Speech recognition by bilateral cochlear implant users in a cocktail-party setting

Philipos C. Loizou[a] and Yi Hu
Department of Electrical Engineering, University of Texas at Dallas, Richardson, Texas 75083-0688

Ruth Litovsky and Gongqiang Yu
Binaural Hearing and Speech Laboratory, Waisman Center, 1500 Highland Avenue, Madison, Wisconsin 53705

Robert Peters and Jennifer Lake
Dallas Otolaryngology Associates, 7777 Forest Lane A-103, Dallas, Texas 75230

Peter Roland
Department of Otolaryngology/Head and Neck Surgery, University of Texas Southwestern Medical Center, 5323 Harry Hines Boulevard, Dallas, Texas 75390

(Received 21 February 2008; revised 30 October 2008; accepted 5 November 2008)

Unlike prior studies with bilateral cochlear implant users which considered only one interferer, the present study considered realistic listening situations wherein multiple interferers were present and in some cases originating from both hemifields. Speech reception thresholds were measured in bilateral users unilaterally and bilaterally in four different spatial configurations, with one and three interferers consisting of modulated noise or competing talkers. The data were analyzed in terms of binaural benefits including monaural advantage (better-ear listening) and binaural interaction. The total advantage (overall spatial release) received was 2–5 dB and was maintained with multiple interferers present. This advantage was dominated by the monaural advantage, which ranged from 1 to 6 dB and was largest when the interferers were mostly energetic. No binaural-interaction benefit was found in the present study with either type of interferer (speech or noise). While the total and monaural advantage obtained for noise interferers was comparable to that attained by normal-hearing listeners, it was considerably lower for speech interferers. This suggests that bilateral users are less capable of taking advantage of binaural cues, in particular, under conditions of informational masking. Furthermore, the use of noise interferers does not adequately reflect the difficulties experienced by bilateral users in real-life situations.
[DOI: 10.1121/1.3036175]

PACS number(s): 43.66.Sr, 43.66.Pn [JCM] Pages: 372–383

I. INTRODUCTION

It is well established that normal-hearing (NH) listeners have a remarkable ability to perceptually segregate a target voice amid a background of competing voices, a formidable task that has been termed the "cocktail-party" problem (e.g., Cherry, 1953). When the target voice and interfering voices (or noise) are spatially separated, listeners are able to take advantage of the favorable signal -to-noise ratio (SNR) at the "better" ear owing to the head-shadow effect. In addition, listeners are able to receive binaural advantage resulting from binaural unmasking in the low frequencies, facilitated by interaural time difference (ITD) differences between competing sources (Bronkorst and Plomp, 1988; Zurek, 1993). Aside from the use of interaural (time and level) differences, NH listeners exploit a number of other cues that help them cope with the cocktail-party problem. Much research (see review by Bronkorst, 2000) has been done to understand the perceptual processes used by NH listeners to segregate a target voice from competing, interfering voices, but relatively little is known about the processes used by bilateral cochlear implant (CI) users.

Bilateral cochlear implantation seeks to restore the advantages of listening with two ears. A number of studies have assessed speech recognition performance of adult (Tyler *et al.*, 2002; Gantz *et al.*, 2002; Muller *et al.*, 2002; van Hoesel and Tyler, 2003; Schleich *et al.*, 2004; Buss *et al.*, 2008) and pediatric (e.g., Litovsky *et al.*, 2006a) bilateral CI users in situations where the target and masker are either spatially coincident or separated. In the study by Tyler *et al.* (2002) data from nine adult subjects were collected three months after bilateral implantation. Speech intelligibility was tested both in quiet and in broadband noise presented from the left (−90°) or right (+90°). The level of the noise was adjusted for each subject to minimize ceiling or floor effects. When the noise was spatially separated from the speech signals, the subjects showed a significant head-shadow advantage but only a few subjects received benefit known as the binaural-interaction benefit, arising from the use of both ears over the ear with better SNR. Muller *et al.* (2002) reported data from nine bilateral implant users. Speech was presented from the

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[a] Author to whom correspondence should be addressed. Electronic mail: loizou@utdallas.edu

front and steady speech-shaped noise was presented at either +90° or −90° azimuth at a fixed SNR (10 dB). Results indicated significant head-shadow benefits as well as an additional, albeit small binaural-interaction benefit. Performance with bilateral implants for monosyllabic word recognition in quiet also showed improvement compared to that obtained with the better ear alone. Buss *et al.* (2008) reported large head-shadow benefits (37–38 percentage points) for 26 bilateral implant users participating in a multicenter clinical trial. Small binaural-interaction benefits (3–10 percentage points) were observed, but only after 1 yr postimplantation. In the bilateral CI studies described above, fixed SNRs were used for testing, which can produce data dominated by floor or ceiling effects. The study by van Hoesel and Tyler (2003) used an adaptive procedure to assess speech recognition performance. Broadband noise (nonmodulated) was used as a masker and presented to the subjects at 0°, 90°, or −90° (target was presented from the front). Overall, subject's performance improved with two implants, and the overall benefit (4–5 dB) was dominated by better-ear listening (head-shadow effect). A considerably smaller improvement of 1–2 dB was attributed to binaural interaction. Schleich *et al.* (2004) measured speech reception thresholds (SRTs) for 21 Med-El Combi 40/40+ bilateral users with continuous noise presented from the left or right. Results indicated a 6.8 dB head-shadow effect, a 0.9 dB binaural-interaction effect, and a 2.1 dB binaural summation effect. Litovsky *et al.* (2006b) measured SRTs in 34 simultaneously implanted adult Nucleus 24 users, after 3 months of bilateral hearing experience. With both target and competing speech in front, 15/34 subjects (44%) demonstrated a "binaural redundancy" effect, whereby the bilateral listening mode produced an advantage over one of the two unilateral conditions. With target in front and competing speech to the side, head-shadow effects averaged 5–6 dB and were found in 32/34 (94%) of subjects for at least one of the head-shadow comparisons (right or left). Binaural interaction, in contrast, averaged 1.95 dB and was found in 16/34 (47%) of subjects.

The above studies provided undoubtedly valuable information as to the benefit introduced via bilateral implants, but were limited in scope in several respects. First, with the exception of the study by Litovsky *et al.* (2006b), most studies used a single noise source making it difficult to predict the bilateral implant user's true performance in more realistic listening scenarios wherein multiple noise sources might be present. It is known from the NH literature that the number of masking sources as well as the spatial configuration of those noise sources can significantly affect performance (Bronkorst and Plomp, 1992; Yost *et al.*, 1996; Peissig and Kollmeier, 1997; Hawley *et al.*, 1999; 2004). Bronkorst and Plomp (1992), for instance, showed that speech intelligibility is reduced when noise sources are placed symmetrically around the target (i.e., across the two hemifields) than when they are placed asymmetrically, in part because the benefit from head shadow is obliterated.

Second, the temporal properties and spectral content of the masker can also affect performance. Hawley *et al.* (2004) observed a larger spatial release from masking by NH listeners when the maskers are comprised of speech or reversed speech, that is, when they contain linguistic content or context, compared to when noise (modulated or nonmodulated) maskers were used. Studies with bilateral implant users to date have been restricted to a single masker type; thus the extent to which the content and/or context of the masker are important remains to be understood. One important issue to recognize from the work of Hawley *et al.* (2004) is that in competing talker listening situations the interfering speech is likely to contain linguistic information which could be distracting or confused with the content of the target speech. This confusion is often classified as a form of "informational masking" (Brungart, 2001). Using a nonspeech pattern identification task, Kidd *et al.* (1998) showed that NH listeners benefited more from the spatial separation of the target and masker signals when the masker was informational in nature (no spectral overlap between target and masker) than when it was energetic (masking caused by the mere spectral overlap between the masker and target signals). When speech intelligibility is assessed using similar paradigms, the advantage of spatial separation is larger when there are substantial similarities in the information transmitted by the target and interferers, thus forcing listeners to rely more heavily on spatial cues to segregate competing sources from the target.

The effect of masker types on spatial separation benefits underscores the need to evaluate performance of bilateral CI users with both speech and nonspeech maskers; the use of nonspeech maskers might underestimate the advantage of bilateral implants for spatially segregated conditions in real-world situations. None of the aforementioned bilateral CI studies focused on this issue. Finally, it is of great interest to know how bilateral implant users perform compared to NH listeners. Such a comparison, however, is difficult to make given the differences in spatial configurations, testing environment (e.g., reverberation), and test material used in the various CI and NH studies. Several studies examined the effect of spectral/temporal characteristics of various maskers on performance in unilateral implant users (Nelson *et al.*, 2003; Stickney *et al.*, 2004) or with CI simulations (Qin and Oxenham, 2003). These studies showed that contrary to the benefit received by NH listeners when the masker is modulated, unilateral implant users did not benefit from such masker modulations (Stickney *et al.*, 2004).

In all, there are multiple factors that may influence the performance of bilateral implant users in real-world listening situations where multiple interfering sources might be present. The influence of these factors on bilateral CI performance is not well understood. The present study aims to assess the performance of bilateral users in more complex listening situations (cocktail party) with multiple competing sources emanating from various directions in space. The purpose of the study is to explore the interaction between the number of interfering noise sources, the magnitude of benefit incurred by better-ear listening for different target-masker spatial configurations, and the effect of informational/energetic masking on speech recognition. In this study we used the same simulated anechoic environment and the same stimuli presented to NH listeners in the study of Hawley *et al.* (2004). We will thus be in a unique position to compare

TABLE I. Biographical data for the bilateral CI subjects tested.

Subject	Duration of deafness (yrs)	Age (yrs)	CI use (yrs) left/right	Speech coding strategy	Probable cause of hearing loss
S1	19	61	5/5	ACE	Noise
S2	38	58	4/4	ACE	Measles
S3	17	36	3/4	ACE	Unknown
S4	11	65	4/3	ACE	Congenital
S5	22	68	5/5	ACE	Unknown
S6	>10	38	5/5	Speak	Unknown
S7	15	36	4/3	ACE	Unknown
S8	22	67	6/6	ACE	Hereditary

the bilateral users' performance against NH listeners' performance in the same listening conditions and ascertain the true benefit of bilateral implantation in more realistic noisy situations.

II. METHODS

A. Subjects

Eight postlingually deafened adults were recruited for testing. The participants were all bilateral CI patients fitted with the Nucleus 24 multichannel implant device manufactured by Cochlear Corporation. They were all native speakers of American English and were paid for their participation. All subjects had a minimum of three years experience with their implant devices. Biographical data for the subjects tested are given in Table I.

B. Experimental research processor

All subjects wore the Cochlear Esprit BTE processor on a daily basis. During their visit, subjects were temporarily fitted with the SPEAR3 wearable research processor. The SPEAR3 processor was developed by the Cooperative Research Center (CRC) for Cochlear Implant and Hearing Aid Innovation, Melbourne, Australia, in collaboration with HearWorks. The SPEAR3 has been used in a number of investigations to date as a way of controlling inputs to the CI system (e.g., van Hoesel and Tyler, 2003). Prior to the subjects' scheduled visit, the Seed-Speak Graphical User Interface (GUI) application was used to program the SPEAR3 processor with the individual users' threshold (T) and comfortable loudness levels (C). In addition, all participants (except subject S6) used the device programmed with the advanced combination encoder (ACE) speech coding strategy (e.g., see Vandali *et al.*, 2000) with all parameters (e.g., stimulation rate, number of maxima, frequency allocation table, etc.) matched to their clinical settings.

C. Speech and interferer stimuli

The speech stimuli were taken from the IEEE corpus (IEEE, 1969). The recordings were produced by two male speakers, each contributing half of the sentences (same stimuli that were used in Hawley *et al.*, 2004). Four of the longest sentences were reserved for use as interferers to ensure that all targets were shorter than the interferers. The remaining sentences were made into 64 lists of ten sentences each maintaining a single talker for each list. The mixture stimuli were constructed by having the interferers precede the target sentence (for about a second), and following the target sentence for another second. The interferer was either a female talker or speech-modulated noise that was computed using one of the four interferer sentences. For the speech-modulated noise, the envelope was extracted from the speech interferer and was used to modulate noise (originally filtered to match the long-term spectrum of the male talker), giving the same coarse temporal structure as speech. The envelope of running speech was extracted using a method similar to that described by Festen and Plomp (1990) by low-pass filtering a rectified version of the waveform. A first-order Butterworth low-pass filter was used with the 3-dB cutoff set at 40 Hz.

D. Simulated anechoic space

A set of free-field-to-eardrum (or anechoic) head-related transfer functions (HRTFs) previously measured in an acoustic manikin (Head Acoustics, HMS II.3) as described in the AUDIS catalog (see Blauert *et al.*, 1998) was used to simulate different spatial locations of the speech target and the interferer signals. HRTFs provide a measure of the acoustic transfer function between a point in space and the eardrum of the listener, and also include the high-frequency shadowing component due to the presence of the head and the torso. It should be noted that the use of HRTFs may not simulate accurately the intended source locations for CI users wearing the behind-the-ear microphones (as they lack pinna directionality), but rather for CI users (e.g., Advanced Bionics Corporation) wearing the in-the-canal microphones. On this regard, the data obtained with HRTFs might slightly overestimate the performance of CI users wearing behind-the-ear microphones. The duration of the impulse response was 256 sample points (at 16 kHz sampling frequency), amounting to a relatively short impulse response duration of 16 ms and therefore negligible reverberation. To generate the multisensor composite signals observed at the pair of microphones, the target and interferer stimulus for each position were convolved with the set of HRTFs for the left and right ears, respectively, thus generating a set of mixture signals for each of the two ears. In all experiments, HRTFs were used for stimuli simulating sources at a conversational distance of 1 m, with the vertical position (or elevation) adjusted at ear level.

All stimuli were presented to the listener through the auxiliary input jack of the SPEAR3 processor in a double-walled sound-attenuated booth (Acoustic Systems, Inc.). During the practice session, subjects were allowed to adjust the volume to reach comfortable level in both ears. For the unilateral conditions, either the left or right implant was activated. In the majority of simulated configurations the interfering virtual sound sources were situated to the listeners' right and were therefore less intense at the left than the right ear.

TABLE II. List of spatial configurations tested.

No. of interferers	Interferer type	Front	Left or distributed on both sides	Right or distributed on right	Right
One interferer	Modulated noise	0	−30°	60°	90°
Three interferers	Modulated noise	0°, 0°, 0°	−30°, 60°, 90°	30°, 60°, 90°	90°, 90°, 90°
One interferer	Female talker	0	−30°	60°	90°
Three interferers	Female talker	0°, 0°, 0°	−30°, 60°, 90°	30°, 60°, 90°	90°, 90°, 90°

E. Conditions

The simulated target location was always at the front (0° azimuth). Subjects were tested in conditions with either one or three interferers. Up to three interferers were placed either in the front (0°,0°,0°), distributed on both sides (−30°,60°,90°), distributed on the right side (30°,60°,90°), or from the same location on the right side (90°,90°,90°). Note that −90° means that the interferer was located to the left of the listener, and 90° means that it was located to the right. Table II summarizes these conditions. The level of each interferer was fixed and the overall level of the interferers was thus naturally increased as more interferers were added.

Each listener completed testing in six to ten sessions of 1–1.5 h each, spanning 2 days. During these sessions, two SRT measurements for each of the 16 conditions (2 numbers of interferers × 4 spatial configurations × 2 interferer types) were obtained. To minimize any order effects, all conditions were randomized among subjects. Different sets of sentences were used in each condition. Subjects S5 and S6 were not available for testing in a subset of the conditions (single interferer with speech-modulated noise).

F. SRT measurement

SRTs were measured using a method similar to that developed by Plomp (1986) and used in the NH study (Hawley *et al.*, 2004) with which the data will be compared. Listeners were seated in the sound-attenuated booth in front of a terminal screen. At the start of each session practice SRTs were given with three interferers for each interferer type to familiarize the subject with the interferer types and the task. At the start of each SRT measurement, the level of the target was initially very low. The subject heard the same target sentence and interferer combination repeatedly. After each presentation, the subject's task was to repeat as many words as possible. After each response, the experimenter pressed the return key and the same target sentence and interferer combination was replayed, but with the signal-to-interferer ratio (computed based on the ratio of signal-to-interferer energies) increased by 4 dB. The subject repeated the words/sentence he/she heard orally, and when the experimenter determined (based on a written sentence transcript) that the subject reproduced more than half of the sentence correctly, the first recording was made of the number of keywords correct. From that point on, a SRT was measured using a one-down/one-up adaptive SRT technique targeting 50% correct speech reception (Levitt, 1971) using an approach that was successfully used in studies with NH listeners (Hawley *et al.*, 2004). After listening to each sentence, the subjects were asked to repeat what they heard. Each IEEE sentence had five designated keywords and these words were in capital letters in the transcript, e.g., "The BIRCH CANOE SLID on the SMOOTH PLANKS." The experimenter compared what was repeated by the subject with the displayed text and typed in the number of keywords found correct. The SNR of the next trial was raised by 2 dB if two or fewer keywords were correct and the SNR was lowered by 2 dB if three or more keywords were correct. The entire transaction was logged in a data file and displayed on the experimenter's computer monitor for verification of scoring reliability. The SRT was determined by averaging the level presented in the last eight trials.[1] The content, number, and locations of the interferers were fixed throughout the run in each condition.

G. Data analysis

The data were analyzed in a similar way to the approach taken by Hawley *et al.*, (2004) in order to draw comparisons from the present results with those of NH listeners. More precisely, we used the raw SRTs for unilateral and bilateral stimulations to derive the following three advantages that are potentially introduced by the availability of binaural listening: total advantage, monaural advantage, and binaural advantage (also known as binaural interaction).

The total advantage is the improvement in performance (decrease in SRT) observed when the masker-target spatial separation is introduced compared with when the interferer and target are both presented from front (0° azimuth). It is determined by subtracting the bilateral SRT of a given spatially-separated condition from the SRT of the corresponding unseparated condition. This overall benefit is also known as spatial release from masking and is assumed to contain the advantages from both head shadow and binaural advantage (binaural interaction).

The monaural advantage is defined as the improvement in performance (decrease in SRT) observed when listening with the better ear, i.e., the ear with the more favorable SNR. It is determined by subtracting the SRT of a given unilateral spatially separated condition corresponding to the ear contralateral to the interferer location, from the SRT of the corresponding unilateral unseparated condition (0° azimuth). So, for instance, if the interferer is presented from the left hemifield (e.g., −30°), the monaural advantage is computed by subtracting the SRT obtained with the right implant from the SRT obtained in the unseparated condition (0°) with the right implant. For the $(-30°,60°,90°)$ condition, the monaural advantage was computed using the SRTs obtained with the left implant since the majority of the interferers came from the right hemifield. Note that the head-shadow advantage was computed differently in other studies in which similar effects in bilateral CI users were measured (van Hoesel and Tyler, 2003; Schleich *et al.*, 2004; Buss *et al.*, 2008). In those studies, head shadow was computed by subtracting the unilateral SRT obtained when the interferer was on the contralateral side of the implant from the SRT obtained when the interferer was on the ipsilateral side of the implant. A different method for measuring the head-shadow advantage is used in the present study for two reasons. First, the intent was to be consistent with the method used in Hawley *et al.* (2004) for assessing better-ear listening. The adoption of the same definition of monaural advantage will enable appropriate comparisons between the two studies. Second, methods used in other studies are better suited for making comparison when the interferer(s) is (are) placed symmetrically across the two hemifields. In this study the interferer(s) was (were) placed mostly on the right and in asymmetrical configurations; thus we are unable to compute the head-shadow advantage in the manner done by others (e.g., van Hoesel and Tyler, 2003; Schleich *et al.*, 2004).

The binaural advantage (or binaural interaction) is thought to assess the contribution of binaural processing to advantages introduced in spatial separation. This advantage reflects the benefit from listening binaurally over listening with just the better unilateral ear (i.e., implant contralateral to the interferer), and is determined by subtracting the monaural advantage with the better-ear condition from the total advantage of separation. That is, binaural advantage is equal to total advantage minus monaural advantage. Binaural advantage data are reported for all conditions, including the condition in which the interferer originated from −30°. Note that the study by Hawley *et al.* (2004) did not report binaural advantage data for interferers at −30°, as they only tested their subjects monaurally with the left ear.

III. RESULTS AND DISCUSSION

The three advantages are discussed next, along with the raw SRT values obtained in the various conditions (see Figs. 1 and 2). For each of the two types of interferers, Analysis of Variances (ANOVAs) were conducted to assess the interaction between the number of interferers and other factors on performance (SRT values). For the speech interferer, a three-way ANOVA (2 numbers of interferers × 3 listening modes × 4 interferer locations) revealed a significant effect $[F(1,5)=16.6,\ p=0.01]$ of the number of interferers (1 versus 3), with SRTs being significantly higher in the presence of 3 versus 1 interferer(s). In addition, there was a significant effect $[F(2,10)=15.9,\ p=0.001]$ of listening mode (bilateral versus unilateral left or unilateral right), a nonsignificant effect of interferer location, a significant interaction $[F(6,30)=5.9,\ p<0.005]$ between listening mode and interferer location, and a nonsignificant interaction between number of interferers and other factors. Similar effects were noted with the noise interferer. Similar ANOVAs were conducted for data analyzed in terms of advantage, and noted no significant interactions between number of interferers and most of other factors. A significant interaction [e.g., for female talker, $F(4,20)=3.7,\ p=0.02$] was only found with listening mode by interferer location.

Given the absence of significant interaction between number of interferers and other factors (with the exception of one interaction found when the data were analyzed in terms of advantage), the data were reanalyzed for main effects and interactions separately for one and three interferers. Results from the one-interferer conditions will be discussed first, followed by results from the three-interferer conditions.

A. One interferer

The results for a single interferer are shown in Fig. 1 (upper left panels).

1. Raw SRTs

Figure 1 [panels (A) and (B)] shows the raw SRTs obtained with a single noise and speech interferers. The discussion on SRTs that follows focuses on differences in performance relative to conditions in which both target and interferers were at 0°. As shown in Fig. 1 [panels (A) and (B)], mean SRT values decreased in the bilateral condition as the interferer moved away from the target (located at 0°) regardless of the interferer type. For the unilateral condition with the left implant alone, mean SRTs increased when the interferer was at −30° and then dropped when the interferer was at 60° and 90° [Fig. 1, panels (A) and (B)]. The increase in SRT was expected since the left ear was on the same side of the interferer. For the unilateral condition with right implant alone, SRTs increased as expected when the interferer was on the right (i.e., at 60° and 90°) and decreased when the interferer was on the left $(-30°)$ [see Fig. 1, panels (A) and (B)]. Overall, the left and right unilateral SRTs mirrored each other, as expected [Fig. 1, panels (A) and (B)]. A three-way ANOVA (2 types of interferers × 3 listening modes × 4 interferer locations) revealed a significant effect $[F(2,8)=5.4,\ p=0.03]$ of listening mode, a significant effect $[F(3,12)=4.1,\ p=0.032]$ of interferer location, a nonsignificant effect of interferer type, a significant interaction $[F(6,24)=33.3,\ p<0.005]$ between listening mode and interference location, and a marginally significant interaction $[F(2,8)=4.4,\ p=0.049]$ between interferer type and listening mode. *Posthoc* analyses on effect of listening mode indicated a significant difference in SRTs $[F(1,6)=8.5,\ p=0.026]$ between the bilateral and right-implant conditions, a nonsignificant difference $[F(1,6)=2.03,\ p=0.21]$ between the bilateral and left-implant conditions and a nonsignificant difference $[F(1,6)=1.4,\ p=0.27]$ between left- and right-implant conditions (a significant interaction was noted, however, in the left- versus right-implant analysis). *Post hoc* analyses on effect of interferer location suggested that SRTs were lower $[F(3,4)=7.8,$

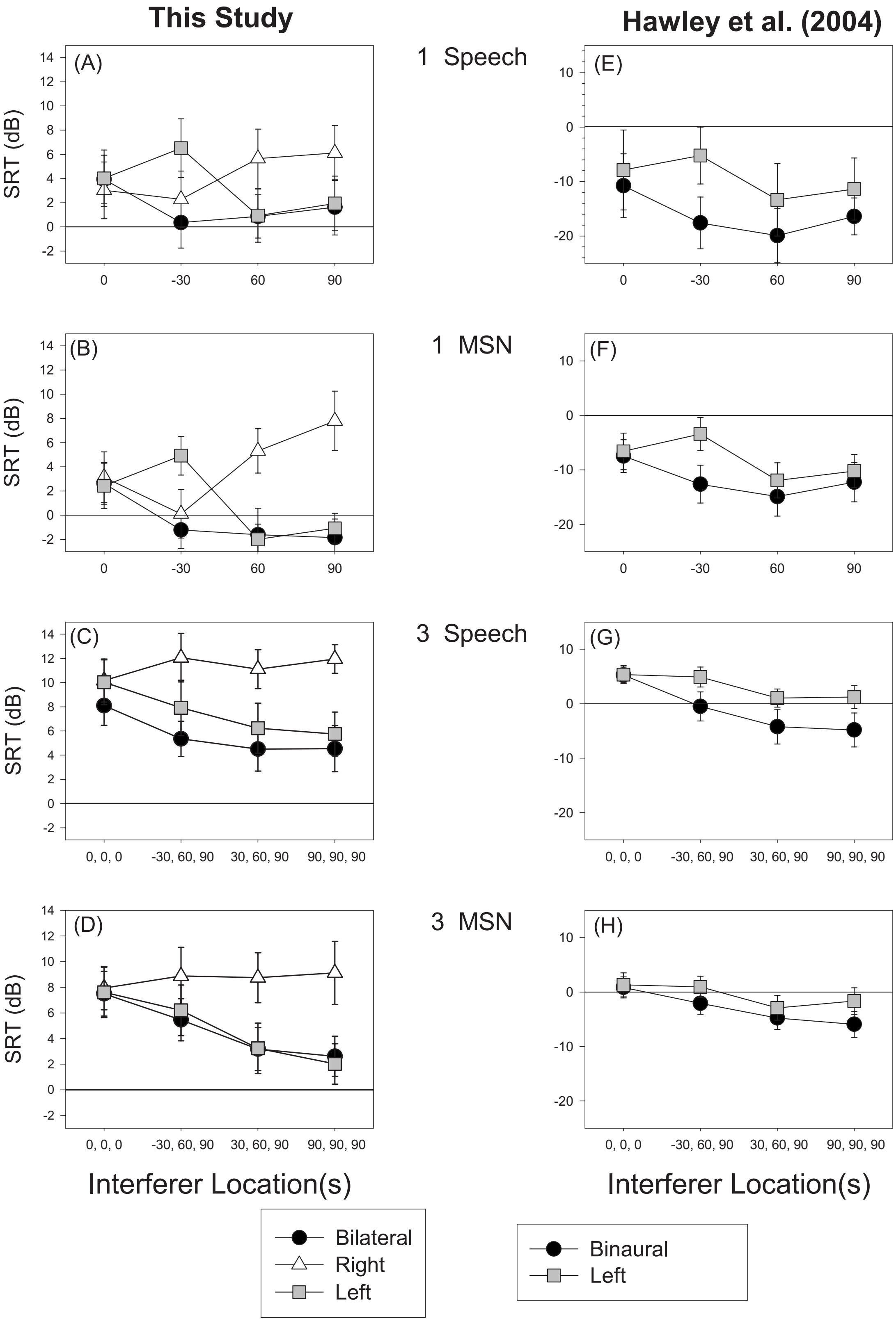

FIG. 1. [Left panels (A)–(D)] Mean SRT values obtained by bilateral CI users in various spatial configurations with different number of interferers. Data for speech and modulated speech-shaped noise interferers are shown separately. [Right panels (E)–(H)] Mean SRT values obtained by NH listeners (Hawley *et al.*, 2004) in the same conditions. Note that the CI data are plotted using a different *y*-axis range for better visual clarity. Error bars indicate standard deviations.

$p=0.037$] when the interferers were at 60° compared to 0°. The interaction between listening mode and interference location was due to the fact that performance improved significantly as the interferers moved away from the target in the bilateral and left-implant conditions but not in the right-implant conditions. This was not surprising since the interferers moved closer to the right implant (i.e., the ear with the lowest SNR). *Post hoc* (Scheffe) tests revealed that the per-

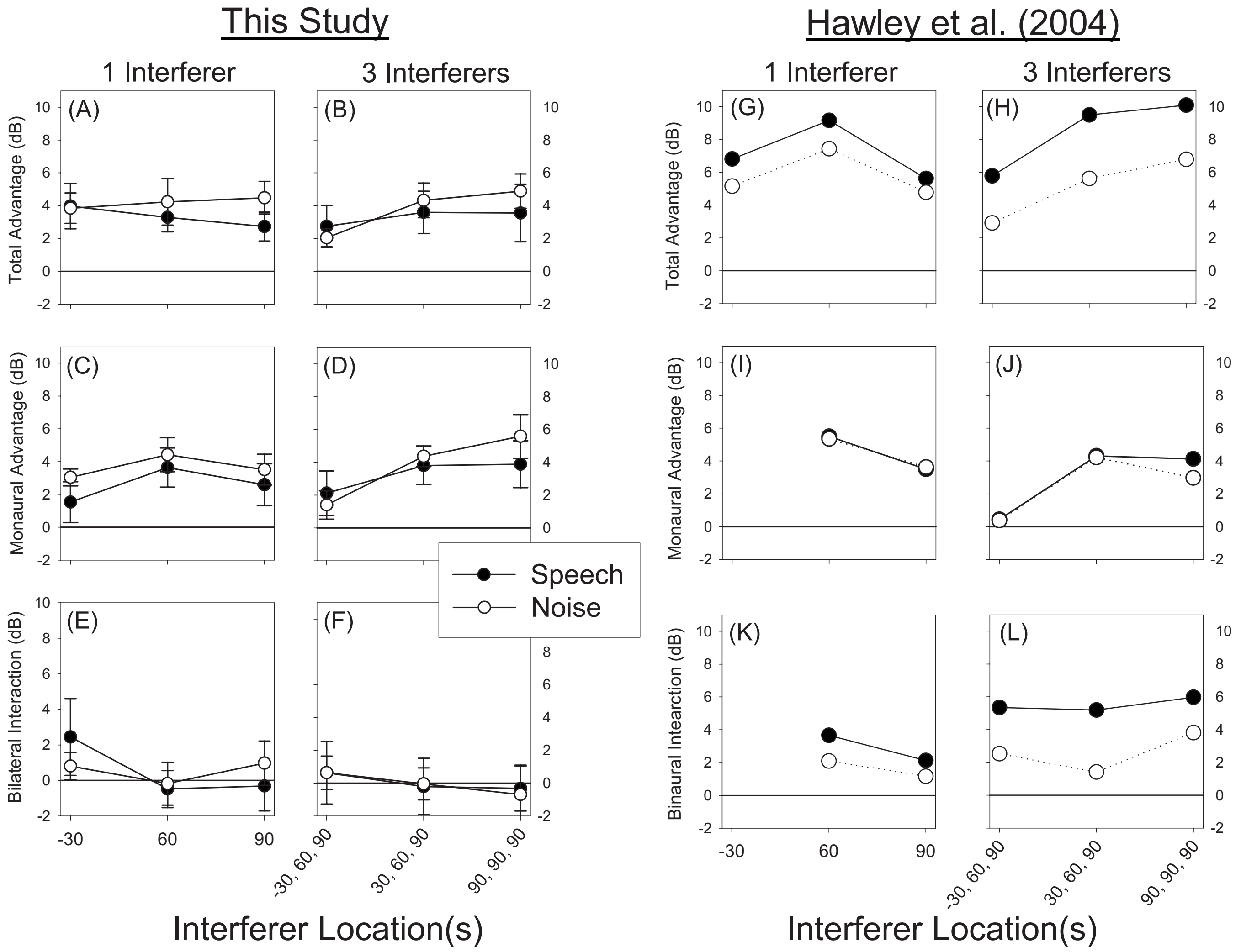

FIG. 2. [Left panels (A)–(F)] Binaural benefits, in terms of total advantage, monaural advantage, and binaural-interaction advantage (see text for details) all measured in decibels, obtained by bilateral CI users. [Right panels (G)–(L)] Binaural benefits obtained by NH listeners (Hawley *et al.*, 2004) in the same conditions. Error bars indicate standard errors of the mean.

formance with interferers at 90° was significantly ($p < 0.05$) better than performance with interferers at 0° with either the bilateral or left-implant condition.

Figure 1 (top two rows) contrasts the SRT values obtained in this study against those obtained by NH listeners in the study by Hawley *et al.* (2004) [see Fig. 1, panels (E) and (F)]. The overall pattern in bilateral performance is the same as that obtained by NH listeners in that performance improves (lower SRT values) as the interferer(s) move away from the target. The absolute SRT values obtained by NH listeners, however, are notably lower, by about 10 dB in the noise-interferer condition and by about 15–20 dB in the speech interferer condition [compare Fig. 1, panels (A) versus (E), and panels (B) versus (F)]. The pattern, however, obtained with the left implant alone does not follow the pattern followed by NH listeners when presented with the stimuli monaurally via the left ear. For the CI users, the unilateral SRT values obtained with the left implant are nearly identical to the SRT values obtained bilaterally [see Fig. 1, panels (A) and (B)]. This outcome reflects the absence of binaural advantage (more on this in Sec. III A 2), since the bilateral SRT values are not better (lower) than those of the better-ear (which is the left implant for interferers at 60° and 90°) SRTs. In contrast, the binaural SRT values obtained by NH listeners [Fig. 1, panels (E) and (F)] were always lower (more so in speech interferers) than the SRT values obtained with the left ear monaurally, reflecting a binaural advantage.

2. Advantages of separation

Figure 2 (leftmost column) quantifies the mean advantage of separation in terms of total advantage [Fig. 2, panel (A)], monaural advantage [Fig. 2, panel (C)], and binaural-interaction advantage [Fig. 2, panel (E)]. The mean (across subjects) total advantage of target-interferer separation was 3–4 dB in all conditions [Fig. 2, panel (A)]. A two-factor ANOVA (3 interferer locations × 2 interferer types) revealed no significant effect [$F(2,10)=0.1$, $p=0.9$] of interferer location, no significant effect of interferer type [$F(1,5)=0.4$, $p=0.5$], and no significant interactions [$F(2,10)=0.4$, $p=0.6$]. This suggests that the total advantage received by bilateral CI users under the conditions tested here was not affected by the location and type of interferer.

The mean monaural advantage [Fig. 2, panel (C)] due to better-ear listening, was around 3–4 dB for the noise interferer (open symbols) and 1–3 dB for the female talker interferer (filled symbol). A two-factor ANOVA (3 interferer locations × 2 interferer types) revealed no significant effects, suggesting that the monaural advantage was not affected by the location or type of interferer. With the exception of one condition (female interferer at 90°), the mean monaural advantage was significantly above zero in all conditions ($p < 0.05$, one-tail t-tests).

The mean binaural advantage [Fig. 2, panel (E)] was smaller than 1 dB in all but one condition. Two-factor ANOVA (3 interferer locations × 2 interferer types) revealed no significant effects. The mean binaural advantage was not significantly ($p > 0.05$) above zero in any condition.

The bilateral implant users' data are contrasted in Fig. 2 [panels (G), (I), and (K)] with the data reported in Hawley *et al.* (2004) with NH listeners. Note that the data for −30° azimuth are missing in Fig. 2 [panels (I) and (K)] because Hawley *et al.* (2004) did not test the right ear monaurally. The total advantage [Fig. 2, panel (G)] seen in NH listeners with the speech interferer is nearly double (7–10 dB) of that obtained by bilateral CI users, but the total advantage received by NH listeners with the noise interferer was lower (5–7 dB) and more similar to that obtained by bilateral CI users. The monaural advantage [Fig. 2, panel (I)] observed in NH listeners for the noise interferer was about 4–6 dB and similar to that received by bilateral CI users. The monaural advantage received by NH listeners for the speech interferer was about 2–3 dB higher than that obtained by bilateral CI users. Similarly, the binaural advantage [Fig. 2, panel (K)] observed in NH listeners was about 2–4 dB higher than that observed in bilateral implant users.

B. Three interferers

The SRT results for three interferers are shown in Fig. 1 (column 2) and results for advantage of separation are shown in Fig. 2 (column 2).

1. Raw SRTs

Figure 1 [panels (C) and (D)] shows the mean raw SRT values obtained with three interferers. SRTs decreased in the bilateral condition as the interferer moved away from the target (located at 0°) for both interferer types. Overall, the mean SRT values with three interferers were 4–6 dB higher than the corresponding SRT values with one interferer in the bilateral condition [compare panels (A) and (C) or panels (B) and (D) in Fig. 1]. A similar, albeit larger, increase in SRT values was also observed with NH listeners (Hawley *et al.*, 2004) with three interferers in the binaural condition [Fig. 1, panels (G) and (H)]. A three-way ANOVA (2 types of interferer × 3 listening modes × 4 interferer locations) revealed a significant effect [$F(2,8)=21.9$, $p<0.001$] of listening mode (bilateral versus unilateral left and unilateral right), a significant effect [$F(3,12)=10.9$, $p<0.001$] of interferer location, a nonsignificant effect of interferer type, a significant interaction [$F(6,24)=4.8$, $p<0.05$] between listening mode and interference location, and a nonsignificant interaction between interferer type and listening mode. As indicated by the above ANOVA, performance was similar to the noise and female talker interferers. *Post hoc* tests indicated that the bilateral performance was significantly [$F(2,4)=22.7$, $p=0.006$] better (i.e., lower SRT values) than the performance obtained with the left-implant alone [Fig. 1, panel (C)], which is the implant with the better SNR in most conditions. This was true for the speech interferers but not for the noise interferers [see Fig. 1, panel (C)]. Performance with the left-implant or bilateral implants at (30°,60°,90°) and (90°,90°,90°) was significantly ($p<0.05$) better than corresponding performance at (0°,0°,0°). The interaction between listening mode and interference location was due to the fact that performance improved significantly as the interferers moved away from the target in the bilateral and left-implant conditions but not in the right-implant conditions [see Fig. 1, panels (C) and (D)]. This was not surprising since the right implant was ipsilateral to the location of the interferers in most conditions.

2. Advantages of separation

Figure 2 (column 2) quantifies the mean advantage of separation in terms of total advantage [Fig. 2, panel (B)], monaural advantage [Fig. 2, panel (D)], and binaural advantage [Fig. 2, panel (F)]. The mean total advantage of target-interferer separation ranged from 2 to 5 dB across conditions (see Fig. 2, panel (B)]. A two-factor ANOVA (3 interferer locations × 2 interferer types) revealed a significant effect [$F(2,12)=6.4$, $p=0.013$] of the interferer's location, but no significant effect of interferer type [$F(1,6)=0.07$, $p=0.8$] and no significant interactions [$F(2,12)=2.1$, $p=0.2$]. *Post hoc* tests indicated that the significant effect of the interferer's location was due to the significant ($p=0.005$) difference in performance between the (−30°,60°,90°) and (90°,90°,90°) configurations in the noise-interferer conditions. There was no significant difference in the size of total advantage with the speech interferers [Fig. 2, panel (B), filled symbols] across the various spatial configurations.

The mean monaural advantage [Fig. 2, panel (D)] was in the range of 1–6 dB for the noise interferers and 2–4 dB for the female talker interferers. A two-factor ANOVA (3 interferer locations × 2 interferer types) revealed a significant effect [$F(2,8)=6.7$, $p=0.02$] of interferers' location, no significant effect of interferer type [$F(1,4)=0.7$, $p=0.4$], and a significant interaction [$F(2,8)=5.3$, $p=0.03$] between interferer type and location. *Post hoc* tests indicated that the interferer's location affected the size of the monaural advantage significantly in the condition with noise interference but not in the condition with the female talker interferer. Monaural advantage was largest when the three interferers were located on the right (90°,90°,90°) and was significantly ($p=0.012$) larger than in the condition in which the interferers were asymmetrically placed around the listener (i.e., −30°,60°,90°) [see Fig. 2, panel (D)].

The mean binaural advantage [Fig. 2, panel (F)] was near 0 dB in all conditions and for both types of interferers. A two-factor ANOVA (3 interferer locations × 2 interferer types) revealed no significant effects, confirming the absence of binaural advantage in all conditions.

The data obtained in Hawley *et al.* (2004) with NH listeners are contrasted in Fig. 2 (column 4). The total advantage [Fig. 2, panel (H)] received by NH listeners with the female interferers is nearly double (7–10 dB) than seen in bilateral CI users (3–4 dB) [see Fig. 2, panel (B)]. In contrast, the total advantage observed in NH listeners with the noise interferers was comparable (only 1–2 dB higher) to that observed in bilateral CI users [compare open symbols in panels (B) and (H) in Fig. 2]. The monaural advantage observed in NH listeners [see Fig. 2, panel (J)] for the noise-interferer conditions was 1–2 dB higher (at most) than that observed by bilateral CI users [see panels (D) and (J), open symbols in Fig. 2], but the monaural advantage observed in NH listeners with the speech interferers was roughly the same as that observed in the bilateral CI users [see panels (D) and (J), filled symbols in Fig. 2]. Finally, the binaural advantage observed in NH listeners [see Fig. 2, panel (L)] was about 2–6 dB higher than that observed in bilateral users [see Fig. 2, panel (F)]. In all, it is clear that the total advantage observed in bilateral users due to the interferer-target spatial separation is dominated by the unilateral benefit, i.e., access to the implant with a more favorable SNR. This benefit persists even when multiple (three) interferers are present [see Fig. 2, panel (D)].

IV. GENERAL DISCUSSION

The present study was intended to assess the performance of bilateral CI users in more complex and realistic listening environments than previously studied. This was achieved by measuring SRTs both unilaterally (one implant alone) and bilaterally in four different spatial configurations with one and three interferers. Experiments were designed to answer the important question of how performance of bilateral CI users is affected by multiple versus single interferers, and whether there are notable effects of the type of interferers on the ability of the listeners to benefit from spatial separation of target speech and interferers. The extent to which performance was affected by the number, type, and location of interferers was directly compared with data from NH listeners, who were presented with the same test material and the same simulated anechoic space (Hawley *et al.*, 2004). The data were analyzed in terms of monaural and binaural effects, with the intent of isolating the individual contributions of the monaural advantage (i.e., better-ear listening) and binaural advantage. The data analysis revealed a number of effects that are discussed next.

A. Monaural advantage

The monaural advantage (i.e., better-ear listening) received by bilateral CI users was significantly better than 0 dB, ranging from 2 to 6 dB, and was largest when the interferer(s) was (were) mostly energetic (speech-shaped noise). As shown earlier, the monaural advantage was not affected by the type of interferer (speech versus noise) used. Nonetheless, the monaural advantage was found to be robust as it was maintained even when three interferers were present. It was comparable to that obtained by NH listeners (Hawley *et al.*, 2004) with the same test material and the same HRTFs (i.e., the same simulated anechoic environment). This suggests that in real-world settings, bilateral users receive significant benefit owing to having access to an implant with a more favorable SNR.

The significant monaural advantage found in the present study is consistent with that found in other studies investigating similar issues in bilateral CI users (van Hoesel and Tyler, 2003; Muller *et al.*, 2002; Buss *et al.*, 2008; Schleich *et al.*, 2004). It should be pointed out that all other studies reported head-shadow advantage, which is measured differently (see Sec. II G), but nonetheless assessed the intelligibility benefit incurred by better-ear listening. A 4 dB head-shadow advantage was found in the study by van Hoesel and Tyler (2003) for a single interferer (speech-shaped noise) presented either to the left or right of the listener. Schleich *et al.* (2004) reported a 6.8 dB head-shadow benefit in bilateral users of the Med-El Combi 40/40+ CI when presented with a single interferer (speech-shaped noise).

B. Binaural advantage

There is ample evidence in the binaural hearing literature suggesting that when both ears are available, NH listeners are able to receive a 3–5 dB binaural advantage (Zurek, 1993; Hawley *et al.*, 2004). Much of this advantage is attributed to good ITD sensitivity, particularly in the low frequencies (Bronkhorst and Plomp, 1988). No such binaural advantage was found, however, with bilateral CI users in the present study. This is consistent with previous reports in which the binaural-interaction effect was found to be very small (1–2 dB) and marginally or nonsignificant (van Hoesel and Tyler, 2003; Muller *et al.*, 2002; Schleich *et al.*, 2004; Buss *et al.*, 2008). Specifically, a 2 dB binaural-interaction benefit was reported for five bilaterally implanted Nucleus CI users in the study by van Hoesel and Tyler (2003). That benefit, however, was found to be only weakly significant ($p=0.04$) and was measured with a single interfering steady-state noise source presented to the left (−90°) or to the right (90°) of the listeners. Similarly, Muller *et al.* (2002) reported a small, but statistically significant, contribution of the binaural-interaction effect of 10.7 percentage points for sentences presented in speech-shaped noise (at a fixed SNR level of 10 dB) from either 90° or −90° azimuth to nine Med-El bilateral users. A 0.9 dB benefit of binaural-interaction effect was reported by Schleich *et al.* (2004) with 21 bilateral Med-El users when presented with a single interferer (speech-shaped noise). Litovsky *et al.* (2006b) reported an average binaural-interaction effect of 1.95 dB. Although this effect was overall statistically significant, there was relatively large intersubject variability (SD=3.3 dB). Examination of individual subject performance suggested that the overall group effect can be attributed to a few individuals with larger effect sizes with some of the subjects also showing a decrement in the bilateral listening conditions. In summary, the binaural-interaction benefit reported in most studies is quite small, often not significant, and variable across subjects.

The lack of binaural interaction (binaural advantage) in bilateral CIs can be attributed to several factors including poor ITD sensitivity (van Hoesel and Tyler, 2003; Grantham *et al.*, 2007), poor spectral resolution (small effective number of frequency channels), and difference/asymmetry in the state of the binaural auditory pathways (Long *et al.*, 2006; Litovsky *et al.*, 2006b). Grantham *et al.* (2007) reported that the best ITD threshold (among 11 bilateral Med-El users) was about 400 μs, with only 5 of 11 subjects achieving thresholds <1000 μs. Moderate ITD threshold values around 100–150 μs were obtained by five nucleus bilateral users in the study by van Hoesel and Tyler (2003), but only at low stimulation rates (<200 pps). These ITD threshold values are still appreciably larger than the ITD values (~ 70 μs) achievable by naive NH listeners (Wright and Fitzgerald, 2001) and more than an order of magnitude larger than the sensitivity of 10–20 μs reported in highly trained listeners (Durlach and Colburn, 1978). The fact that bilateral CI users may not achieve benefits from binaural hearing may be due to the fact that the etiology of hearing loss might differ in the two ears. This is further complicated by possible differences in electrode insertion depth in the two ears. Some might argue that such a mismatch in insertion depth might be beneficial in terms of providing complementary information and contributing to a binaural summation effect (Schleich *et al.*, 2004; Buss *et al.*, 2008), but can be quite harmful to the mechanisms involved in processing ITD information (Long *et al.*, 2003). Finally, the lack of synchronization of the two (independently run) speech processors worn by bilateral CI users can affect the coding of ITD information in the fine structure of the signal (Majdak *et al.*, 2006), at least for pulse rates as high as 800 pulses/s. The outcome of the present study, as well as those of others, highlights the importance of developing strategies capable of preserving ITD information in a way that will be perceived by bilateral CI users.

C. Informational and energetic masking

Energetic masking is typically present in noise interferers and is generally accounted for by peripherally based models of the auditory periphery that take into account spectral overlap of the target and the interferer. Unlike the noise interferers, however, the speech interferers (e.g., competing talkers) produce both energetic and nonenergetic components of masking. The nonenergetic masking, often called informational masking, is attributed to confusion that may be caused by content similarity between the target and the interferer. In complex listening situations informational masking is thought to be at least partly responsible for the difficulty that listeners experience in teasing apart the content carried by the target in the presence of the interferer (Brungart, 2001).

There is evidence to suggest that informational masking is reduced considerably when the target and interferer signals are spatially separated, and the benefit of spatial separation can be significantly larger in the presence of speech interferers compared with noise interferers (Peissig and Kollmeier, 1997; Kidd *et al.*, 1998; Hawley *et al.*, 2004). That was not found to be the case in the present study with bilateral CI users. The benefit from spatial separation was roughly the same with either noise or speech interferers (Fig. 2).

It is interesting to note that the total advantage as well as the monaural advantage received by bilateral users were comparable (within 1–2 dB) to that of NH listeners (Hawley *et al.*, 2004) in nearly all noise-interferer conditions for both single and multiple interferers. In contrast, a large difference (4–7 dB) was observed in nearly all speech interferer conditions between bilateral CI users and NH listeners. We cannot attribute this disparity to differences in the way that the target was "glimpsed" during momentary dips in the amplitude of the interferer since both speech and (modulated) noise interferers contained "envelope dips" which provided occasional favorable SNR segments. Rather, we consider the possibility that the difference in performance with speech interferers reflects the poorer ability of bilateral CI users to take advantage of directional cues under conditions of informational masking. In NH listeners (e.g., Hawley *et al.*, 2004), binaural cues are relied on more heavily to segregate target and interfering sounds particularly when other cues for source segregation are not available. That is, when the target and interferers can be more easily confused with one another, as is the case when the interferers consists of speech rather than noise, binaural cues that provide differential spatial information for the target and interferers become particularly salient (see also Freyman *et al.*, 2001, 2007). The bilateral CI users tested here did not demonstrate such release, suggesting that their weaker ability to integrate binaural cues reduced their experience of spatial advantage under conditions of informational masking. In fact, although there were no statistically significant effects regarding advantage of spatial separation and interferer type, there was a slight trend for a larger advantage in the presence of noise interferers rather than speech.

Another indicator of informational masking would have been higher SRTs in the conditions with speech interferers compared with noise interferers. Several unilateral implant studies (e.g., Stickney *et al.*, 2004; Nelson *et al.*, 2003; Nelson and Jin, 2004) have shown that CI users generally perform better with noise interferers (modulated or nonmodulated) than with speech interferers, suggesting the presence of informational masking. However, a different outcome emerged in the present study. There was no significant difference in performance (in terms of absolute SRT values) with the noise and speech interferers when either single or multiple interferers were present. One factor that could account for the difference in outcome between prior studies (Stickney *et al.*, 2004; Nelson and Jin, 2004) and the present study is that here we used a different-sex talker for the interferer, which may have reduced the extent of informational masking (Brungart, 2001). CI users in this study operated at SNR levels generally above 0 dB (see Fig. 1), a range over which it may be unlikely for them to have successfully extracted information from the interferer, i.e., confused the interferer at low SNRs. Thus, it is possible that the speech and noise interferers resulted in similar degradation of information in the target and that the large SRTs for the CI users abolish the potential differences in interferer type as far as energetic versus informational masking effects are concerned. Alternatively, in the present study, informational masking may have occurred in the presence of both speech and noise interferers. Given that degraded spectral information occurs readily in CI users, it is possible that listeners confounded the target and interferers just as readily in both conditions and that the advantage of spatial separation seen here was due to release from a combination of energetic and informational masking regardless of the type of interferer.

In addition, although persons fitted with bilateral CIs demonstrate measurable benefits from having a second CI compared with listening unilaterally, the SNR at which they are able to hear speech in the presence of interferers is markedly higher than the levels at which NH listeners are able to cope with in the same challenging situation. In the presence of a single speech interferer [Fig. 1, panels (A)–(D)], bilateral CI users consistently require target speech that is several decibels higher than the interferer, compared with NH listeners who can perform the task at negative SNRs [Fig. 1, panels (E)–(H)]. This result is consistent with anecdotal reports by CI users that everyday noisy situations are challenging even with a second CI.

V. CONCLUSIONS

Unlike previous bilateral studies (van Hoesel and Tyler, 2003; Schleich *et al.*, 2004; Buss *et al.*, 2008) which considered only one interferer (steady-state noise) emanating from a single location in space, the present study considered more realistic listening situations wherein multiple interferers were present, and in some cases originating from both hemifields. Aside from noise interferers, speech interferers which are known to contain informational masking were also considered. This was done to examine whether bilateral CI users receive any release of informational masking when the target and interferer are spatially separated, as found in the NH literature (e.g., Kidd *et al.*, 1998). SRTs were measured both unilaterally (one implant alone) and bilaterally in four different spatial configurations with one and three interferers. The data were analyzed in terms of binaural benefits including better-ear listening and binaural advantage (binaural interaction). After comparing the present data with those by NH listeners (Hawley *et al.*, 2004) who were presented with the same test material in the same listening environment, we can draw the following conclusions.

- The SRT values obtained by bilateral CI users are significantly higher (worse), by about 10 dB in the noise-interferer condition (one interferer) and by about 15–20 dB in the speech interferer condition (one interferer), than those obtained by NH listeners in the same listening conditions. This may have rendered the speech and noise maskers equally difficult to ignore for this population.
- The difference between NH and CI users in terms of the overall spatial release of masking (total advantage) was considerably smaller than the differences between groups in raw SRTs.
- The overall total advantage (overall spatial release of masking) of target-interferer separation ranged from 2 to 5 dB across all conditions. This advantage was maintained even when multiple interferers were present. A larger overall advantage (5–10 dB) was observed with NH listeners (Hawley *et al.*, 2004), particularly with speech interferers.
- The monaural advantage (i.e., better-ear listening) received by bilateral CI users was large ranging from 1 to 6 dB and was largest when the interferers were mostly energetic. This benefit was comparable (within 1–2 dB) to that obtained by NH listeners (Hawley *et al.*, 2004) in nearly all conditions.
- No binaural advantage (binaural interaction) was found in the present study with either type of interferer (speech or noise).
- The total advantage as well as the monaural advantage received by bilateral users were comparable (within 1–2 dB) to that of NH listeners (Hawley *et al.*, 2004) in nearly all noise-interferer conditions for both single and multiple interferers. In contrast, a large difference (4–7 dB) was noted in nearly all speech interferer conditions between bilateral CI users and NH listeners. This difference is due to the fact that there was no effect of interferer type for the CI users, and suggests that bilateral users are less capable of taking advantage of binaural cues for source segregation under conditions of informational masking compared with NH listeners. In fact, there is little evidence that bilateral users experience informational masking in a way that is akin to that experienced by NH listeners. This outcome also indicates that the use of steady-state noise interferers (which are utilized extensively in bilateral studies) does not adequately reflect the difficulties bilateral implant users experience in real-life noisy situations.

The present study extended the findings of prior bilateral studies to complex listening settings (cocktail party) and showed that bilateral implants can yield substantial benefit when the target and interferers are spatially separated. This benefit is dominated for the most part by better-ear listening, i.e., access to an implant with a favorable SNR. Compared to NH listeners who receive a moderate benefit (3–5 dB) from binaural interaction (Zurek, 1993), bilateral users do not receive such benefit. A highly plausible reason for the lack of binaural interaction is the poor ITD sensitivity of bilateral users (van Hoesel and Tyler, 2003; Grantham *et al.*, 2007), particularly at high (>1000 pulses/s) stimulation rates commonly used in commercial implant devices. Further research is warranted to develop signal processing strategies that preserve ITD information (even at high stimulation rates). Such strategies will hold promise for introducing binaural advantage in bilateral CIs.

ACKNOWLEDGMENTS

The authors would like to thank the two anonymous reviewers for their valuable comments and suggestions. Research was supported by Grant No. R01 DC007527 to P. C. Loizou and Grant No. R01 DC003083 to R. Litovsky from the National Institute of Deafness and other Communication Disorders, NIH.

[1] Following the procedure used in Hawley *et al.* (2004), the SRT was computed as the average of the SNR levels on trials 4 through, and including, 11. There was no 11th trial, but we used instead the level that would have been presented by the result of the 10th trial.

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