Binaural advantages in users of bimodal and bilateral cochlear implant devices

Kostas Kokkinakis[a] **and Natalie Pak**
Department of Speech-Language-Hearing: Sciences and Disorders, University of Kansas, Lawrence, Kansas 66045
kokkinak@ku.edu, nataliespak@ku.edu

Abstract: This paper investigates to what extent users of bilateral and bimodal fittings should expect to benefit from all three different binaural advantages found to be present in normal-hearing listeners. Head-shadow and binaural squelch are advantages occurring under spatially separated speech and noise, while summation emerges when speech and noise coincide in space. For 14 bilateral or bimodal listeners, speech reception thresholds in the presence of four-talker babble were measured in sound-field under various speech and noise configurations. Statistical analysis revealed significant advantages of head-shadow and summation for both bilateral and bimodal listeners. Squelch was significant only for bimodal listeners.

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1. Introduction

Listening with two ears as opposed to one leads to improved speech recognition in the presence of competing noise for individuals with normal-hearing (NH) abilities (Bronkhorst and Plomp, 1989; Schleich *et al.*, 2004). Recent studies have investigated whether cochlear implant (CI) users may also benefit from binaural listening advantages through the addition of a second CI or a contralateral hearing aid (HA). Patients with both bilateral (CI + CI) and bimodal (CI + HA) devices have reported favorable perceptual benefits from a binaural configuration (e.g., see Schafer *et al.*, 2011). Various studies have also quantitatively assessed the binaural advantages available under bilateral and bimodal listening conditions.

Three specific binaural effects are believed to benefit NH listeners and those with a hearing impairment toward speech perception in noise: head-shadow (HS), binaural squelch (SQ), and binaural summation (SU). HS is a physical phenomenon, which occurs when speech and noise sources are spatially separated. The intensity of the noise source is reduced at the ear further from the source due to attenuation by the head and shoulders, hence benefiting the contralateral ear with a better signal-to-noise ratio (SNR) for speech perception (e.g., see Morera *et al.*, 2005). SQ relies upon the ability of the central auditory system to compare interaural differences when the speech and noise sources are spatially separated and to selectively target the speech signal for improved intelligibility. For the SU effect, when speech and noise sources coincide in space, the identical signals presented to both ears are centrally integrated, leading to increased perceptual loudness and improved speech perception abilities (e.g., see Litovsky *et al.*, 2006). For NH listeners, HS has been found to produce a benefit ranging from 8.9 to 10.7 dB, SQ from 2.0 to 4.9 dB, and SU from 1.1 to 1.9 dB (Bronkhorst and Plomp, 1989; Schleich *et al.*, 2004).

Several studies indicate that these effects may improve speech recognition by bilateral CI users, thereby reducing the performance gap between this group and NH

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[a]Author to whom correspondence should be addressed.

listeners. Schleich *et al.* (2004) measured speech reception thresholds (SRTs) in 18 adults fitted with bilateral CIs under three listening conditions and three speech and noise spatial configurations. Analysis of the results indicated significant advantages from all three binaural effects. Average improvement from HS amounted to 6.8 dB, from SQ to 0.9 dB, and from SU to 2.1 dB. Using a similar experimental design, Litovsky *et al.* (2006) reported largely consistent findings with those of Schleich *et al.* (2004). The largest improvement in SRTs was attributed to HS, and SQ was also found to be significant. However, SU was significant only when comparing binaural listening to monaural listening with the left ear. The binaural advantage over the right ear alone was not significant. Buss *et al.* (2008) assessed speech recognition of sentences presented at a fixed SNR by 26 bilateral cochlear implantees. Twelve months post-implantation, all the participants tested exhibited evidence of all three binaural advantages, with HS again resulting in the greatest effect. Median score improvements reported across all participants were: 38 percentage points for HS, 11 percentage points for SQ, and 6 percentage points for SU.

The contributions of these three binaural effects to bimodal speech perception are uncertain. Ching *et al.* (2004) tested 21 adults with bimodal devices (CI + HA). Although the data were not specifically analyzed for HS, SQ, and SU effects, speech perception in noise did improve significantly with binaural listening as opposed to monaural listening with either the CI or the HA. This was true both when speech and noise were spatially coincident and spatially separated. Morera *et al.* (2005) also evaluated speech perception at a fixed SNR for 12 adults with bimodal devices at 6 months post-implantation. Contrary to the large effect of HS observed in studies with bilateral CIs, Morera *et al.* (2005) reported no evidence of a significant effect of HS for bimodal listeners. Likewise, there was no significant effect of SU when comparing the bimodal listening condition to listening with the CI alone. A significant effect of SQ, however, was observed both with the noise situated closer to the participant's CI (average improvement of 33 percentage points) and closer to the HA (average improvement of 17 percentage points).

More recently, Schafer *et al.* (2011) resorted to a meta-analytic approach to evaluate current findings on binaural advantages associated with bilateral and bimodal device fittings. Forty-two articles were included for review, and standardized effect sizes (d) were calculated in order to compare across studies that used dissimilar measurement paradigms. Effect sizes were interpreted as small ($d = 0.2$), medium ($d = 0.5$), or large ($d = 0.8$), with positive values indicating a binaural advantage. HS produced the most pronounced effect sizes, with bilateral listening conditions yielding a large effect ($d = 1.26$) and bimodal device conditions yielding a medium effect ($d = 0.69$). A small-to-medium effect of SQ was found for bilateral conditions ($d = 0.37$), but the effect of SQ for bimodal conditions was not significant ($d = 0.16$). Small-to-medium effect sizes of SU were found for both bilateral and bimodal conditions ($d = 0.42$ and $d = 0.46$, respectively). While these results indicate an overall advantage of binaural listening as opposed to monaural listening, analysis of effect sizes for bilateral as opposed to bimodal listening conditions revealed no significant differences for any of the three binaural advantages.

These findings are largely consistent with those reported in the aforementioned studies with bilateral populations (e.g., see Schleich *et al.*, 2004; Litovsky *et al.*, 2006; Buss *et al.*, 2008). However, the significant effects of HS and SU for bimodal conditions run contrary to the findings of Morera *et al.* (2005), who reported SQ to be the only significant binaural effect under bimodal listening conditions. In an experiment to directly compare bilateral and bimodal listening conditions, Schoof *et al.* (2013) used simulations of listening conditions as well as simulations of spatial separation of speech and noise. Stimuli were presented through headphones to 12 NH listeners, and SRTs were measured under each condition. In the simulated bilateral condition, significant improvements in SRTs were observed due to HS (average of 7.5 dB across subjects) and SU (average of 3.0 dB across subjects). For the bimodal conditions, only SU was significant, with a large average improvement in SRTs of 10.2 dB across subjects.

Based on the aforementioned studies, there is strong evidence to suggest that HS may be the largest binaural advantage for speech recognition in noise under bilateral CI listening conditions. Nonetheless, the relative contributions of SQ and SU to the improved binaural perception observed in noise remain unclear. For bimodal listening conditions, recent studies offer inconclusive results on the relative contributions of HS, SQ, and SU to speech understanding in noise. In this contribution we assess to what extent listeners with bilateral and bimodal fittings should expect to benefit from all three different binaural hearing advantages. The contralateral HA will provide additional low-frequency spectral and temporal information that is largely unavailable with a CI. We can thus hypothesize that bimodal listeners are likely to receive substantially different benefits to those observed in bilateral CI users.

2. Methods

2.1 Participants

Seven post-lingually deafened adult bilateral cochlear implant (CI + CI) users (four female, three male) with a fully inserted (i.e., long electrode array) CI in each ear took part in this study. Seven experienced bimodal listeners (four female, three male) with a CI on one side (right) and aided low-frequency hearing in the contralateral (left) ear (HA + CI) were also recruited. All 14 subjects were native speakers of American English, and had acquired at least 18 months of experience with their device post-implantation prior to testing. Demographic information for these individuals is presented in Table 1. This study was approved by the Human Subjects Committee of the University of Kansas in Lawrence. All subjects gave written informed consent prior to the beginning of testing and a case history interview was conducted with each subject to determine eligibility in this study. Subjects with a performance score greater than 70% on the consonant-nucleus-consonant test were included.

Table 1. Participant demographic information.

Subject	Gender	Age at testing	Months of experience with bimodal or bilateral stimulation	Etiology of hearing loss	CI type	Contralateral HA or CI type	Consonant-nucleus-consonant word-recognition score in quiet (% correct)
CI1	M	49	19	Noise exposure	Nucleus 5	Nucleus 5	92%
CI2	F	22	70	Unknown	Freedom	Freedom	94%
CI3	M	67	40	Meniere's	Nucleus 5	Nucleus 5	75%
CI4	F	51	64	Hereditary	Nucleus 5	Nucleus 5	91%
CI5	M	75	36	Unknown	Nucleus 5	Nucleus 5	81%
CI6	F	34	35	Unknown	Nucleus 5	Nucleus 5	84%
CI7	F	45	32	Unknown	Nucleus 5	Nucleus 5	90%
MEAN		49.0	42.3				87%
SD		18.1	18.2				7%
HA1	M	66	28	Unknown	Nucleus 5	Phonak Naida	88%
HA2	M	54	32	Noise exposure	Nucleus 5	Phonak Naida	92%
HA3	F	57	27	Unknown	Nucleus 5	ReSound Pixel	84%
HA4	F	55	24	Unknown	Nucleus 5	Phonak Naida	75%
HA5	F	71	78	Unknown	Nucleus 5	Oticon 380P	92%
HA6	F	45	21	Unknown	Nucleus 5	Phonak Naida	83%
HA7	M	84	24	Unknown	Nucleus 5	Phonak Naida	82%
MEAN		61.7	33.4				85%
SD		13.0	20.0				6%

2.2 Test environment and stimuli

Sentence recognition in noise experiments was conducted using the Revitronix R-SPACE (Revitronix, Braintree, VT) sound simulation system. This system consisted of an eight-loudspeaker array placed in a circular pattern around the subject. Each loudspeaker was placed at a distance of 60 cm from the listener's head. The loudspeakers were each separated by 45°. The Bamford-Kowal-Bench Speech in Noise (BKB-SIN) Test Audio CD (Etymotic Research, Elk Grove Village, IL, 2005) was chosen as the test material. The BKB-SIN test consisted of 18 equivalent list pairs. Short, simple sentences were presented against four-talker babble noise. Four-talker babble is a difficult but realistic stimulus, since it is perceptually complex. There were three key words per sentence, except for the first sentence, which contained four key words. The level of background noise increased by 3 dB between each sentence. The listener repeated the sentence, and key words were scored as correct or incorrect. SNRs of +21 dB to −6 dB were assessed. The SRT, referred to as the SNR yielding 50% correct performance, was calculated for each list pair using a formula provided by the developers of the test material.

2.3 Procedure

The participants were seated inside the double-walled IAC sound-attenuating booth at the center of the eight-loudspeaker array. The target speech was presented from the front loudspeaker placed at 0° azimuths (S_0). The target was presented at 65 dB sound pressure level (SPL) measured at the subject's head. The noise signal was presented from: (1) the same location as the target (S_0N_0), (2) the right loudspeaker placed at 90° (S_0N_{90}), and (3) the left loudspeaker placed at −90° (S_0N_{-90}). For each subject population, testing was conducted in three different listening conditions. In bilateral CI users, the listening conditions tested were: left CI only, right CI only, and CI + CI. In bimodal users, the listening conditions tested were: CI-alone, HA-alone, and CI + HA. In the CI-alone conditions, the HA device was turned off and removed. A silicone rubber earplug was inserted in the non-implanted ear. Subjects participated in a total of nine experimental conditions (three listening conditions × three noise conditions). The presentation of the experimental conditions was randomized to decrease order effects. Each testing session lasted approximately 2 h.

For all conditions tested, the participants were asked to use the settings (e.g., programs) that they would normally use for everyday listening. The noise reduction programs on the speech processors were disabled. The bilateral CI participants were asked to adjust the levels on each speech processor to ensure that speech stimuli were "balanced" between ears. The loudness balance between the two ears was checked by determining whether sounds presented from the front were heard in the center when both devices were used. The bimodal listeners were also asked to adjust the individual settings on the HA device to match the loudness of their CI device for the voice of the tester, which was presented at 65 dB SPL. For both populations, in the CI-alone conditions, the settings of the CI device (volume and sensitivity controls) were not adjusted again in order to ensure that the same settings were retained.

3. Results

3.1 SRT calculation

For all bilateral and bimodal subjects tested, SRTs were calculated as a function of the listening condition (*lc*) and noise condition (*nc*). For each condition, we measured the SRT(*lc*,*nc*), with *lc* equal to left, right, or both devices and *nc* equal to S_0N_0, S_0N_{90}, or S_0N_{-90} (e.g., see Schleich *et al.*, 2004; Morera *et al.*, 2005; Buss *et al.*, 2008). The three binaural advantages were calculated as described below:

(1) The HS effect for *lc* equal to either the left or right device was calculated by subtracting the unilateral SRT obtained when the noise was on the contralateral side of the

activated listening device from the SRT obtained when the noise was located on the ipsilateral side, such that

$$\mathrm{HS}(lc) = \mathrm{SRT}(lc, \mathrm{ipsilateral}) - \mathrm{SRT}(lc, \mathrm{contralateral}). \quad (1)$$

(2) The SQ effect for nc equal to S_0N_{90} or S_0N_{-90} was calculated by subtracting the SRT obtained when listening with both devices from the SRT obtained when listening with the device located contralateral to the noise, such that

$$\mathrm{SQ}(nc) = \mathrm{SRT}(\mathrm{contralateral},\ nc) - \mathrm{SRT}(\mathrm{both},\ nc). \quad (2)$$

(3) The SU advantage for lc equal to either the left or right device was calculated by subtracting the SRT with both devices from the SRT with either the left or right device in the S_0N_0 condition (i.e., when identical stimuli are available in both ears):

$$\mathrm{SU}(lc) = \mathrm{SRT}(lc, S_0N_0) - \mathrm{SRT}(\mathrm{both},\ S_0N_0). \quad (3)$$

The average values of the three binaural effects were calculated by applying Eqs. (1)–(3) to the mean SRT values reported in Table 2. SRT values were averaged across participants and across right and left listening conditions. For the bilateral subjects tested, the average improvement from HS amounted to 8.1 dB, from SQ to 0.9 dB, and from SU to 2.5 dB. For the bimodal listeners tested, the average improvement from HS was equal to 6.7 dB, from SQ to 2.9 dB, and from SU to 7.6 dB. The mean values of the HS, SQ, and SU effects for both populations are plotted in Fig. 1.

3.2 Statistical analysis

In all statistical analyses, a critical value equal to 0.05 was used as the significance level. To determine the presence of the binaural effects of HS, SQ, and SU in each of

Table 2. SRTs measured in seven bilateral (CI1–CI7) and seven bimodal (HA1–HA7) users.

	S_0N_{-90}			S_0N_0			S_0N_{90}		
Subject	Left	Both	Right	Left	Both	Right	Left	Both	Right
CI1	18.0	1.0	1.5	21.5	6.0	8.5	6.0	13.5	3.0
CI2	18.0	4.5	7.5	10.0	9.5	9.5	10.5	6.5	18.5
CI3	12.0	−3.0	−0.5	1.5	0.5	1.0	−2.5	−2.0	7.5
CI4	5.0	4.5	6.0	5.0	9.0	13.0	5.5	0.5	18.5
CI5	7.0	1.5	−0.5	8.5	5.5	3.0	0.0	−1.5	7.5
CI6	15.0	1.5	4.0	13.5	5.5	7.5	8.5	8.0	12.5
CI7	13.0	2.5	1.5	6.0	4.5	7.0	3.0	1.0	8.0
MEAN	12.57	1.79	2.79	9.43	5.79	7.07	4.43	3.71	10.79
SD	5.06	2.55	3.13	6.55	3.00	4.01	4.60	5.77	5.94
HA1	15.5	1.0	2.5	19.0	1.5	2.5	14.5	10.0	4.0
HA2	22.0	−3.5	−1.0	21.0	4.0	5.0	17.0	6.0	4.5
HA3	19.0	1.0	0.5	14.0	4.0	9.5	10.5	6.0	13.0
HA4	18.5	−1.0	−4.5	14.0	7.5	9.0	8.5	11.0	9.0
HA5	18.5	−2.0	−2.5	18.5	3.5	2.0	18.0	11.5	8.5
HA6	14.5	1.0	2.0	11.0	1.0	9.5	14.5	5.5	13.0
HA7	22.5	2.0	3.0	21.0	7.0	8.0	16.0	10.0	10.0
MEAN	18.64	−0.21	0.00	16.93	4.07	6.50	14.14	8.57	8.86
SD	2.98	2.00	2.80	3.92	2.47	3.29	3.46	2.62	3.61

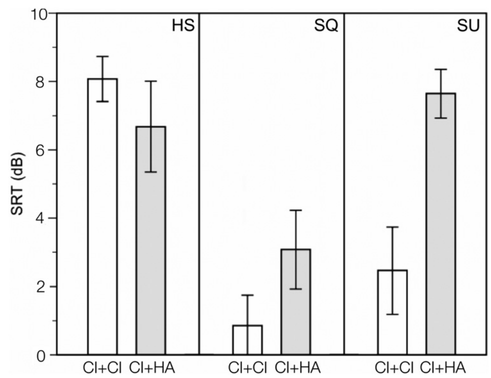

Fig. 1. Mean values of HS, SQ, and SU effects measured in seven bilateral (CI + CI) and seven bimodal (CI + HA) users. Error bars indicate standard errors of the mean.

the two subject populations, one-sample Wilcoxon signed rank tests were used to assess whether or not a certain effect was significantly different from zero. The results for bilateral users indicated significant effects of HS ($p = 0.009$) and SU ($p = 0.03$), while the binaural SQ benefit contributed no statistically significant benefit to bilateral performance in noise ($p = 0.14$). The results obtained for the bimodal users indicated significant effects of HS ($p = 0.008$), SU ($p = 0.002$), and also a weak significance for SQ ($p = 0.048$). Non-parametric Mann-Whitney tests were also used to directly compare each of the three binaural effects between the two populations tested. The overall differences observed in the magnitudes of the HS and SQ effects were not statistically significant for bilateral as opposed to bimodal stimulation. However, the effect of SU evidenced by the bimodal listeners was significantly different from the SU benefit that was observed in the bilateral group of listeners ($p = 0.007$).

4. Summary and discussion

The data for the bilateral CI listeners tested are consistent with previous findings reported in recent literature in that the binaural benefit due to HS is generally the most robust and consistent effect observed for this group (Schleich *et al.*, 2004; Litovsky *et al.*, 2006; Buss *et al.*, 2008; Schafer *et al.*, 2011; Schoof *et al.*, 2013), and it is comparable to the magnitude of HS previously reported for NH listeners (e.g., see Schleich *et al.*, 2004; Buss *et al.*, 2008). In fact, our findings suggest that the HS effect can lower the SRT in four-talker babble noise by about 8.1 dB. A similar average improvement of 6.8 dB attributed to the HS has been previously reported by Schleich *et al.* (2004), while an average improvement of 6.4 dB due to HS was measured in the study by Litovsky *et al.* (2006). The same advantage ranging from 8.9 to 10.7 dB has been found in NH listeners (Bronkhorst and Plomp, 1989). This benefit is generally attributed to the listeners' ability to detect interaural level differences (ILDs) well. The finding that the difference due to HS was not significant between the bilateral and bimodal users may indicate that these groups can use ILDs to an equal extent. This is consistent with previous findings that preservation of ILDs is possible even when restricting auditory stimulation to a low-frequency range below 500 Hz on one side (Francart *et al.*, 2008).

In terms of the SQ component, the mean benefit observed in the bilateral group was 0.9 dB, while on average binaural advantages due to SQ reported in recent literature are between 0.9 and 1.9 dB. Thus, the observed benefit is consistent with prior research, suggesting that bilateral CI users may only benefit from a very small advantage due to SQ (e.g., see Schleich *et al.*, 2004; Litovsky *et al.*, 2006; Buss *et al.*, 2008). The absence of a significant SQ effect, noted in the present as well as previous studies with bilateral CI users, may be attributed to several factors with the most prominent being the poor sensitivity to interaural time difference (ITD) cues (Litovsky *et al.*, 2006; Francart *et al.*, 2009).

It is widely accepted that bilateral users have only poor-to-moderate access to ITDs due to the fact that temporal fine-structure information derived from the input cannot be adequately encoded by the speech coding strategy of the device. Nonetheless, SQ may increase over time for bilateral users (Buss *et al.*, 2008; Eapen *et al.*, 2009). The wide range of bilateral listening experience among our participants (19 to 70 months) may have played a role in the absence of a SQ effect observed for this group. In contrast, bimodal listeners showed an elevated average SQ benefit of 2.9 dB. The difference in magnitude in the two populations was not significant but SQ was (weakly) different from zero in the bimodal group. This implies that the contribution of binaural SQ in bimodal perception is still open to question. Schafer *et al.* (2011) noted that in bimodal listeners, SQ can be relatively small, occasionally significant, and sometimes entirely absent.

The effect of SU yielded a significant release from masking in both groups. The SU benefit of 2.5 dB obtained with CI users was somewhat similar to the advantage obtained in prior studies with NH listeners whereby SU was found to range between 1.1 and 1.9 dB (Bronkhorst and Plomp, 1989) and studies with CI users where SU was estimated between 1.9 and 2.1 dB (e.g., see Schleich *et al.*, 2004; Litovsky *et al.*, 2006). The average SU achieved by bimodal listeners was 7.6 dB. This indicates that bimodal listeners were able to benefit from the integration of redundant information from both ears to a much greater extent than bilateral users. In other words, the delivery of low-frequency acoustic cues to the opposite side by the HA complemented the transmission of higher frequencies by the implant. These findings suggest that despite the positive outcomes observed with bilateral devices, bimodal fittings may be superior in terms of the binaural advantages that they can elicit.

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