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Factors constraining the benefit to speech understanding of combining information from low-frequency hearing and a cochlear implant.

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Abstract

Many studies have documented the benefits to speech understanding when cochlear implant (CI) patients can access low-frequency acoustic information from the ear opposite the implant. In this study we assessed the role of three factors in determining the magnitude of bimodal benefit -- (i) the level of CI-only performance, (ii) the magnitude of the hearing loss in the ear with low-frequency acoustic hearing and (iii) the type of test material. The patients had low-frequency PTAs (average of 125, 250 and 500 Hz) varying over a large range (<30 dB HL to >70 dB HL) in the ear contralateral to the implant. The patients were tested with (i) CNC words presented in quiet (n=105) (ii) AzBio sentences presented in quiet (n=102), (iii) AzBio sentences in noise at +10 dB signal-to-noise ratio (SNR) (n=69), and (iv) AzBio sentences at +5 dB SNR (n=64). We find maximum bimodal benefit when (i) CI scores are less than 60 percent correct, (ii) hearing loss is less than 60 dB HL in low-frequencies and (iii) the test material is sentences presented against a noise background. When these criteria are met, some bimodal patients can gain 40-60 percentage points in performance relative to performance with a CI.

1. Introduction

Many studies have documented the benefits to speech understanding when cochlear implant (CI) patients can access low-frequency acoustic information from the ear opposite the implant (e.g., Ching et al. 2004; Kong, Stichney & Zeng 2005; Mok et al. 2006; Gifford et al. 2007; Dorman et al. 2008; Zhang et al. 2010). Estimates of the magnitude of the

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‘bimodal’ benefit vary greatly among studies. Some have shown little-to-no bimodal benefit for CNC words (Mok et al., 2006; Gifford et al., 2014) whereas others have shown benefit in the range of 20- to 30-percentage points (e.g., Gifford et al., 2007; Dorman et al., 2008; Zhang et al., 2010). For speech recognition in noise, most studies have documented significant bimodal benefit. However, the magnitude of the benefit has ranged from 5- to 10-percentage points (e.g., Kong et al., 2005; Mok et al., 2006) to 30- to 50-percentage points (e.g., Gifford et al., 2007; Dorman et al., 2008; Zhang et al., 2010) for sentences at +10 dB signal-to-noise ratio (SNR). The large variability in scores is not surprising given the between-study differences in the CI-alone performance of the patients, the differences in pure-tone thresholds in the non-implanted ear, the differences in the test material (e.g., words vs. sentences) and in the test conditions (i.e., quiet vs. noise). In this report we describe the relevance of these factors to the magnitude of bimodal benefit for a large group of CI patients.

It is reasonable to suppose that each of the variables described above could influence the magnitude of bimodal benefit. The level of performance with the CI-only is relevant because if that level is high, then the absolute benefit will be constrained. For example, if the CI-only performance is 85% correct on a test, then the maximum percentage point gain is 15-percentage points. On the other hand, if the CI-only performance is 20% correct, then the maximum percentage point gain is 80-percentage points.

The magnitude of hearing loss in the non-implanted ear is relevant because loss of audibility and suprathreshold distortion combine to alter the information available to the listener (e.g., Bernstein et al., 2013; Grant et al., 2013; Summers et al., 2013). We should expect that listeners with mild to moderate hearing loss in low frequencies would benefit more from low-frequency hearing than patients with greater hearing loss.

Both the type of test material and listening environment (quiet or in noise) are also likely to affect bimodal benefit. Because low-frequency acoustic information contains significant information about word boundaries, this information may be of more value for word recognition in sentences than in isolated word recognition and may be more useful in noise than in quiet (Li and Loizou, 2008; Spitzer et al., 2009).

In this study we tested bimodal patients who had low-frequency PTAs (average of 125, 250 and 500 Hz) varying over a large range (<30 dB HL to >70 dB HL). The patients were tested with (i) CNC words presented in quiet (n=105) (ii) AzBio sentences presented in quiet (n=102), (iii) AzBio sentences in noise at +10 dB signal-to-noise ratio (SNR) (n=69), and (iv) AzBio sentences at +5 dB SNR (n=64). We show how the magnitude of the bimodal advantage is affected by the CI-only level of performance for each type of material and by the magnitude of threshold elevation. Finally, we used 95% critical difference scores for single syllable words (Carney and Schlauch, 2007; Thornton and Raffin, 1978) and the AzBio sentences (Spahr et al., 2012) to determine the proportion of patients who benefit from bimodal stimulation.

2. Methods

2.1 Participants

Individuals fit with a CI and who had low-frequency hearing in the opposite ear were invited to participate in this study. The listeners were recruited from, and tested at, three locations: Arizona State University, Vanderbilt University Medical Center and the University of Ottawa Faculty of Medicine. The criterion for participation was consistent use of a CI in one ear and low-frequency hearing in the opposite ear. Because this project evolved over time, not all listeners were tested with all of the test materials.

The listeners, who ranged in age from 21 to 90 years (mean = 66), were assigned to three groups, approximating traditional mild, moderate and severe loss categories, based on low-frequency audiometric thresholds. For one group, the mean audiometric thresholds at 125, 250 and 500 Hz varied over the range 0 to 40 dB HL; for a second group, mean thresholds varied over the range 41-60 dB HL and for a third group mean thresholds were 61dB HL. The mean audiograms for the three groups of listeners, in the CNC word condition, are shown in Figure 1. For the listeners in the 0-40 dB HL group, the mean thresholds at 125, 250, 500, 750, 1000, 2000 and 4000 Hz were 24, 27, 46, 61, 77, 98 and 104 dB HL respectively. For the listeners in the 41-60 dB HL group the thresholds were 41, 50, 62, 75, 85, 99 and 110 dB, respectively. For the listeners in the 61dB HL group, the thresholds were 62, 73, 82, 87, 88, 97, and 106 dB respectively. The mean age and the mean duration of CI use for the listeners in each group is shown in Table 1.

Hearing aid settings were verified before testing, using probe microphone measurements to match output to National Acoustic Laboratories (NAL-NL1) targets (Dillon et al. 1998) for 60-dB-SPL speech. In cases where target audibility was not being met by the listener's current hearing aid settings, the hearing aid(s) were reprogrammed and outputs verified before testing.

2.1 Task and materials

The listeners were tested in audiometric test booths with CNC monosyllabic words (Peterson and Lehiste, 1962) and the AzBio sentences (Spahr et al., 2012) presented in quiet, +10 and +5 dB SNR. The signal presentation level was 60 dB SPL (A weighted) for both sets of materials. For CNC words, one 50-item list was used. For AzBio sentences, one 20-item list was used in each condition. For bimodal patients, in the CI-only condition the contralateral ear was plugged (EAR Classic) and muffed (UltraSonic).

3. Results

3.1 Performance data

The changes in speech understanding in the bimodal test conditions relative to the CI- only test conditions for CNC words and for the AzBio sentences in quiet and noise are shown in Figure 2. On each plot the percentage point change in performance with bimodal stimulation is plotted as a function of the CI-only level of performance for patients with 0-40 dB HL

low-frequency thresholds (blue symbols), for patients with 41-60 dB HL thresholds (brown symbols) and for patients with ≥ 61 dB HL thresholds (red symbols).

On the plot for CNC word recognition, the dashed lines indicate the critical difference scores for CNC words (Carney and Schlauch, 2007). On the plots for AzBio sentence recognition the dashed lines indicate the critical difference scores for the AzBio sentences (Spahr et al., 2012). The use of these functions enabled us to calculate the number of patients with significant benefit to speech understanding. For visual reference, on each plot a diagonal line indicates the maximum percentage point change that could be achieved. The results are summarized in Table 2 for all groups in all test conditions in terms of percentage point improvement and proportion of listeners whose scores exceeded the critical difference scores.

3.2 CNC words

Figure 2 - top left- shows the performance of listeners tested with CNC words. The mean improvement in performance for listeners with low frequency thresholds between 0 and 40 dB ($n=20$) was 16-percentage points. 35 percent of the sample achieved bimodal scores that exceeded the 95% critical difference score for the CI-alone condition. For listeners with low-frequency thresholds between 41 and 60 dB HL ($n = 41$), the mean improvement in performance was 9-percentage points. 29 percent achieved bimodal scores that exceeded the critical difference score for the CI-alone condition. For listeners with low-frequency thresholds ≥ 61 dB ($n=44$), the mean improvement in performance was 4-percentage points. For this group with the most severe hearing losses, 7 percent achieved bimodal scores exceeding the critical difference score for the CI-alone condition.

An analysis of differences in the proportion of listeners with significant benefit (<http://www.statstutorials.com/SAS/CHISQ>) indicated a main effect for groups ($\chi^2=9.40$, $p=0.0091$). Post tests indicated that the proportion of listeners who benefited was significantly greater for the 0-40 dB group than for the ≥ 61 dB group. The proportion of listeners who benefited did not differ for the 0-40 dB group and the 41-60 dB group. The proportion of listeners who benefited was greater for the 41-60 dB group than for the ≥ 61 dB group.

3.3 Sentences in quiet

Figure 2 -top right - shows the performance of listeners tested with the AzBio sentences in quiet. Because the results were severely constrained by a ceiling effect, the data are of limited value. However, we report the data for completeness and because the data document the very high level of sentence recognition attained by many bimodal listeners when listening in quiet.

The mean improvement in performance was 13-percentage points for listeners ($n=19$) with low-frequency thresholds between 0 and 40 dB HL. 37 percent achieved bimodal scores exceeding the critical difference score for the CI-alone condition. For listeners with low-frequency thresholds between 41 and 60 dB HL ($n = 40$), the mean improvement in performance was 7-percentage points. 15 percent achieved bimodal scores that exceeded the

critical difference score for the CI-alone condition. For listeners with low-frequency thresholds ≤ 61 dB HL ($n=43$), the mean improvement in performance was 5-percentage points. 19 percent achieved bimodal scores that exceeded the critical difference score for the CI-alone condition.

3.4 Sentences at +10 dB SNR

Figure 2 - bottom left - shows the performance of listeners tested with the AzBio sentences at +10 dB SNR. For listeners ($n=16$) with low frequency thresholds between 0 and 40 dB HL, the mean improvement in performance was 26-percentage points. 75 percent of the listeners achieved bimodal scores that exceeded the critical difference score for the CI-alone condition. For listeners with low-frequency thresholds between 41 and 60 dB HL ($n = 23$), the mean improvement in performance was 21-percentage points. 70 percent of the listeners achieved bimodal scores that exceeded the critical difference score for the CI-alone condition. For listeners with low-frequency thresholds ≤ 61 dB HL ($n=30$), the mean improvement in performance was 8-percentage points. 23 percent of the listeners achieved bimodal scores that exceeded the critical difference score for the CI-alone condition.

An analysis of differences in the proportion of listeners with significant benefit indicated a main effect for groups ($\chi^2= 16.04$, $p=0.003$). Post tests indicated that the proportion of listeners who benefited was significantly greater for the 0-40 dB HL group than for the ≤ 61 dB HL group.

The proportion of listeners who benefited did not differ for the 0-40 dB HL group and the 41-60 dB HL group. The proportion of listeners who benefited was greater for the 41-60 dB HL group than for the ≤ 61 dB HL group.

3.5 Sentences at +5 dB SNR

Figure 2 - bottom right - shows the performance of listeners tested with the AzBio sentences at +5 dB SNR. The mean improvement in performance was 28 percentage points for listeners ($n=15$) with low frequency thresholds between 0 and 40 dB HL. 67 percent achieved scores that exceeded the critical difference score for the CI-alone condition. For listeners with low-frequency thresholds between 41 and 60 dB HL ($n = 19$), the mean improvement in performance was 17 percentage points. 47 percent achieved scores that exceeded the critical difference score for the CI-alone condition. For listeners with low-frequency thresholds ≤ 61 dB HL ($n=30$), the mean improvement in performance was 6 percentage points. 20 percent achieved scores that exceeded the critical difference score for the CI-alone condition.

An analysis of differences in the proportion of listeners with significant benefit indicated a main effect for groups ($\chi^2= 9.93$, $p=0.007$). Post tests indicated that the proportion of listeners who benefited was significantly greater for the 0-40 dB group than for the ≤ 61 dB group. The proportion of listeners who benefited did not differ for the 0-40 dB group and the 41-60 dB group. The proportion of listeners who benefited did not differ for the 41-60 dB group and for the ≤ 61 dB group.

3.6 Benefit for words vs. sentences in noise

Inspection of Table 2 suggests that a greater proportion of listeners benefited from bimodal stimulation in the two sentences-in-noise conditions than in the CNC word condition. An analysis of differences in the proportion of listeners with significant benefit revealed a main effect for type of material (CNC words vs. sentences in noise) ($\chi^2 = 15.17$, $p < 0.001$). A post test indicated that fewer listeners benefited in the CNC word condition than in the combined AzBio +10 condition and +5 conditions.

4. Discussion

In the introduction we noted that the magnitude of bimodal benefit for CI listeners varies widely among studies. In an effort to account for some of that variability, we assessed the role of three variables -- the level of CI-only performance, threshold elevation in the ear with low-frequency acoustic hearing and the type of test material -- in determining bimodal benefit.

4.1 CI-only performance

Figure 2 indicates that, for individual patients, the maximum gain in performance, when a low-frequency acoustic signal was added to the CI signal, could be greater than 40 percentage points. Thus, experiments in which some, or all, patients exhibit CI-only scores of greater than 60% correct will likely report artificially reduced mean scores for bimodal benefit. Moreover, for a given CI-only level of performance, a high level of variability in bimodal benefit exists across patients. Thus, the vagaries of small samples can result in a wide range of outcomes.

One approach to the problem of variation in the CI-only level of performance is to assess and report the proportion of patients who show a significant bimodal advantage relative to the confidence limits of the CI-only score. Using this measure, we find that a large proportion (approximately 0.72) of patients with low-frequency hearing thresholds up to 60 dB HL benefit from bimodal stimulation when the test materials are the AzBio sentences at +10 dB. The proportion of patients who benefit falls to 0.23 for patients with low-frequency hearing thresholds ≥ 61 dB HL. Although the proportion of patients who benefit is much lower in the ≥ 61 dB HL group, it is important to note that many do benefit.

4.2 Threshold elevation

The magnitude of low-frequency threshold elevation, as expected, had a large influence on the magnitude of the bimodal benefit. For both CNC words and the AzBio sentences in noise, listeners with 0-40 dB HL thresholds achieved greater bimodal benefit, both in terms of percentage point improvement in scores and the proportion of patients who benefit, than patients with thresholds ≥ 61 dB HL. Listeners with 41-60 dB HL thresholds behaved, most generally, in a fashion similar to listeners with 0-40 dB HL thresholds. Of course, threshold elevation, *per se*, may not be the critical issue in determining bimodal benefit.

Elevated auditory thresholds are commonly accompanied by other distortions that alter the representation of the signal. In a recent paper (Zhang et al., 2012), we reported that spectral

modulation detection (SMD) thresholds -- a measure of spectral envelope perception -- are a better predictor of bimodal benefit than audiometric thresholds. In that study, for a relatively small sample of bimodal listeners ($n=22$), the correlation between benefit and auditory threshold was -0.81 ; the correlation between benefit and SMDT was -0.89 . Critically, only SMD thresholds were correlated with performance *within* a group of listeners with mild to moderate threshold elevation (-0.83) and a group of listeners with severe threshold elevation (-0.90). Nonetheless, in the absence of a clinical test of SMD thresholds (e.g., Gifford et al. 2014; Drennan et al., 2014) the audiogram can be of significant value when advising patients about the probable outcomes of bimodal hearing.

4.3 Type of test material

Inspection of Table 2 suggests that the type of test material also had a clear influence on bimodal benefit. For each group of listeners, more individuals achieved significant benefit when the test material was sentences-in-noise than when the test material was CNC words. This outcome is consistent with the view that the low-frequency acoustic signal, in addition to transmitting information about segmental voicing and manner (Ching, 2005), contains acoustic landmarks (Stevens, 2002) that aid in the determination of lexical boundaries (Li and Loizou, 2008; Spitzer et al., 2009).

4.4 Dead regions

As shown in Figure 1, the hearing losses of our listeners could be characterized, most generally, as moderately to steeply sloping. A cochlear dead region (Moore, 2001) is common in ears with this type of hearing loss (Vinay and Moore, 2007). Zhang et al. (2014) studied 11 bimodal listeners with a documented dead region in the ear with low-frequency acoustic hearing and assessed bimodal benefit in conditions (i) when amplification was restricted to frequencies below the dead region and (ii) when amplification was wide band. Restriction of amplification, based on the edge frequency of the dead region, produced, on average, a 10-11 percentage point improvement in intelligibility and improved the sound quality of music and speech. This outcome suggests that the results of the present study, in which amplification was *not* modified based on the existence of cochlear dead regions, underestimates, at least slightly, the benefit of bimodal stimulation.

5. Conclusions

We assessed the role of three variables -- (i) the level of CI-only performance, (ii) the magnitude of the hearing loss in the ear with low-frequency acoustic hearing and (iii) the type of test material -- in determining bimodal benefit. We find that patients show maximum bimodal benefit when (i) CI scores are less than 60 percent correct, (ii) hearing loss is less than 60 dB in low-frequencies and (iii) the test material is sentences in noise. When these criteria are met, some bimodal patients can gain 40-60 percentage points in performance relative to performance with a CI.

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- Bimodal cochlear implant patients receive both electric and acoustic stimulation.
- Three factors constrain the benefit from acoustic hearing.
- Benefit is greatest when CI-only performance is less than 60 percent correct.
- Benefit is greatest when low-frequency hearing loss is less than 60 dB HL.
- Benefit is greatest when speech signals are presented in noise.

Figure 1.

Group mean thresholds in dB HL for three groups of listeners. Filled circles indicate thresholds for group 0-40 dB, grey filled squares are for group 41-60 dB and open circles are for group ≥61 dB. Symbols are offset slightly on the x-axis to aid reading.

Figure 2.

Percentage point benefit in speech understanding for three groups of listeners when tested with CNC words, AzBio sentences in quiet, AzBio sentences at +10 dB SNR and AzBio sentences at +5 dB SNR. Dotted lines indicate 95 percent critical difference scores for the test material. The solid diagonal line indicates the maximum possible score.

Table 1

Age and duration of CI use for patients in three hearing loss categories. The number of patients is the maximum number that participated in any test condition.

	Threshold		
	0-40 dB HL	41-60 dB HL	61dB HL
Age (years)	64.25	67.95	63.00
Duration CI use (years)	2.45	1.65	3.63
Number of patients	20	41	44

Table 2

Mean percentage point benefit (points) and the proportion of patients who benefit (proportion) for three groups of bimodal listeners (0-40, 41-60 and 61 dB HL thresholds) for four types of test material.

	CNC words		AzBio Quiet		Az Bio +10		AzBio +5	
	points	proportion	points	proportion	points	proportion	points	proportion
0-40 dB	16	.35	13	.37	26	.75	28	.67
41-60 dB	9	.29	7	.15	21	.70	17	.47
61 dB	4	.07	5	.19	8	.23	6	.20