Fitting Bimodal Devices in Children – A Review

Lisa S. Davidson, PhD.

Abstract

Bimodal device use cochlear implant (CI) plus hearing aid (HA) on the non-implanted ear is one way to achieve some degree of binaural stimulation of the auditory pathways for children with severe to profound hearing loss requiring cochlear implantation. Bimodal devices are able to partially alleviate many of the listening challenges related to unilateral CI use. The numbers of children using bimodal devices will likely increase as children with more residual hearing are considered as candidates for cochlear implantation. The need for a coordinated fitting between the CI and the HA becomes more relevant as bimodal device users present with greater degrees of residual hearing at the non-implanted ear. This paper will summarize the issues related to fitting the cochlear implant and the hearing aid for bimodal use and review the research literature related to bimodal fittings.

The normal auditory system is highly reliant upon input from both ears for recognizing, localizing and understanding speech in everyday listening environments. For children with severe to profound sensorineural hearing losses requiring cochlear implantation, some degree of binaural stimulation of the auditory pathways may be achieved by wearing a cochlear implant (CI) coupled with a hearing aid (HA) at the non-implanted ear or a CI at both ears (Ching, van Wanrooy, & Dillon, 2007; Sammeth, Bundy, & Miller, 2011). Combining electrical hearing via a CI with acoustic hearing via a HA at the non-implanted ear is frequently referred to as bimodal device use. Bimodal fittings can at least partially alleviate many of the listening challenges encountered when listening with only one CI including localization and listening in noise. Bimodal benefits for children and adults have varied across studies and have included improved speech perception in quiet and noise, localization, speech quality, music appreciation/recognition & ease of listening (Ching et al., 2007; Sammeth et al., 2011; Schafer, Amlani, Paiva, Nozari, & Verret, 2011). In addition to improved listening skills, recent evidence suggests that a period of bimodal device use may result in improved language outcomes and emerging literacy skills for children receiving CIs (Nittrouer, Caldwell, Lowenstein, Tarr, & Holloman, 2012; Nittrouer & Chapman, 2009).

Although the mechanisms underlying bimodal benefits are not completely understood, most research suggests that low-frequency acoustic cues from the HA are primarily responsible for the improvements observed in speech perception (Ching et al., 2007; Dorman, Gifford, Spahr, & McKarns, 2008; Sheffied, 2011; Tyler et al., 2002). Furthermore, several studies have suggested that low frequency acoustic cues allow for transmission of a higher quality fundamental frequency (F0) than that provided by electrical stimulation with current CI systems (Brown & Bacon, 2009; Chang, Bai, & Zeng, 2006; Kong, Stickney, & Zeng, 2005; Qin & Oxenham, 2006; Turner, Gantz, Vidal, Behrens, & Henry, 2004; Vongphoe & Zeng, 2005). In addition, improved phoneme perception including consonant voicing and manner and transmission of low frequency phonemes such as nasals, diphthongs and glides have been documented in bimodal users (T. Ching et al., 2005; M. Mok, D. Grayden, R. C. Dowell, & D. Lawrence, 2006).

Consistent audibility in a variety of listening situations is a necessary prerequisite for spoken language development and it becomes paramount for children with congenital hearing loss (Bess, Dodd-Murphy, & Parker, 1998; Flexer, 1999; Ross, 1990). Children using unilateral CIs are at a great disadvantage for localizing sounds and for understanding speech in the presence of background noise, therefore many audiologists are considering either bimodal or bilateral CIs in their clinical fitting protocols. Bimodal fittings are likely to increase as cochlear implant candidacy guidelines expand to include individuals with a greater degree of residual hearing (Gifford, Dorman, Shallop, & Sydlowski, 2010). Adults and children with residual hearing thresholds that are within the CI Candidacy range for one ear (i.e. severe to profound), but have less severe losses at the opposite ear are now being considered for CIs in order to capitalize on binaural stimulation through bimodal device use (Cadieux, Firszt, & Reeder, 2013; Firszt, Holden, Reeder, Cowdrey, & King, 2012). The need for a coordinated fitting between the CI and the HA becomes more relevant as bimodal device users present with greater degrees of residual hearing at the non-implanted ear.

There are several obstacles related to fitting bimodal devices which combine acoustic and electric stimulation from the HA and CI respectively. These not only stem from psychophysical mismatches across the two devices for timing, intensity and frequency cues, but also mismatches in amplitude processing with current available commercial devices (Francart & McDermott, 2013). While there are no standardized or validated fitting protocols for bimodal devices, some studies suggest that a coordinated fitting between the two devices may be necessary for optimal benefit (Blamey, Dooley, James, & Parisi, 2000; T. Ching, Psarros, Hill, Dillon, & Incerti, 2001). Ching et al. (2001) reported on 16 children (age 6-18 years) with a Nucleus 22 or 24 CI who used a hearing aid in the non-implanted ear. Children were evaluated on several outcome measures including tests of speech perception, localization and surveys of communicative function. The HAs for the non-implanted ear were initially fit using National Acoustics Laboratories-Revised Profound [NAL-RP (Byrne, Parkinson, & Newall, 1991) targets and the frequency response was further adjusted so that the loudness between both devices was balanced. Results revealed that all children tested for binaural effects demonstrated benefit on at least one of the measures used when the individual fitting of the hearing aid was set to match the loudness of the cochlear implant. Subsequent studies have not directly examined the effects of coordinated loudness procedures on bimodal outcomes; however they have been careful to outline that some type of loudness balancing was done. A study conducted on 14 adult bimodal users reported on a fitting procedure where 7 of the participants adjusted the volume of the HA to match the overall loudness of the CI using running speech at conversation levels ~ 65 dB SPL. The HAs were initially set to match NAL-RP targets (M. Mok et al., 2006). A subsequent study of 8 adult and 12 pediatric bimodal participants (age 3 -14 years) outlined a fitting procedure where the HAs were initially set to meet Desired Sensation Level (DSL) targets (Cornelisse, Seewald, & Jameson, 1994). Loudness scaling procedures, speech perception testing and subjective reports were conducted with each device alone and both devices combined (bimodal) and adjustments were made to each device in an in an attempt to obtain a bimodal score that was superior to either device alone (Keilmann, Bohnert, Gosepath, & Mann, 2009). Notably, the authors reported that children age 10 years or older were able to complete the loudness scaling task required for the bimodal fitting and the total length of the fitting session lasted between 3-5 hours. The authors concluded that most adults and children that could undergo the fitting procedures showed bimodal benefit (i.e. CI+HA scores better than CI or HA alone).

While the reported procedures for balancing loudness between the two devices have varied and are not standardized, there is a general consensus that some form of loudness balancing may be beneficial. Determining how frequency information should be allocated to the CI and the HA is much less clear. For the audiologist fitting these devices this entails determining the degree of frequency overlap, if any, between the CI and HA. When parsing the benefits of bimodal devices according to the frequency information transmitted, it is generally accepted that the benefits of the HA are related to low frequency regions and the CI are related to high frequency regions. This seems reasonable given that the typical hearing threshold profile for the non-implanted ear (i.e. HA ear) show thresholds ranging from mild to severe in the low to mid frequency region (~250-1000 Hz) and severe to profound in the high frequency regions (2000-4000Hz). Earlier studies of frequency overlap between the CI and HA were conducted using combined acoustic and electric stimulation (EAS) at the same ear (sometimes called ipsi-lateral EAS). Fitting procedures, research methods and not surprisingly conclusions varied across theses studies with recommendations ranging from no frequency overlap to some degree of overlap (Gantz & Turner, 2004; James et al., 2006; Kiefer et al., 2005; Simpson, McDermott, Dowell, Sucher, & Briggs, 2009; Vermeire, Anderson, Flynn, & Van de Heyning, 2008). One study in particular stressed that the EAS fitting should take into account the degree and configuration of the acoustic thresholds (Vermeire et al., 2008).

Based on our basic understanding of bimodal mechanisms it seems reasonable for audiologists to primarily focus on the low frequency regions, or regions with the greater degree of residual hearing when setting the gain and output of the HA for bimodal fittings. This would be in contrast to routine bilateral HA fittings where audibility across the greatest frequency range is targeted. The results from studies to date have been inconclusive. A study of nine pediatric bimodal recipients found that better low frequency aided thresholds with the HA and poorer aided thresholds at 4000 Hz were associated with greater bimodal benefit for speech perception in quiet and noise (Mok, Galvin, Dowell, & McKay, 2010). The authors suggest that this may have been the result of frequency mismatch between the CI and HA, and that a possible solution would be to limit the gain of the HA at the higher frequency regions. Results from an earlier study with adult bimodal recipients demonstrated that poorer aided thresholds in the high frequency region were associated with greater bimodal benefits (Mansze Mok, David Grayden, Richard C. Dowell, & David Lawrence, 2006). Potts and colleagues (Potts, Skinner, Litovsky, Strube, & Kuk, 2009) found a different pattern of results for adult bimodal recipients for speech recognition and localization, showing that better audibility at 2000Hz was related to better performance. These studies, however did not systematically examine the effects of frequency overlap across devices.

A study of adult bimodal users examined the benefits of reducing the frequency overlap between the acoustic signal and the electric signal using open set word recognition in quiet and sentence recognition in noise (Zhang, Spahr, & Dorman, 2010). The electrical signal was presented directly to the CI device in the following conditions: unfiltered and high pass filtered at 250, 500 and 750 Hz. The acoustic signal was delivered via a headphone as follows: unfiltered and low pass (LP) filtered at 250, 500 and 750 Hz. The gain and output of the acoustic signal for each participant was based on unaided thresholds and NAL-RP targets. Participants were tested in each condition using electric and acoustic alone and in the combined condition pairing the LP and HP conditions (i.e. unfiltered acoustic + unfiltered CI or widest, 250 LP acoustic +250 HP CI, 500 LP acoustic+, 500 HP CI etc.). Performance in the widest conditions was best for electric and acoustic stimulation alone and the combined conditions, thus reducing the frequency overlap for these bimodal users did not improve performance. Notably, the acoustic frequency range < 250 Hz accounted for the majority of benefit in the acoustic and electric combined condition. This led the authors to conclude that: 1) even participants with only limited low frequency residual hearing at the HA may benefit from bimodal stimulation 2) reducing high frequency gain of the HA may reduce acoustic feedback, prolong battery life and prevent off frequency listening. A more recent study addressed the topic of frequency overlap across the two devices with a couple of key differences (Neuman & Svirsky, 2013). The first difference was that each participant's personal HA was used instead of an earphone. The second difference was that the CI frequency allocation remained the same (widest) and only the HA frequency bandwidth was varied. Fourteen adult bimodal recipients were tested with words in quiet and sentences in noise with the 4 different HA frequency responses. The wideband HA frequency response was determined by matching the gain and output to NAL-RP targets as closely as possible. The bandwidth of the HA was then systemically restricted at 500, 1000 and 2000 Hz. Bimodal benefit was defined as better scores in the bimodal condition/s compared to the CI only. The best performance was obtained when the gain and output were amplified across the widest frequency range of usable residual hearing. Furthermore, restricting the gain below 1000 Hz did not provide greater benefit.

There has also been increasing interest in using frequency lowering technology available in HAs for bimodal fittings. Different manufacturers employ various algorithms and use different names for HA technology that is designed to shift high frequency information to a lower frequency region (Glista et al., 2009). Non-linear frequency compression (NLFC) is one type of algorithm that is implemented in HAs by only compressing higher frequencies in a predetermined range and leaving lower frequencies unchanged. This allows for improved audibility of consonants without possible distortion of low frequency vowel formants. These parameters, referred to as the cut-off frequency and compression ratio, are adjusted by the clinician (McDermott & Henshall, 2010). In general, the default settings recommend that the minimum amount of compression be employed as increasing the range of frequencies that are compressed can cause detriments to sound quality and discrimination of vowel sounds. Individuals with severe to profound hearing loss in the high frequency range are typical candidates for frequency lowering HAs since many are unable to achieve adequate high frequency audibility due to limited gain and acoustic feedback.

High frequency audibility assumes a critical role in linguistic development for children acquiring spoken English skills. Specifically, many consonant sounds consist of high frequency energy that contributes to overall speech intelligibility (Miller & Nicely, 1955) and the English phonemes /s/ and /z/ serve as important markers for plurality and possession (Moeller, Hoover, Putman, Arbataitis, Bohnenkamp, Peterson, Lewis, et al., 2007; Moeller, Hoover, Putman, Arbataitis, Bohnenkamp, Peterson, Wood, et al., 2007; P. G. Stelmachowicz, Lewis, Choi, & Hoover, 2007). This is supported by several studies demonstrating that children require a wider frequency bandwidth for optimal perception of speech compared to adults (Pittman, Lewis, Hoover, & Stelmachowicz, 2005; Pittman & Stelmachowicz, 2000; Patricia G. Stelmachowicz, Pittman, Hoover, & Lewis, 2002). Modest positive results, especially for detection of high frequency phonemes, have been documented for children with moderate to severe hearing loss using frequency lowering HAs (McCreery, Venediktov, Coleman, & Leech, 2012). This has led many clinicians and researchers to examine if NLFC should be considered for bimodal recipients.

Alternatively, it may be reasonable to be concerned that this type of processing could interfere with the CI processing given that for most bimodal recipients the transmission of high frequency information is transmitted via the CI. Differences in the place of high frequency stimulation of the cochlea across the two devices as well as overall processing differences may be expected to interfere with binaural processing. To date the literature for adult and pediatric bimodal recipients has produced mixed results. Two studies with adult bimodal recipients failed to demonstrate benefits of NLFC over the conventional HA setting (NLFC not activated). One study with eight adult bimodal recipients did not find any benefit, or detriment with NLFC activated vs. not activated for consonant perception in quiet and sentences in noise, however participants readily accepted NLFC (McDermott and Henshall, (2010). A recent study on 10 adult bimodal recipients found no benefits for NLFC for spondee recognition in noise or localization and many of the participants reported that NLFC produced a “harsh” or “distorted” sound quality (Perreau, Bentler, & Tyler, 2013). A study of 11 pediatric bimodal participants found no benefit with HAs with NLFC vs. without NLFC for word and consonant recognition in quiet and sentence recognition in noise, however many of these pediatric participants preferred using NLFC (Park, Teagle, Buss, Roush, & Buchman, 2012). The compression cut-off frequency and compression ratio were set for participants in these studies based on individual hearing thresholds. The verification procedures varied across studies with some verifying audibility using live voice presentation of the phonemes /s/ and / sh / and measuring the simulated real ear output compared to the unaided thresholds from 2000-4000 Hz. Others presented recorded 4000 and 6300 Hz speech bands or high frequency inputs generated from a probe microphone system.

The review of the literature on the effects of various HA settings on bimodal benefit have mainly included leaving the CI program unchanged (i.e. widest frequency allocation) and varying the HA frequency response to some degree. The results from Zhang et al (2010) support allowing the CI map to cover the standard frequency range (i.e. 250-4000 Hz) and to consider various options for the HA response. This seems to be reasonable given that most, though not all, bimodal recipients consider the CI their primary device. The fact that these studies have produced such mixed results is not necessarily surprising given the variability across research methods, HA fitting procedures, outcome measures, hearing threshold profiles and clinical populations (i.e. adults vs. pediatric). A common component of many of these studies is that there is a considerable degree of individual variability as to the best “condition” (McDermott & Henshall, 2010; Park et al., 2012). Clinical audiologists know that their patients present with a variety of hearing backgrounds, individual needs and abilities, thus there is no “one size fits all” for fitting devices. Likewise, fitting procedures, targets and recommendations for adults may not necessarily apply to children. In order to best serve their pediatric bimodal population, audiologists should attempt some type of procedure for balancing audibility and loudness across the two devices. There are no standardized procedures or guidelines; however several of the studies mentioned above outline some protocols for doing so. Most start with using a prescriptive fitting target for the HA with gain and output modified when listening with the CI and HA combined. The ability to conduct a detailed protocol will necessarily be limited by the age and abilities of the child; however setting both devices for good audibility is a good start. This would involve aided thresholds near 20 dB HL from 250-6000 Hz for the CI and matching prescriptive targets for the HA at input levels (i.e. DSL targets) from soft to loud.

Summary

Audiologists may consider modifying the frequency response of the HA for individuals demonstrating minimal bimodal benefit with conventional settings. This may include restricting the gain to low or mid frequency regions depending on the residual hearing. The audiologist may consider activating NLFC as well. Careful monitoring and testing would be important. Verification of audibility should be conducted using all or some combination of live voice detection of phonemes or audibility of recorded speech bands (4000 and 6300 Hz) with a real ear measurement system. A variety of speech measures that replicate real world listening conditions is needed and may include measures beyond word and sentence recognition in quiet and noise. Among those to be considered would be localization tasks, music/melody perception, talker discrimination and parent/self report questionnaires.

Conclusion

Given that receiving a second CI will require a surgical intervention, clinicians and parents must carefully weigh the decision to proceed from bimodal to bilateral CIs and careful monitoring and testing should be conducted. It is important to note that reviews of the literature on bimodal vs. bilateral CIs have not produced definitive results as to the device configuration that will provide the greatest benefit for an individual (Ching et al., 2007; Schafer et al., 2011). It will also be important to consider bilateral CIs for those children who demonstrate little or no benefit from bimodal fittings.

References

Bess, F. H., Dodd-Murphy, J., & Parker, R. A. (1998). Children with minimal sensorineural hearing loss: prevalence, educational performance, and functional status. *Ear and Hearing,* 19(5), 339-354.

Blamey, P. J., Dooley, G. J., James, C. J., & Parisi, E. S. (2000). Monaural and binaural loudness measures in cochlear implant users with contralateral residual hearing. *Ear and Hearing,* 21(1), 6-17.

Brown, C. A., & Bacon, S. P. (2009). Low-frequency speech cues and simulated electric-acoustic hearing. *Journal of the Acoustical Society of America,* 125(3), 1658-1665. doi: 10.1121/1.3068441

Byrne, D., Parkinson, A., &, & Newall, P. (1991). Modified hearing aid selection procedures for severe/profound hearing losses. In G. A. Studebaker, F. H. Bess, & L. Beck (Eds.), *Vanderbilt hearing aid report II* (pp. (pp. 295–300). Parkton, MD: York Press.

Cadieux, J. H., Firszt, J. B., & Reeder, R. M. (2013). Cochlear implantation in nontraditional candidates: preliminary results in adolescents with asymmetric hearing loss. *Otology and Neurotology,* 34(3), 408-415. doi: 10.1097/MAO.0b013e31827850b8

Chang, J. E., Bai, J. Y., & Zeng, F. G. (2006). Unintelligible low-frequency sound enhances simulated cochlear-implant speech recognition in noise. *IEEE Transactions in Biomedical Engineering,* 53(12 Pt 2), 2598-2601. doi: 10.1109/TBME.2006.883793

Ching, van Wanrooy, E., & Dillon, H. (2007). Binaural-bimodal fitting or bilateral implantation for managing severe to profound deafness: a review. *Trends in Amplification,* 11(3), 161-192. doi: 11/3/161 [pii] 10.1177/1084713807304357

Ching, T., Hill, M., Brew, J., Incerti, P., Priolo, S., Rushbrook, E., & Forsythe, L. (2005). The effect of auditory experience on speech perception, localization, and functional performance of children who use a cochlear implant and a hearing aid in opposite ears. *International Journal of Audiology,* 44(12), 677-690. doi: Doi 10.1080/00222930500271630

Ching, T., Psarros, C., Hill, M., Dillon, H., & Incerti, P. (2001). Should children who use cochlear implants wear hearing aids in the opposite ear? *Ear and Hearing,* 22(5), 365-380.

Cornelisse, L. E., Seewald, R. C., & Jameson, D. G. (1994). Fitting wide dynamic range compression hearing aids: the DSL approach. *Hearing Journal,* 47, 23-29.

Dorman, M. F., Gifford, R. H., Spahr, A. J., & McKarns, S. A. (2008). The benefits of combining acoustic and electric stimulation for the recognition of speech, voice and melodies. *Audiology and Neurotology,* 13(2), 105-112. doi: 10.1159/000111782

Firszt, J. B., Holden, L. K., Reeder, R. M., Cowdrey, L., & King, S. (2012). Cochlear implantation in adults with asymmetric hearing loss. *Ear and Hearing,* 33(4), 521-533. doi: 10.1097/AUD.0b013e31824b9dfc

Flexer, C. A. (1999). The importance of hearing and the impact of hearing problems. *Facilitating Hearing and Listening in Young Children* (Second Edition ed., pp. 1-22). San Diego: Singular Publishing Group.

Francart, T., & McDermott, H. J. (2013). Psychophysics, fitting, and signal processing for combined hearing aid and cochlear implant stimulation. *Ear and Hearing,* 34(6), 685-700. doi: 10.1097/AUD.0b013e31829d14cb

Gantz, B. J., & Turner, C. (2004). Combining acoustic and electrical speech processing: Iowa/Nucleus hybrid implant. *Acta Otolaryngolica,* 124(4), 344-347.

Gifford, R. H., Dorman, M. F., Shallop, J. K., & Sydlowski, S. A. (2010). Evidence for the expansion of adult cochlear implant candidacy. *Ear and Hearing,* 31(2), 186-194. doi: 10.1097/AUD.0b013e3181c6b831

Glista, D., Scollie, S., Bagatto, M., Seewald, R., Parsa, V., & Johnson, A. (2009). Evaluation of nonlinear frequency compression: clinical outcomes. *International Journal of Audiology,* 48(9), 632-644. doi: 10.1080/14992020902971349

James, C. J., Fraysse, B., Deguine, O., Lenarz, T., Mawman, D., Ramos, A., . . . Sterkers, O. (2006). Combined electroacoustic stimulation in conventional candidates for cochlear implantation. *Audiology and Neurotology,* 1(11 Suppl), 57-62. doi: 10.1159/000095615

Keilmann, A. M., Bohnert, A. M., Gosepath, J., & Mann, W. J. (2009). Cochlear implant and hearing aid: a new approach to optimizing the fitting in this bimodal situation. *European Archives of Otorhinolaryngology,* 266(12), 1879-1884. doi: 10.1007/s00405-009-0993-9

Kiefer, J., Pok, M., Adunka, O., Sturzebecher, E., Baumgartner, W., Schmidt, M., . . . Gstoettner, W. (2005). Combined electric and acoustic stimulation of the auditory system: results of a clinical study. *Audiology and Neurotology,* 10(3), 134-144. doi: 84023 [pii] 10.1159/000084023

Kong, Y. Y., Stickney, G. S., & Zeng, F. G. (2005). Speech and melody recognition in binaurally combined acoustic and electric hearing. *Journal of the Acoustical Society of America,* 117(3 Pt 1), 1351-1361.

McCreery, R. W., Venediktov, R. A., Coleman, J. J., & Leech, H. M. (2012). An Evidence-Based Systematic Review of Frequency Lowering in Hearing Aids for School-Age Children With Hearing Loss. *American Journal of Audiology,* 21(2), 313-328. doi: 10.1044/1059-0889(2012/12-0015)

McDermott, H., & Henshall, K. (2010). The use of frequency compression by cochlear implant recipients with postoperative acoustic hearing. *Journal of the American Academy of Audiology,* 21(6), 380-389. doi: 10.3766/jaaa.21.6.3

Miller, G. A., & Nicely, P. E. (1955). An Analysis of Perceptual Confusions Among Some English Consonants. *Journal of the Acoustical Society of America,* 27(2), 338-352.

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B., . . . Stelmachowicz, P. (2007). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part II–transition to words. *Ear and Hearing,* 28(5), 628-642. doi: 10.1097/AUD.0b013e31812564c9

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B., . . . Stelmachowicz, P. (2007). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I–phonetic development. *Ear and Hearing,* 28(5), 605-627. doi: 10.1097/AUD.0b013e3181256 4ab00003446-200709000-00002 [pii]

Mok, M., Galvin, K. L., Dowell, R. C., & McKay, C. M. (2010). Speech perception benefit for children with a cochlear implant and a hearing aid in opposite ears and children with bilateral cochlear implants. *Audiology and Neurotology,* 15(1), 44-56. doi: 000219487 [pii]10.1159/000219487

Mok, M., Grayden, D., Dowell, R. C., & Lawrence, D. (2006). Speech Perception for Adults Who Use Hearing Aids in Conjunction With Cochlear Implants in Opposite Ears. *Journal of Speech, Language, and Hearing Research,* 49(2), 338-351.

Mok, M., Grayden, D., Dowell, R. C., & Lawrence, D. (2006). Speech perception for adults who use hearing aids in conjunction with cochlear implants in opposite ears. *Journal of Speech, Language and Hearing Research,* 49(2), 338-351. doi: 10.1044/1092-4388(2006/027)

Neuman, A. C., & Svirsky, M. A. (2013). Effect of hearing aid bandwidth on speech recognition performance of listeners using a cochlear implant and contralateral hearing aid (bimodal hearing). *Ear and Hearing,* 34(5), 553-561. doi: 10.1097/AUD.0b013e31828e86e8

Nittrouer, S., Caldwell, A., Lowenstein, J. H., Tarr, E., & Holloman, C. (2012). Emergent literacy in kindergartners with cochlear implants. *Ear and Hearing,* 33(6), 683-697. doi: 10.1097/AUD.0b013e318258c98e

Nittrouer, S., & Chapman, C. (2009). The effects of bilateral electric and bimodal electric–acoustic stimulation on language development. *Trends in Amplification,* 13(3), 190-205. doi: 10.1177/1084713809346160

Park, L. R., Teagle, H. F., Buss, E., Roush, P. A., & Buchman, C. A. (2012). Effects of frequency compression hearing aids for unilaterally implanted children with acoustically amplified residual hearing in the nonimplanted ear. *Ear and Hearing,* 33(4), e1-e12. doi: 10.1097/AUD.0b013e31824a3b97

Perreau, A. E., Bentler, R. A., & Tyler, R. S. (2013). The contribution of a frequency-compression hearing aid to contralateral cochlear implant performance. *Journal of the American Academy of Audiology,* 24(2), 105-120. doi: 10.3766/jaaa.24.2.4

Pittman, A. L., Lewis, D. E., Hoover, B. M., & Stelmachowicz, P. G. (2005). Rapid word-learning in normal-hearing and hearing-impaired children: effects of age, receptive vocabulary, and high-frequency amplification. *Ear and Hearing,* 26(6), 619-629. doi: 00003446-200512000-00008 [pii]

Pittman, A. L., & Stelmachowicz, P. G. (2000). Perception of voiceless fricatives by normal-hearing and hearing-impaired children and adults. *Journal of Speech, Language and Hearing Research,* 43(6), 1389-1401.

Potts, L. G., Skinner, M. W., Litovsky, R. A., Strube, M. J., & Kuk, F. (2009). Recognition and localization of speech by adult cochlear implant recipients wearing a digital hearing aid in the nonimplanted ear (bimodal hearing). *Journal of the American Academy of Audiology,* 20(6), 353-373.

Qin, M. K., & Oxenham, A. J. (2006). Effects of introducing unprocessed low-frequency information on the reception of envelope-vocoder processed speech. *Journal of the Acoustical Society of America,* 119(4), 2417-2426.

Ross, M. (1990). Implications of delay in detection and management of deafness. *Volta Review,* 92, 69-79.

Sammeth, C. A., Bundy, S. M., & Miller, D. A. (2011). Bimodal Hearing or Bilateral Cochlear Implants: A Review of the Research Literature. *Seminars in Hearing,* 32(01), 003-031. doi: 10.1055/s-0031-1271945

Schafer, E. C., Amlani, A. M., Paiva, D., Nozari, L., & Verret, S. (2011). A meta-analysis to compare speech recognition in noise with bilateral cochlear implants and bimodal stimulation. *International Journal of Audiology,* 50(12), 871-880. doi: 10.3109/14992027.2011.622300

Sheffied, B. M. Z., F. G. (2011). The relative phonetic contributions of a cochlear implant and residual acoustic hearing to bimodal speech perception. *Journal of the Acoustical Society of America,* 131(1), 518-530.

Simpson, A., McDermott, H. J., Dowell, R. C., Sucher, C., & Briggs, R. J. S. (2009). Comparison of two frequency-to-electrode maps for acoustic-electric stimulation. *International Journal of Audiology,* 48(2), 63-73. doi: doi:10.1080/14992020802452184

Stelmachowicz, P. G., Lewis, D. E., Choi, S., & Hoover, B. (2007). Effect of stimulus bandwidth on auditory skills in normal-hearing and hearing-impaired children. *Ear and Hearing,* 28(4), 483-494. doi: 10.1097/AUD.0b013e31806dc26500003446-200708000-00006 [pii]

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2002). Aided Perception of /s/ and /z/ by Hearing-Impaired Children. [Article]. *Ear & Hearing* 23(4), 316-324.

Turner, C. W., Gantz, B. J., Vidal, C., Behrens, A., & Henry, B. A. (2004). Speech recognition in noise for cochlear implant listeners: benefits of residual acoustic hearing. *Journal of the Acoustical Society of America,* 115(4), 1729-1735.

Tyler, R. S., Parkinson, A. J., Wilson, B. S., Witt, S., Preece, J. P., & Noble, W. (2002). Patients utilizing a hearing aid and a cochlear implant: speech perception and localization. *Ear and Hearing,* 23(2), 98-105.

Vermeire, K., Anderson, I., Flynn, M., & Van de Heyning, P. (2008). The influence of different speech processor and hearing aid settings on speech perception outcomes in electric acoustic stimulation patients. *Ear and Hearing,* 29(1), 76-86. doi: 10.1097/AUD.0b013e31815d6326

Vongphoe, M., & Zeng, F. G. (2005). Speaker recognition with temporal cues in acoustic and electric hearing. *Journal of the Acoustical Society of America,* 118(2), 1055-1061.

Zhang, T., Spahr, A. J., & Dorman, M. F. (2010). Frequency Overlap Between Electric and Acoustic Stimulation and Speech-Perception Benefit in Patients with Combined Electric and Acoustic Stimulation. *Ear and Hearing,* 31(2), 195-201. doi: Doi 10.1097/Aud.0b013e3181c4758d