EFFECT OF HEARING AID BANDWIDTH

ON SPEECH IDENTIFICATION

IN CHILDREN USING BIMODAL DEVICES

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CERTIFICATE

This is to certify that this dissertation entitled **'Effect of hearing aid bandwidth on speech identification in children using bimodal devices'** is the bonafide work submitted in part fulfilment for the degree of Master of Science (Audiology) of the student Registration Number: 17AUD014. This has been carried out under the guidance of the faculty of the institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this dissertation entitled **'Effect of hearing aid bandwidth on speech identification in children using bimodal devices'** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **'Effect of hearing aid bandwidth on speech identification in children using bimodal devices'** is the result of my own study under the guidance of Dr. P. Manjula, Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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Abstract

Individuals with severe to profound degree of hearing loss who undergo cochlear implantation in one ear are recommended to use a second cochlear implant or a hearing aid in the contralateral ear. Addition of a second device in the non-implanted ear enables improved speech perception mainly in the presence of noise and sound localization. Since bilateral cochlear implant (CI) is not an affordable option, most of the children use a hearing aid (HA) in the ear contralateral to the cochlear implant. Hence, a coordinated fitting between the cochlear implant and hearing aid is important. The frequency range of the hearing aid that needs to be amplified in bimodal stimulation is not quite clear. The aim of the present study was to determine the effect of hearing aid bandwidth on speech identification in a group of 12 children with severe to profound degree of hearing loss. Three different frequency bandwidths were stored in three different memories/programs of the hearing aid, i.e., wideband amplification in Program 1, low pass with a cut-off set to 2 kHz in Program 2 and low pass with a cut-off set to 1 kHz in Program 3.

The speech identification was measured using bi-syllabic words of the speech identification test for Kannada speaking children (Vandana, 1998) at two presentation levels, i.e., 45 dB HL and 75 dB HL in closed-set. The speech identification score (SIS) was obtained in four aided conditions i.e., CI alone condition, CI + HA with hearing aid in wideband response (CI+WB HA), CI + HA with low pass cut-off at 2 kHz (CI+2k HA), CI + HA with low pass cut-off at 1 kHz (CI+1k HA) at each presentation level.

Repeated measures ANOVA was carried out to compare the scores in four aided conditions followed by Bonferroni pair-wise analysis. The results revealed that the best SIS was obtained in CI+WB HA condition and CI+2k HA condition followed by CI+1k

HA and CI alone condition. To conclude, the study showed that amplification of a wide frequency region or at least till 2 kHz was required to provide best bimodal benefit. Though amplification till 1 kHz was not sufficient to provide optimum bimodal benefit, the mean scores were better than CI alone condition. Thus, it can be inferred that bimodal stimulation provides benefit in terms of speech identification.

Key words: bimodal, cochlear implant, hearing aid, speech identification, bandwidth.

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Chapter 1

Introduction

A cochlear implant is a device that by-passes the outer, middle, and inner ear to directly stimulate the auditory nerve (Clark, 2003). In India, most of the children who undergo cochlear implant surgery are implanted unilaterally as bilateral cochlear implantation is expensive. In order to prevent auditory deprivation and to obtain binaural advantage, a hearing aid is recommended in the non-implanted ear. This is referred to as bimodal stimulation. In bimodal stimulation, as defined by Clark (2003), one ear gets the electric stimulation through cochlear implant, and the other ear with residual hearing gets the acoustic stimulation, through a hearing aid.

Addition of a second device in the non-implanted ear enables improved speech perception mainly in the presence of noise and sound localization (Seeber, Baumann, & Fastl, 2004; Keilmann, Bohnert, Gosepath, & Mann, 2009). The binaural advantage for perceiving speech in noise could be due to two processes, binaural squelch effect and binaural summation. Binaural squelch effect is the ability of an individual to attend to the ear with better SNR when speech and noise sources are spatially separated. Binaural summation is the ability to centrally integrate the signal heard at each ear simultaneously which has identical timing and intensity cues (Morera et al., 2005). In addition, binaural hearing allows individuals to utilize the inter-aural time and intensity differences to localize the sound (Ching, Wanrooy, & Dillon, 2007).

When a hearing aid and cochlear implant are used simultaneously in opposite ears, it provides complementary information i.e., low frequency information given through a hearing aid is combined with high frequency information provided through a cochlear implant. The low frequencies contain information regarding the fundamental frequency which helps to identify the talker and also provide voicing cues. On the other hand, the high frequencies provide information regarding the manner and place of articulation of consonants (Miller & Nicely, 1955). Hence when the low frequencies, where residual hearing is comparatively good, are amplified using hearing aid, they can deliver voice pitch cues that help to segregate the speaker from the competing voices (Ching et al., 2007). Though speech perception is not possible in hearing aid alone condition, the low frequency pitch information conveyed through a hearing aid complements the mid-frequency and high-frequency information delivered through cochlear implant to improve speech intelligibility.

Studies have shown that addition of a hearing aid in the contralateral ear in individuals with unilateral cochlear implant (CI) provides supplementary benefits like improvement in speech understanding, better localization, and improved functional performance (Ching, Incerti, & Hill, 2004; Hamzavi, Pok, Gstoettner, & Baumgartner, 2004; Litovsky, Johnstone, & Godar, 2006; Mok, Galvin, Dowell, & McKay, 2010). However, for some people there is no improvement in speech perception when the hearing aid is used in addition to the cochlear implant (Tyler et al., 2002; Dunn, Tyler, & Witt, 2005; Mok, Grayden, Dowell, & Lawrence, 2006). Studies have also shown that in few cases, use of a hearing aid in the contralateral ear may actually degrade speech perception (Armstrong, Pegg, James, & Blamey, 1997; Dunn et al., 2005; Litovsky et al., 2006; Mok et al., 2006). This variability in results may be due to the effect of residual hearing of the subjects and the characteristics of the hearing aid.

Since there are increased number of bimodal users in the recent years, the need for a coordinated fitting between the CI and the hearing aid has become more relevant.

The frequency allocation that can be given to both the devices (hearing aid and cochlear implant) is not well understood. In a few research studies, frequency overlap between the CI and HA were studied using combined acoustic and electric stimulation (EAS). Fitting procedures, research methods and conclusions varied across these studies with recommendations ranging from no frequency overlap to some degree of overlap. A few studies have concluded that a small amount of overlap between acoustic and electric stimulation is beneficial (Kiefer et al., 2005; Vermeire, Anderson, Flynn, & Heyning, 2008) whereas other studies recommended no overlap between the acoustically amplified signal from the hearing aid and electrical signal from the cochlear implant (Gantz & Turner 2004; James Fraysse, Deguine, Lenarz, Mawman, Ramos, & Sterkers, 2006). In addition, certain studies found no significant difference in performance between the two (Simpson, McDermott, Dowell, Sucher, & Briggs, 2009). However, Vermeire, Anderson, Flynn and Heyning (2008) suggested that for bimodal fittings, the fitting of the hearing aid should depend on the degree and configuration of the hearing thresholds and the amount of gain that can be provided.

Certain studies imply that amplification of only low frequencies is enough to improve speech perception when hearing aid is used simultaneously in the ear contralateral to the cochlear implant (Büchner, Schüssle, & Battmer, 2009; Zhang, Dorman, & Spahr, 2010a; Sheffield & Zeng, 2012). This is because the low frequency information from the hearing aid is considered as the primary contributor to the bimodal benefit. Also, restricting to low frequency region avoid any possible negative interactions between the acoustic signal at mid-and-high frequencies and the electrical signal from the cochlear implant (Mok et al., 2006).

Most of the studies were carried out mainly on individuals with steeply sloping hearing loss with quite good residual hearing in low frequencies. Hence, it is unclear whether these findings can be generalized to bimodal users who have poor residual hearing in the low frequency region, but who have usable residual hearing over a relatively wide frequency range.

Neuman and Svirsky (2013) tried to investigate the effect of hearing aid bandwidth on bimodal speech recognition in a group of adults with post-lingual hearing loss with severe-profound degree in the non-implanted ear, but with adequate residual hearing for wideband amplification using NAL-RP prescriptive rules. Their unaided thresholds were better than 95 dB HL till 2 kHz. They found out that limiting the hearing aid bandwidth to only low-frequency amplification (below 1 kHz) did not produce significant improvements in speech recognition when compared to CI alone. This suggest the importance of fitting the hearing aid, with amplification given across as wide a frequency range as possible depending on the hearing thresholds of the individual.

1.1. Need for the Study

Bilateral cochlear implant may not be an affordable option in many individuals. Therefore, a hearing aid is recommended in the non-implanted ear. The use of hearing aid in the contralateral ear in children with unilateral cochlear implant provide binaural advantages like improved localization ability, enhanced speech recognition especially in noise and also helps to prevent auditory deprivation in the non-implanted ear (Ching, Incerti, & Hill, 2004; Hamzavi, Pok, Gstoettner, & Baumgartner, 2004; Litovsky, Johnstone, & Godar, 2006; Mok, Galvin, Dowell, & McKay, 2010). However, a small number of individuals exhibited no improvement or poor performance in speech recognition with the addition of a hearing aid in unilateral cochlear implant users.

The frequency range of the hearing aid that needs to be amplified in bimodal users is a matter of question. A few studies emphasize that only low-frequency amplification is sufficient to provide bimodal benefit as high-frequency information is provided through the cochlear implant (Büchner et al., 2009; Zhang et al., 2010a; Sheffield & Zeng, 2012). In contrast, a few studies emphasize on providing amplification across as wide a frequency region as permitted by audiometric thresholds in the hearing aid used by bimodal users (Zhang, Spahr, & Dorman, 2010b; Neuman & Svirsky, 2013).

Most of the studies assessing bimodal benefit were done in adults with post-lingual hearing loss. Since these individuals had a period of acoustic hearing and previous experience, the findings cannot be generalized to children with pre-lingual hearing loss who use cochlear implant and a hearing aid in the contralateral ear. Further studies are required in children with severe to profound hearing loss to determine whether low-frequency amplification (till 1 kHz) is sufficient or a wide frequency range amplification is required to provide optimum bimodal benefit.

1.1. Aim of the Study

The aim of the present study was to examine the effect of hearing aid bandwidth on speech perception in a group of children with severe to profound hearing loss, who were using a hearing aid in the ear contralateral to the ear with cochlear implant.

1.2. Objectives of the Study

The specific objectives of the study were to evaluate the following in children with severe to profound hearing loss who use unilateral cochlear implant and contralateral hearing aid:

- To determine the effect of bimodal stimulation on speech identification scores (SIS) in children fitted with cochlear implant in conjunction with hearing aid in the opposite ear by comparing the SIS in quiet, cochlear implant alone (CI) condition and cochlear implant with hearing aid in wide band condition (CI + WB HA).
- To determine the effect of hearing aid bandwidth on speech identification in bimodal users by comparing the SIS in the following three conditions:
    a. CI + hearing aid (HA) in wide band condition (CI+WB HA)
    b. CI + HA with low pass set to 2 kHz (CI+2k HA)
    c. CI + HA with low pass set to 1 kHz (CI+1k HA)
- To study the effect of intensity (45 dB HL & 75 dB HL) on SIS in quiet.

Chapter 2

Review of Literature

Hearing loss is a major health issue which affects the quality of life. Tremendous effort has been made to resolve the difficulties faced by people with permanent hearing loss. This involves hearing aids, assistive listening devices, and communication strategies. Further, with the advancement in technology, implantable hearing devices came into the scenario. Out of the implantable hearing devices, cochlear implant has achieved more acceptance as they provide improved awareness to environmental sounds, good speech perception, and better quality of life, especially in individuals with severe to profound hearing loss.

Most of the children in India who undergo cochlear implant surgery are implanted unilaterally as bilateral cochlear implantation is not affordable. Hence, children tend to rely on monaural cues. Studies have revealed the advantages of binaural fitting compared to monaural fitting (Carhart, 1958; Gelfand & Silman, 1993; Freyaldenhoven, Plyler, Thelin, & Burchfield, 2006). Thus, the contralateral ear has been recommended to be fitted with hearing aid when bilateral cochlear implantation is not an affordable option. Use of a hearing aid and cochlear implant in the opposite ears simultaneously refers to a bimodal condition (Clark, 2003). The bimodal stimulation helps to serve the purpose of binaural benefits in individuals with unilateral cochlear implant. This binaural benefit can be studied in terms of improvement in speech recognition scores in quiet and noise, improvement in localization, and using other subjective questionnaires.

Studies relevant to the present research are being reviewed under the following headings:

2.1. Speech perception in individuals with bimodal stimulation

2.2. Effect of hearing aid bandwidth on speech recognition with bimodal stimulation

2.1. Speech Perception in Individuals with Bimodal Stimulation

Tyler et al. (2002) conducted a pilot study in three adults who used unilateral cochlear implant and a hearing aid in the opposite ear in order to determine the speech recognition skills in bimodal conditions. Speech recognition was assessed using City University of New York (CUNY) sentences (Boothroyd, Hanin, & Hnath, 1985) and Consonant-Nucleus-Consonant monosyllabic words, NU-6 (Tillman & Carhart, 1966) in quiet and in speech-shaped noise. The measurement was done in three conditions where the noise was presented either from the front, or from 90° Azimuth to the right or left. In addition to the speech recognition measurement, localization ability of the participants was also assessed. Noise bursts were presented from loudspeaker at 45° azimuth to the left or right. The task was to judge from which side the noise bursts were presented, i.e., from the left or the right loudspeaker. The results showed that only one out of the three subjects exhibited improved word recognition in quiet for bimodal condition and none for the sentences. When speech and noise, both were presented from front, two patients exhibited better scores with bimodal devices than with either device alone. At the same time, when speech was presented from front and noise from the hearing aid side, no binaural benefit was observed; but when noise was presented from the cochlear implant side, one patient exhibited a binaural advantage. Two of the three subjects were able to localize better when both the devices (cochlear implant and hearing aid) were used simultaneously in opposite ears. This led to the conclusion that when unilateral cochlear implant is combined with a hearing aid in the contralateral ear, they can provide bimodal benefits. The subject who did not exhibit bimodal benefit had the lowest performance in hearing aid alone condition.

Ching, Incerti, and Hill (2004) examined the speech recognition skills in 21 adults using a hearing aid in the ear contralateral to the ear with cochlear implant. NAL-NL1 prescriptive rule were used to fit the hearing aid followed by fine tuning using a paired-comparison test. This was done to find the frequency response that was best for speech recognition. A loudness balancing test was also done to make sure that the overall loudness perceived in both ears are same. The speech recognition in noise was measured in diotic and dichotic listening situations using BKB/A sentences (Bench & Doyle, 1979). The scores were compared in three conditions, i.e., cochlear implant and hearing aid in opposite ears (CI+HA), cochlear implant alone (CI), and hearing aid alone (HA) conditions. The results revealed that the speech perception in noise was significantly better with CI+HA than with CI alone or HA alone condition.

Hamzavi, Pok, Gstoettner, and Baumgartner (2004) carried out a retrospective cohort study in seven adults with post-lingual hearing loss, who had undergone cochlear implantation in the poorer ear and used a hearing aid in the opposite ear. They used three speech perception tests in quiet, they include Freiburger Numbers, Freiburger Monosyllables, and Innsbrucker Sentence Test, for three conditions, i.e., cochlear Implant (CI) alone, hearing aid (HA) alone, and CI+HA conditions. This was done in order to determine the improvement in speech perception scores in bimodal condition. In most of the tests and subjects, the scores were better in CI alone compared to hearing aid alone condition, and the bimodal (CI+HA) condition obtained the highest scores when compared to other two conditions. Thus, it was concluded from the study that there is an improvement in speech recognition when CI is used in conjunction with a hearing aid.

Luntz, Shpak, and Weiss (2005) evaluated bimodal auditory benefit and the way it changes over time when a hearing aid is fitted to individuals with unilateral cochlear implant with residual hearing in the non-implanted ear. The study included 12 participants with unilateral cochlear implant, three post-lingual adults and nine pre-lingual adults and older children. The post-lingual adults were tested with City University of New York (CUNY) sentences in background noise and the pre-lingual children were assessed using common phrase sentences in background noise. The speech material was presented at 55 dB HL with a signal-to-noise ratio of +10 dB. Both speech and noise were presented from 0° Azimuth. Speech recognition measurement was carried out in three listening conditions, i.e., cochlear implant (CI) alone; hearing aid (HA) alone; and CI+HA. Speech perception skills were assessed twice i.e., after 1 to 6 months of concomitant use of both devices and 7 to 12 months. At the first testing session, the mean score in background noise was more in CI+HA condition (41.1%) compared to CI alone condition (34.9%). Seven subjects could recognize sentences in noise with CI alone, and four of them exhibited benefit with added amplification. At the second session, all subjects could recognize sentences in noise with the CI alone, and seven exhibited better performance in CI+HA condition. The mean score also improved from 60.6% with CI alone to 75.5% with both devices. The study concluded that the bimodal benefit obtained by a contralateral hearing aid in subjects using unilateral cochlear implant improves over time, mainly during the first year of implantation.

Litovsky, Johnstone, and Godar (2006) compared the binaural benefit in CI+HA and binaural cochlear implant CI+CI conditions. Twenty children in the age range from 4 to 14 years participated in the study, ten with CI+HA and the other ten using CI+CI. The speech recognition threshold (SRT) was measured using a recorded version of two-word spondee list (male voice) in quiet and in the presence of two talker competing signal (female voice). The target stimulus was always presented from the front (0° Azimuth) and competing signal was presented from either front (0° azimuth), or right (+90° azimuth) or left (-90° azimuth). The results revealed that the SRTs were significantly lower in CI+CI condition compared to CI+HA condition, which in turn exhibited lower scores compared to CI alone condition, i.e., CI+HA > CI+CI > Ci alone.

Mok, Grayden, Dowell, and Lawrence (2006) conducted a study to examine the effect of using bimodal device, i.e., a hearing aid in combination with a cochlear implant in opposite ears on speech recognition in quiet and noise. The study involved 14 adults who either had used a hearing aid in the non-implanted ear for at least 75% of waking hours after cochlear implantation, and/or, hearing thresholds better than 90 dB HL in the non-implanted ear for low frequencies. Speech recognition scores were obtained in three conditions – cochlear implant (CI) alone condition, hearing aid (HA) alone condition and CI+HA condition. Three speech perception tests were used, i.e., consonant-vowel nucleus-consonant (CNC) words in quiet, City University of New York style (CUNY) sentences with signal and noise presented from the same direction (coincidental), and spondees in coincidental and with signal and noise presented from different directions. The results showed a significant bimodal benefit in open-set speech recognition task for six individuals and in closed-set spondees for five individuals. However, two of the subjects obtained poorer speech recognition in CI+HA condition when compared to CI alone condition. The study concluded that while most of the bimodal device users received speech perception benefit from bimodal fitting, others do not. For a very few individuals, bimodal fitting might even have a detrimental effect on speech recognition. This inconsistency in results may be due to the differences in aided thresholds in the non-implanted ear. Individuals with poorer aided thresholds in the mid- to high- frequencies exhibited more bimodal benefit.

Ullauri, Crofts, Wilson, and Titley (2007) assessed the benefit of using a bimodal device in seven children, aged 7 years and above. The children underwent a hearing aid trial in the contralateral ear after balancing the loudness with that of the cochlear implant, for a period of eight to nine weeks. Speech perception abilities were evaluated later using City of New York sentences (CUNY) or BKB (Bamford-Kowal-Bench sentences list) in quiet and in background noise. All the children showed improved scores in bimodal condition (CI+HA) when compared to CI alone condition.

Beijen, Mylanus, Leeuw, and Snik (2008) compared the speech perception abilities of 22 children in bimodal fitting and cochlear implant alone condition. The mean age of the children was 12 years. All the children were using hearing aid before surgery and continued to use it in the non-implanted ear even after implantation. The mean duration of hearing aid usage was 9 years 11 months. The phoneme recognition score was measured in quiet and noise with standard phonetically balanced word lists of a Dutch monosyllabic word test presented at 65 dB SPL in two conditions, i.e., CI alone condition and bimodal condition. On the phoneme recognition test in quiet, 18 of the 22 children showed a bimodal benefit. At the group level, there was a significant improvement in scores for the bimodal condition which could be attributed to the binaural summation. Of the 21 children who underwent the phoneme recognition in noise test, 16 exhibited a bimodal benefit when a hearing aid was used along with the cochlear implant. There was a significant improvement in performance in the bimodal condition as compared to cochlear implant alone condition. They concluded that a hearing aid should be recommended in the contralateral ear to all children with unilateral implants, in order to provide them a chance to experience bimodal benefit.

Lim et al. (2009) studied the effect of bimodal hearing in the open-set speech perception test in quiet and noisy situations (+10 dB SNR and +20 dB SNR). The study was conducted on 19 children using Korean language who had used bimodal hearing over a period of 8 months. The scores were obtained for CI alone condition and CI+HA condition. It was found that there was no significant difference between the speech recognition scores in quiet in CI alone and CI+HA condition. Whereas, speech recognition scores were significantly better in noise in CI+HA condition when compared to CI alone condition, accounting for the spatial release of masking.

Mok, Galvin, Dowell, and McKay (2010) studied the effect of using a second device (hearing aid/cochlear implant) in the contralateral ear on speech recognition in noise. Thirteen school-going children were involved in the study, out of which nine were with bimodal fitting and four with bilateral CI fitting. For bimodal subjects, speech perception scores were obtained for three device conditions, i.e., CI alone (CI), HA alone (HA), and both devices together (CI + HA). Consonant-nucleus-consonant (CNC) words were presented from the front and noise either from the front or 90° on the side of the CI (for bimodal subjects). Most of the subjects exhibited significant improvement in speech recognition in bimodal condition in at least one noise situation.

Cullington and Zeng (2011) carried out a study on 26 English speaking adult cochlear implant users. Thirteen of them were using bilateral cochlear implant and the other 13 were using bimodal (CI+HA) stimulation. They were tested on speech perception in the presence of the three competing-talker maskers i.e., male voice, female voice, and child voice were used as competing maskers. No significant differences were seen on hearing in noise test (HINT) scores with different types of competing maskers between CI+HA and CI+CI conditions. Although individual data analysis revealed that participants in bimodal group (CI+HA) performed better than the bilateral cochlear implant group (CI+CI), the results were not statistically significant. Thus, it can be inferred that bimodal stimulation is more effective for speech perception in noise, with respect to cost and surgical risks involved in case of bilateral cochlear implant condition.

Incerti, Ching, and Hill (2011) compared consonant perception in 15 adults with a post-lingual onset of hearing loss. All the participants had stable map with the cochlear implant for a period of at least six months. The consonant perception was tested using 24 VCV nonsense syllables where the vowel was always /a/ with 24 different English consonants. The scores were obtained in two conditions, i.e., CI alone and CI+HA conditions. The statistical analysis revealed a significant improvement in consonant perception in CI+HA condition when compared to CI alone condition.

2.2. Effect of Hearing Aid Bandwidth on Speech Recognition with Bimodal Stimulation

Most of the individuals with unilateral cochlear implant benefit from the use of a hearing aid in the contralateral ear as it can deliver low frequency information like fundamental frequency and lower harmonics which would complement to the high frequency information delivered through CI. But how to fit the hearing aid which is used in conjunction with the CI is not well understood. Whether the hearing aid amplification should be restricted to only low frequency or to be extended to provide amplification over a wide frequency range is quite unclear.

Though hearing aid alone with only low frequency amplification would not help in speech recognition, it can improve speech perception when used in conjunction with the cochlear implant (Büchner et al., 2009; Zhang et al., 2010a; Sheffield & Zeng, 2012). One limitation of these studies is that they have considered subjects with steeply sloping hearing loss i.e., comparatively better hearing at low frequencies.

Mok et al. (2006) found out that bimodal users with poorer aided thresholds at 1 kHz and 2 kHz acquired more bimodal benefit than individuals with better aided thresholds. In addition, individuals whose hearing aid did not provide gain at 4 kHz (due to the severity of hearing loss) obtained more benefit than those who did. These results have been interpreted as indicating possible negative interactions between the acoustically amplified signal at mid- and high- frequencies and the electrical signal from the cochlear implant.

Zhang, Spahr, and Dorman (2010b) tried to find out the minimum bandwidth of the acoustic information required by unilateral CI users to yield bimodal benefit. The study included nine adults with post-lingual hearing loss and all of them had a steeply sloping hearing loss except one. The non-implanted ear had thresholds less than or equal to 60 dB HL till 500 Hz and greater than 60 dB HL beyond 1000 Hz. The Consonant–Nucleus Vowel-Consonant (CNC) word lists in quiet and AzBio sentence lists in noise (+10 dB SNR) were used to evaluate speech perception ability of the participants. The acoustic speech stimuli were unfiltered (wideband) or low pass (LP) filtered (LP cut-offs of 250, 500 or 750 Hz) and amplified for each participant according to NAL-RP prescriptive formula (Byrne, Parkinson, & Newall, 1990). The electric stimuli were unfiltered or high pass (HP) filtered (HP cut-offs of 250, 500 or 750 Hz). In the combined condition unfiltered acoustic stimulus was paired with unfiltered electric stimulus, and corresponding low pass and high pass stimuli were paired in other bandwidth conditions. It was observed that the highest scores in combined conditions were obtained when unfiltered acoustic stimulus was combined with unfiltered electric stimulus. The study concluded that reducing the frequency overlap between acoustic and electric stimulation would not result in improved speech recognition ability in individuals with low-frequency residual hearing in the non-implanted ear.

Though the study done by Zhang et al. (2010b) revealed a better performance in the wideband condition of the acoustic and electric stimulation, this could not be generalized to bimodal users with poorer low-frequency residual hearing. A second aspect that needs to be considered is that they had simulated a hearing aid and an earphone was used to deliver the acoustic stimuli. The filtered acoustic signal presented through the ear phone (hearing aid simulation) in the study may not be similar to the filtering that could be provided through conventional hearing aids. Therefore, it is important to attain information about the possible contribution of low-, mid-, and high-frequency acoustic information to bimodal benefit through actual hearing aids.

Neuman and Svirsky (2013) tried to determine the effect of hearing aid bandwidth on bimodal speech perception in a group of 14 adults with severe-profound hearing loss in the non-implanted ear. The unaided thresholds were not poorer than 95 dB HL till 2000 Hz and the hearing aid was programmed using NAL-RP prescriptive formula. Four different frequency responses differing in bandwidth were programmed into four memories of the hearing aid. Modified bandwidths included low pass with 0.5, 1 and 2 kHz cut-off. The AzBio sentence material was used to test speech recognition performance in quiet and noise which was presented through sound field. The bimodal benefit was highest in the wideband condition. Thus, limiting the hearing aid bandwidth to only low-frequency amplification (below 1 kHz) did not yield significant improvements in performance over listening with the CI alone.

From the studies reported in literature, it is evident that the use of hearing aid in the ear contralateral to that with cochlear implant, would provide additional benefits to most of the individuals. But very few individuals did not obtain any bimodal benefit or some of their scores even deteriorated with the addition of a hearing aid. Most of these studies were done in adults and older children. The frequency range of the hearing aid that needs to be amplified in bimodal users is quite unclear. There are limited studies investigating the effect of hearing aid bandwidth on speech recognition, especially in children with pre-lingual, severe to profound hearing loss. When a few researchers recommend to limit the hearing aid amplification till 1 kHz, a few others recommend to provide as wide frequency range amplification as possible. This variation in result might be due to the difference in the degree and configuration of hearing loss of individuals involved in the study. The present research attempted to see the effect of hearing aid bandwidth on speech recognition in children using bimodal devices.

Chapter 3

Methods

The study aimed at examining the effect of hearing aid bandwidth on speech identification in a group of children using hearing aid in the ear contralateral to the ear with cochlear implant. The specific objectives of the study were: (a) to see the effect of bimodal stimulation on speech identification score (SIS), (b) to determine the effect of hearing aid bandwidth on SIS in bimodal stimulation, (c) to see the effect of intensity on SIS in bimodal stimulation. The method followed in the study is given in the following sections.

3.1. Participants

The participants included children implanted with cochlear implant (CI) and using a hearing aid in the contralateral ear. A total number of 12 children participated in the study with mean age of 5.9 years. Convenient sampling was used for the inclusion of participants in the study. Age of the 12 participants, duration of the cochlear implant use and duration of bimodal experience are tabulated in Table 3.1.

3.1.1. Inclusion criteria

- Bilateral severe to profound hearing loss fitted with cochlear implant in one side and hearing aid in the opposite side.
- Aided thresholds of the ear with hearing aid, not poorer than 60 dB HL up to 2 kHz.
- Aided thresholds of the implanted ear well within/better than the upper range of speech spectrum.

- Stable map of the cochlear implant and a minimum of three months usage of cochlear implant and hearing aid together (bimodal condition).
- Auditory skill of at least, at a level of closed-set speech identification score of >60%.
- Kannada as their mother tongue.

Table 3.1: *Age, duration of cochlear implant use and duration of bimodal experience of 12 children*

Subject No	Age (years)	Cochlear Implant	CI Experience (months)	Bimodal Experience (months)
1	5	Nucleus Freedom	12	11
2	6	Nucleus Freedom	12	11
3	3.8	Nucleus Freedom	8	7
4	6	Nucleus Freedom	12	11
5	7.4	Nucleus Freedom	7	6
6	7	Nucleus Freedom	11	10
7	6.6	Nucleus Freedom	12	10
8	6	Nucleus Freedom	6	5
9	6.8	Nucleus Freedom	16	15
10	5.11	Nucleus Freedom	11	10
11	7	Nucleus Freedom	14	13
12	4.6	Nucleus Freedom	6	5

3.1.2. Exclusion criteria

- Children with any other associated problems like intellectual disability, autism, hyperactivity, etc.
- Children not cooperative or exhibiting inconsistent responses for aided testing.

3.2. Equipment and Test Material

- A calibrated two-channel diagnostic audiometer, with loudspeaker at 0° azimuth and 1 meter distance from the participant, to find out aided thresholds and speech identification score.
- A high power programmable digital behind the ear (BTE) hearing aid, to give three frequency responses differing in bandwidths. The hearing aid having 12 channels with a fitting range from mild to severe degree of hearing loss and three programs. All the participants were tested with this same hearing aid, the test hearing aid.
- NOAH and hearing aid programming software installed in a computer, HiPro interface and programming cables to program the digital behind the ear hearing aid.
- Speech identification test for Kannada speaking children (Vandana, 1998) for speech identification task in closed-set. It consists of two phonemically balanced word lists, each with 25 bi-syllabic words. Picture book to perform the closed-set speech identification task which

contain three familiarization items and 50 test items comprising the two-word lists. Each page contains four pictures including the target word.

3.3. Test Environment

Air-conditioned, sound treated single or double room suite was used to obtain the aided thresholds and speech identification scores. The noise levels were within the permissible levels.

3.4. Procedure

Routine audiological evaluations such as pure-tone audiometry, speech audiometry, aided testing was carried out in order to ensure that the participants met the inclusion criteria. The pure-tone thresholds of the participants varied from 70 to 120 dB HL across the audiometric frequencies (0.25 to 8 kHz). The average pure-tone thresholds of the participants across frequencies are tabulated in Table 3.2.

For the purpose of the study, the procedure is being given under the following sub-headings:

3.4.1. Programming of hearing aid

3.4.2. Measurement of aided thresholds

3.4.3. Optimization of hearing aid in the ear contralateral to CI

3.4.4. Measurement of aided speech identification score

3.4.1. Programming of hearing aid

- A high power digital BTE hearing aid with three programs, was used for testing all the participants. The hearing aid was connected to the computer with hearing aid programming software through the Hi Pro interface and the programming cables. The hearing aid was programmed using NOAH and hearing aid software. The hearing aid was programmed for NAL-RP prescriptive formula. The hearing aid was programmed according to the pure-tone thresholds of the child.

- Three programs were stored in the hearing aid, each differing in terms of bandwidth of the frequency response, i.e.,
    - full bandwidth in program 1
    - low pass with a cut-off at 2kHz in program 2
    - and low pass with a cut-off at 1kHz in program 3

- The microphone was set to omnidirectional and other features in the hearing aid like comfort fit, frequency compressor, low frequency boost and wind barrier were disabled. The volume control was also disabled. The program push button was enabled to change the programs during the testing.
- Electroacoustic measurement of the hearing aid was done using a hearing aid analyser. Measurements were done after selecting IEC 60118-7 2005 standards in order to verify the parameters and to confirm that the equivalent input noise level and total harmonic distortion were well within acceptable limit.

3.4.2. Measurement of aided thresholds. The child was seated comfortably on a chair inside the air conditioned sound treated double room. The loud speaker of the audiometer kept at 0° azimuth and 1 meter from the child. Initially, the aided performance of the cochlear implant alone was obtained. Later, aided thresholds of the hearing aid alone in the contralateral ear was obtained. The aided thresholds with the hearing aid was obtained with the hearing aid set in program 1 (wideband condition).

Warble tones were presented from a calibrated two channel diagnostic audiometer, through loud speaker at 0° azimuth. The aided thresholds at 0.5 kHz, 1 kHz, 2 kHz, and 4 kHz were found out. The child's responses were obtained using conditioned play audiometry. The average aided thresholds of the participants across frequencies are tabulated in Table 3.2. Aided thresholds of the non-implanted ear of 12 children involved in the study are given in Table 3.3.

Table 3.2: *Mean pure tone thresholds and aided thresholds in CI+ WB HA condition of the participants across frequencies*

Frequency	**Pure-Tone Thresholds**		**Aided Thresholds with Hearing Aid**	**Aided Thresholds with Cochlear Implant**
	Right	Left		
0.25 kHz	89.58	92.92	-	21.25
0.5 kHz	99.17	98.33	42.08	22.92
1 kHz	106.25	105.83	45.42	23.75
2 kHz	>90	>90	52.08	23.75
4 kHz	>90	>90	74.17	24.17
6 kHz	-	-	-	23.75
8 kHz	>90	>90-	-	26.25

Table 3.3: *Aided thresholds (dB HL) of the non-implanted ear of 12 children across the frequencies*

Subject No	0.5 kHz	1 kHz	2 kHz	4 kHz
1	45	40	50	90
2	40	40	45	85
3	45	50	60	60
4	40	45	55	80
5	35	35	45	80
6	45	50	55	70
7	45	50	55	70
8	40	45	50	60
9	40	45	45	85
10	45	50	55	70
11	40	45	55	70
12	45	50	55	70

3.4.3. Optimization of hearing aid in the ear contralateral to CI. To check the optimization of hearing aids the child wearing the two devices (cochlear implant and the hearing aid) was tested using warble tones (0.5 kHz, 1 kHz, 2 kHz) and the Ling's six sound test. The stimuli were presented from the loud speaker of the audiometer at 45 dB HL. The child was instructed to point to the ear/ears where the stimuli are heard. One of these three forms of responses were considered to indicate that the loudness of two devices are equal and is localized to the midline, i.e., child points to both ears or child points to the centre of the head or child report that he/she cannot make out from which side the signal occurs. In case the child localized the sound mainly towards the side of the hearing aid, the gain of the hearing aid was reduced till the loudness was equalized. If the child localized the stimulus to the side of cochlear implant, gain of the hearing aid was increased, whenever possible. The protocol and response form developed by Yathiraj and Megha (2013) was used to record the response.

3.4.4. Measurement of aided speech identification score. The speech identification scores with cochlear implant alone was measured in the sound field condition through monitored live voice condition. The words of the speech identification test for Kannada speaking children (Vandana, 1998) were presented at two levels of presentation, i.e., 45 dB HL (normal conversation level) and 75 dB HL (a higher presentation level) through the calibrated loud speaker of the audiometer. The word-list was shown to the caregiver prior to the test in order to make sure that the child was familiar with all the words in the list. The word-list was randomized in the four aided conditions. The child was provided with the picture book in which each page contains four pictures. Of the four pictures, one was that of the target word. The child was instructed to listen to the target word and point to the picture of the target word from a choice of four (closed set). The number of correct words identified were noted down for each aided condition for each participant. For each participant, the speech identification scores were found out in the four aided conditions. The aided conditions included testing in:

- CI alone
- CI + HA in wideband condition (set at program 1)

- CI + HA with low pass set to 2 kHz (set at program 2)
- CI + HA with low pass set to 1 kHz (set at program 3)

The order of different aided conditions in which speech identification scores were obtained was randomized to avoid order effect. In order to avoid practice, effect the speech identification scores were obtained for one level (45 dB HL) of presentation on one day (4 conditions) and the other level (75 dB HL) of presentation on another day (4 conditions). A break time of 10-15 minutes were given after each condition to maintain the attention of the child.

The SIS obtained in four aided conditions, at two presentation levels (45 dB HL & 75 dB HL), were tabulated for each participant. The scores were compared across the four conditions using statistical package for social science (SPSS) software (version 20). Shapiro Wilk test was carried out to test for the normality of the data. Repeated measures ANOVA was carried out to see the main effect of different aided conditions (CI, CI+WB HA, CI+2k HA and CI+1k HA), intensity levels (45 & 75 dB HL) and interaction effect between aided conditions and intensity levels. Bonferroni pair-wise analysis was performed to see the pair-wise significant effect of intensity and aided conditions. This helped to determine the effect of presentation level on speech identification scores in bimodal stimulation, to compare the effect of hearing aid bandwidth on speech identification, and also to suggest which bandwidth gives the best speech perception.

Chapter 4

Results

The present study evaluated the effect of frequency bandwidth of the hearing aid in bimodal stimulation on speech identification scores (SIS) at two presentation levels (45 dB HL & 75 dB HL). The aided conditions included cochlear implant alone (CI) and bimodal condition. In the bimodal condition, cochlear implant and hearing aid in wideband condition were fitted in the opposite ears (CI+WB HA), and cochlear implant and hearing aid with low pass set to 2 kHz (CI+2k HA) as well as 1 kHz (CI+1k HA) were considered. The aided SIS in the four aided conditions for each participant was tabulated. The data thus obtained were subjected to statistical analyses using Statistical Package for the Social Sciences (SPSS, version 20) software.

The mean and standard deviation of the SIS obtained in the four conditions at two presentation levels are given in Table 4.1.

Table 4.1: *Mean SIS (Max. SIS = 25) in CI alone and three bimodal conditions, (i.e., CI+WB HA, CI+2k HA, CI+1k HA), at two presentation levels (i.e., 45 & 75 dB HL)*

Aided Test Conditions		**45 dB HL**		**75 dB HL**	
		Mean	**SD**	**Mean**	**SD**
Cochlear implant alone (CI)		21.25	1.49	22.42	1.73
Bimodal condition	CI+WB HA	23.17	1.19	23.83	0.94
	CI+2k HA	22.67	1.30	23.58	0.99
	CI+1k HA	22.08	0.99	22.83	1.29

The data obtained were subjected to Shapiro Wilk test to check the distribution of the data. The results revealed that the data was distributed normally ($p>0.05$). The repeated measures ANOVA was carried out to see the main effect of aided conditions (CI alone, CI+WB HA, CI+2k HA, CI+1k HA), intensity levels (45 & 75 dB HL), and the interaction effect between aided conditions and intensity levels (aided conditions*intensity levels). It was found that there was a main effect of aided conditions on SIS [$F (3, 33) = 19.78$; $p<0.001$; partial $\eta^2 = 0.64$] and main effect of intensity on SIS [$F (1, 11) = 14.06$; $p<0.05$; partial $\eta^2 = 0.56$]. There was no interaction between the aided conditions and intensity levels [$F (3, 33) = 0.78$; $p>0.05$]. Bonferroni pair-wise analysis was done to see the pair-wise significant effect of intensity levels and aided conditions. The performance of the participants in the four aided conditions are discussed in the following headings:

4.1. Effect of bimodal stimulation on SIS

4.2. Effect of bandwidth of hearing aid (wide band, up to 2k Hz, & up to 1k Hz) on SIS in bimodal stimulation

4.3. Effect of intensity (45 & 75 dB HL) on SIS in bimodal stimulation

4.1. Effect of Bimodal Stimulation on SIS

In order to see the effect of bimodal stimulation on SIS, the SIS were compared in CI alone condition and CI+WB HA condition. The SIS obtained from each of the participants in CI alone and CI+WB HA at 45 dB HL presentation level (n = 12) are shown in Figure 4.1. All the participants, except participant No. 4, showed an improvement in score in CI+WB HA condition when compared to CI alone condition. In participant No. 4, the SIS in these two aided conditions were the same.

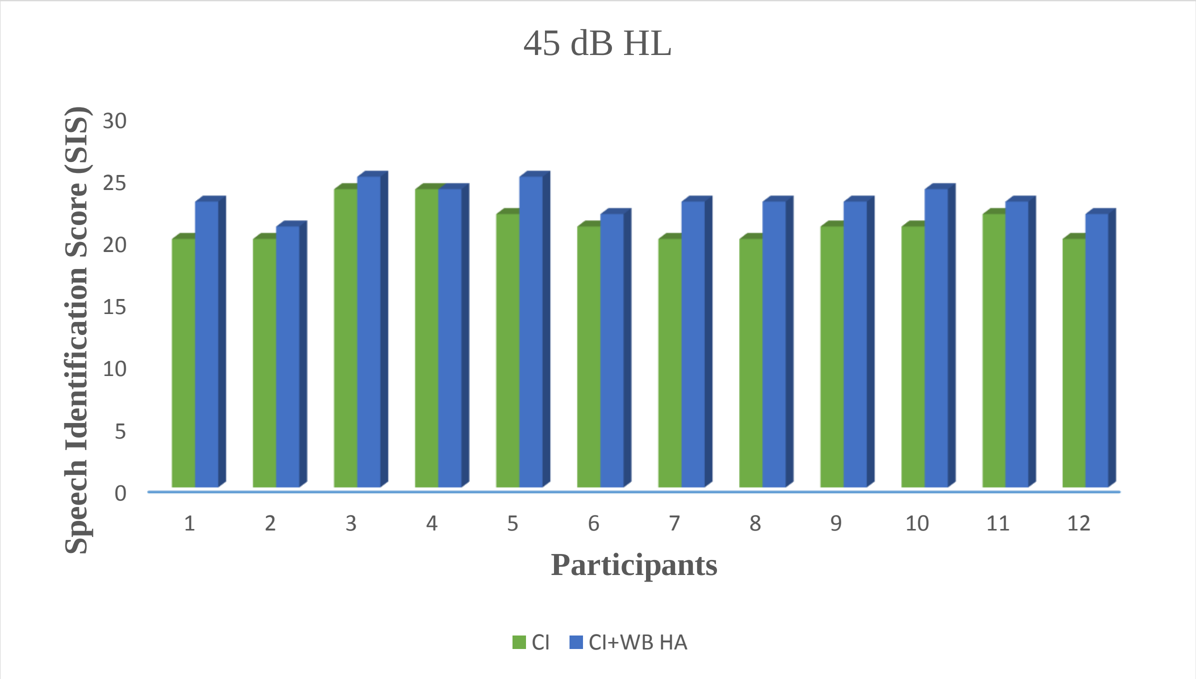

Figure 4.1: Speech Identification Scores (max. SIS = 25) obtained from each of the participants in CI alone and CI+WB HA, presented at 45 dB HL

The SIS obtained for each of the participants in CI alone and CI+WB HA at 75 dB HL presentation level (n=12) are shown in Figure 4.2. All the participants except participants No. 3, 5, and 11 showed an improvement in SIS scores in bimodal condition when compared to CI alone condition. Participants No. 3, 5, and 11 did not exhibit any difference in SIS in CI alone and CI+WB HA conditions.

From Table 4.1, it is clear that the mean SIS was better in CI+WB HA condition as compared to CI alone condition at both the presentation levels (45 & 75 dB HL). Statistical analysis revealed that the difference in scores between CI alone condition and CI+WB HA was significant ($p<0.001$). This means that there is a significant improvement in performance with CI+WB HA when compared to CI alone condition, i.e., cochlear implant with hearing aid set in wideband condition yielded better scores.

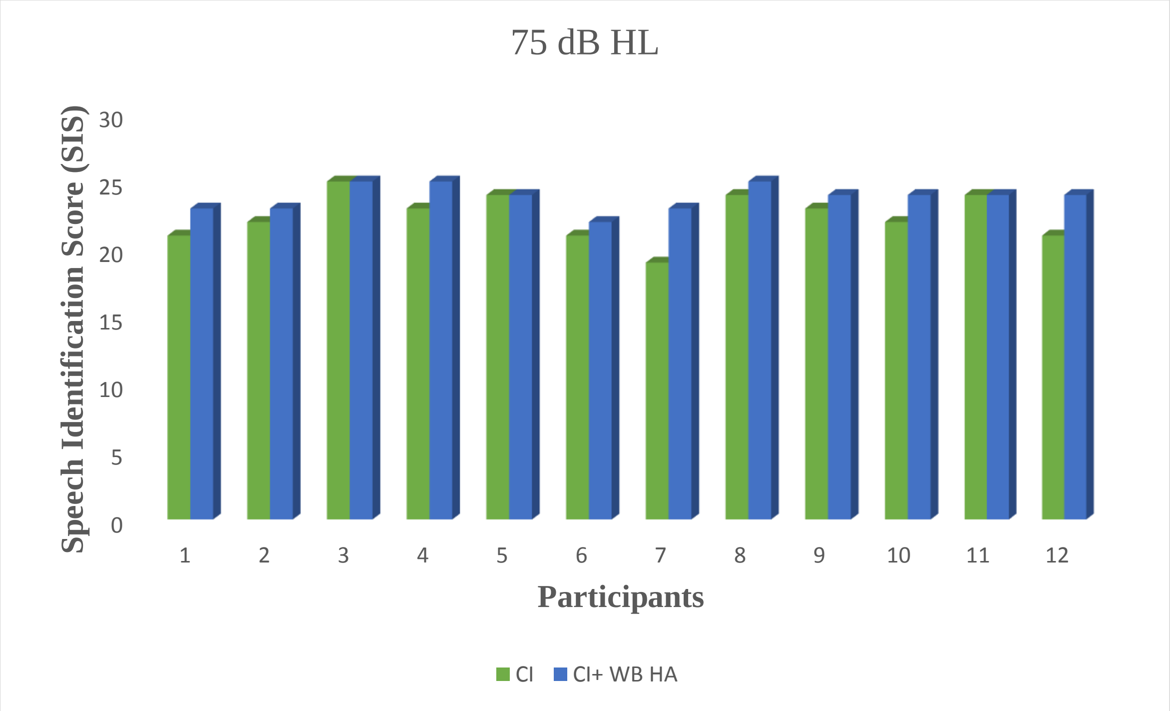

Figure 4.2: Speech Identification Scores (max. SIS = 25) obtained from participants in CI alone and CI+ WB HA, at 75 dB HL

4.2. Effect of Bandwidth of Hearing Aid on SIS in Bimodal Stimulation

In order to see the effect of hearing aid bandwidth on SIS, scores were compared between the three aided conditions, i.e., CI+HA set to wide band condition (CI+WB HA), CI+HA set to low pass with 2 kHz cut-off (CI+2k HA), and CI+HA set to low pass with 1 kHz cut-off (CI+1k HA). The SIS in these three conditions were in turn compared with CI alone condition to determine which one provided a better bimodal benefit. Figure 4.3 shows the SIS for each of the participant (n=12), presented at 45 dB HL obtained in four aided conditions, i.e., CI alone, CI+WB HA, CI+2k HA, and CI+1k HA.

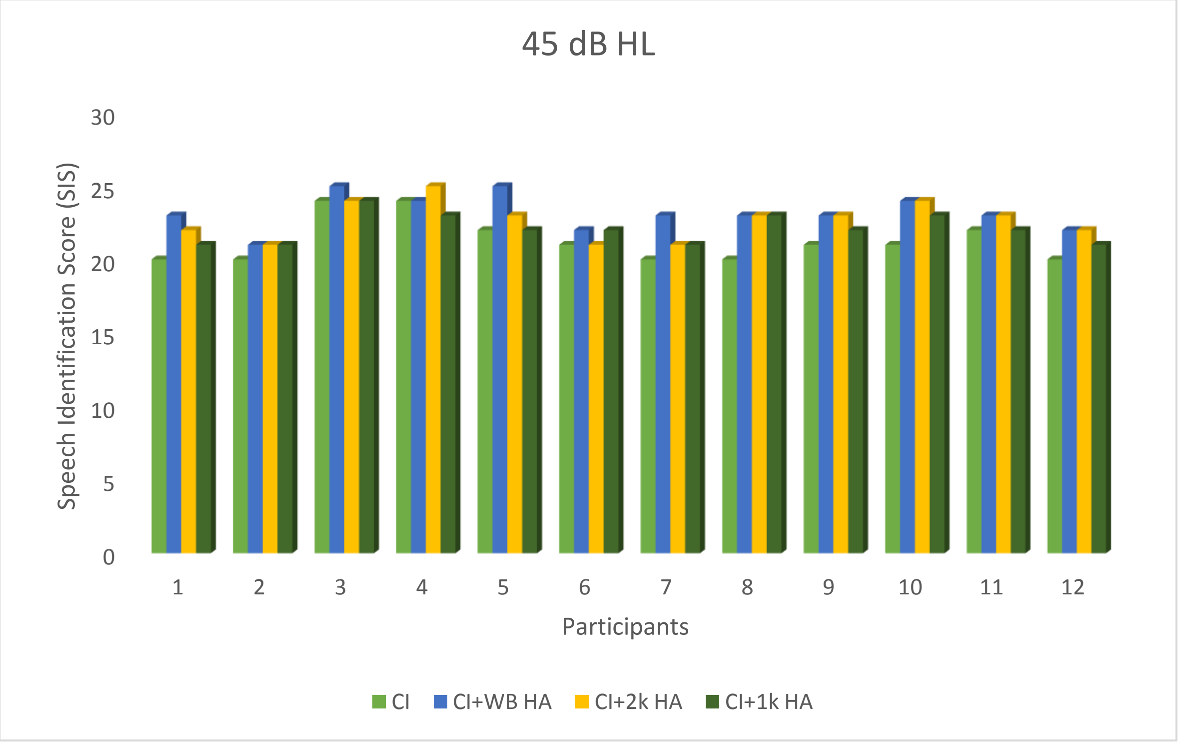

Figure 4.3: Speech Identification Scores (max. SIS = 25) obtained from each of the participant in four aided conditions (CI alone, CI+WB HA, CI+2k HA and CI+1k HA), presented at 45 dB HL

Figure 4.3 shows that while comparing the three bimodal conditions, i.e., CI+WB HA, CI+2k HA and CI+1k HA, participants No. 1, 3, 5, and 7 exhibited better SIS in CI+WB HA condition. Participants No. 9, 10, 11, and 12 exhibited similar scores in CI+WB HA and CI+2k HA conditions. Participants No. 2 and 8 did not show any difference in SIS across the three bimodal conditions. It is to be noted that in all the three bimodal conditions, the scores were better than or same as that of CI alone condition except in participant No. 4, where the SIS in CI+1k HA was poorer than in CI alone condition.

Figure 4.4 shows the SIS for each of the participants (n=12) presented at 75 dB HL obtained in four aided conditions, i.e., CI alone, CI+WB HA, CI+2k HA and CI+1k HA. Figure 4.4 reveals that while comparing the three bimodal conditions, i.e., CI+WB HA, CI+2k HA and CI+1k HA, participants No. 1, 4, 10, and 12 obtained similar scores in CI+WB HA and CI+2k HA conditions. Participants No. 2 and 7 exhibited better SIS in CI+WB HA condition. Participants No. 1 and 6 exhibited better SIS in CI+2k HA condition. Participants No. 8 and 9 did not show any difference in SIS across the three bimodal conditions. It is to be noted that in all the three bimodal conditions, the scores were better or same as that of CI alone condition except in participants No. 3, 5, and 11.

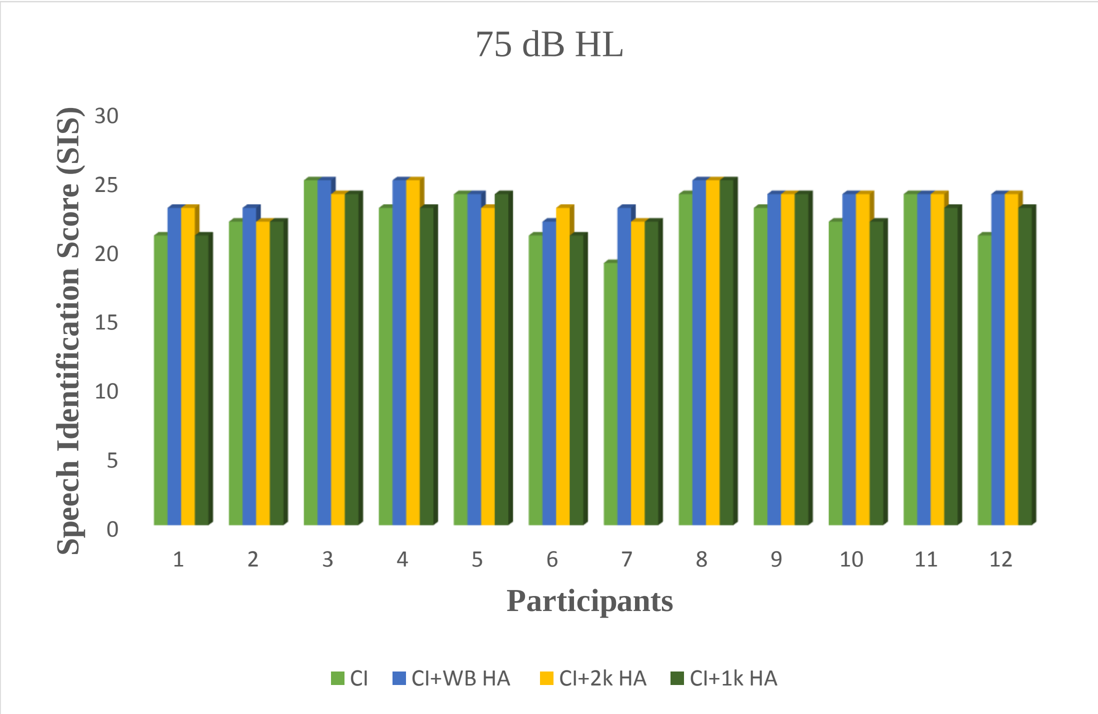

Figure 4.4: Speech Identification Scores (max. SIS = 25) obtained from each of the participants in four aided conditions (CI alone, CI+WB HA, CI+2k HA and CI+1k HA), presented at 75 dB HL

From Table 4.1, it is understood that among the three bimodal conditions, (i.e., CI+WB HA, CI+2k HA and CI+1k HA), CI+WB HA exhibited the best mean SIS scores, followed by CI+2k HA and CI+1k HA. Further, all the three bimodal conditions exhibited better mean SIS when compared to CI alone condition.

Bonferroni (post-hoc) pair-wise comparison was carried out to find out which among the four conditions showed a significant difference. The Bonferroni pair-wise analysis revealed a significant difference in the SIS between CI+WB HA and CI+1k HA ($p<0.001$) and CI+2k HA and CI+1k HA ($p<0.05$) among the three bimodal conditions. There was no significant difference between the SIS scores of CI+WB HA and CI+2k HA ($p>0.05$). This means that among the three bimodal conditions, when the hearing aid was set to wideband condition or with low pass set to 2 kHz yielded better scores.

Though all the three bimodal conditions exhibited better mean SIS when compared to CI alone condition, Bonferroni pair-wise analysis revealed that the significant differences in scores were seen between CI alone and CI+WB HA ($p<0.001$), CI alone and CI+2k HA ($p<0.05$) condition. There was no significant difference in scores between CI alone and CI+1k HA ($p>0.05$). This means that better SIS was obtained when cochlear implant was combined with hearing aid which was set to wideband condition or with low pass set to 2 kHz cut-off.

4.3. Effect of Intensity (45 & 75 dB HL) on SIS in Bimodal Stimulation

Table 4.1 reveals that in all the bimodal conditions, mean SIS was better at a higher presentation level, i.e., 75 dB HL when compared to 45 dB HL. Repeated measures ANOVA revealed that there was a main effect of intensity on SIS [$F(1, 11) = 14.06$;

p<0.05]. This implies that there was a significant improvement in mean SIS ($p<0.05$) when the presentation level was increased from 45 dB HL to 75 dB HL.

To summarize the findings:

- The mean SIS of CI+WB HA condition was significantly better than that of CI alone condition.
- Among the three bimodal conditions, maximum mean SIS was obtained in CI+WB HA condition followed by CI+ 2k HA and CI+1k HA condition. Inferential statistics revealed that:
  - There was a significant improvement in scores in CI+WB HA when compared to CI+1k HA.
  - There was no significant difference between the scores of CI+WB HA and CI+2k HA condition.
- The mean SIS of all the three bimodal conditions were better than CI alone condition. Statistical analysis revealed that:
  - The performance was significantly better in CI+WB HA and CI+2k HA condition when compared to CI alone condition.
  - There was no significant difference between the performance in CI alone and CI+1k HA condition.
- There was a main effect of intensity on SIS in bimodal stimulation, indicating that the performance was significantly better at 75 dB HL presentation level when compared to 45 dB HL.

The results and the findings of the study are discussed in the following chapter.

Chapter 5

Discussion

The aim of the present study was to examine using bimodal devices, the effect of hearing aid bandwidth on speech identification in a group of children with severe to profound hearing loss. The objectives of the study were attained by obtaining speech identification scores (SIS) in quiet, at two presentation levels (45 & 75 dB HL) in four aided conditions, i.e., cochlear implant alone (CI), CI with hearing aid (HA) set to wideband condition (CI+WB HA), CI + hearing aid with low pass set to 2 kHz cut-off (CI+2k HA), and CI + hearing aid with low pass set to 1 kHz cut-off (CI+1k HA) conditions. The results of the present study are discussed under the following sub-headings:

5.1. Effect of bimodal stimulation on SIS

5.2. Effect of bandwidth of hearing aid on SIS in bimodal stimulation

5.3. Effect of intensity (45 and 75 dB HL) on SIS in bimodal stimulation

5.1. Effect of Bimodal Stimulation on SIS

In the present study, the mean SIS was significantly better in CI+WB HA condition when compared to CI alone condition. At 45 dB HL presentation level, all the children except one exhibited improved scores in bimodal condition. Whereas at 75 dB HL, eight out of 12 children exhibited better scores in bimodal condition when compared to CI alone condition. The participants who did not show any improvement in bimodal condition obtained same SIS scores in CI alone and CI+WB HA conditions. Thus, addition of a hearing aid in the contralateral ear in children with unilateral cochlear implant improved the performance in speech identification. In few children, though there was no improvement in scores in bimodal stimulation, the SIS never decreased with the addition of a hearing aid in the contralateral ear in children with unilateral cochlear implant.

The results of the present study were in agreement with the previous studies. Hamzavi et al. (2004) reported that the speech perception ability was significantly better in CI+HA condition when compared to CI alone condition when tested using Freiburger Numbers, Freiburger Monosyllables, and Innsbrucker Sentence Test. Litovsky et al. (2006) have also reported similar results, wherein children using CI+HA obtained lower speech recognition threshold (SRT) when compared to CI alone condition when measured using a recorded version of two-word spondee list. Ulluari et al. (2007) also found out that children showed better performance on CUNY or BKB sentences in CI+HA condition when compared to CI alone condition.

The results of the present study were also in concurrence with the results reported by Beijen et al. (2008) who revealed significant better scores in CI+HA condition when compared to CI alone condition on a phoneme recognition task in quiet. Similar findings were reported by Incerti et al. (2011) i.e., better performance on VCV non-sense syllables in CI+HA condition when compared to CI alone condition.

However, the results of the present study contradicted with that reported by Lim et al. (2009) in a group of 19 children who reported that there was no significant difference in speech perception score in quiet between CI+HA condition and CI alone condition. This may be due to the language used in the study i.e., Korean language which is a tonal language, for assessing the speech perception scores.

The additional benefit obtained in bimodal condition on speech identification in quiet was reported across different types of speech recognition test materials like phoneme recognition (Beijen et al., 2008), word recognition (Litovsky et al., 2006) and sentence recognition (Ulluari et al., 2007) in both adults and children. In the present study, phonemically balanced bi-syllabic words were used to test the SIS. The bimodal benefit on SIS may be due to binaural cues, which helps the subjects to integrate the signal received in both ears resulting in better speech recognition (Morera et al., 2005). In addition, when a hearing aid and cochlear implant are used simultaneously in the opposite ears, it provides complementary information which again might lead to bimodal benefit. The hearing aid in the contralateral ear can provide low frequency information like fundamental frequency and lower harmonics which would complement the high frequency information delivered through cochlear implant.

5.2. Effect of Bandwidth of Hearing Aid on SIS in Bimodal Stimulation

When the SIS was compared between the four aided conditions, the best mean score was obtained in CI+WB HA condition followed by CI+2k HA then by CI+1k HA conditions and the least in CI alone condition. Inferential statistics revealed that there was a significant difference between CI+WB HA condition and CI+1k HA condition. Also there was a significant difference between CI+ 2k HA and CI+1k HA conditions. But there was no significant difference between CI+WB HA and CI+2k HA. In addition, the difference between CI alone and CI+1k HA conditions were also not significant.

Hence, amplification of the hearing aid in a wide frequency range as prescribed in NAL-RP prescriptive formula or at least till 2 kHz was required to provide bimodal benefit. Amplification till 1 kHz although resulted in better mean SIS when compared to CI alone condition, the difference was not significant. Thus, amplification till 1 kHz was not sufficient to provide the best bimodal benefit. Nonetheless, the performance with bimodal condition, irrespective of the bandwidth, was always higher than CI alone condition.

The results of the present study were in agreement with the results reported by Zhang et al. (2010) which revealed better performance in wideband conditions i.e., when unfiltered acoustic stimulus was combined with unfiltered electric stimulus in opposite ears. The study was done on a group of adults with post-lingual hearing loss with steeply sloping configuration whose thresholds were better than or equal to 60 dB HL till 0.5 kHz. The acoustic and electric stimuli were unfiltered or filtered with different cut offs, and presented in different combinations. Thus, the study concluded that reducing the frequency overlap between acoustic and electric stimulation would not result in improved speech recognition ability in individuals especially in individuals with sloping hearing loss.

The present study also supports the findings reported by Neuman and Svirsky (2013), which showed that the bimodal benefit was highest in the wideband condition. Thus, limiting the hearing aid bandwidth to only low-frequency amplification (below 1 kHz) did not yield significant improvements in performance over listening with the CI alone. The study was conducted in adults with post-lingual hearing loss of severe to profound degree whose unaided thresholds were better than 95 dB HL till 2 kHz. Four different frequency responses differing in bandwidths were programmed into four memories/programs of the hearing aid. Modified bandwidths included were low pass with 0.5, 1, and 2 kHz cut-off.

The previous studies examining the effect of hearing aid bandwidth was conducted in adults with post-lingual hearing loss and better thresholds at least in the low frequencies. Whereas, the present study was done in children with pre-lingual hearing loss with poorer thresholds, i.e., mean unaided thresholds greater than 90 dB HL in all the frequencies. The low pass cut-off of the hearing aid bandwidth, used in the previous studies were also different from that of the present study. In spite of all these differences, the results of the present study were in agreement with the literature recommending amplification in a frequency range as wide as possible.

Though the mean unaided thresholds of the children involved in the present study were greater than 90 dB HL throughout the audiometric frequencies, their aided thresholds in the non-implanted ear ranged from 40 to 55 dB HL till 2 kHz. At 4 kHz, the aided thresholds were out of speech spectrum, i.e., greater than 60 dB HL. This could be the reason why, though highest SIS was obtained in the wideband condition of the hearing aid, there was no significant difference between wideband condition and hearing aid amplification till 2 kHz. This means that when the hearing aid amplification was extended beyond 2 kHz in wideband condition, there was no significant improvement in SIS as the aided thresholds of the children at high frequencies (4 kHz) were out of the speech spectrum.

The present study did not conform to the findings of Mok et al. (2006) in which they reported that participants with poorer aided thresholds at 1 kHz and 2 kHz demonstrated greater bimodal benefit. They suggested that mid- to high- frequency amplification of hearing aid could have adverse effects on bimodal hearing. In contrast, the results of the present study suggested that the hearing aid amplification in the non-implanted ear should not be restricted to low-frequency region, instead it should amplify a frequency region as wide as possible, or at least up to 2 kHz. This is in agreement with the data reported by Potts, Skinner, Litovsky, Strube, and Kuk (2009) who emphasized the importance of providing mid-frequency amplification in hearing aids in bimodal fitting.

5.3. Effect of Intensity (45 & 75 dB HL) on SIS in Bimodal Stimulation

The results of the present study revealed that there is a main effect of intensity on SIS in bimodal stimulation. The SIS scores were better at the higher presentation level, i.e., 75 dB HL compared to 45 dB HL as the audibility increased at a higher sensation level. A similar trend was seen in both the presentation levels, i.e., in both the presentation levels, wideband amplification of the hearing aid provided best bimodal benefit, though they were no statistically significant difference from that provided by hearing aid amplification till 2 kHz. Among the three bimodal conditions, least scores were obtained when the hearing aid provided amplification till 1 kHz.

Thus, the present study confirmed that the performance improves with the addition of a hearing aid in the ear contralateral to the cochlear implant. Thus, the hearing aid input serves as a complementary information, i.e., high-frequency information obtained from cochlear implant is complemented by the more low-frequency information obtained from the hearing aid. Therefore, additional cues are derived by integrating the information received from two ears, which would not be possible if the individual uses only one device. Further, limiting the hearing aid amplification to low frequencies is not sufficient to provide the optimum bimodal benefit. Amplification in a wide frequency range or at least till 2 kHz is required for better speech recognition in bimodal condition.

Chapter 6

Summary and Conclusions

The aim of the study was to determine the effect of hearing aid bandwidth on speech identification in a group of children using bimodal devices. The specific objectives were:

- To determine the effect of bimodal stimulation on speech identification score (SIS).
- To see the effect of hearing aid bandwidth on SIS in bimodal stimulation.
- To determine the effect of intensity levels (45 & 75 dB HL) on SIS in bimodal stimulation.

A total number of 12 children, fitted with cochlear implant in one ear and hearing aid in the opposite ear were included in the study using convenient sampling. All the 12 participants had severe to profound degree of hearing loss, and the mean unaided thresholds were greater than 90 dB HL in all the audiometric frequencies. The aided thresholds of the ear with cochlear implant were well within the upper range of speech spectrum. The aided thresholds of the non-implanted ear varied from 40 to 55 dB HL till 2 kHz, and were out of the speech spectrum at 4 kHz.

A high-power digital behind the ear (BTE) hearing aid was programmed for NAL-RP prescriptive formula, according to the pure-tone thresholds of the child. Three programs/memories were stored in the hearing aid, each differing in terms of bandwidth of the hearing aid, i.e., wideband condition in program 1, low pass with cut-off set to 2 kHz in program 2, and low pass with cut-off set to 1 kHz in program 3. The SIS was obtained using phonemically balanced bi-syllabic words in four aided conditions, i.e., cochlear implant alone (CI), CI + hearing aid (HA) with wideband amplification (CI+WB HA), CI + HA with low pass cut-off at 2 kHz (CI+2k HA), CI + HA with low pass cut-off at 1 kHz (CI+1k HA). The SIS was obtained at two presentation levels, i.e., conversational level (45 dB HL) and at a higher level (75 dB HL).

The data obtained were analysed using statistical package for social science (SPSS) software (version 20). Descriptive and inferential statistics (based on test of normality) were used to compare the scores between different aided conditions. The following were the results of the present study:

- The mean SIS of CI+WB HA condition was significantly better than that of CI alone condition, i.e., CI+WB HA > CI alone.
- Among the three bimodal conditions, maximum mean SIS was obtained in CI+WB HA condition followed by CI+ 2k HA and CI+1k HA condition. Inferential statistics revealed that:
    - There was a significant difference between the scores of CI+WB HA and CI+1k HA condition, i.e., CI+WB HA > CI+1k HA.
    - There was no significant difference between the scores of CI+WB HA and CI+2k HA condition.
- The mean SIS of all the three bimodal conditions were better than CI alone condition. Statistical analysis revealed that:
    - There was a significant difference in performance between CI alone and CI+WB HA as well as CI alone and CI+2k HA, i.e., CI alone < CI+WB HA; CI alone < CI+2k HA.

  - There was no significant difference between the performance in CI alone and CI+1k HA condition.

- There was a main effect of intensity on SIS in bimodal stimulation, indicating that the performance was significantly better at 75 dB HL presentation level when compared to 45 dB HL.
- From the results of the present study, it can be construed that addition of a hearing aid in the non-implanted ear provides bimodal benefit. This may be due to the ability of the subject to integrate the information received at the two ears. Further, the study also suggest that amplification of a wide frequency region (WB HA) or at least till 2 kHz (2k HA) provides optimum bimodal benefit. However, hearing aid amplification till low frequency region (1 kHz) may not be sufficient to provide bimodal benefit. But it needs to be noted that amplification till 1 kHz did not deteriorate the performance obtained by cochlear implant alone. As the sensation level increases, the performance also increases due to improved audibility at a higher presentation level.

6.1. Clinical Implications of the Study

- All the children with unilateral cochlear implant benefit from hearing aid in the contralateral ear. Hence, they need to be recommended and counselled for the continuous use of hearing aid in the non-implanted ear to provide bimodal advantage. The other benefits of bimodal stimulation (though not evaluated in the present study) include improvement of performance in the presence of background noise and in localization. It also prevents auditory deprivation in the contralateral ear.

- Hearing aid in the non-implanted ear should be amplified over a frequency region as wide as possible though the aided thresholds are at the lower range or out of the speech spectrum.

6.2. Future Directions of the Study

- Further research need to be carried out to determine the effect of hearing aid bandwidth on speech identification in noise.
- Studies need to be carried out to examine the effect of hearing aid bandwidth on localization.
- Further study can be carried out in individuals with better residual hearing in order to see whether the hearing aid bandwidth has a similar effect on speech identification.
- An open-set speech material can be used in older children in further studies.
- A detailed phoneme error analysis and/or feature error analysis can be done in different aided conditions.
- The bimodal benefit over a period of use of bimodal devices needs to be probed.

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