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The relationship between auditory function of non-implanted ears and bimodal benefit

Ting Zhang¹, Anthony J. Spahr¹, Michael F. Dorman¹, and Aniket Saoji²

¹Arizona State University, PO Box 870102 Tempe, AZ 85287-0102

²Advanced Bionics, LLC, Valencia, CA 91355

Abstract

Objectives—Patients with a cochlear implant (CI) in one ear and a hearing aid in the other ear commonly achieve the highest speech understanding scores when they have access to both electrically and acoustically stimulated information (EAS). At issue in this study was whether a measure of auditory function in the hearing-aided ear would predict the benefit to speech understanding when the information from the aided ear was added to the information from the CI.

Design—The subjects were 22 bimodal listeners with a CI in one ear and low-frequency acoustic hearing in the non-implanted ear. The subjects were divided into two groups -- one with mild to moderate low-frequency loss and one with severe to profound loss. Measures of auditory function included (i) audiometric thresholds at 750 Hz, (ii) speech understanding scores (words in quiet and sentences in noise), and (iii) spectral modulation detection (SMD) thresholds. In the SMD task, one stimulus was a flat spectrum noise and the other was a noise with sinusoidal modulations at 1.0 peak/octave.

Results—Significant correlations were found among all three measures of auditory function and the benefit to speech understanding when the acoustic and electric stimulation were combined. Benefit was significantly correlated with audiometric thresholds ($r = -0.814$), acoustic speech understanding ($r = 0.635$), and SMD thresholds ($r = -0.895$) in the hearing-aided ear. However, only the SMD threshold was significantly correlated with benefit within the group with mild-moderate loss ($r = -0.828$) and within the group with severe-profound loss ($r = -0.896$).

Conclusions—The SMD threshold at 1 cycle/octave has the potential to provide clinicians with information relevant to the question of whether an ear with low-frequency hearing is likely to add to the intelligibility of speech provided by a CI.

INTRODUCTION

It is increasingly common to find that individuals who qualify for a cochlear implant (CI) have some measurable low-frequency acoustic hearing in at least one ear. The amount of useful hearing varies, of course, among patients. In some cases, candidates exhibit mild-to-moderate hearing loss in the low frequencies (250 Hz) and severe-to-profound hearing loss in the higher frequencies (1000 Hz). For these individuals, combining one impaired ear with a cochlear implant in the contralateral ear (bimodal hearing) has proven to be a successful treatment option.

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In general, the acoustic signal from the non-implanted ear (A-alone) provides little to no open-set speech understanding. The electric signal from the cochlear implant (E-alone) typically provides the essential information for speech understanding. However, combining the acoustic and electric signals often brings about the highest level of speech understanding and sound quality (e.g., Shallop et al., 1992; Armstrong et al., 1997; Tyler et al., 2002; Ching et al., 2004; Kong et al., 2005; Gifford et al., 2007a; Dorman et al., 2008; Zhang et al., 2010).

The additional benefit provided by the acoustic hearing of the non-implanted ear (acoustic benefit) varies significantly across patients. Some patients receive substantial benefit, with monosyllable word recognition in quiet improving by 20–30 percentage points and sentence recognition in noise improving by 30–40 percentage points (e.g., Gifford et al., 2007a; Dorman et al., 2008; Helbig et al., 2008; Gstoettner et al., 2006, 2008; Zhang et al., 2010). Other patients receive much less, or even no benefit. There have also been cases in which combining the two signals produced poorer speech understanding scores than that observed with the CI alone (e.g., Tyler et al., 2002; Ching et al., 2004; Mok et al., 2006).

One account for the variability in benefit is differences in basic auditory function in the region of acoustic hearing (Turner et al., 2004; Kong et al., 2005). It is reasonable to suppose that ears with better hearing would provide more acoustic benefit than ears with poorer hearing. Gantz et al. (2009) tested 27 subjects who received both acoustic and electric stimulation in the same ear (hybrid/hearing preservation patients). At issue was the relationship between low-frequency audiometric thresholds of the residual acoustic hearing and the magnitude of the acoustic benefit in noise. Gantz et al. (2009) reported a significant relationship ($r = -0.62$) between audiometric thresholds and benefit. However, that correlation was strongly influenced by the lack of benefit observed in individuals with profound hearing loss. The authors reported that “the advantage for speech recognition in noise of preserving residual hearing exists unless the low-frequency postoperative hearing levels approach profound levels”. However, other studies have not found a relationship between acoustic hearing thresholds and the degree of benefit (Wilson et al., 2002; Gifford et al., 2010).

Attempts to link acoustic benefit to other aspects of auditory function have not been successful. No significant relationship has been found between acoustic benefit and (i) nonlinear cochlear processing (Schroeder-phase effect), (ii) frequency resolution (auditory filter shape at 500 Hz), and (iii) temporal resolution (temporal modulation detection) (Gifford et al., 2007b, 2008, 2010; Golub et al., 2012).

Here, we describe the relationship between another measure of auditory function in the region of low-frequency acoustic hearing – spectral envelope perception (e.g., Eddins and Bero, 2007; Litvak et al., 2007) – and the gain in intelligibility, for speech in quiet and in noise, when both acoustic and electric stimulation are available.

The spectral envelope refers to the overall shape of the spectrum, or frequency-amplitude curve, of an acoustic signal. Tests of spectral envelope perception are different from more traditional tests of spectral resolution, such as frequency selectivity, which are used to define the width of an auditory filter or “channel” (for review, see Moore, 1998). Spectral envelope perception refers to the ability to encode and compare patterns of intensity or amplitude across the spectrum. Spectral envelope perception of normal-hearing listeners is typically better than for hearing-impaired listeners and cochlear implant users (e.g., Summers and Leek, 1994; Lentz and Leek, 2002, 2003; Henry and Turner, 2003; Shrivastav et al., 2006; Henry et al., 2005; Saoji et al., 2009).

Spectral envelope perception has been assessed using variations of a ripple phase-reversal test (Supin et al., 1994; Henry and Turner, 2003; Henry, Turner and Behrens, 2005; Won et al., 2007; 2011). In these tasks, a log-spaced spectral modulation, or ripple, is applied to a broadband noise carrier. The spectral modulation depth is commonly fixed to provide an obvious (e.g. 30 dB) peak-to-valley contrast. The position of spectral peaks and valleys are reversed in the standard and comparison signals by changing the ripple phase by π radians. The spectral modulation (ripple) frequency, or number of peaks/octave, is varied adaptively to determine the maximum spectral-peak density in which the phase-reversal can be reliably detected. It is highly likely that this task involves integrating cross-channel information instead of depending on a local intensity cue for spectral-ripple discrimination for cochlear implant listeners (Won et al., 2011a)

Henry and colleagues (2005) evaluated the spectral envelope sensitivity of normal-hearing, hearing-impaired, and cochlear implant listeners. They reported that the average phase-reversal threshold for normal-hearing listeners was 4.84 peaks/octave, or a spacing of 0.2 octaves between adjacent spectral peaks. They also found that hearing-impaired listeners and cochlear implant listeners were far less sensitive to phase-reversals, with average thresholds of 1.77 peaks/octave (0.56 octave spacing) and 0.62 peaks/octave (1.6 octave spacing), respectively. Henry and colleagues (2005) concluded that the minimum phase-reversal thresholds necessary to support a high level of vowel and consonant recognition fell somewhere between 1.0 and 2.0 peaks/octave. Additionally, the authors reported phase-reversal thresholds were significantly correlated with vowel identification scores ($r^2 = 0.64$) and consonant identification scores ($r^2 = 0.66$). Others have also reported significant correlations between phase-reversal thresholds and monosyllabic word recognition and sentence understanding in noise (Won et al., 2007; Won et al., 2011b). Only one study (Anderson et al., 2011) reported no significant correlation between phase-reversal thresholds and speech measures in noise and quiet.

Another measure of spectral envelope perception is spectral modulation detection (SMD). This task requires discrimination of a modulated (rippled) spectral envelope from an unmodulated (flat) spectral envelope. In this task, the spectral modulation frequency (peaks/octave) of the rippled noise is fixed and the spectral modulation depth (peak-to-valley contrast) is varied adaptively. Threshold is defined as the minimum spectral modulation depth (dB) required for reliable discrimination of the modulated and unmodulated stimuli (e.g., Bernstein and Green, 1987; Summers and Leek, 1994; Amagai et al., 1999; Eddins and Bero, 2007; Saoji and Eddins, 2007; Saoji et al., 2009). Plotting SMD thresholds as a function of spectral modulation frequency produces a spectral modulation transfer function (SMTF), similar in concept to a temporal modulation transfer function (TMTF; e.g., Viemeister, 1979).

In general, SMD thresholds increase as spectral modulation frequency increases. Further, hearing-impaired listeners and cochlear implant users typically require greater spectral modulation depth for discrimination than do normal-hearing listeners (Summers and Leek, 1994; Saoji and Eddins, 2007; Saoji et al., 2009). This difference is most apparent at spectral modulation frequencies of 1.0 peak/octave or higher. SMD thresholds of CI listeners at low modulation frequencies (0.25 and 0.5 peaks/octave) have been correlated with vowel and consonant identification (Litvak et al., 2007) and sentence understanding in quiet and noise (Spahr et al., 2011). Saoji and colleagues (2009) found that the SMD thresholds of most CI listeners increased significantly at modulation frequencies of 1.0 peaks/octave and above. This outcome led to the conclusion that an inability to perceive fine spectral detail (1.0 peaks/octave and above) caused most CI listeners to rely on information in the broad spectral envelope (0.25 & 0.50 peaks/octave) for speech understanding.

The current study was one part of a larger study investigating the benefits of combining acoustic and electric hearing. The SMD task was selected as a gross measure of spectral resolution in the non-implanted ear because (i) stimuli could be adapted for testing at very low frequencies, and (ii) thresholds on this type of task had been correlated with performance in CI users. It was expected that the non-implanted ears of bimodal listeners would be less sensitive to spectral modulations than normal ears due to the broad auditory filters associated with cochlear hearing loss (Glasberg & Moore, 1986; Summer & Leek, 1994; Henry, Turner & Behrens, 2005). However, it was thought that the degree of impairment could be related to the degree of benefit realized when pairing the ear with a contralateral cochlear implant. Given time constraints and concern of patient fatigue from the already extensive test battery, it was decided that SMD thresholds would only be assessed at a single spectral modulation frequency. A test frequency of 1.0 peaks/octave was selected because (i) it is not well represented in the electric signal, (ii) it is associated with a breakdown in speech understanding (Henry, Turner & Behrens, 2005), and (iii) it would allow 2–3 spectral peaks and valleys to be presented within the range of audibility in the listener's non-implanted ear.

The major goals for this study were to (i) quantify the hearing acuity of the non-implanted ear of bimodal listeners using various measures that could be collected preoperatively (i.e. audiometric thresholds, speech understanding scores, and spectral envelope perception); (ii) assess the relationship among those measures; (iii) assess the relationship between acoustic hearing acuity and performance with only the contralateral cochlear implant; and (iv) assess the relationship between acoustic hearing acuity and the degree of acoustic benefit received when that ear is paired with a contralateral cochlear implant.

METHOD

Subjects

A total of 22 adult bimodal listeners, with a CI in one ear and some degree of residual hearing in the non-implanted ear, participated in this study. The mean age across all subjects was 68 years (s.d. = 11). All subjects gave informed consent and were compensated for their time.

Stimuli and Conditions

Audiometric Thresholds—Pure tone thresholds were obtained in the non-implanted ear at test frequencies of 125, 250, 500, 750, 1000, 2000, and 4000 Hz using standard audiometric procedures. It was expected that our bimodal listeners would exhibit a wide range of audiometric thresholds in their non-implanted ears. Further, it was expected that the degree of acoustic benefit would vary with the degree of hearing loss, especially at lower frequencies. Thus, we chose to group subjects by degree of low-frequency (< 750 Hz) hearing loss. Averaged low-frequency thresholds (125, 250, 500, and 750 Hz) less than 60 dB HL were considered to be within the mild-moderate range and those at or greater than 60 dB HL were considered to be within the severe-profound range.

Speech Understanding—Speech perception was evaluated in three listening conditions: (i) electric stimulation alone (E-alone), (ii) acoustic stimulation alone (A-alone), and (iii) combined electric and acoustic stimulation (EAS). The test material included CNC words (Peterson & Lehiste, 1962) and the AzBio sentences in the presence of a competing babble at +10 dB SNR (Spahr et al., 2012). Speech stimuli were presented at 70 dB SPL from a single loudspeaker placed in front of the subject (0° azimuth) at a distance of 1 meter. Listeners were tested using their own hearing aid (HA) and CI, using their “everyday” programs and volume control settings. Prior to testing, subjects were presented with sample

test items and reported to the examiner that sounds were “comfortably loud” and, in the case of EAS testing, that the acoustic and electric signals were balanced.

Normalized Acoustic Benefit

Acoustic benefit is commonly described as the difference in performance between the EAS and E-alone conditions. One shortcoming of this dependent measure is that it fails to account for the limited potential for improvement if the starting level for E-alone is high. For example, subjects with E-alone scores of 40% and 80% are both confined to a ceiling of 100%. If both subjects were to achieve scores of 100% in the EAS condition, the calculated bimodal benefit would be 60 and 20 percentage points, respectively. This would suggest differences in benefit, despite both subjects reaching a ceiling on the test. For this reason, we have used a measure of **normalized acoustic benefit**. The calculation divides the measured improvement by the potential improvement and then multiplies the quotient by 100 to produce an indexed score of acoustic benefit (i.e., $100 * ((EAS - E \text{ alone}) / (100 - E \text{ alone}))$). For cases where EAS scores are lower than E-alone scores, the equation is reworked so that the denominator describes the potential drop in performance (i.e., $100 * ((EAS - E \text{ alone}) / (E \text{ alone}))$). This calculation controls for starting level of performance in the E-alone condition and allows scores to range from -100 (scores drop to 0% in the EAS condition) to +100 (scores improve to 100% in the EAS condition).

Spectral Modulation Detection—Spectral modulation detection thresholds were obtained in the A-alone condition for all subjects. During testing, all subjects were seated comfortably in a sound-treated booth and the speech processor of the implanted ear was removed.

Stimulus generation—Stimuli for the spectral modulation task were generated using Matlab®. Stimulus generation involved first creating the desired spectral shape and then applying that shape to a noise carrier. The desired spectral shape took the form expressed by the following equation:

$$F(f) = \begin{cases} 10^{\frac{m}{20} \sin(2\pi(\log_2(f/125))f_c + \theta_0)/20} & 125 < f < 5600 \\ 0 & \text{otherwise} \end{cases}$$

where $F(f)$ is the amplitude of the bin with frequency f (Hz), m is the spectral modulation (peak-to-valley) depth in dB, f_c is the spectral modulation frequency, θ_0 is the modulation starting phase (randomized), and 125 is a constant that corresponds to the low-frequency edge of the noise band. For each presentation interval, the corresponding phase spectrum was generated by assigning a random phase (uniformly distributed between 0 and 2π radians) to each frequency bin (bin width = 0.5 Hz). An inverse Fourier transform on the complex buffer pair resulted in a noise band with the desired spectral shape. The flat noise stimuli were synthesized by setting the modulation depth to zero ($m=0$). Within each trial, all stimuli were scaled to have an equivalent overall level. Stimulus duration was 400 ms and the inter-stimulus-interval was 400 ms.

Signal Presentation—It was expected that hearing sensitivity would vary significantly across listeners. Thus, it was decided that signals would be presented at a comfortable listening level, determined by a loudness scaling procedure. A response card was used to help listeners adjust the presentation level. The response card was a continuous scale, labeled with “very soft”, “soft”, “medium”, “comfortable”, “loud”, and “uncomfortably loud”. The presentation level was adjusted until the subject perceived the volume as “comfortable”.

Initially, all listeners were to be evaluated in an unaided condition and signals were to be presented to the non-implanted ear via headphone (Sennheiser HD250 linear II). However, due to the severity of their hearing loss, 6 of the 22 listeners were unable to achieve a comfortable listening level at the maximum output level (92 dB SPL) of the headphones in an unaided condition. For these individuals, signals were presented via loudspeaker (Lifeline Amplification System, Model-LLF-50) while the listener wore their hearing aid.

Procedure—Spectral modulation detection thresholds were obtained in the A-alone condition using a cued, three-interval, two-alternative, forced-choice procedure. The first interval of each trial was always the cued interval and contained a flat spectrum noise. A second flat spectrum noise was randomly assigned to interval two or three. The spectrally modulated stimulus was assigned to the remaining interval. Following each trial, listeners were asked to identify the interval (2 or 3) containing the “different” (i.e., spectrally modulated) signal. Feedback was given after each trial. The spectral modulation depth of the comparison stimulus was varied adaptively, using a 3-down, 1-up, procedure to track 79.4% correct responses (Levitt, 1971). A run consisted of 60 trials and began with a modulation depth of 30 dB. The initial step size of the modulation depth was 2 dB and was reduced to 0.5 dB after three reversals. An even number of at least six reversal points, excluding the first three, were averaged to determine the threshold of an individual run. The reported threshold is an average of thresholds from three consecutive runs.

RESULTS

Audiometric Thresholds

Audiometric thresholds of the non-implanted ear of all subjects are displayed in Figure 1. Thresholds at lower test frequencies (i.e. 125 & 250 Hz) ranged from within-normal-limits (< 20 dB HL) to profound loss (> 80 dB HL). At higher test frequencies (i.e. >750 Hz) the range was compressed, as all thresholds fell within the severe-to-profound range of hearing loss.

To group subjects by degree of low-frequency hearing loss, audiometric thresholds for frequencies of 125, 250, 500, and 750 Hz were averaged for each subject. After averaging, thresholds of 12 subjects (shown by filled circles) fell within the mild-moderate range (< 60 dB HL) and 10 subjects (shown by open circles) fell within the severe-profound range (> 60 dB HL). Mean audiometric thresholds of the two groups were significantly different ($p < 0.0001$) at 125, 250, and 500 Hz, but not at higher test frequencies. Mean ages for the mild-moderate and severe-profound groups were 65 years (s.d. = 8) and 72 years (s.d. = 13), respectively. There were no significant differences in age at test, duration of deafness (non-implanted ears or implanted ears), experience with the hearing aid, or experience with the cochlear implant for the two groups. Individual data are displayed in Table 1.

Speech Understanding

CNC word scores (percent correct) in the A-alone, E-alone, and combined EAS conditions are shown in the left panel of Figure 2. A two-way repeated-measures ANOVA was used to compare performance by listening condition (A-alone, E-alone, and EAS) and degree of hearing loss (mild-moderate, and severe-profound). The analysis revealed a significant main effect of listening condition ($F_{(2,20)} = 1.5$, $p < 0.001$) and degree of hearing loss ($F_{(1,20)} = 5.5$, $p = 0.029$), with no significant interaction ($p = 0.187$). A pairwise, multiple comparison (Tukey Test) revealed significant differences between the A-alone (mean = 28%, s.d. = 20), the E-alone (mean = 56%, s.d. = 15), and EAS (mean = 74%, s.d. = 18) conditions. The mean level of performance in the A-alone, E-alone, and combined EAS conditions was 33%, 58%, and 82% for subjects with mild-moderate hearing loss and 21%, 54%, and 63% for

subjects with severe-profound hearing loss. Group mean scores of subjects with mild-moderate and severe-profound loss were not significantly different in the A-alone ($p = 0.14$), or E-alone ($p = 0.55$) conditions, but were significantly different in the combined EAS condition ($p = 0.005$).

Sentence in noise scores (percent correct) in the A-alone, E-alone, and combined EAS conditions are shown in the right panel of Figure 2. A two-way repeated-measures ANOVA was used to compare performance by listening condition (A-alone, E-alone, and EAS) and degree of hearing loss (mild-moderate, and severe-profound). This analysis revealed a significant main effect of listening condition ($F_{(2,20)} = 54.1$, $p < 0.001$), and degree of hearing loss ($F_{(1,20)} = 6.6$, $p = 0.018$), with a significant interaction ($p = 0.012$). The mean scores of all subjects in the A-alone, E-alone, and combined EAS conditions (20%, 45%, and 70%, respectively), were all significantly different from one another ($p < 0.001$). Group mean scores in the A-alone, E-alone, and combined EAS conditions were 31%, 45%, and 83% for subjects with mild-moderate hearing loss and 10%, 46%, and 56% for subjects with severe-profound hearing loss. Group mean scores of subjects with mild-moderate and severe-profound loss were not significantly different in the E-alone condition ($p = 0.89$), but were significantly different in the A-alone ($p = 0.008$) and in the combined EAS condition ($p = 0.002$).

For all subjects, A-alone scores for words in quiet and sentences in noise were averaged to obtain a single point estimate of **acoustic speech understanding**. The mean acoustic speech understanding score for all listeners was 24% (s.d. = 18). Group mean scores for subjects with mild-moderate loss and severe-profound loss were 32% (range: 8% – 66%) and 15% (range: 0% – 48%), respectively. Group mean scores of subjects with mild-moderate and severe-profound loss were significantly different ($p = 0.03$).

For all subjects, E-alone scores for words in quiet and sentences in noise were averaged to obtain a single point estimate of **electric speech understanding**. The mean electric speech understanding score for all listeners was 51% (s.d. = 17). Group mean scores for subjects with mild-moderate loss and severe-profound loss were 51% (range: 28% – 74%) and 50% (range: 13% – 79%), respectively. Group mean scores of subjects with mild-moderate and severe-profound loss were not significantly different ($p = 0.86$).

Normalized Acoustic Benefit

As described above, normalized acoustic benefit is an indexed score. There are concerns about this type of index when performance in the reference condition (i.e. E-alone) is within a few points of the floor or ceiling. In this sample, individual scores in E-alone condition had room to drop or improve on both the CNC word test (range 10% to 78%) and the AzBio sentence test (range 11% to 79%). There is also some concern that such a measure might be biased by level of performance in the E-alone condition (i.e., as E-alone performance increases, the same absolute change in performance yields higher normalized acoustic benefit scores). However, there was no significant correlation between normalized acoustic benefit and E-alone speech scores for CNC words ($r = -0.14$) or AzBio sentences in noise ($r = -0.02$).

Normalized acoustic benefit on CNC words was +39 points for all subjects (range -12 to +91), +54 points (range +6 to +91) for subjects with mild-moderate loss, and +20 points (range -12 to +62) for subjects with severe-profound loss (Figure 3). The difference in benefit scores between the two groups was not significant ($p = 0.004$).

Normalized acoustic benefit on AzBio sentences in noise was 47 points (range -1 to +91) for all subjects, +69 points (range +41 to +91) for subjects with mild-moderate hearing loss,

and +21 (range -1 to +55) for subjects with severe-profound loss (Figure 3). The averaged benefit achieved by the two groups was significantly different ($p < 0.001$).

For all subjects, normalized acoustic benefit scores on words in quiet and sentences in noise were averaged to obtain a single point estimate of **normalized acoustic benefit**. The mean of these normalized acoustic benefit scores was +43 points (range -2 to +91) for all subjects, +62 points (range +24 to +91) for subjects with mild-moderate loss, and +21 points (range -2 to +58) for subjects with severe-profound loss. The averaged benefit achieved by the two groups was significantly different ($p < 0.001$).

Spectral modulation detection thresholds

The mean SMD threshold at 1.0 peak/octave was 17 dB (range = 9 to 36 dB) for all subjects, 13 dB (range 9 to 18 dB) for subjects with mild-moderate loss, and 22 dB (range 10 to 36 dB) for subjects with severe-profound loss. There was a significant difference in group SMD thresholds ($p < 0.001$).

Correlations

There were many planned correlations in this experiment between and among the estimates of acoustic hearing acuity and performance. The three unique estimates of hearing acuity included: (i) **audiometric thresholds** – averaged for test frequencies 750 Hz; (ii) **acoustic speech understanding** – averaged performance on CNC words in quiet and AzBio sentences in noise using only the non-implanted ear; and (iii) **acoustic SMD thresholds** – an estimate of spectral envelope perception from the non-implanted ear. Outcome measures of performance included (i) **electric speech understanding** – averaged performance on CNC words in quiet and AzBio sentences in noise using only the implanted ear; and (ii) **normalized acoustic benefit** – averaged normalized acoustic benefit scores calculated from CNC words in quiet and AzBio sentences in noise. Given the 15 correlations calculated from the same data set, the level of significance was adjusted to $p = 0.0033$ (Bonferroni-Holm correction).

Correlations among measures of acoustic hearing acuity

A Pearson correlation revealed significant relationships between all possible combinations of acoustic ear measures. Significant correlations were found between audiometric thresholds and acoustic speech understanding ($r = -0.48$, $p = 0.02$), audiometric thresholds and acoustic SMD thresholds ($r = 0.817$, $p < 0.001$), and acoustic speech understanding and acoustic SMD thresholds ($r = -0.598$, $p = 0.003$).

Correlations between auditory function and CI performance

A Pearson correlation revealed no significant relationship between electric speech understanding of the implanted ear and audiometric thresholds ($r = -0.02$, $p = 0.94$), acoustic speech understanding ($r = -0.06$, $p = 0.79$), or acoustic SMD thresholds ($r = -0.20$, $p = 0.37$) from the contralateral ear.

Correlations between auditory function and normalized acoustic benefit

A Pearson Product Moment correlation was used to determine significance of relationships between measures of acoustic hearing acuity and normalized acoustic benefit for all subjects, and for groups with mild-moderate loss and severe-profound loss (Figure 4).

For all subjects, a Pearson correlation revealed a significant relationship between normalized acoustic benefit and audiometric thresholds ($r = -0.814$, $p < 0.0001$), acoustic speech understanding ($r = 0.635$, $p = 0.001$), and acoustic SMD thresholds ($r = -0.895$, $p < 0.0001$).

For subjects with mild-moderate loss in the non-implanted ear, no significant relationship was found between normalized acoustic benefit and audiometric thresholds ($r = -0.38$, $p = \text{n.s.}$) or acoustic speech understanding ($r = 0.36$, $p = \text{n.s.}$). A significant relationship was found between normalized acoustic benefit and acoustic SMD thresholds ($r = -0.828$, $p < 0.001$).

For subjects with severe-profound loss in the non-implanted ear, no significant relationship was found between normalized acoustic benefit and audiometric thresholds ($r = -0.65$, $p = \text{n.s.}$) or acoustic speech understanding ($r = 0.52$, $p = \text{n.s.}$). A significant relationship was found between normalized acoustic benefit and acoustic SMD thresholds ($r = -0.896$, $p < 0.001$).

Correlations calculated using absolute acoustic benefit instead of normalized acoustic benefit

The significant correlations above remained the same when we used traditional score of benefit, i. e., the absolute change in percent correct, rather than change normalized for starting (E-only) level of performance. For example, the correlations between averaged benefit and auditory-alone speech understanding, pure tone average and SMT, were 0.68 ($p < 0.001$), -0.773 ($p < 0.001$) and -0.775 ($p < 0.001$), respectively. The correlations for pure tone average and benefit for patients with mild-moderate loss and with severe-profound loss were -0.75 ($p < 0.001$) and -0.59 ($p < 0.001$), respectively. The correlations for SMD and benefit for the two groups were -0.70 ($p < 0.001$) and -0.78 ($p < 0.001$).

Regression model

Audiometric thresholds, acoustic speech understanding scores, and acoustic SMD thresholds were included in a forward stepwise regression analysis to determine the most appropriate model to account for the variability in normalized acoustic benefit. The results indicated that acoustic SMD thresholds were most closely correlated with normalized acoustic benefit. Audiometric thresholds and acoustic speech understanding did not improve the predictive power offered by acoustic SMD thresholds alone and were not selected for inclusion in the regression model.

DISCUSSION

The primary objective of this study was to determine whether measures of auditory function in a hearing-aided ear could be related to the improvement in speech understanding when that ear was paired with the contralateral implanted ear.

Speech understanding in the auditory alone-condition

Of the three measures of auditory functioning, speech understanding scores in the A-alone condition were the least accurate predictor of acoustic benefit ($r = .635$). This can be attributed to the different role played by the non-implanted ear in the A-alone condition and the EAS condition. In the A-alone condition, the listener relies solely on the non-implanted ear for understanding. Given that few bimodal listeners have functional acoustic hearing above 750 or 1000 Hz, A-alone scores are severely constrained by the absence of high frequency information. However, in the EAS condition, the electric signal from the CI provides the basic information for speech understanding and the acoustic signal provides supplemental information that is either omitted or poorly represented electrically. For most listeners, the majority of benefit can be achieved with a very limited acoustic signal. For example, Zhang and colleagues (2010) restricted the acoustic information available to bimodal listeners using a steep low-pass filter at 125 Hz – effectively removing all but the F0 and low-frequency envelope cues. They found that the filtered signal accounted for the

majority of the benefit provided by a wide-band signal. A nearly identical outcome has been reported by Brown and Bacon (2009) who restricted the acoustic signal to a tonal representation of the fundamental frequency and its amplitude modulation.

These restricted acoustic signals provide cues for voicing and syllabic stress. Stress, in turn, provides information about lexical boundaries (Cutler and Norris, 1988). In conditions of poor consonant and vowel intelligibility, listeners appear to rely on the lexical boundary cues provided by stress to improve word recognition (Spitzer et al., 2009; Mattys, White and Melhorn, 2005; Li & Loizou (2009). Though the cues are not sufficient to support speech understanding in isolation, they are beneficial when paired with the electric representation of the speech signal. Thus, word understanding in the non-implanted ear is not a prerequisite for significant acoustic benefit in the EAS condition.

Audiometric thresholds

Audiometric threshold (750 Hz) was highly correlated with acoustic benefit when considering all subjects ($r = -0.81$). The finding that ears with better hearing are, most generally, more useful than ears with very poor hearing is neither surprising nor novel (e.g., Hamzavi et al., 2004; Gantz et al., 2009). Audiometric threshold, however, failed to account for the variability of benefit observed for individuals with similar degrees of hearing loss (correlations of -0.38 and -0.65 for the mild-moderate patients and the severe-profound patients, respectively).

SMD thresholds

The novel contribution of this study is that the traditional clinical measures used to assess the integrity of a non-implanted ear (pure-tone thresholds and speech understanding scores) are less predictive of the degree of benefit than a single measure of spectral resolution (SMD thresholds). The correlation between SMD threshold and acoustic benefit (-0.895) was slightly higher than for audiometric threshold and benefit (-0.81) and accounted for a greater amount of variance when considering all subjects. Moreover, the SMD threshold was the only measure that was strongly correlated with the acoustic benefit observed within groups of subjects having mild-moderate loss ($r = -0.83$) and severe-profound loss ($r = -0.90$).

In the introduction we noted that Gifford et al. (2007b, 2008, 2010) found no relationship between a measure of frequency selectivity (width of the auditory filter at 500 Hz) in the aided ear and benefit from combining acoustic and electric stimulation. The absence of a relationship between that measure and benefit and the presence of a strong relationship between SMD and benefit indicates that the two measures do not test the same underlying auditory function.

The potential translational value of this study is for pre-implant evaluation. It is increasingly common for cochlear implant candidates to have some degree of useable hearing in both ears. For cases where candidates present with significant asymmetries in hearing thresholds and speech understanding scores, the most common clinical decision is to implant the poorer ear. However, for cases where the candidate presents with symmetric hearing loss and speech understanding scores, traditional clinical measures provide no guidance about which ear to implant. Patients are often advised that either ear is a viable candidate for implantation, as performance with the cochlear implant alone will generally exceed performance with the non-implanted ears. In most of these cases some degree of benefit will be observed when combining the two modes of hearing. Thus, the proverbial coin-flip used in the decision making process is rewarded by a successful outcome. However, the degree of

benefit that would have been observed had the opposite ear been implanted remains unknown.

The strong correlation between spectral modulation detection thresholds and average normalized acoustic benefit on word and sentence understanding suggests the potential for a method to identify ears best suited to complement electric hearing (i.e., the ear that should not be implanted). In the absence of a pre-implant measure that can reliably identify the ear which will achieve the highest level of performance with a cochlear implant, a measure that predicts acoustic benefit could prove to be a significant advance in the clinical management of hearing-impaired listeners.

Benefits other than increases in intelligibility

Our measure of ‘benefit’ was speech intelligibility. This is not the only reasonable measure of benefit. Some subjects reported that, in addition to improved speech intelligibility, the acoustic hearing made for a “richer”, “fuller”, and “more colorful” sound than could be provided by the CI alone. In the worst cases, subjects indicated that the residual hearing did not improve speech understanding with the CI, but they benefited from a perceived sense of “balance” with the bilateral inputs. Thus, it is clear that the perception of benefit from combining acoustic and electric stimulation extends beyond speech understanding, and, in some cases, extends beyond sound quality.

CONCLUSION

The primary objective of this study was to determine whether measures of auditory function in a hearing-aided ear could be related to the improvement in speech understanding when that ear was paired with the contralateral implanted ear. We found (i) that pre-implant auditory-alone speech understanding was the poorest predictor of improvement; (ii) that audiometric thresholds (> 750 Hz) were a better predictor but failed to account for the variability of benefit for individuals with similar degrees of hearing loss and (iii) that the best predictor of improvement was SMD threshold.

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Short Summary

It is increasingly common to find cochlear implant users with some degree of hearing in the contralateral ear. Combining the acoustic signal from the non-implanted ear with the electric signal from the cochlear implant often improves sound quality and speech understanding. However, the degree of auditory function in these non-implanted ears and the degree of benefit they provide varies considerably across listeners. We describe the relationship between benefit and three measures of auditory function: audiometric thresholds, speech understanding, and spectral envelope perception. Of these measures, the one most closely correlated with benefit was spectral envelope perception ($r = 0.89$)

Figure 1.

Pure tone thresholds of the non-implanted ear of 22 bimodal listeners. Individuals with average pure tone thresholds (test frequencies of 125, 250, 500, and 750 Hz) less than 60 dB HL (n=12) are shown as filled circles (mean shown as solid line) and those with thresholds of 60 dB HL or more (n=10) are shown as open circles (mean shown as dashed line). Asterisks (*) indicate test frequencies where significant differences ($p < 0.05$) were found between the two groups.

Figure 2.

Monosyllabic word scores (LEFT) and AzBio sentence scores in noise (RIGHT) of 22 bimodal subjects with acoustic hearing alone (A-alone), electric hearing alone (E-alone), and combined electric acoustic hearing (EAS). Subjects are grouped by averaged audiometric thresholds for test frequencies of 125, 250, 500, and 750 Hz. Those with average thresholds in the mild-to-moderate range (< 60 dB HL) are shown as filled circles (mean shown as solid line), and those with average thresholds in the severe-to-profound range (≥ 60 dB HL) are shown as open circles (mean shown as dashed line). Asterisks (*) indicate significant ($p < 0.05$) differences between subject groups within that condition.

Figure 3.

Normalized acoustic benefit received by adding the non-implanted ear to the implanted ear as a function of monosyllabic (CNC) word understanding (left column), AzBio sentences in noise (middle column), and the averaged normalized acoustic benefit scores for the two speech tests (right column). Subjects are grouped by averaged audiometric thresholds for test frequencies of 125, 250, 500, and 750 Hz. Those with average thresholds in the mild-to-moderate (MM) range (< 60 dB HL) are shown as filled circles, and those with average thresholds in the severe-to-profound (SP) range (≥ 60 dB HL) are shown as open circles. Asterisks (*) indicate significant ($p < 0.05$) differences between subject groups within that condition.

Figure 4.

Average normalized acoustic benefit received by adding the non-implanted ear to the implanted ear for monosyllabic (CNC) words and AzBio sentences in noise as a function of audiometric thresholds (top), acoustic speech understanding (middle), and acoustic SMD thresholds (bottom). Subjects are grouped by average audiometric thresholds for test frequencies of 125, 250, 500, and 750 Hz. Those with average thresholds in the mild-to-moderate (MM) range (< 60 dB HL) are shown as filled circles, and those with average thresholds in the severe-to-profound (SP) range (≥ 60 dB HL) are shown as open circles. Correlation coefficients are shown for all subjects and for the two groups. Asterisks (*) indicate significant (adjusted $p < 0.0056$) correlations.

Table 1

		Non-Implanted Ear		Implanted Ear	
Pure Tone Average Threshold (750 Hz)	Age at Test	Duration of hearing loss ^a (years)	Hearing aid experience (years)	Duration of hearing loss ^a (years)	Cochlear implant experience (years)
35	61	47	25	47	1
36	70	54	30	54	3
41	49	35	15	35	5
43	64	44	0	44	0.5
46	63	23	23	23	1
46	69	40	25	40	0.33
48	70	23	21	23	0.33
49	79	35	18	35	2
51	54	46	45	46	3
51	73	27	21	21	5
53	62	40	24	40	0.67
54	66	16	13	16	2
60	77	30	30	30	3
61	67	32	0	32	10
63	82	14	14	14	7
68	84	33	11	33	5
74	52	46	30	46	0.5
76	80	42	22	42	0.83
81	65	58	48	58	10
86	78	76	44	76	2
93	51	19	14	19	2
96	87	41	3	41	3