Appendix 2. Summary of Selected Adult Bilateral Cochlear Implant Studies

Study	Objectives	Participants	Methods	Results	Conclusions
Buss E, et al. Multicenter U.S. bilateral MED-EL cochlear implantation study: Speech perception over the first year of use. Ear Hear. 2008 Jan;29(1):20-32. Speech recognition	Evaluate the benefits of bilateral implant performance in adults.	26 adults bilaterally implanted at 5 US centers. All but 1 of the participants had simultaneous surgeries.	CNC words in quiet, CUNY sentences in CCITT noise at individually set SNRs. Speech was presented from the front and noise from the front, 90º from the right or 90º from the left. All stimuli were presented via direct audio input which bypasses the compression circuitry of the speech processor. Testing was conducted at 1, 3, 6, and 12 months post-implant.	Mean bilateral CNC scores improved by 5.8% at the 1-month interval and 11% at the 12-month interval. CUNY sentences in noise showed significant bilateral benefit at 6 and 12 months post implant. Median improvements were approximately 38% due to head shadow effects and 2-8% due to binaural summation effects. At the 12 month interval, binaural squelch benefits were observed for most subjects with a median improvement of approximately 11%.	Bilateral improvements may continue through one year of bilateral implant use. Ear differences occur, but an individual's ear dominance is not necessarily consistent over time. Binaural squelch benefits may require longer periods of use compared to other bilateral benefits such as head shadow and summation effects.
Dunn CC, et al. Effects of converting bilateral cochlear implant subjects to a strategy with increased rate and number of channels. Ann of Oto Rhinol Laryngol 2006. 115: 425-432. Speech recognition	Identify the result of conversion from CIS to a HiResolution strategy; evaluate speech recognition with HiResolution Paired (HiRes P) and HiResolution Sequential (HiRes S).	7 adult simultaneously implanted bilateral Clarion CII recipients who had used 8 channel CIS (813 pps & PW = 75µs) for at least 18 months.	Conversion to 16 channel HiRes included providing both HiRes P (5156 pps & PW = 11µs) and HiRes S (2900 pps & PW = 11µs) on each participants' speech processor. Speech recognition testing was completed in CIS prior to conversion and in HiRes P and HiRes S immediately after conversion and after 1 month's use alternating between HiRes P & HiRes S daily. Speech recognition was evaluated again after 3 & 6 months use of the preferred program(s). Speech recognition: CUNY sentences at 70 dbC in multi-talker babble with speech and noise from the front at individually set SNRs. All testing was conducted in the bilateral condition.	Immediate crossover: 5 of 6 tested participants had significant improvement with HiRes and 1 participant had significant decline with HiRes. 1 month HiRes P vs. HiRes S: no significant difference for the group; HiRes P was better for 2 of 7 participants. 1 month best HiRes vs. CIS: HiRes scores on sentences in noise improved by 30-60% for 6 participants compared to CIS. 6+ month HiRes vs. CIS: 5 participants still used HiRes and scored significantly better with HiRes than CIS; re-test CIS after 6 months HiRes experience was improved over initial CIS testing for 2 participants.	Large improvement (30-60%) in speech recognition in noise with HiRes after 1 month's use compared to baseline CIS. Improvement maintained at 3 months; 4 out of 5 maintained improvement at 6+ months. No difference between HiRes P and HiRes S strategies. Authors suggest additional study of the effects of rate vs. channel number.
Grantham DW, et al. Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. Ear Hear. 2007 Aug;28(4):524-41. Localization	Assess the horizontal localization ability of bilaterally implanted adults for noise and speech stimuli and compare localization abilities over time. Investigate the contributions of ILD and ITD cues for horizontal localization with noise.	22 bilaterally implanted adult recipients of devices from 6 CI centers. All but two of the participants had simultaneous surgeries.	Localization: 43 loudspeaker array spaced along a 180º arc of which 17 speakers along a 160º arc were active. White Gaussian noise bursts and speech stimuli ("hey") were used, both filtered from 100 – 4k Hz. Results were reported as adjusted constant error ($\hat{C}$) for which 50.5º is chance. ILD & ITD cues: Low-pass, high-pass, and slow-onset noise stimuli were included in addition to the noise burst and speech stimuli described above for sub groups of the participants. Testing was conducted for each CI individually and bilaterally after 5 months device use for all participants and then repeated 10 months later for 12 participants.	Unilateral condition: $\hat{C}$ was near chance for all participants. Unilateral better ear performance was near chance (47.9º). In the unilateral condition, participants had a strong bias to hear all stimuli as originating from the side with the active device. Bilateral condition: $\hat{C}$ varied from 8.1º to 43.4º with a mean of 24.1º for noise bursts. Average $\hat{C}$ for speech (21.5º) was significantly lower. For all but 2 participants who were retested after 15 months of bilateral device use, there was no significant change in performance. Two participants had considerable improvement, however their $\hat{C}$ decreased by half. There was no significant difference in localization between using the noise bursts and the high-pass or slow-onset noise. There was, however, a significant increase in errors for the low-pass stimuli compared to the noise bursts.	Individuals with bilateral cochlear implants localize well on the horizontal plane using both devices but not when using only one device. They localized speech stimuli slightly better than noise stimuli. The ability to localize sounds had stabilized by 5 months of bilateral device use for most participants. For horizontal plane localization, bilaterally implanted adults rely primarily on ILD cues and are unable to benefit from ITD cues.

Study	Objectives	Participants	Methods	Results	Conclusions
Grantham DW, et al. Interaural time and level difference thresholds for acoustically presented signals in post-lingually deafened adults fitted with bilateral cochlear implants using CIS+ processing. Ear Hear. 2008 Jan;29(1):33-44. ITD/ILD Thresholds	Measure ITDs and ILDs in bilaterally implanted adults using noise signals; compare ILD and ITD thresholds to localization error scores.	11 bilaterally implanted adults who were a subset of the participants in Grantham et al 2007 listed above. 3 participants had ~5 months and 7 participants had ~15 months of bilateral device use.	ITD and ILD thresholds were measured using acoustic stimuli (200-msec Gaussian noise burst) via headphones. Thresholds were measured both with compression activated on the speech processor (~45 dB threshold) and with compression deactivated. An adaptive 2-alternative forced-choice procedure was used where the participant indicated if the noise was moving from right to left or left to right. Feedback was provided. ILD and ITD thresholds were compared to the error scores obtained in the localization task described in Grantham et al 2007 (above).	ILD thresholds were significantly lower with compression turned off. The mean ILD threshold was 3.8 dB (range = 1.2 - 10.7) with compression turned on compared to a mean threshold of 1.9 dB (range = 0.9 - 3.3) with compression turned off. ITD thresholds were poor; 5 were ~400 - 1000μs with the rest being > 1000 μs and two individuals were not able to distinguish the direction up to 10,000 μs. ILD, particularly with compression off, correlated with the total error score on the localization task where as ITD did not correlate.	Poor sensitivity to ITD with this task supports the notion that ITD cues can not be used for localization of noise stimuli by bilaterally implanted adults (using a CIS envelope extraction strategy). Horizontal plane localization is primarily dependent on ILD cues.
Laszig R, et al. Benefits of bilateral electrical stimulation with the Nucleus cochlear implant in adults: 6-month postoperative results. Otol Neurotol 2004; 25:958-68. Speech recognition Localization	Evaluate speech recognition and localization abilities of adults who are bilateral cochlear implant recipients.	37 adults with bilateral CIs, 15 were sequentially implanted (0.4 – 5.6 yrs between surgeries) and 22 had both surgeries simultaneously. Participants were from several German-speaking clinics in Germany and Switzerland.	Speech recognition: FMW words and OLSA or HMS sentences at 70 dB SPL; OLSA sentences in noise (CCITT) using an adaptive procedure resulting in a SNR for 50% correct; HMS sentences at 70 dB SPL with a fixed 10 dB SNR. Localization: 12 loudspeakers spaced 30º apart in a circle around the participant using a shortened HMS sentence at 65-70 or 55-60 dB SPL. Results are reported as RMS error.	Speech recognition in quiet: Binaural benefit demonstrated compared to either unilateral condition for OLSA sentences and compared to the poorer ear for FMW & HSM sentences. Speech recognition in noise: Binaural benefit noted with either unilateral condition for adaptive OLSA sentences and compared to the poorer ear for HMS sentences with the speech and noise both from the front. For spatially separated speech in noise, there was a consistent interaural performance advantage for the ear closest to the speech source whether or not the better ear was closest to the speech signal (head shadow benefit). Bilateral stimulation always provided superior performance than unilateral listening with either ear when ipsilateral to the noise source. Localization: 15 of 16 participants had better localization with bilateral device use than with unilateral use. In the unilateral condition, the tendency was to respond on the side of the device.	Bilateral CI use provides advantages to some recipients over unilateral CI use for listening in quiet and in noise and for most recipients for localization. Head shadow is the most robust effect, although some individuals seem to benefit from binaural squelch and binaural redundancy in some situations. Bilateral cochlear implantation allows binaural auditory processing that can assist with communication in everyday listening situations.

Study	Objectives	Participants	Methods	Results	Conclusions
Litovsky RY, et al. Bilateral cochlear implants in adults and children. Arch Otolaryngol Head Neck Surg 2004; 130:648-55 Speech recognition Localization	Investigate speech recognition and localization abilities for adults and children with bilateral CIs.	17 adult participants (14 postlingual and 3 perilingual) who received CIs in simultaneous procedures.	Speech recognition using an adaptive procedure with 4-talker babble and BKB sentences that results in a SNR for 50% correct (BKB-SIN). Speech was presented from the front and noise from the front, 90º right, and 90º left. Localization: 8 loudspeakers spaced along a 140º arc using bursts of pink noise at 65 dB SPL (± 6). Participants indicated the speaker source for each sound. Results are reported as RMS error. Testing was conducted for each CI individually and bilaterally after 3 months of bilateral CI experience.	Speech recognition: Bilateral advantage seen when the babble was on the side of the poorer CI. Localization: Bilateral performance was better than either unilateral performance. Adults: Bilateral hearing leads to better localization performance and speech intelligibility when the noise is near the poorer of the two ears.	Results indicate advantages for bilateral CI use over unilateral use for localization and understanding speech in noise. Since participants only had 3 months of bilateral CI experience, the potential bilateral benefit from longer periods of use is unknown.
Litovsky RY, et al. Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. Ear Hear. 2006 Dec;27(6):714-31. Speech recognition Questionnaire	Investigate speech recognition abilities of bilaterally implanted adults with simultaneous surgeries.	37 adults with simultaneous bilateral Nucleus 24 Contour cochlear implants from 11 CI centers in the US.	Speech recognition: CNC words and HINT sentences in quiet at 65 dB SPL. BKB-SIN as described above in Litovsky et al. 2004. Questionnaire: At the 3 month post-implant interval, participants underwent a 3 week period of unilateral device use (better ear). The APHAB was completed at the end of that unilateral experience and again at the 6 month interval after returning to bilateral device use. All participants were tested after 1, 3, and 6 months of device use.	Speech recognition: The bilateral condition was significantly better than either unilateral condition at all post-implant test intervals for the CNC and at all except the 3 month interval for the HINT sentences. In noise, the bilateral condition was better than either unilateral with average head shadow effects of 4.9 for noise-right and 6.3 for noise-left and average binaural squelch effects of 1.9 for noise at either side. Questionnaire: On average, participants scored the bilateral condition significantly higher than the unilateral for ease of communication, reverberant conditions, and background noise.	Subjective reports from participants as well as speech recognition results support bilateral benefit for postlingually deafened adults who are implanted simultaneously.
Muller J, et al. Speech understanding in quiet and noise in bilateral users of the Med-El Combi 40/40+ cochlear implant system. Ear Hear 2002; 23:198-206. Speech recognition	Investigate speech understanding in quiet and noise in bilaterally implanted adults.	9 adults with bilateral cochlear implants. 6 were implanted with sequential surgeries (~ 1 – 4 yrs apart) and 3 had both ears implanted during the same surgery.	FMW words in quiet at 65 dB SPL. HSM sentences at 65 dB SPL in noise (CCITT) at +10 dB SNR.	All participants had higher speech scores in the bilateral condition than with either ear in the unilateral condition on at least one measure, and most for all measures. Average sentence understanding increased an average of 31% with bilateral compared to a unilateral CI ipsilateral to the noise, and 11% compared to a unilateral CI contralateral to the noise. The average word recognition score increased 19% with bilateral CIs compared to a unilateral CI. All differences in average scores were significant.	Bilateral cochlear implantation can provide improved speech recognition in quiet and in noise. Duration of deafness did not seem to be a contraindication for bilateral implantation for this small sample.

Study	Objectives	Participants	Methods	Results	Conclusions
Neuman AC, et al. Sound-direction identification with bilateral cochlear implants. Ear Hear. 2007 Feb;28(1):73-82. Localization	Investigate the effect of stimulus type (speech vs. pink noise bursts) on horizontal plane localization for adults with bilateral cochlear implants.	8 adults (1 pre-lingually deafened) with bilateral cochlear implants that had both ears implanted simultaneously. All had 5-11 mos of device use.	9 loudspeakers spaced along a 180º arc using speech ("Where am I now?") and pink noise bursts at 70 dB SPL (± 3 dB). Participants indicated the speaker source for each sound. Results reported as RMS error.	There were individual differences between participants. Most participants had better localization in the bilateral condition in terms of more correct responses and less error for incorrect responses. Localization was better for the centrally located speakers than for the ones at the ends of the arc and was better in the bilateral condition (mean RMS = 29º) than either unilateral condition (mean right RMS = 47º; mean left RMS = 54º). Results with pink noise and speech stimuli were similar.	Bilateral CIs provide significant benefit related to horizontal plane sound localization. Results with pink noise and speech did not differ, suggesting either is acceptable for localization testing.
Nopp P, et al. Sound localization in bilateral users of Med-El Combi 40/40+ cochlear implants. Ear Hear 2004; 25:205-14. Localization	Investigate sound localization with bilateral compared to unilateral CIs.	20 adults (1 pre-lingually deafened) bilaterally implanted during adolescence or later. 3 had both ears implanted simultaneously and the others during sequential surgeries (~ 4 mos to 5.5 yrs apart). All had at least 1 month of bilateral CI experience.	9 loudspeakers spaced along a 180º arc using bursts of CCITT noise at random levels of 60, 70, or 80 dB SPL. Participants indicated the speaker source for each sound. Results reported as mean deviation (d) between azimuth of presentation and response.	Bilateral implants had substantial and significant benefit. All but two participants (with early onset of deafness) substantially improved their sound localization ability when using both implants compared to either one alone. With bilateral CIs, average accuracy with which subjects can localize sounds improves more than 30 degrees. Minimal bias is seen for participants in the bilateral condition whereas large bias is seen in the unilateral condition toward the side of device use. In addition, the judgments were more consistent with bilateral CIs.	Sound localization was substantially improved with bilateral CIs for these adults who were primarily postlingually deafened with short duration of deafness before implantation. The authors suggest that individuals with early onset of deafness may achieve better bilateral benefit, if implanted at younger ages and that additional investigation is needed.

Study	Objectives	Participants	Methods	Results	Conclusions
Ramsden R, et al. Evaluation of bilaterally implanted adult subjects with the Nucleus 24 cochlear implant system. Otol Neurotol 2005; 26(5): 988-98. Speech recognition	Evaluate binaural benefit in speech recognition while controlling for binaural summation for adults who have been successful with one implant and receive a 2nd implant.	30 adults from 7 CI clinics in the UK who received sequentially implanted CIs. Participants had at lest 9 mos of unilateral CI experience, open-set sentence understanding & < 15 years of deafness in the 2nd CI ear.	CUNY sentences & CNC words in quiet at 70 dB SPL. CUNY sentences at 70 dB SPL with 8-talker babble at + 10 dB SNR pre-op and individually determined SNRs post-op. Testing occurred pre-op and at 1 week, 3 months, and 9 months post-activation. Speech in noise: Speech was always from the front. Noise was from the front, 90º to the right, or 90º to the left. Half the participants were implanted in the 2nd ear upon enrollment in the study. The other half were implanted 9 months later to allow for quality of life comparisons. The results of the 2 groups are combined and the quality of life measures were not discussed.	Data is available for 29 participants. 27 patients preferred sound quality w/ both CIs and use them both daily. In quiet, no bilateral advantage was demonstrated compared to the 1st CI alone at 3 or 9 months. Performance with the 2nd CI was significantly worse than the 1st for sentences and words. With noise from the front, bilateral performance was significantly better than 1st CI performance at 3 & 9 months. Comparison of the best unilateral score to the bilateral score at 9 months indicates a significant redundancy effect. With noise toward the 1st CI, bilateral scores were better than 1st CI scores at 3 & 9 months. Group data did not show a significant head shadow or binaural squelch effect but 18 of 29 participants had a head shadow effect and 6 of 18 participants had binaural squelch benefit. With noise toward the 2nd CI, bilateral scores are better than 2nd CI scores at 3 & 9 months. Head shadow effects ere present at 3 & 9 months but no significant squelch effect for the group. 5 of 18 participants, however had binaural squelch benefit.	Bilateral benefit, head shadow, squelch, and redundancy effects were demonstrated for some participants but not all. Benefit can be obtained by adding a 2nd CI for previously implanted adults, particularly in noise. Some participants with long periods of time between surgeries had poorer 2nd ear performance and limited bilateral benefit.
Ricketts T et al. Speech recognition for unilateral and bilateral implant modes in the presence of uncorrelated noise sources. Ear Hear 2006;Dec 27(6):763-773. Speech recognition	Compare speech recognition in multiple noise sources for bilateral and better unilateral conditions at 2 different time periods post implant, and to assess the effect of different SNRs on speech recognition.	16 bilateral implanted adults. 14 received simultaneous implants. The other 2 had the 2nd surgery 7 and 14 months after the 1st surgery.	Speech was presented from the front and noise from multiple sources around the listener (30º to 330º). Adaptive HINT with amplitude-normalized cafeteria noise presented at 60 dBA resulting in a SNR for 50% correct. Connected Speech Test (CST) with passages presented at 70 dBA and a +10 dB SNR using 5 uncorrelated babble samples. A subset of 10 participants was retested 9 months later on the CST at +10 dB SNR; 6 of these participants were tested at 4 SNRs (+20, +15, +10, +5).	Bilateral implant condition was superior to better ear unilateral by 3.3 dB for the adaptive SNR task, and 9% for the fixed SNR CST test. In addition, bilateral performance improved with experience. 8 of 10 had improvements (11-20%) on CST at the retest interval. Performance in quiet and noise differed, even at the greatest SNRs and the most difficult SNR resulted in the largest bilateral advantage.	Results support previous studies that indicate a bilateral advantage for speech recognition in noise from multiple noise sources. The authors suggest the improvement is due to the effects of binaural summation and squelch. The binaural advantage of ~ 10% over the best unilateral condition continued to be present over time.

Study	Objectives	Participants	Methods	Results	Conclusions
Schleich P, et al. Head shadow, squelch, and summation effects in bilateral users of the Med-El combi 40/40+ cochlear implant. Ear Hear 2004; 25:197-204. Speech recognition	Investigate speech recognition in noise for adults with bilateral cochlear implants.	21 German-speaking adults (1 prelingually deafened) with bilateral cochlear implants. 3 had both ears implanted during the same surgery and the others implanted during sequential surgeries (4 mos to 5.5 yrs between surgeries). All had at least 1 month bilateral experience.	OLSA sentences in noise (continuous noise matching the long-term speech spectrum) using an adaptive procedure resulting in a SNR for 50% correct. Speech was presented from the front and noise was presented at 60 dB SPL from the front, 90º right, or 90º left.	Significant improvement was observed in all listening conditions but one (the squelch effect for noise from the right side, probably due to the relatively small number of subjects). No correlation between any effects (head shadow, squelch, summation) and duration of deafness of first and second deafened ear, average duration of deafness across ears, or theses factors expressed as a fraction of age.	Bilateral CI users benefit significantly from head shadow, squelch, and summation effects, which are known effects for normal-hearing subjects.
Schoen F, et al. Speech reception thresholds obtained in a symmetrical four-loudspeaker arrangement from bilateral users of Med-El cochlear implants. Otol Neurotol 2002; 23:710-4. Speech recognition	Investigate speech recognition in noise for adults with bilateral CIs.	9 adults with bilateral CIs, implanted either sequentially (n=6) or simultaneously (n=3).	HSM sentences at 70 dB SPL in quiet and at 5 SNRs (+20 to 0 dB), performed in a 4 loudspeaker setup (45º, 135º, 225º, 315º) to eliminate any head shadow effect. Speech was presented from the two speakers toward the better CI and noise from the two speakers toward the poorer CI. Results are reported in change of SNR for 50% correct for the bilateral condition compared to unilateral.	Speech recognition increased with increasing SNRs. All participants showed substantial gain in SNRs (approximately 4 dB on average; ranging from 1.3 – 6.6 dB) that remained essentially stable over time. The bilateral advantage was evident shortly after implantation of the second CI and did not require lengthy experience.	Bilaterally implanted adults showed a substantial and statically significant bilateral benefit over performance with the better hearing ear. Bilateral CI users can process speech binaurally and take advantage of binaural effects in addition to the head shadow effect.
Seeber BU & Fastl H. Localization cues with bilateral cochlear implants. J Acoust Soc Am. 2008 Feb;123(2):1030-42. Localization	Evaluate the contribution of binaural cues to localization using variations of spectral and temporal content in stimuli, a modified placement of CI processor microphones, and altered head related transfer functions to offset ITDs or ILDs.	2 bilaterally implanted CI recipients who had very good horizontal localization abilities.	Localization was conducted in a darkened anechoic chamber with an 11 loud speaker array spaced along a 100º arc (although the listener was able to select a source location along a 140º arc). Stimuli were presented at roving levels from 61 – 69 dB SPL. The participant indicated the source for each sound using a computer-controlled laser pointer to allow 2º accuracy. Results with various noise types were compared as were the results with pulsed wide-band noise (WBN) for 2 microphone placements, and for WBN for stimuli with ILD and ITD shifts.	Both subjects were able to localize stimuli that differed in spectral and temporal structure. Placement of speech processors above the head (w/o head block) resulted in left – right discrimination whereas, placing a piece of cardboard between the processors improved localization. Even when ITDs were artificially emphasized, localization was more dependent on ILDs.	ILDs were the primary cues used for localization with only minor contribution from ITDs. This is in contrast to NH listeners who rely primarily on ITDs. Because of this, the authors predict that, although the subjects were very good at localizing in this controlled test environment, their ability would deteriorate in situations with multiple sounds where the ILD cues may be unreliable.

Study	Objectives	Participants	Methods	Results	Conclusions
Senn P, et al. Minimum audible angle, just noticeable interaural differences and speech intelligibility with bilateral cochlear implants using clinical speech processors. Audiol Neurotol 2005; 10:342-52 Speech recognition Localization	Assess the minimal audible angle (MAA) in NH adults and bilateral CI recipients and assess speech recognition in bilaterally implanted adults.	5 participants with sequentially implanted bilateral CIs (2 prelingually deafened teens and 3 postlinguistically deafened adults). 5 participants with NH who were matched for age.	Speech recognition: HSM sentences presented at 70 dB SPL in CCITT noise at individually set SNRs. Speech was presented from the front and noise from the front, 90º right, or 90º left. Localization: A MAA task using 4 reference points for teens and 8 for adults - equally spaced in a circle around the participant. White noise bursts were presented from the reference position and then from a loudspeaker on a boom that allowed any angle 45º or less. Participants were asked to indicate the direction the sound moved (right/left or front/back).	Speech recognition: Percentage of correctly understood words was significantly higher using bilateral CI than only CI ipsilateral to noise sources. Average increase of 33% (range 1-51%) on the left and 56% (range 37-78%) on the right, consistent with head shadow effect, were observed. Localization: The MAAs in the bilateral condition (3-8º) were significantly smaller than in either unilateral condition and only slightly higher than those of normal hearing controls when the reference point was at 0º (left-right discrimination). Front-back discrimination when the reference was on either side, was poor.	All patients benefited substantially from bilateral CI for speech recognition in noise as the result of a head shadow effect. Binaural squelch and summation effects were seen in some but not all participants. Left-right discrimination was at near normal MAA values but front-back discrimination was poor. The 2nd CI performance lagged behind the 1st, suggesting earlier implantation of the 2nd side might be more beneficial.
Tyler RS, et al. Three-month results with bilateral cochlear implants. Ear Hear 2002; 23(1 Suppl):80S-89S. Speech recognition Localization	Evaluate speech recognition and localization in adults receiving bilateral CIs after 3 months experience.	9 adults with bilateral cochlear implants, implanted simultaneously.	Speech recognition: CNC words and CUNY sentences in quiet and CUNY sentences in noise. Speech was presented at 70 dB SPL from the front and noise at individually determined SNRs from 90º to the right or left. Localization: 2 speaker set up at 45º to the right and left. Bursts of noise were presented randomly at 70 dB SPL (± 5 dB). Participants were asked to indicate whether the sound was from the right or left speaker.	Speech recognition: In quiet, statistically significant binaural advantages observed for sentences in 5 participants and words for 2 participants. For speech in noise, 4/9 had significant improvement with noise from the front, 1/9 with noise from the left, 3/9 with noise from the right. All participants showed a significant advantage of binaural versus monaural hearing for at least one of the 4 speech perception measures. Localization: 6 of 7 participants tested had a binaural advantage with localization significantly better in the bilateral condition than either unilateral condition.	All subjects prefer using both CIs. Results suggest that binaural benefits can be obtained, even with two different processors. Future studies will include more realistic localization and speech recognition measures.
Tyler RS, et al. Speech perception and localization with adults with bilateral sequential cochlear implants. Ear Hear. 2007 Apr;28(2 Suppl):86S Speech recognition Localization	Investigate localization and speech recognition abilities for a diverse group of bilateral implant recipients.	7 sequentially implanted adults (6y 8m to 17y between surgeries). Devices varied across participants and 3 individuals had different devices for each ear. Duration of bilateral device use ranged from 2 mos to 6 yrs.	Speech recognition: Speech material presented at 70 dB SPL. CNC words in quiet & CUNY sentences at individually determined SNR using MTB. 4 participants were tested with the noise from each side to determine the presence of binaural squelch. All were tested with speech front and noise front. Localization: 8 loudspeaker array spaced along a 180º arc. 2 participants were tested in the unilateral condition prior to 2nd side implantation. All were tested in the bilateral condition.	Speech recognition: Testing in quiet indicated ear differences for 4 of the participants whereas ear differences were present for all participants when tested in noise. All 4 participants tested for binaural squelch demonstrated significant binaural squelch for at least one side. Localization: The 2 participants tested in the unilateral condition prior to 2nd side implantation demonstrated improvement in localization with bilateral device use. For the 7 participants, RMS values ranged from about 12º to about 45º in the bilateral condition (chance = 46 º).	Individuals can benefit from bilateral implantation even if there are long periods of time between surgeries, the processing strategies are dissimilar, or the recipients have pre- or post-linguistic onset of deafness.

Study	Objectives	Participants	Methods	Results	Conclusions
van Hoesel RJ et al. Sound direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. Ear Hear. 2002 Apr;23(2):137-149. Speech recognition Localization Psychophysics	Investigate bilateral benefits using measures of ITD sensitivity, localization, and speech recognition in noise.	One bilaterally implanted patient who received CIs in both ears during a single surgery.	Speech recognition: Sentences similar to CUNY sentences presented at 70 dB SPL in multi-talker babble at an individually determined SNR. Speech was presented from the front and noise from front, 90º right, and 90º left. Low and high update rate strategies were evaluated. Localization: 11 loudspeaker array spaced along a 180º arc. Pink noise bursts were presented at 70 & 60 dB SPL (± 3 dB). The participant indicated the speaker source for each sound and results were reported in mean absolute errors. Psychophysics: ITD JNDs were measured with a 3 AFC design with 70% accuracy. Stimuli were pulse trains using low rates and high rates modulated at 100 Hz presented to 2 matched bilateral place pairs of electrodes.	Speech recognition: Bilateral improvements due to head shadow effects but not for binaural squelch. There was no effect of low and high rate update strategies in the test conditions. Localization: At 70 dB SPL, mean absolute errors were 81° and 73° for LE and RE, and 16° for bilateral implants. At 60 dB SPL (no AGC), the mean error in the bilateral condition improved to 8°. Psychophysics: Best ITD JND was 350-400 µsec for low rate pulse trains. Increased rates resulted in larger JNDs.	Although ITD cues are not well perceived with bilateral cochlear implants, there is improved localization and speech understanding in noise. These benefits can be an advantage in every day communication for cochlear implant recipients.
van Hoesel RJ & Tyler RS Speech perception, localization, and lateralization with bilateral cochlear implants. J Acoust Soc Am. 2003 Mar;113(3): 1617-1630. Speech recognition Localization Psychophysics	Assess localization and speech recognition in bilateral and unilateral conditions; evaluate the effects of varied ITD and ILD cues with direct electrical stimulation.	5 bilateral simultaneously implanted participants with a minimum of 1 year CI experience.	Speech recognition: BKB sentences in noise (BBN) using an adaptive procedure resulting in a SNR for 50% correct. Speech was presented from the front at 65 dB SPL, and noise from the front, 90º from the right, and 90º from the left. Localization: 8 loudspeaker array spaced along a 108° arc. Pink noise bursts at 65 dB SPL (±4 dB). The participant indicated the speaker source for each sound and results were reported as RMS errors. A new processing strategy designed to better preserve ITD cues (referred to as PDT, or peak derived timing) was used in addition to the clinical strategy for localization testing. Psychophysics: Participants made left-right judgments relative to a reference and absolute lateral position decisions as ILDs and ITDs were adjusted on place matched and loudness balanced electrodes from the two sides.	Speech recognition: When speech and noise were both from the front, the bilateral score was similar to the best unilateral score. There were significant improvements when speech and noise were spatially separated due to head shadow effects. Bilateral scores compared to the shadowed ear (binaural squelch) indicated a 1-2 dB difference that was marginally significant. Localization: Averaged RMS errors were smaller (10°) for bilateral conditions than for unilateral conditions (20-60°) ; chance = 50%. Results were comparable with the clinical or research processors. Psychophysics: Good sensitivity for ILDs that was better than 1dB for some participants. ITD sensitivity was moderate, around 100 µsec, and decreased for stimuli with rates above a few hundred Hz using unmodulated pulse trains.	Bilateral implantation provides improvement for localization and listening in noise when the sound source and speech are spatially separated, primarily due to head shadow effects. Psychophysical experiments indicate good sensitivity to ILDs. ITD cues rely on the availability of low rate information below a few hundred Hz.

Study	Objectives	Participants	Methods	Results	Conclusions
van Hoesel RJ Exploring the benefits of bilateral cochlear implants. Audiol Neurotol. 2004;9:234-246. Psychophysics Localization	Assess 1) effect of place-matching on ITD sensitivity; 2) binaural loudness summation for broadband stimuli; 3) signal detection in noise; and 4) effects of array span, signal characteristics, loudspeaker location, and sound processing strategy.	One to two bilateral adult implant recipients per experiment.	Exp 1: ITD JNDs for pulse trains as a function of place of stimulation at a comfortably loud level using a medial electrode for the LE and a range of electrodes for the RE. Exp 2: Loudness estimation with broadband pink noise bursts. 10 electrodes from each side were loudness balanced for each ear as well as between ears near threshold and maximal comfort levels. Noise bursts were presented across a 32 dB range for LE, RE, and bilateral. Exp 3: Measures of binaural masking level differences (BMLD) with 500 Hz pulsed tones (in & out of phase at right/left processor inputs) separated by 0.5-1.5s periods of silence and NBN centered at 500 Hz. Participants adjusted the level of the tone until the on/off gating was detectable. Exp 4: Localization measures with 8 loudspeakers spaced along a 180º arc using pulsed pink noise and 50-Hz click trains at roved levels (60-68 dB SPL). Lateralization measures with direct routing into audio input of the speech processor.	Exp 1: Small place differences did not substantially change ITD sensitivity and JND scores were within 2x as large when place varied by 3-4 mm and within 3x as large when place varied by 7-8 mm. Exp 2: Bilateral stimulation resulted in mean loudness values 1.8 times greater than unilateral conditions and was a factor of 2 across most presentation levels (e.g. bursts were twice as loud when presented bilaterally). Exp 3: BMLDs in two subjects were considerably lower than what would be expected with NH subjects suggesting minimal binaural speech unmasking to be expected from the CI participants. Exp 4: Adding low rate ITD cues may improve localization performance for wider array spans; in the lateralization task, ITD sensitivity was better for click trains than pink noise.	Data support previous findings that in bilateral implant users, ILD cues are primarily used for localization and speech recognition in noise rather than ITD cues. The inability of current cochlear implant devices to code fine timing information at high rates may impede access to ITD cues used in the normal hearing system.
van Hoesel RJ Sensitivity to binaural timing in bilateral cochlear implant users. J Acoust Soc Am. 2007 Apr;121(4):2192-206. Psychophysics	Investigate various ways that electrical stimulation might provide binaural timing cues and their perception in implant recipients.	3 bilaterally implanted adults who were fairly good at identifying ITD sensitivity at a low rate (100 pps).	Data were collected over a 4-12 month time period for each participant. Several experiments were conducted to 1) evaluate ITD sensitivity with various pulse rates, stimulus levels and durations; 2) investigate time-varying ITDs rather than static ITDs and determine if subjects perceive beats with higher pulse rates, and 3) assess sensitivity to later cues in the signal compared to the onset.	Individual subject differences were present however in general, higher pulse rates, lower stimulation levels, and shorter durations resulted in higher ITD thresholds. Subjects perceived time-varying ITD cues at 100 pps but could not at 300 pps. Poor ITD discrimination was found on the second pulse of a two-pulse stimulus when the gap between the two pulses was a few milliseconds in duration.	To date, electrical stimuli are not able to transmit timing cues that are available to NH listeners. The authors suggest this may be due to issues related to synchrony, refractory patterns, effects of deafness and distorted place-rate relationships. ITD cues may be more easily identified with the use of a fine-timing based strategy than envelope based strategies, however channel interaction issues may limit practical benefits.

Study	Objectives	Participants	Methods	Results	Conclusions
Verschuur CA, et al. Auditory localization abilities in bilateral cochlear implant recipients. Otol Neurotol 2005; 26:965-71. Localization	Study localization by bilateral CI recipients and investigate the effectiveness of dual microphones with one implant to improve localization.	20 bilaterally implanted adults recruited from UK multicenter CI trial.	Localization testing was conducted with 11 loudspeakers spaced along a 180º arc using a variety of stimuli (speech, speech + reverberation, pulsed pink noise, white noise w/simulated reverberation, tone bursts), most at 60 dB SPL, but also pulsed pink noise at 70 dB SPL in order to activate the AGC of the speech processors. Results were reported as mean angular errors. Testing was conducted for each CI individually and bilaterally as well dual microphones providing input to the 1st CI.	Marked improvement in horizontal sound localization with bilateral compared to unilateral CI and dual microphones. Small variation in bilateral performance; modest differences in localization performance for different stimuli. Performance differences associated with level were relatively small and confined to unilateral conditions. Bilateral localization benefit was consistent for a range of stimuli with different temporal and spectral characteristics and for all subjects.	Bilateral CIs are able to provide significantly improved localization over unilateral CIs. All participants demonstrated benefit with all stimuli types. Dual microphones provided no localization benefit.

Note: For all studies, testing was conducted with each device alone and also in the bilateral condition. APHAB = Abbreviated Profile of Hearing Aid Benefit; BKB = Bamford-Knowal-Bench; CCITT = Comite Consultatif Internationale de Telegraphie et Telephonie (International Telephone and Telegraph Consultative Committee); CI = cochlear implant; CIS = Continuous Interleaved Sampling; CNC = Consonant-Nucleus-Consonant; CUNY = City University of New York; dB = decibels; FMW = Freiburber Monosyllabic Words; HMS = Hochmair-Schultz-Mozer sentences; ILD = Interaural Level Difference; ITD = Interaural Time Difference; JND = just noticeable difference; OLSA = Oldenburger sentences; pps = pulses per second; PW = pulse width; RMS = root mean square; SNR = signal-to-noise ratio; SPL = sound pressure level.