Appendix 1. Summary of Selected Adult Bimodal (CI+HA) Studies

Study	Objectives	Participants	Methods	Results	Conclusions
Ching TY, et al. Binaural benefits for adults who use hearing aids and cochlear implants in opposite ears. Ear Hear. 2004; 25(1):9-21. Speech recognition Localization Questionnaire	Investigate HA adjustments when a HA is used contralateral to a CI; identify whether interference results from use of a HA contralateral to a CI; and determine whether adults benefit from bimodal device use.	21 adult CI recipients, 12 were experienced bimodal wearers, 9 were fit with HAs and new to bimodal use.	Participants fit with Bernafon AF120 BTEs approximating NAL-NL1 targets as possible. A paired-comparison task was used to identify the preferred frequency response for the HA. A loudness balancing task was used to attempt equal loudness for CI and HA. Speech recognition: BKB/A sentences at 70 dB SPL and 8-talker babble (+10 or +15 dB SNR depending on loudspeaker arrangement). Testing conducted with speech & noise from front (+10 SNR) or noise at 60º on CI side and speech 60º on HA side (+10 and + 15 SNR). Localization: 11 loudspeakers spaced along a 180º arc using pulsed pink noise at 70 dB SPL (± 3 dB). Participant indicated the speaker source for each sound. Results reported as RMS error. Questionnaire: Related to functional performance in daily living situations. Completed after 1 week use in each wear arrangement.	HA preference and fitting: 5 participants did not have significant frequency response preferences. 3 preferred slightly greater high frequency emphasis and 4 less high frequency emphasis than the prescribed targets. There was considerable variation in preferred gain settings. There were no significant differences between the prescribed and preferred frequency response and gain settings. Speech recognition: CI results were higher than HA results and CI+HA higher than CI results for both speech and noise from the front as well as speech and noise spatially separated. Localization: No significant difference between the experienced and new bimodal participants. RMS values were significantly lower in the bimodal condition compared to the CI or HA alone. Questionnaire: Responses for the bimodal condition were significantly better than CI alone for 10 participants (at least 1 subscale or overall scores) and significantly better than the HA alone score for all participants.	The use of a HA on the ear contralateral to the CI provides advantages for speech recognition, localization, and reported function in every day listening situations. Bimodal fittings are recommended for adults who use a CI, and the NAL-NL1 prescriptive targets are reasonable for an initial HA fitting.
Ching TY, et al. Binaural redundancy and inter-aural time difference cues for patients wearing a cochlear implant and a hearing aid in opposite ears. Int J Audiol. 2005; 44(9):513-21. Speech recognition	Investigate binaural redundancy and inter-aural time difference cues as they relate to speech recognition by bimodal listeners.	Adult participants included: 9 with NH, 9 using bilateral HAs, and 4 using bimodal devices.	BKB sentences in noise (BBN) using an adaptive procedure resulting in a SNR for 50% correct. Stimuli were presented via direct connect to the HA or speech processor for hearing impaired participants and through headphones for NH participants. Stimuli presented to each ear individually, to both ears simultaneously, and to both ears with a 700μs delay in the noise to one ear. Bimodal participants were tested in the CI only and bimodal conditions.	Binaural redundancy: For NH participants, the SNR scores for each ear alone were significantly different than the binaural condition but not for RE vs. LE. For bilateral HA and bimodal participants, monaural vs. binaural presentation was significant. Inter-aural time difference cues aided in speech recognition for NH adults (3 dB on average); and for adults who used bilateral HAs, but not adults who had bimodal fittings.	A bimodal advantage for adults is present when speech and noise are spatially separated due to the head shadow effect. There is also a small benefit from binaural redundancy when speech and noise are from the same source.

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Dunn CC, et al. Benefit of wearing a hearing aid on the unimplanted ear in adult users of a cochlear implant. J Speech Lang Hear Res. 2005;48(3):668-80. Speech recognition Localization	Evaluate speech recognition and localization abilities of adults who use bimodal fittings.	12 adults with at least 3 mo of bimodal experience. All but one had extensive bilateral HA experience pre-implant.	Speech recognition: CNC words at 70 dBC; CUNY sentences at 70 dBC and multitalker babble with individually set SNRs. Noise and speech were presented from the front and also with the noise at 90º from the right or left. Localization: 8 loudspeaker array spaced along a 108º arc. Everyday sounds were presented at 70 dBC. The participant indicated the speaker source for each sound and the results were reported as RMS error.	Speech recognition: 4 of the 12 demonstrated binaural summation for CNC words in quiet, scoring significantly higher in the bimodal condition than with either CI or HA alone. 10 of the 12 scored significantly higher for CNC words with CI only than HA only. 7 of 11 had significantly higher scores on CUNY in noise with bimodal than CI or HA only. Group results indicated benefit from the use of the HA contralateral to the CI. One participant had a decrease in performance with the addition of the HA and for another, it did not provide either benefit or detriment. Localization: 3 patterns of results. 3 participants had relatively good localization with RMS values of 27 - 42 and responses to the correct side of presentation. 3 participants had RMS values of 46.8 – 48.6 with responses primarily to the side with the CI. 6 participants had RMS values from 38.6 – 48.7 with the responses falling more centrally, toward the 0º.	Binaural benefit was more likely to be seen in the presence of noise than in quiet. All participants continued to prefer bimodal device use, however the majority of adult CI recipients at the author's center do not choose to wear a HA in the nonimplanted ear. The authors suggest additional study is needed to understand why some individuals are able to integrate the two signals and others are not.
Hamzavi J, et al. Speech perception with a cochlear implant used in conjunction with a hearing aid in the opposite ear. Int J Audiol. 2004 Feb;43(2):61-5. Speech recognition	Evaluate speech recognition provided by bimodal fittings.	7 implanted adults who continued to use a HA on the contralateral ear. Participants had at least 1 yr experience with their CI. There was a wide range of residual hearing in HA ear.	Freiburger Numbers; Freiburger Monosyllables; Innsbrucker Sentences presented at 70 dB SPL in the sound-field.	On most measures for most individuals, the CI only performance was higher than HA only and bimodal was higher than CI only. One person did not follow this pattern and had a small decrease in bimodal compared to CI only for numbers and higher scores with the HA only than CI only for monosyllables. Ceiling effects were present for several participants, particularly on the numbers and sentences measures. Differences in mean scores for CI only and CI + HA were significant for sentences, monosyllables and numbers.	Study results indicate that bimodal use may provide improved speech recognition compared to the use of a CI alone. The possibility of post-implant use of a HA contralateral to the CI may need to be considered when deciding ear of implantation.
Kong YY, et al. Speech and melody recognition in binaurally combined acoustic and electric hearing. J Acoust Soc Am. 2005 Mar;117(3 Pt 1):1351-61. Speech recognition Melody recognition	To investigate the contribution of residual low frequency hearing in the nonimplanted ear to pitch perception and possible improvement in music and speech perception for CI recipients.	4 postlingual adult CI recipients in the first experiment. An additional person was included in the second experiment.	Speech recognition in noise: IEEE sentences presented at 65 dBA with another sentence spoken by a different talker used as the noise at 5 different SNRs (+20, +15, +10, +5 & 0 dB). Melody recognition: 3 sets of 12 single note versions of familiar tunes with rhythmic information removed so pitch was the only available cue. Participants selected the title of the tune they heard from a closed-set.	Speech recognition in noise: No speech recognition at any SNR for HA only condition. CI only and bimodal both had increasing levels of performance as the SNR was increased. The bimodal performance was higher than CI only for all participants, and that difference was significant at +15 & +10 dB SNRs. Melody recognition: Great variation between participants. On average, HA only melody recognition was 45% and CI only recognition was 28%. Bimodal was comparable to HA only. A single participant was evaluated with SAS and MPS strategies. The SAS strategy provided improved CI only melody recognition over the MPS strategy.	The provision of fine structure through low frequency acoustic hearing in the nonimplanted ear can improve speech perception in noise and music perception. It is important to include encoding of fine-structure cues in cochlear implants to allow for improved listening in noise and music perception even though these cues may not significantly improve speech understanding in quiet.

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Mok M, et al. Speech perception for adults who use hearing aids in conjunction with cochlear implants in opposite ears. J Speech Lang Hear Res. 2006 Apr;49(2):338-51. Speech recognition	Investigate the effect of bimodal device use for speech recognition in quiet and in noise. Identify additional speech information available in the bimodal condition compared to the CI alone condition.	14 adult CI recipients who either regularly wore a HA in the contralateral ear or had aidable hearing and were fit with a HA using NAL-RP prescription targets.	Speech recognition was tested with CNC words in quiet, CUNY sentences in noise (4-talker babble) at +10 dB SNR, and an adaptive spondee measure that resulted in a SNR. Speech was presented at 65 dB SPL from the front and noise was presented either from the front or 90º to the right or left.	CNC Words: Only 1 participant had significantly higher scores with bimodal than CI only and one subject had significantly higher scores with CI only (however the average word score for this participant in the CI only condition was <10%). Transformational analysis indicated a HA when combined with a CI provided low frequency information such as F1, diphthongs and nasals. CUNY Sentences in Noise: Group means indicated significantly higher scores for bimodal than CI only at +10 dB SNR. Adaptive Spondees in Noise: Group data indicated significant improvement with bimodal over CI only when the speech and noise were both from the front and when the noise was toward the CI. Significant improvement was not found for the group when the noise was toward the HA with one individual having significant improvement with bimodal over CI only and one individual having a significant decrement with bimodal compared to CI only.	Most adults who use a bimodal configuration receive benefit from the addition of the HA to the CI, however there are a few individuals who had some negative effect for speech recognition with the addition of the hearing aid to the CI, at least for some conditions. The bimodal listeners with greater aided levels in the mid to high-frequency range tended to have the worst performance in the bimodal condition. The authors suggest it is possible that the mid to high frequency information provided by both the CI and the HA may conflict. They recommend additional studies to evaluate the effects of bimodal device use.
Morera C, et al. Advantages of binaural hearing provided through bimodal stimulation via a cochlear implant and a conventional hearing aid: a 6-month comparative study. Acta Otolaryngol. 2005 Jun;125(6):596-606. Speech recognition	To examine the benefits of bimodal fittings for CI recipients who have enough residual hearing in the contralateral ear to benefit from a HA.	12 adults from 4 CI centers in Spanish hospitals who were implanted in the poorer hearing ear. Average unaided thresholds in the CI ear were 100 – 110 dB HL and in the non-implant ear were 85-95 dB HL.	Speech recognition was conducted with sentences and words at 70 and 55 dB SPL. Words in noise (+10 dB SNR with 4-talker babble) were presented with the speech and noise from the front, speech from the front and noise toward the CI, and speech from the front and noise toward the HA. Participants were evaluated pre-op and at 3 & 6-months post-op.	No significant difference between CI only and CI + HA, primarily due to ceiling effects for half the participants in the CI only condition. When speech and noise were both presented from the front, bimodal scores were significantly higher than HA only for 10 of the 12 participants and higher than CI only for 6 of the 12 participants. With speech from the front and noise toward the HA, 10 of the 12 performed significantly better in the bimodal than HA only condition. All participants performed better in the bimodal condition than either monaural condition, but this difference was only significant for half the participants compared to the CI only condition and 75% of the participants for the HA only condition.	Bimodal fittings can provide benefits at soft and conversational levels both in quiet and in noise. There is a trend for better bimodal performance for individuals with higher pre-operative speech recognition abilities in the ear that will continue to use a HA post-implant.

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Potts LG. Recognition and Localization of Speech by Adult Cochlear Implant Recipients Wearing a Digital Hearing Aid in the Non-implanted Ear (Bimodal Hearing) Doctoral Thesis. St. Louis, MO: Washington University School of Medicine; 2006. Speech recognition Localization Questionnaire	Evaluate the effects of using a well-fit digital HA contralateral to a CI.	19 adults who were experienced CI recipients fit with a digital HA. All participants used a Nucleus CI and Widex Senso Vita 38 HA.	Sound-field thresholds with FM tones and loudness growth contours. Localization: 15 loudspeaker array spaced along a 140º arc. CNC words were presented at 60 dB SPL (± 3 dB). Participants indicated the speaker source for each word and the results were reported as RMS error. Speech recognition: Roving-source speech recognition task with CNC words presented as with localization task. Participants repeated the word and the results were reported as % words correct. Questionnaire: Participants were given the SSQ.	Sound-field thresholds and loudness growth contours indicated binaural summation. Lower sound-field thresholds were noted in the bimodal condition compared to the CI only condition. The bimodal condition was significantly better for localization and roving-source speech recognition than the CI only or HA only conditions. In addition, performance was better in the monaural conditions (HA-only and CI-only) when the stimuli was presented from the amplified side of the array (i.e. side closest to the ear wearing the device). In the bimodal condition, performance was equivalent whether stimuli were presented on the CI or HA side. Variables related to audibility of sound in the HA ear were predictors of performance for these measures.	Unilateral CI recipients may benefit from the use of a HA on the contralateral ear, if efforts are made to ensure optimal fitting of an appropriate hearing aid. Sound detection, speech recognition and localization abilities all benefited from the bimodal condition compared to the CI only condition.
Seeber BU, et al. Localization ability with bimodal hearing aids and bilateral cochlear implants. J Acoust Soc Am 2004; 116(3):1698-709. Localization	Assess localization ability of adult CI recipients.	11 adult bimodal listeners and 4 bilateral implant recipients.	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). Gaussian white noise presented at 70 dB SPL (±6 dB). The participant indicated the source for each sound using a computer-controlled laser pointer to allow 2º accuracy.	Bimodal group: 4 participants were unable to localize at all; 4 were able to localize side of presentation; 2 had some limited localization ability; and 1 had excellent localization skills in the bimodal condition. Of the 7 who were able to localize, 2 had substantial residual hearing and 4 could localize to some degree with a single device. Bilateral CI group: One subject showed near-normal localization accuracy and could also locate the side of presentation using the first CI alone. The other 3 showed limited localization ability in the bilateral condition, one of whom demonstrated side-discrimination ability with the 1st device only.	CI recipients may be able to localize on the horizontal plane to varying degrees through either bilateral CIs or, with sufficient residual hearing, through bimodal device use. The best performing subjects showed accuracy near to normal-hearing subjects.

Study	Objectives	Participants	Methods	Results	Conclusions
Tyler RS, et al. Patients utilizing a hearing aid and a cochlear implant: speech perception and localization. Ear Hear. 2002;23(2):98-105. Speech recognition Localization Questionnaire	A pilot study to evaluate speech recognition and localization abilities for individuals using a HA contralateral to a CI.	3 of 9 adults who responded to a questionnaire about continued HA use and were willing to participate in studies.	Questionnaire: Asked participant why each continued HA use, where sound was heard (center of head or closer to HA/CI ear), loudness of sound (equal, louder HA /CI), and whether the sound from the HA and CI became fused. Speech recognition: CUNY sentences and NU6 words at 70 dB SPL. Speech was presented from front and noise (multi-talker babble) from front or 90º to the right or left. Localization: 2 speakers set up at 45º to the right and 45º to the left. Bursts of speech noise were presented randomly at 73, 77 or 83 dB SPL. Participants were asked to indicate whether the sound was from the right or left speaker.	Questionnaires: 2 of the 3 participants had fused sounds. Speech recognition: None of the 3 scored higher in the bimodal condition compared to the CI only for words or sentences in quiet. 2 of the 3 scored significantly higher in the bimodal than the CI only condition for CUNY sentences in noise when noise was from the front. When speech and noise were separated, only 1 participant showed improvement in the bimodal condition and that was with noise on the CI side. Localization: All 3 participants were at chance for HA only, 2 were at chance with CI only, all were above chance in the bimodal condition and 1 was above chance in the CI only condition.	This pilot study indicated that bimodal advantages are present for some individuals and that some testing arrangements are more sensitive to bimodal benefit than others. The authors suggest that more coordinated processing or efforts to complement the information provided by each device may improve bimodal benefit.

Note: For all studies, testing was conducted with each device alone and also in the bimodal condition. BBN = broad band noise; BKB = Bamford-Knowal-Bench; BKB/A = Bamford-Knowal-Bench, Australian version; BTE = behind-the-ear; CI = cochlear implant; CNC = Consonant-Nucleus-Consonant; CUNY = City University of New York; dB = decibels; HA = hearing aid; HL = hearing level; LE = left ear; MPS = multiple pulsatile sampler; NAL = National Acoustic Laboratories; NH = normal hearing; RE = right ear; RMS = root mean square; SAS = simultaneous analog stimulation; SNR = signal-to-noise ratio; SPL = sound pressure level.