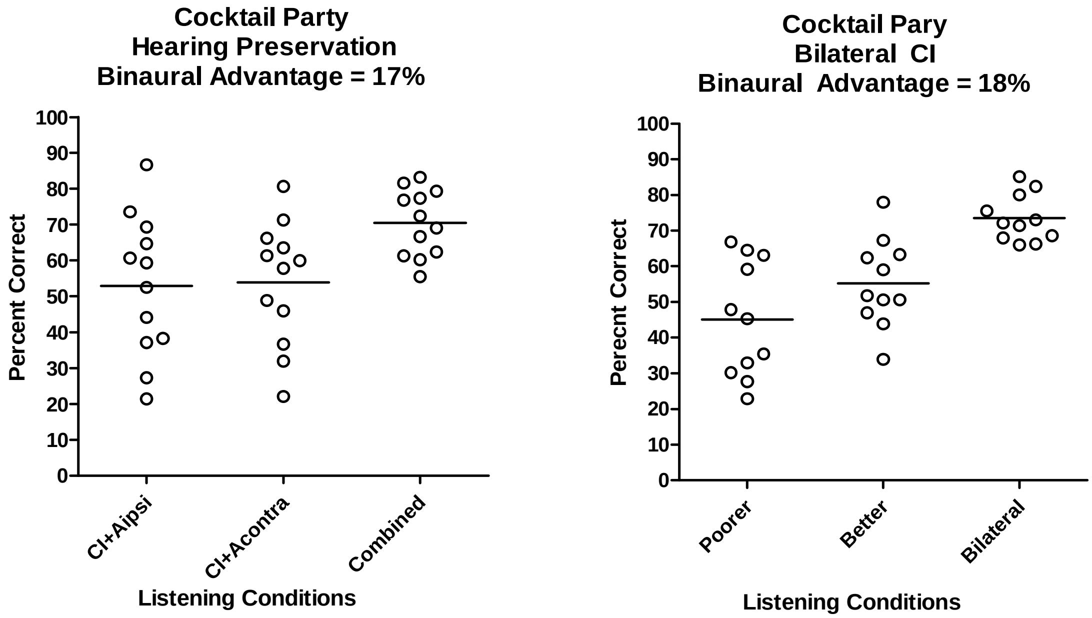

Figure 30. Binaural advantage for hearing preservation and bilateral listeners in Cocktail Party plotted as percent correct as a function of listening condition. Conditions: CI= cochlear implant, A_{ipsi} = ipsilateral acoustic hearing, A_{contra} = contralateral acoustic hearing, combined = CI + bilateral acoustic hearing, poorer CI ear, better CI ear, and bilateral CI.

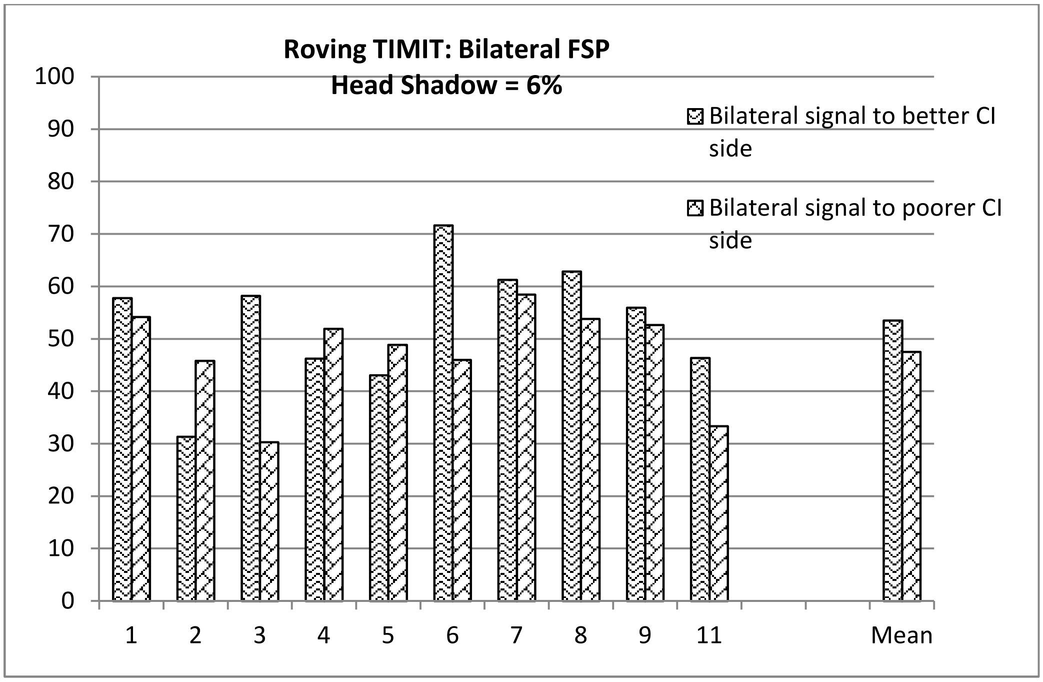

Figure 31. Head shadow, in percent correct, for bilateral listeners in Roving TIMIT.

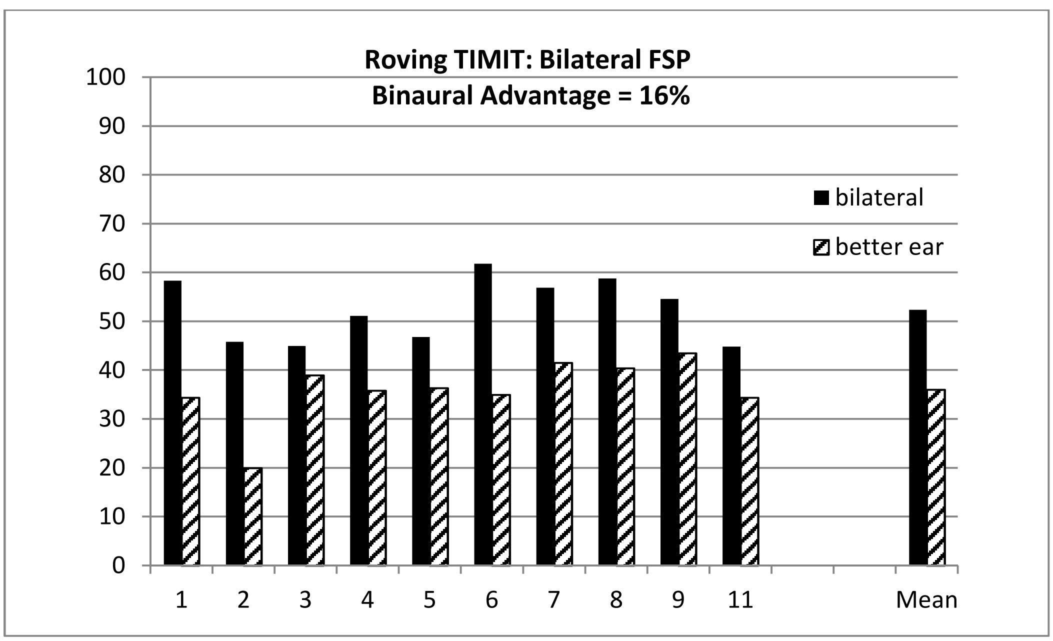

Figure 32. Binaural advantage, in percent correct, for bilateral listeners in Roving TIMIT.

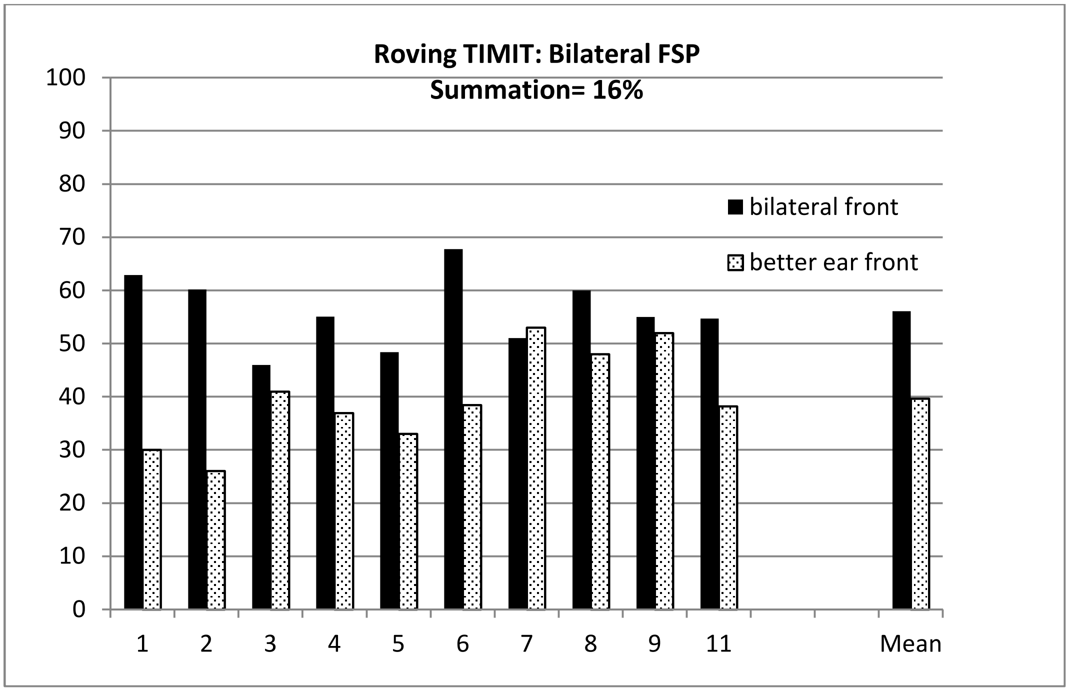

Figure 33. Summation, in percent correct, for bilateral listeners in Roving TIMIT.

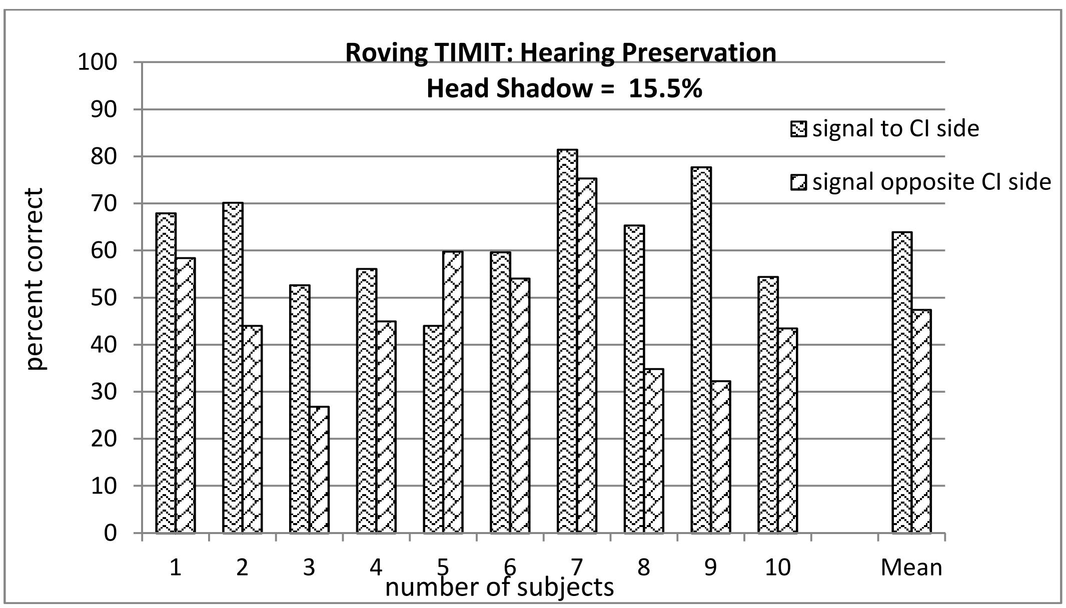

Figure 34. Head shadow, in percent correct, for the hearing preservation group in Roving TIMIT.

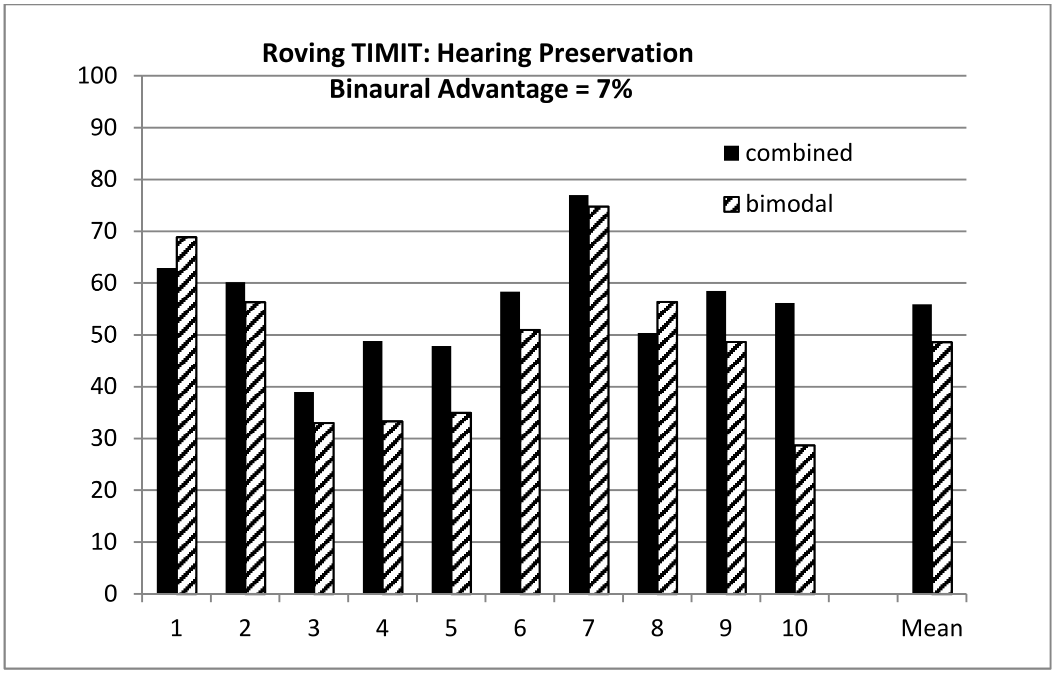

Figure 35. Binaural advantage, in percent correct, for the hearing preservation group in Roving TIMIT.

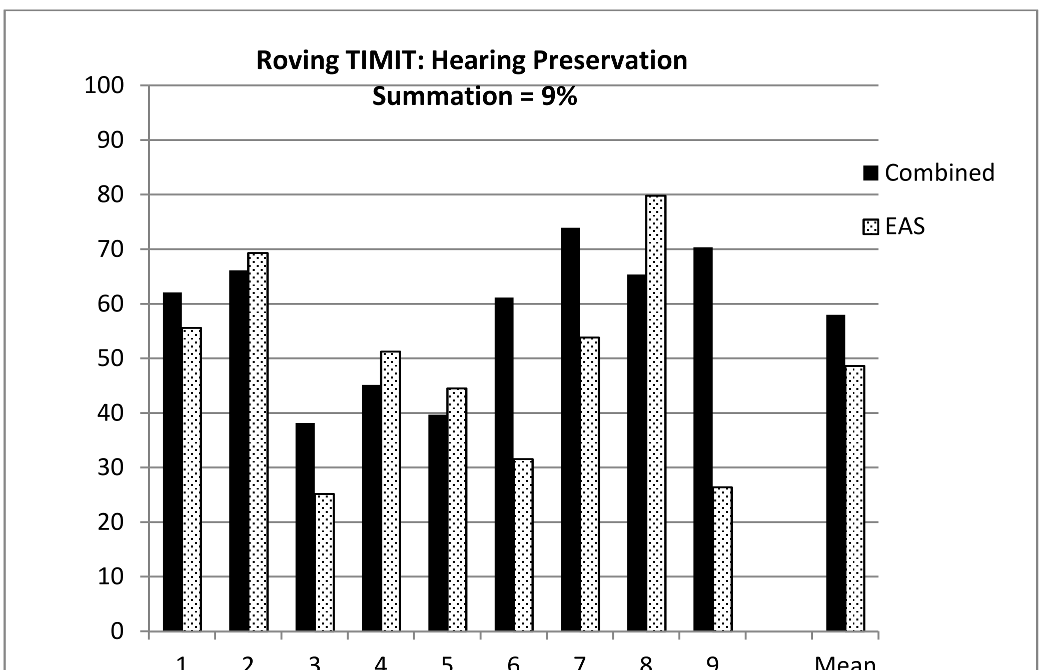

Figure 36. Summation, in percent correct, for hearing preservation listeners in Roving TIMIT.

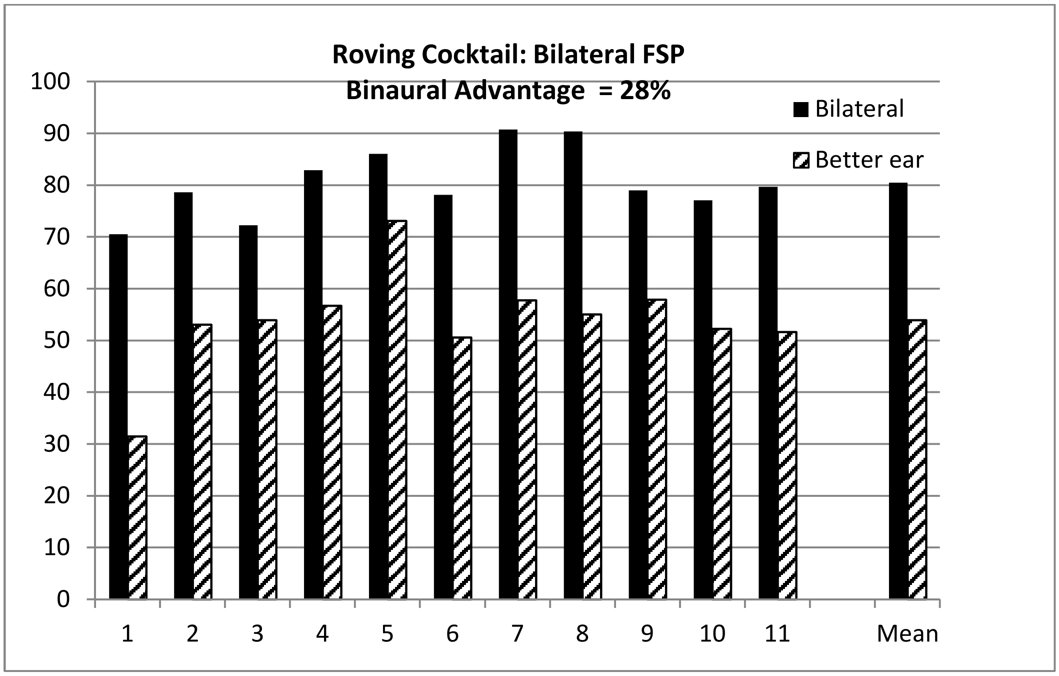

Figure 37. Binaural advantage, in percent correct, for the bilateral listeners in Roving Cocktail.

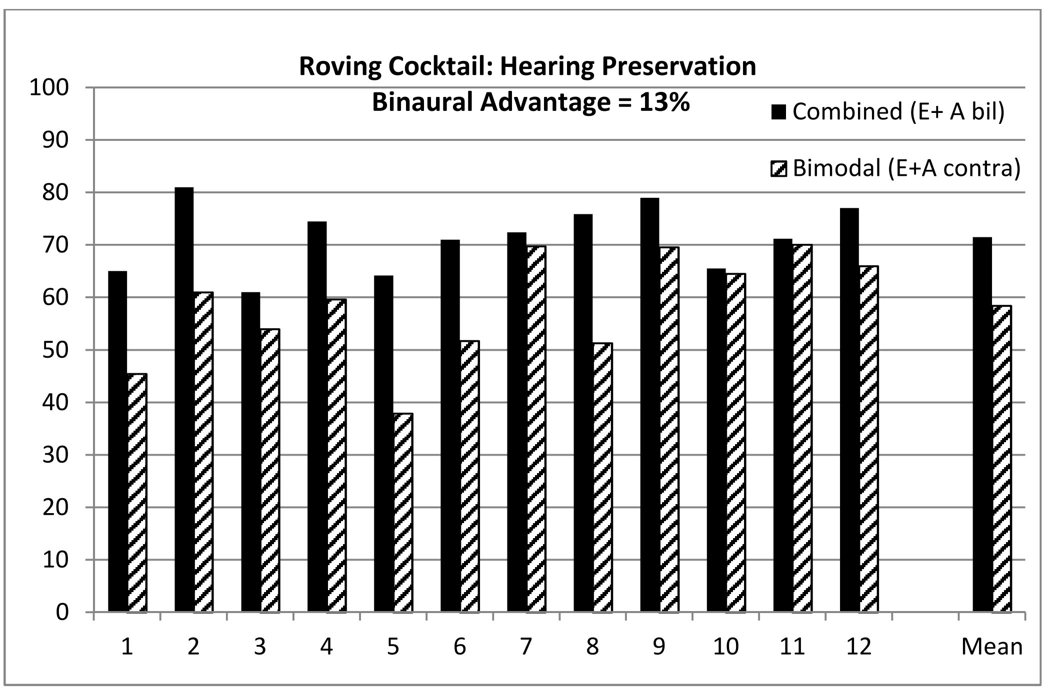

Figure 38. Binaural advantage, in percent correct, for the hearing preservation listeners in Roving Cocktail.

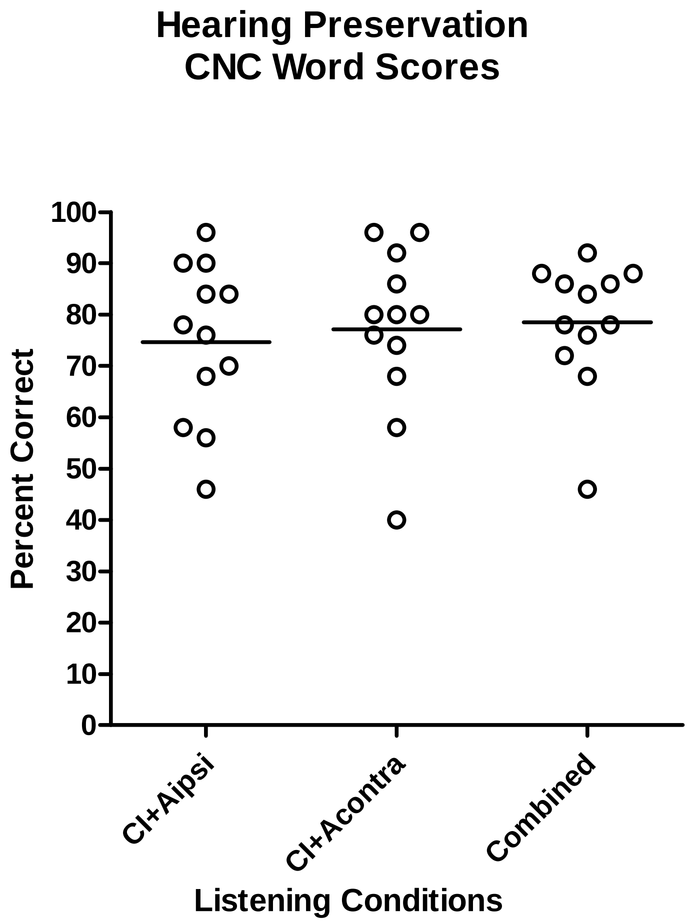

Figure 39. CNC word scores, in percent correct, plotted as a function of the three conditions for the hearing preservation group: CI = cochlear implant, Aipsi = ipsilateral acoustic hearing, Acontra = contralateral acoustic hearing, and combined = CI plus bilateral acoustic hearing. Straight lines indicate the mean scores.

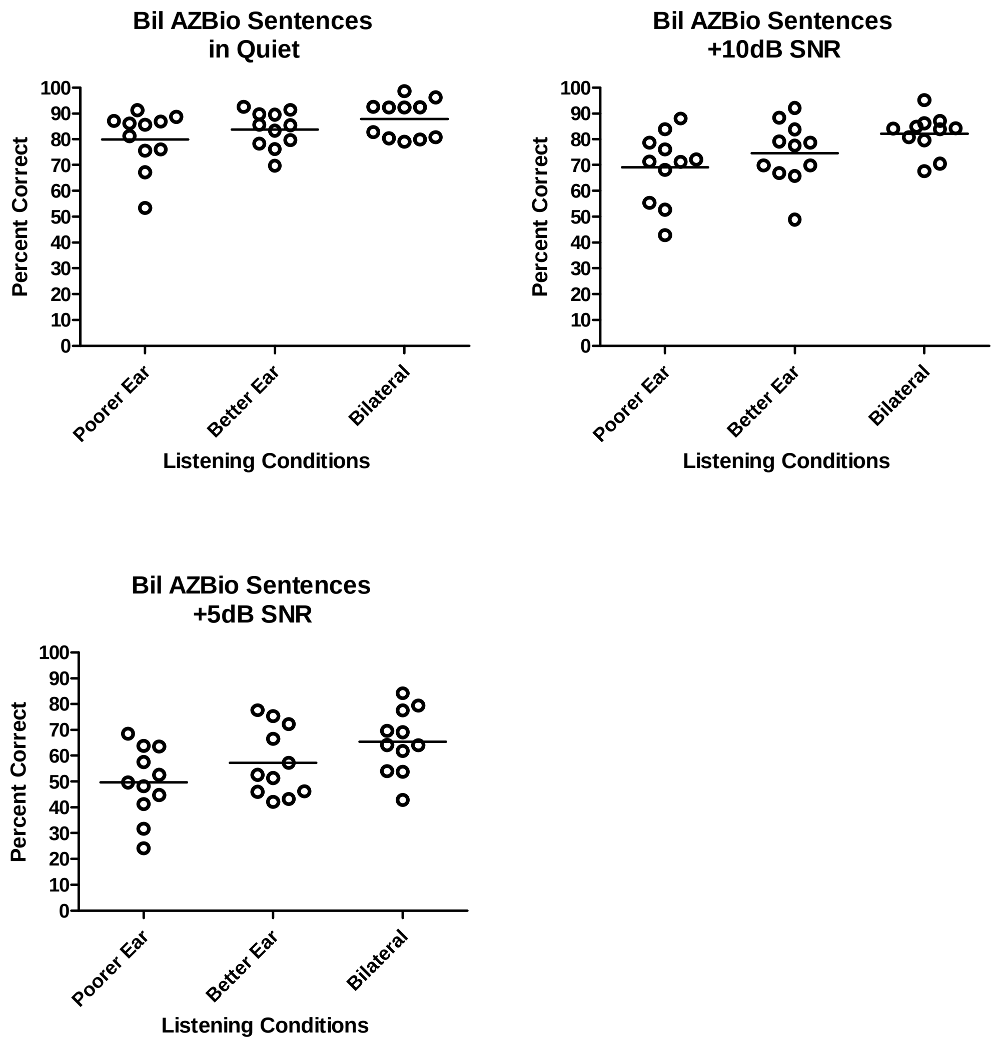

Figure 40. AZBio Sentences, in percent correct, for the bilateral listeners in quiet and at signal-to-noise ratios of +10 and +5dB. Conditions are the poorer CI ear, better CI ear, and bilateral CI. Straight lines indicate the mean scores.

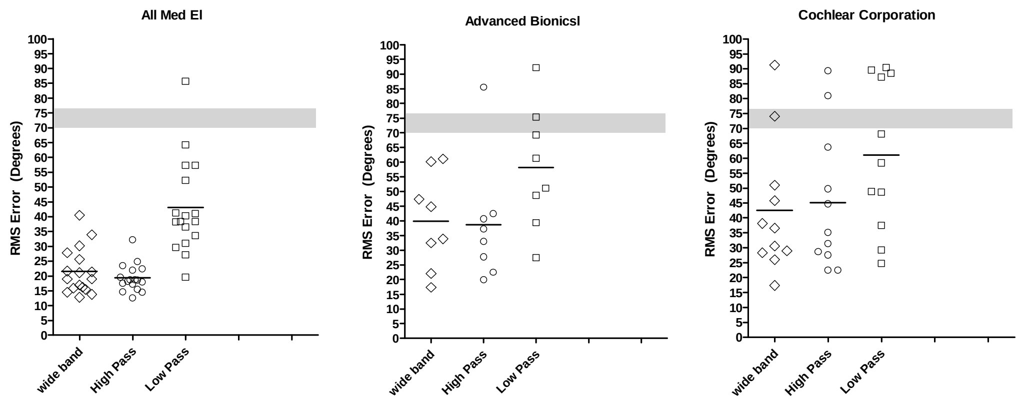

Figure 41. Localization errors for WB, HP, and LP stimuli for the three CI companies. MED-EL is on the left, Advanced Bionics is in the middles, and Cochlear Corp. is on the right.

APPENDIX A

IRB APPROVAL

ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Michael Dorman COOR
From:	Mark Roosa, Chair Soc Beh IRB
Date:	08/24/2012
Committee Action:	**Renewal**
Renewal Date:	08/24/2012
Review Type:	Expedited F4 F7
IRB Protocol #:	0111001097
Study Title:	AUDITORY FUNCTION AND COCHLEAR IMPLANTS
Expiration Date:	08/24/2013

The above-referenced protocol was given renewed approval following Expedited Review by the Institutional Review Board.

It is the Principal Investigator's responsibility to obtain review and continued approval of ongoing research before the expiration noted above. Please allow sufficient time for reapproval. Research activity of any sort may not continue beyond the expiration date without committee approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol on the expiration date. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

This approval by the Soc Beh IRB does not replace or supersede any departmental or oversight committee review that may be required by institutional policy.

Adverse Reactions: If any untoward incidents or severe reactions should develop as a result of this study, you are required to notify the Soc Beh IRB immediately. If necessary a member of the IRB will be assigned to look into the matter. If the problem is serious, approval may be withdrawn pending IRB review.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, or the investigators, please communicate your requested changes to the Soc Beh IRB. The new procedure is not to be initiated until the IRB approval has been given.

Please retain a copy of this letter with your approved protocol.

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