# OPTIMIZATION AND EVALUATION OF A HEARING AID IN THE EAR CONTRALATERAL TO THAT WITH COCHLEAR IMPLANT

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A dissertation submitted in part fulfillment for the degree of

Master of Science (Audiology)

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MANASAGANGOTHRI, MYSORE - 570 006

JUNE 2011

*DEDICTED TO*

*MOM, DAD, SUSH*

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*BACCHU*

# CERTIFICATE

This is to certify that this dissertation entitled **'Optimization and evaluation of a hearing aid in the ear contralateral to that with cochlear implant'** is a bonafide work in part fulfillment for the degree of Master of Science (Audiology) of the student **Registration No.: 09AUD025**. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any diploma or degree.

**Prof. S. R. Savithri**

Director

All India Institute of Speech & Hearing

Manasagangothri, Mysore - 570 006

Mysore

June 2011

# CERTIFICATE

This is to certify that this dissertation entitled **'Optimization and evaluation of a hearing aid in the ear contralateral to that with cochlear implant'** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to any other university for the award of any diploma or degree.


**Prof. P. Manjula**

Guide

Professor in Audiology

All India Institute of Speech & Hearing

Mansagangothri, Mysore - 5 70 006


Mysore

June 2011

# DECLARATION

This is to certify that this dissertation entitled '**Optimization and evaluation of a hearing aid in the ear contralateral to that with cochlear implant'** is the result of my own study and has not been submitted earlier to any other university for the award of any degree or diploma.

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Registration No:
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# Chapter 1

## Introduction

It is a standard procedure to fit an individual with the hearing devices in both the ears when he/she has hearing loss in both ears (Ching, Wanrooy, Hill, & Incerti, 2006). Fitting devices in both ears is mandatory especially in case of children. These devices can be either hearing aids or cochlear implants. A cochlear implant is a device that helps an individual with severe to profound hearing impairment when the inner ear is damaged or not developed. The cochlear implant by-passes the inner ear and provides information to the hearing centres through direct stimulation of the hearing nerve (Clark, 2003).

In India, majority of the children who undergo cochlear implant surgery are implanted unilaterally which is evident from the studies reported in the literature (Desa Souza, D'Souza, Kochure, & D'Souza, 2004; Deka et al., 2010). Unilateral implantation enables majority of children with hearing impairment to acquire spoken language (Rubinstein, 2002). However, the individual who receives a unilateral hearing aid or a unilateral cochlear implant will have to rely on monaural cues. These children are deprived of the binaural cues which would affect their listening skills.

It is well documented that the individuals with normal hearing combine auditory information from both ears in order to understand speech, better in complex listening conditions and to locate the sources of sounds. The ability to locate sounds is reported to be important for one's safety and survival (Ching et al., 2006). Human auditory system makes use of inter-aural time and level differences to localize the source of sounds in the horizontal plane which would be possible only in the binaural hearing situation (Moore, 2004). Hence, individuals with hearing loss need to be provided with an alternative means of auditory input through hearing aids, cochlear implants and assistive listening devices in both ears in case of binaural aidable hearing loss.

As cochlear implant candidacy is now being extended, individuals who receive a cochlear implant in one ear, have residual hearing in the other ear are increasing.These individuals  can benefit from conventional amplification in the contralateral ear (Keilmann, Bohnert, Gosepath, & Mann, 2009).  Providing a hearing aid in the ear contralateral to that with a cochlear implant refers to a bimodal stimulation. Bimodal stimulation, as defined by Clark (2003) is the electrical stimulation in one ear with a cochlear implant, and the presentation of sound to the other ear with residual hearing, through a hearing aid. Bimodal stimulation takes the advantage of binaural hearing.

The major advantages of the additional information provided through binaural hearing enables the individuals to use binaural processing to enhance speech perception, especially in the presence of noise, and sound localization (Keilmann et al., 2009; Seeber, Baumann, & Fastl, 2004; Dorman, Gifford, Spahr, & McKarns, 2008). Very few individuals with unilateral cochlear implant continue to use a hearing aid in the contralateral ear. The binaural advantage for perceiving speech in noise can be explained in terms of three different effects: binaural summation, head shadow, and binaural release from masking. The first two effects refer to the physical phenomena, whereas the effect of binaural release from masking involves neurological processes dealing with binaural interactions (Schoof, 2010). Binaural hearing allows listeners to localize sound sources by attending to the ear with the better signal-to-noise (SNR) ratio and use of inter-aural level and inter-aural time differences (Litovsky, 2005).

Ching, Incerti, and Hill (2003) have reported that wearing a hearing aid with a cochlear implant may provide greater benefit than a cochlear implant alone. Bimodal fittings provide complementary information. Delivering low-frequency information which is better represented, especially through a hearing aid in the contralateral ear, improves speech perception in noise (Chang, Bai, & Zeng, 2006). It helps to access the finer spectral and temporal cues in the speech signal that is not well resolved by a single cochlear implant. Bimodal stimulation provides an opportunity for future advances in hearing restoration or future cochlear implantation. Specifically, the lower frequencies provided by the hearing aid can provide information about the fundamental frequencies of a talker's voice and vowel information, while the mid-frequency and the high-frequency information is provided from the cochlear implant which is necessary for perception of manner and place of articulation (Haurt & Sammeth, 2008; Cullington & Zeng, 2011).

Seeber et al. (2004) claim the successful restoration of the localization ability in the frontal horizontal plane in individuals with hearing impairment by the means of bilateral cochlear implantation or in the case of sufficient residual hearing for one ear by the means of bimodal fitting. Localization ability is reported to be poor for unilateral cochlear implant users and it is improved when a hearing aid is worn in the ear contralateral to the implanted ear, both in children (Ching, Psarros, Hill, Dillon, & Incerti, 2001) and adults (Ching, Incerti, & Hill, 2004; Tyler et al., 2002).

Ching (2005) and Lovett, Kitterick, Hewitt, and Summerfield (2010) have proposed the main motivation for aiding the contralateral ear so as to (1) to create the potential for binaural hearing which will help to understand speech better, especially in noisy situation, and to help an individual to better localize the sounds (2) to ensure that the more responsive auditory nerve is stimulated i.e., to avoid auditory deprivation, and (3) to provide a back-up in the event of device failures, and (4) to provide an opportunity for the future advances in hearing restoration. Thus, most of the earlier studies conducted on adult population have reported better perception of speech in quiet, as well as in noise, and better localization abilities in individuals using cochlear implant and a hearing aid in opposite ears.

**Need for the study**

Binaural cochlear implants may not be an affordable option for many individuals. Establishing a bimodal fitting protocol will help the individuals using the unilateral cochlear implant for better speech perception and localization abilities. Hence, there is a need to establish a protocol to fit a hearing aid in the ear contralateral to the implanted ear for the individuals who may not be able to afford binaural cochlear implant.

An individual needs both low and high frequency information for better speech perceptual abilities. Cochlear implants provide better high frequency cues; whereas hearing aids would provide better low frequency cues (Ching et al., 2003; Chang et al., 2006). The use of unilateral cochlear implant may not provide sufficient cues required for optimum benefit. Thus, an added advantage of bimodal fitting was that the low frequency cues provided by acoustic hearing complemented the high frequency cues conveyed by the electric hearing in the perception of speech and music (Ching, Massie, Wanrooy, Rushbrooke, & Psarros, 2009; Chang et al., 2006).

There is a dearth of literature regarding the speech perception in quiet, speech perception in noise and localization abilities in a bimodal situation in a paediatric population. Most of the studies on the evaluation of benefit in bimodal situation are mainly in adult population (Tyler et al., 2002; Ching et al., 2003; Iwaki, Blamey, & Kubo; 2008; Keilmann et al., 2009; Berrittini, Pasetti, Giannarelli, & Forli, 2010). This research would throw light on  the benefits of the bimodal fitting in the paediatric population.

The studies conducted on speech perception in noise, assess the benefit in terms of percentage of correct recognition in quiet or at a fixed signal-to-noise ratio. However, with such measures, there may be a risk of ceiling effect. Hence, the use of measures like signal-to-noise ratio - 50 (i.e., SNR-50) values will overcome this limitation. In the present study, SNR-50 will be used to evaluate the benefit from bimodal fitting. SNR-50 is defined as the signal-to-noise ratio required for an individual to correctly identify 50 % of the words being presented. There is a dearth in literature regarding the localization abilities in children using hearing aid and cochlear implant simultaneously in opposite ears.

Thus, the present research attempts to evaluate the role of binaural hearing through bimodal stimulation, in children, on speech perception in quiet, as well as in noise and localization tasks.

**Objectives of the study**

The objectives were to evaluate the following in children who were using cochlear implant in one ear and fitted with a hearing aid in the contralateral ear:

1) To validate a protocol in order to optimize the hearing aid in the ear contralateral to that with a cochlear implant.

2) To compare the speech identification scores (SIS) in quiet in three aided conditions, hearing aid alone (HA alone), cochlear implant alone (CI alone), and cochlear implant plus hearing aid (CI+HA) conditions.

3) To compare the performance on speech in noise, through the SNR-50 measure (i.e., signal-to-noise ratio required for 50 % of identification scores) in three aided conditions, HA alone, CI alone and CI+HA conditions.

4) To compare the performance on a localization task through the measure of root mean square degree of errors (rmsDOE) in three aided conditions, viz: HA alone, CI alone and CI+HA conditions.

## Chapter 2

## Review of literature

The benefit obtained by fitting the hearing devices to children with hearing loss (Fujikawa & Qwens, 1978; Haggard, Foster, & Iredale; 1981) has been well documented. These devices can be either hearing aids or cochlear implants. Traditionally, children with hearing impairment are being fitted with hearing aids over the past many decades. However, the number of children with hearing impairment using cochlear implants has increased drastically during the past couple of decades.

It is a standard procedure to fit the hearing aids in both ears for individuals with bilateral hearing loss, especially in case of children. The concept of fitting hearing aid in both ears is due the fact that individuals with normal hearing sensitivity have better speech perception in noise and improved localization abilities when listening through both ears (Van Deun, Van Wieringen, & Wouters, 2010). The benefit of the binaural hearing aid is well documented both in case of symmetrical and asymmetrical hearing loss.

For individuals with bilateral severe to profound hearing loss, cochlear implant provides better speech perception ability when compared to hearing aids. Although the concept of binaural cochlear implant is proposed to be beneficial in providing binaural advantage, majority of the children in India who undergo cochlear implant surgery are implanted unilaterally and they continue to use a cochlear implant in only one ear which is evident from the studies reported in literature (Desa Souza et al., 2004; Deka et al., 2010). Since cochlear implant is expensive, it is not an affordable solution to recommend bilateral cochlear implants for majority of the individuals.

Cochlear implantation enables majority of the children with hearing impairment to acquire spoken language (Rubinstein, 2002). However, an individual who receives a unilateral cochlear implant will have to rely on monaural cues. As mentioned earlier, binaural cochlear implant may not prove to be affordable by majority of the individuals. In addition, with the extension of the cochlear implant candidacy, number of individuals using unilateral cochlear implant with useful residual hearing in the contralateral ear is increasing (Dowell, 2005). Hence, the concept of fitting the contralateral ear having residual hearing with a conventional amplification device is being recommended from the past few years. Using a hearing aid and a cochlear implant in the opposite ears simultaneously refers to a bimodal condition (Clark, 2003). Bimodal stimulation was initiated at the Human Communication Research Centre (HCRC) at the university of Melbourne / Bionic ear Institute in 1989 (Clark, 2003). Studies have indicated that the bimodal stimulation may help to serve the purpose of binaural benefits in individuals using unilateral cochlear implant.

Bilateral auditory input enables increased speech intelligibility both in quiet and in noisy situations and improved localization abilities in normals as well as in individuals using bilateral hearing aids (Dillon, 2001) or bilateral cochlear implants. Several studies have reported such improvements even with bimodal condition (Keilmann et al., 2009; Ching, Incerti, Hill, & Brew, 2004) which could be explained by different frequency characteristics of the devices, i.e., the hearing aid providing better low frequency information and cochlear implant providing better high frequency information.

The reason for understanding speech better through binaural condition than monaural condition in a noisy situation, can be explained by head shadow effect, head diffraction, binaural redundancy and binaural squelch (Ching, Incerti, Hill, & Brew, 2004). Head shadow effect refers to the fact that when one ear is closer to the source or is farther from the noise, listener can attend to the ear with better signal-to-noise ratio which provides approximately 3 dB advantage. However, when speech and noise are arriving from the same direction, binaural redundancy plays a role giving an advantage of around 2 dB which is referred to as binaural squelch (Ching, 2005). Several studies have demonstrated the binaural squelch effect in normals (Van deun et al., 2010) and also in individuals with hearing impairment using binaural hearing aids (Dillon, 2001; McCullough, & Abbas, 1992) or bilateral cochlear implants (Laske et al., 2009; Chan, Freed, Vermiglio, & Soli, 2008; Ricketts, Grantham, Ashmead, Haynes, & Labadie, 2006) or bimodal conditions (Tyler et al., 2002; Ching, Incerti, Hill, & Brew, 2004; Keilmann et al., 2009).

Ching (2005) and Lovett et al. (2010) have proposed the main motivation for aiding the contralateral ear so as to (1) to create the potential for binaural hearing which will help to understand speech better, especially in noisy situation, and to help an individual to localize the sounds better, (2) to ensure that the more responsive auditory nerve is stimulated i.e., to avoid auditory deprivation, and (3) to provide a back-up in the event of device failures.

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

2.1. Bimodal amplification and speech perception in quiet and noisy situations.

2.2. Bimodal amplification and horizontal plane localization.

**2.1. Bimodal amplification and speech perception in quiet and noisy situation.**

Clear benefits are being reported in speech perception when listening through both the ears. The auditory system and the brain can combine information from both ears giving rise to a central representation than would be had with information only from one ear. These benefits include better understanding of speech in quiet and in noise (Justus, 2008). As mentioned earlier, the reason for understanding speech better through binaural condition than in monaural condition, in noisy situation, can be explained by head shadow effect, head diffraction, binaural redundancy and binaural squelch (Ching, Incerti, Hill, & Brew, 2004). Since head shadow effect is a physical phenomenon, it will occur whenever the sounds are audible to the human ears whether the stimulation is acoustic or electric or the combination of both (Ching, 2005).

Ching et al. (2001) addressed the issue of whether the children who use cochlear implant should wear a hearing aid in the contralateral ear. They considered 11 children with congenital hearing impairment who continued to use hearing aid in the contralateral ear after the cochlear implant. They tested the participants on a speech perception task i.e., non-sense syllable recognition and sentence recognition tasks in four conditions, HA alone, CI alone, CI+ HA $_{worn}$ (not optimized) and CI+HA $_{adj}$ (optimized). The results revealed that CI+HA$_{adj}$ resulted in better scores when compared to HA alone or CI alone or CI+HA$_{worn}$ conditions. The CI+HA$_{worn}$ condition led to significantly better performance when compared to CI alone condition followed by HA alone condition. No indication of binaural interference was reported.

Tyler et al. (2002) tested three adults with post lingual hearing loss on monosyllabic word and sentence recognition tasks in quiet and in the presence of speech noise in different aided conditions namely hearing aid alone (HA alone), cochlear implant alone (CI alone), and cochlear implant + hearing aid (CI+HA) conditions. Participants were using a stable map in the cochlear implant. Speech was always presented from the front ($0^0$ Azimuth) at a distance of one meter at 70 dB SPL. The number of correct responses was noted. Results revealed that speech perception tests in quiet, showed a binaural advantage for only one of the three participants for words alone and not for sentences. They reported that two out of three participants showed ceiling effect. The other participant obtained the maximum score in HA alone condition where the benefit of bimodal fitting could not be explained. The same measures were carried out in the presence of noise. Noise was presented either from the front ($0^0$ A), the right ($+90^0$A), or the left ($-90^0$ A). With speech and noise both from front, two participants performed better with both devices than with either device alone, exhibiting the binaural squelch in bimodal condition. With speech in front and noise on the hearing aid side, no binaural advantage was seen. But with noise on the cochlear implant side, one participant showed a binaural advantage.

Ching et al. (2003) carried out a study on six adults, three males and three females, who were using a unilateral cochlear implant with a stable map. They were fitted with a hearing aid in the contralateral ear and loudness optimized using NAL-NL1 prescriptive formula. The speech perception ability was assessed after four weeks of usage of hearing aid using BKB sentence list and VCV consonant lists in the presence of noise in three aided conditions namely, CI alone, CI+HA, CI with bilateral microphone conditions. The CI with bilateral microphone condition refers to unilateral cochlear implant with input from two microphones, one placed on each ear. Speech perception abilities were significantly better in CI+HA condition than CI alone condition. However, no significant differences were seen between CI+HA and CI alone with bilateral microphone condition.

A two article series by Ching, Hill, Dillon, and Wanrooy (2004a, b) evaluated the fitting of hearing aid and found that the using hearing aid in the ear contralateral ear to that of cochlear implant can help to improve the quality of life of the recipient and the recipient's family. It also can eliminate the negative impact of auditory deprivation in the non-implanted ear. This may enhance the speech perception in noise and provide enhanced sound quality. Hence, they recommended that the bimodal fitting should be made mandatory, provided there is a useful residual hearing in the ear contralateral ear to that of cochlear implant.

Hamzavi, Pok, Gstoettner, and Baumgartner (2004) evaluated speech perception abilities in quiet using Freiburger numbers, Freiburger Monosyllables and Innsbrucker Sentence Test on seven participants, three females and four males. All the participants had used hearing aid in the contralateral ear which was loudness balanced with the cochlear implant at least for a period of 12 months. Speech perception abilities were assessed in three different aided conditions namely hearing aid alone (HA), cochlear implant alone (CI alone) and bimodal condition (CI+HA). Results revealed that in majority of the tests, the participants performed better in CI alone when compared to HA alone condition. They performed better in the bimodal (CI+HA) condition when compared to CI alone condition.

Litovsky, Johnstone, and Godar (2006) conducted a study to compare the binaural benefit in CI+HA and binaural cochlear implant (CI+CI) condition. 20 children were considered, 10 using CI+HA and 10 using CI+CI. Cochlear implants used by the participants had a stable map. In the binaural condition, both the devices were loudness balanced with each other. Participants had undergone intensive auditory verbal therapy and/or speech therapy. They assessed the speech recognition thresholds (SRT) of the children through a recorded version of two-word spondee list, in male voice, in the presence of competing two-talker signal in female voice. The target stimuli was always presented from the front ($0^0$ A) and competing signal was presented either from front ($0^0$ A) or left ($-90^0$ A) or right ($+90^0$ A). Although they reported that the SRTs were significantly lower in CI+CI condition when compared to CI+HA condition, the SRTs were significantly lower even in CI+HA condition when compared to CI alone condition.

Ullauri, Crofts, Wilson, and Titley (2007) carried out a pilot study to develop a protocol to fit a hearing aid in children, aged seven years and above, who were using unilateral cochlear implant. Seven children underwent a trial to use a hearing aid in the contralateral ear after being loudness balanced with the cochlear implant, for a period of eight to nine weeks. Later, they were assessed for speech recognition abilities on a sentence perception test in quiet and in the presence of noise. All the children showed improvement in both the tasks of sentence perception in quiet and sentence perception in noisy conditions in bimodal condition (CI+HA) when compared to CI alone condition.

Ching, Wanrooy, and Dillon (2007) evaluated speech perception on two adults on three aided conditions namely, CI alone condition, bimodal condition (CI+HA) and binaural cochlear implant (CI+CI) condition. The tasks were carried out six months post switch-on of second cochlear implant. SNR-50 measure was used to measure the speech perception ability in noise. Both the participants were found to have better perception in CI+CI condition as compared to CI+HA condition. The benefit of speech perception in the presence of noise was found to be the greatest for CI+CI condition when compared to CI+HA condition followed by CI alone condition. Although they reported that the CI+CI condition provided better benefit than CI+HA condition, they proposed that the complementary information with respect to low frequency information is better delivered to the individuals through CI+HA condition when compared to CI+CI condition. Hence, the individuals using unilateral cochlear implant should be fitted with hearing aid or a cochlear implant in the contralateral ear.

Iwaki et al. (2008) evaluated six female post-lingual adults with hearing loss aged 36 years to 78 years, on speech perception through bimodal stimulation on Japanese hearing in noise test (JHINT), with and without Adaptive Dynamic Range Optimization (ADRO) devices. All the participants were implanted unilaterally and were using hearing aid with Wide Dynamic Range Compression (WDRC) in the contralateral ear before implantation and at least for a period of 12 months post implant. The participants were fitted with hearing aids with and without ADRO technology which was loudness balanced with that of the cochlear implant. Scores in JHINT revealed that simultaneous use of ADRO technology in hearing aid and with cochlear implant in contralateral ear showed significantly better supra threshold speech perception over non-ADRO devices. Hence, they recommended the use of ADRO devices in bimodal stimulation.

Beijen, Emmanuel, Mylanus, Leeuw, and Snik (2008) carried out a study on 22 children with unilateral cochlear implant with a stable map. All the children used hearing aids in the contralateral ear and continued to do so after the cochlear implant surgery. The hearing aid was loudness balanced with cochlear implant in the contralateral ear for all the participants. All the participants were evaluated on a phoneme recognition test in quiet and noise. This was done in two aided conditions, CI alone and CI+HA conditions. Analysis of the group data revealed a significant better performance on phoneme recognition task in CI+HA conditions when compared to CI alone condition, both in quiet and noise. They also addressed the issue of choice of hearing aid, since it is associated with the moderate costs and hence, it is cost-effective to recommend to all children with unilateral implant in order to offer a chance to experience binaural benefit.

Keilmann et al. (2009) evaluated 20 participants whose age ranged from three to 78 years (12 children and eight adults). They had an experience of using cochlear implant in one ear for a period of at least six months. All the participants were fitted with a hearing aid which was loudness optimized with cochlear implant in the contralateral ear. Speech perception in quiet and in noise were tested in hearing aid alone (HA), cochlear implant alone (CI) and bimodal conditions (CI+HA). They presented the noise through loudspeakers placed at back ($180^0$ A) and speech from front ($0^0$ A). Seven out of 12 children performed better on speech recognition scores, in quiet, in CI+HA condition when compared to CI alone followed by HA alone condition. Four children did not reveal any difference between the CI+HA and CI alone conditions. One child had better scores in CI alone condition when compared to CI+HA condition. Nine children were examined on speech perception in noise. Out of which five children scored better in CI+HA condition when compared to CI alone condition. One child showed no improvement and three children showed worsening of speech perception scores with CI+ HA condition compared to CI alone condition. This was because the participants were experienced hearing aid users and were accustomed to the hearing aid fitting earlier to cochlear implantation which had high gain at low-frequencies. Eight adult participants were considered for the speech perception task. Six out of eight showed improvement in speech perception in CI+HA condition when compared to CI alone condition in quiet. However, all the participants showed improvement on speech perception in noise on CI+HA condition when compared to CI alone condition. They hypothesized that the cochlear implant and hearing aid provide complementary information regarding high frequency and low frequency cues respectively enabling better speech perception in case of bimodal condition.

Lim et al. (2009) conducted a study on 19 children in Korean language who underwent cochlear implant . They evaluated the participants on an open-set speech perception task in quiet and in the presence of noise (+10dB SNR and +20 dB SNR) in two aided conditions, CI alone and CI+HA conditions. The results revealed that there was no significance difference between the speech perception scores in quiet in CI alone and CI+HA condition. Whereas, scores on speech perception task in noise were significantly better in CI+HA condition when compared to CI alone condition accounting for the spatial release from masking.

Berrettini et al. (2010) evaluated speech perception abilities in Italian language on 10 adult participants, four males and six females with pre-lingual hearing loss, using unilateral cochlear implant. The participants were using cochlear implant in one ear for a period at least one year and a stable map for at least six months. All the participants had residual hearing in the contralateral ear and testing was carried out after six months of hearing aid use which was loudness balanced with cochlear implant. They assessed the speech perception abilities in quiet and in noise. Speech was always presented from the front and noise from either front or cochlear implant side or hearing aid side or from back. Significant benefit on an open set speech perception was revealed in CI+HA condition when compared to CI alone condition. The benefit was highest when noise was presented from front ($0^0$ Azimuth) compared to noise presented from cochlear implant side or hearing aid side. Significant difference was also reported on the open set speech identification tests after six months use of hearing aid when compared to initial fitting of hearing. Participants reported that they perceived the speech to be more natural while using CI+HA than CI alone condition in real-life.

Cullington and Zeng (2011) carried out a study on 26 English speaking adult cochlear implant users. Thirteen of them wore binaural cochlear implant (CI) and the other 13 used 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 nosie test (HINT) test 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 binaural cochlear implant group (CI+CI), the results were not statistically significant. Thus, it can be inferred that bimodal stimulation (CI+HA) is more effective for speech perception in noise, with respect to cost and surgical risks involved as in case of binaural cochlear implant condition (CI+CI).

Sammeth, Bundy, and Miller (2011) reviewed the literature regarding the use of bimodal implants (CI+HA) and binaural implant (CI+CI). They attributed the benefit of speech perception in quiet and noise to binaural summation/ redundancy effects, head shadow effect and binaural squelch / unmasking effect. The fact that use of hearing aid in the contralateral ear in individuals using unilateral cochlear implant improve localization abilities and prevent auditory deprivation was addressed. They reported that although binaural CI or CI+HA condition improves speech perception in noise, and localization abilities, CI+HA would be affordable by majority of the individuals when compared to binaural cochlear implants.

Incerti, Ching, and Hill (2011) compared the abilities of consonant perception in 15 adults with a post-lingual onset of hearing loss. All the participants had a stable map with the cochlear implant for a period of over at least six months. Consonant perception abilities were tested using 24 VCV non-sense syllables where the vowel was always /a/ and 24 different English consonants spoken by a male with general Australian accent. The speech identification scores were obtained in CI alone and CI+HA condition. Statistical analysis revealed a significantly higher consonant perception in bimodal condition (CI+HA) than in CI alone condition. Benefit of bimodal condition was more evident for speech perception in noise than for speech perception in quiet. A detailed analysis of the data revealed that voicing and manner of articulation were better perceived than the place of articulation especially in the presence of noise. This may be due to the better availability of the $F_0$ and voicing cues provided by the hearing aid because of its better frequency response at lower frequencies. Hence, they recommended that the bimodal stimulation must be a standard practice for the clinical management.

**2.2. Bimodal amplification and horizontal localization.**

The ability to locate sounds is reported to be important for one's safety and survival (Ching et al., 2006). Human auditory system makes use of inter-aural time and inter-aural level differences to localize the source of sounds on the horizontal plane which would be possible only in the binaural hearing situation (Moore, 2004). Binaural hearing helps the listeners with normal hearing sensitivity to localize sound sources by attending to the ear with the better signal-to-noise ratio (SNR) (Litovsky, 2005; Ching, 2005). Hence, for an individual with hearing loss in both ears, it is a standard procedure to fit them with hearing devices in both ears in order to help them in localization of sound sources.

Ching et al. (2001) addressed the issue of whether the children who use cochlear implant should wear a hearing aid in the contralateral ear. They considered 11 children with congenital hearing impairment who continued to use hearing aid in the contralateral ear after the cochlear implant. They tested the participants on a localization task in four aided conditions, HA alone, CI alone, CI+ $HA_{worn}$ (not optimized) and CI+$HA_{adj}$ (optimized). The rmsDOE was used as a measure to represent the localization task.

Although there was no significant difference reported between CI+ HA $_{worn}$ and CI+HA$_{adj}$ conditions, the CI+HA $_{adj}$ resulted in a significantly better localization abilities when compared to CI alone or HA lone condition. They accounted the better localization in CI+HA $_{adj}$ to the availability of low-frequency information providing extra cues of inter-aural time differences.

Tyler et al. (2002) tested localization abilities in individuals fitted with cochlear implant in one ear and hearing aid in the other ear with noise burst presented at $45^0$ from right or left. Results revealed that localization abilities improved in bimodal situation in two of three patients tested. The two participants had almost similar localization scores in hearing aid alone and cochlear implant alone condition. Localization abilities significantly were better in bimodal condition (CI+HA) when compared to CI alone or HA alone condition. The third patient had above-chance localization ability with the implant alone condition (CI alone). The localization scores were significantly better in CI alone and CI+HA condition compared to HA alone condition but did not show any significant difference between CI alone and CI+HA condition. The varying results found in the study may be due to less number of participants used because of which the results could not be generalized across the participants considered for the study. The authors concluded that there were clear signs of advantages observed while using a hearing aid in the ear contralateral to that with a cochlear implant.

Ching et al. (2003) carried out a study to test the localization abilities in adults using unilateral cochlear implant. Localization abilities were tested by placing 11 loudspeakers spanning over a range of $180^0$ with an interval of $18^0$ between the consecutive speakers. A train of four pink noise pulses of 0.83 second duration was presented in a random order from the speakers at 70 dB SPL. The root mean square degree of error (rmsDOE) were calculated in three different aided conditions namely CI alone, CI+HA, CI alone with bilateral microphone. The rmsDOEs were found to be least for CI+HA condition followed by CI alone and CI alone with bilateral microphone conditions. The CI with bilateral microphone rather caused confusion with respect to horizontal plane localization. Hence, they suggested that the CI+ HA stimulation would be a better option followed by CI alone stimulation for localization abilities.

Seeber et al. (2004) evaluated the localization abilities on 11 adults, eight females and three males with post-lingual hearing loss using bimodal implant and four adults with post-lingual hearing loss using bilateral cochlear implant. They carried out the study by placing 11 loudspeakers spanning over an angle of $+50^0$ Azimuth to $-50^0$ Azimuth with a constant interval between them at a distance of 1.95 meter from the participant's head. The results revealed better localization abilities in bimodal condition (CI+HA) followed by CI alone and HA alone conditions. The group with binaural cochlear implants (CI+CI) condition also showed significantly better localization abilities when compared with unilateral conditions of first cochlear implant alone or second cochlear implant alone. The participants performed better in the unilateral condition of first cochlear implant alone condition when compared with second cochlear implant alone condition. This may be due the practice effect with the first cochlear implant when compared to that with second cochlear implant. They attributed the better localization in the participants using binaural devices, i.e., CI+CI or CI+HA condition, to the use of inter-aural level differences and inter-aural time difference cues.

Litovsky et al. (2006) carried out a study to test localization abilities in 14 children, six children using CI+CI and eight children using bimodal cochlear implant (CI+HA) through the measure of minimal audible angel (MAA). MAA is defined as the smallest angle at which performance reaches a score of 70.9%. Fifteen loudspeakers were placed with constant interval spanning from -70$^0$ A to +70$^0$ A. Items from the spondee list were presented in random order from the loudspeakers. The task of the participant was to inform whether the signal arrived from left or right. The distance between the two loudspeakers was slowly decreased till the child achieved a score less than 75%. All the participants showed better performance on MAA in CI+CI condition when compared to CI alone condition. However, only four out of eight participants showed better performance on MAA in CI+HA condition when compared to CI+CI condition. The results on the MAA were correlated with the speech perception abilities as mentioned earlier in section 2.1. The results revealed that there was no correlation between the improvements observed on the speech perception task when compared to improvement on MAA task. This suggests that the two tasks may depend on different auditory mechanisms.

Ullauri et al. (2007) collected feedback from seven children who used a hearing aid in the ear contralateral to the ear with cochlear implant for period of eight to nine weeks in the contralateral ear. Participants had to report whether they found hearing aid on the contralateral ear to be useful in localization in a real-life when used simultaneously with the cochlear implant in the other ear. They reported that four children found hearing aid useful in the contralateral ear as it helped in localizing the sound. One child did not find any use from wearing hearing aid in contralateral ear and was not happy because of the cosmetic appeal due to the size of the hearing aid. Another child did not report benefit from using hearing aid along with cochlear implant and one did not like using it. However, benefit from bimodal condition was reported in all the children by collecting the feedback from parents and teachers using the questionnaire titled Client Oriented Scale of Improvement for children (COSI-C). Berrettini et al. (2010) also reported eight out of ten adult participants in the study experienced better localization abilities in the real-life in CI+HA condition when compared to CI alone condition. However, this was not evident through structured task of localization. These results recommend the mandatory fitting of hearing aid in the ear contralateral to that with cochlear implant to avail better localization abilities in real-life situation.

Ching et al. (2007) tested the horizontal localization abilities through root mean square degree of errors (rmsDOE) on two adults in three conditions, CI alone, CI+HA condition and CI+CI condition. Significant decrease in the rmsDOE was reported in CI+HA condition as compared to CI alone ($p<0.05$) and also in CI+CI condition as compared to CI+HA ($p<0.05$). They concluded that the errors were found to be least in CI+CI condition followed by CI+HA and CI alone conditions at the time of fitting. However, these results were based on a sample number of two participants.

Thus from the studies reported in the literature, it is evident that the use of hearing aid in the ear contralateral to that with cochlear implant, would benefit the individuals. The benefit is in terms of better speech perception in quiet, also in the presence of noise and improved localization abilities. However, there is a dearth in literature regarding the same in pediatric population. The present research is an attempt to study the benefit of bimodal stimulation in children.

# Chapter 3

# Method

The aim of the present study was to validate a protocol to fit a hearing aid to the ear contralateral to the ear with a cochlear implant. The specific objectives were to compare the performance on localization, speech perception in quiet and speech perception in noise (SNR-50) in three aided conditions, namely, hearing aid alone (HA alone), cochlear implant alone (CI alone) and cochlear implant plus hearing aid (CI+HA) conditions. The following method was adopted to investigate the aims of the study.

## Participants

The data were collected from a total of 10 participants who were using a unilateral cochlear implant.  The participants were assigned to one of the two groups based upon the task that they were supposed to carry out. The first group (Group I) consisted of nine children, who were evaluated on speech perception in quiet and speech perception in noise (SNR 50) tasks. The degree of hearing loss in the ear with cochlear implant before the implantation was found to be severe to profound hearing loss with pure tone average ranging from 85 to 120 dB HL. In the contralateral ear, they had severe to profound degree of hearing loss with a pure tone average ranging from 88.3 to 120 dB HL. Their age ranged from 5 years 5 months to 17 years 10 months, with mean age of 10 years and standard deviation of 3 years 8 months. They had undergone cochlear implantation in one ear and were using a stabilized map for a period of at least three months. The age at which the participants were implanted unilaterally ranged from 3years 2 months to 10 years 2 months.

Immittance evaluation in both the ears revealed ‘A’ Type tympanogram with absent reflexes. Transient Evoked Oto-Acoustic Emissions (TEOAEs) revealed outer hell cell dysfunction in both ears. The participants had residual hearing in the contralateral ear and the aided thresholds of the participants with a suitable hearing aid alone in the contralateral ear fell within the speech spectrum at least up to 2000 Hz. In addition to the listening training, the participants were undergoing speech and language therapy in Kannada language. All the participants were able to perform at least an open-set speech identification task. The participants had no other significant history of any neurological or cognitive deficits. All the participants were using hearing aids in both the ears for a period of at least two years, before the cochlear implantation.

The second group (Group II) who had to carry out the localization task consisted of eight children with hearing impairment. The degree of hearing loss in the ear with cochlear implant before the implantation was found to be severe to profound hearing loss with pure tone average ranging from 90 to 120 dB HL. In the contralateral ear, they had greater than severe degree of hearing loss with a pure tone average ranging from 88.3 to 103.3 dB HL. Their age ranged from 5 years 5 months to 17 years 10 months, with a mean age of 10 years 5 months years and a standard deviation of 7 years 3 months. They had undergone cochlear implantation in one ear and were using a stabilized map, for a period of at least three months. The age at which the participants were implanted ranged from 3 year 2 months to 10 years 2 months.

Immittance evaluation revealed ‘A’ Type tympanogram with absent reflexes. Transient Evoked Oto-Acoustic Emissions (TEOAEs) revealed outer hell cell dysfunction in both the ears. All of them had aidable residual hearing in the contralateral ea. The aided thresholds, with a suitable hearing aid, in the contralateral ear of the participants fell within the speech spectrum at least up to 2000 Hz. The participants had no significant history of any neurological or cognitive deficits. Participants from the Group I were also considered to carry out the task of localization.

## Instrumentation

A calibrated two channel diagnostic audiometer, Madsen Orbiter 922 with TDH 39 headphones encased in MX 41AR ear cushion was used for performing the Pure Tone Audiometry (air-conduction and bone-conduction) and Speech Audiometry. This audiometer with Madsen loud speakers were used for performing speech identification and localization tasks in different aided conditions. For carrying out the localization task, five loudspeakers were connected to the audiometer. The placements of the loudspeakers are as shown in block diagram (Figure 1). One loud speaker each was placed at $+90^0$A, $+45^0$A, $0^0$A, $-45^0$A, and $-90^0$A. The loudspeakers were located at a distance of one meter away from the participant, in a semicircle. One channel of the audiometer was connected to the loudspeaker placed at $0^0$ A. During the localization task, a toggle switch was used to route the signal of the other channel of the audiometer to any of the four speakers placed at $+45^0$ A, $+90^0$ A, $-45^0$ A, or $-90^0$ A. The output of the loudspeaker was calibrated using a sound level meter (SLM) (Larson-Davis system 824, model no. 2540) with a 1/2” free-field microphone fitted to its preamplifier. The microphone of the sound level meter was placed at the position of the head of the participant, during calibration, at a distance of one meter. This process was carried out by presenting the stimuli through the loudspeakers, one at a time, and measuring the output during the calibration. Thus, the loud speakers were calibrated to emit the output that would result in equal dB HL at the microphone at a distance of one metre.

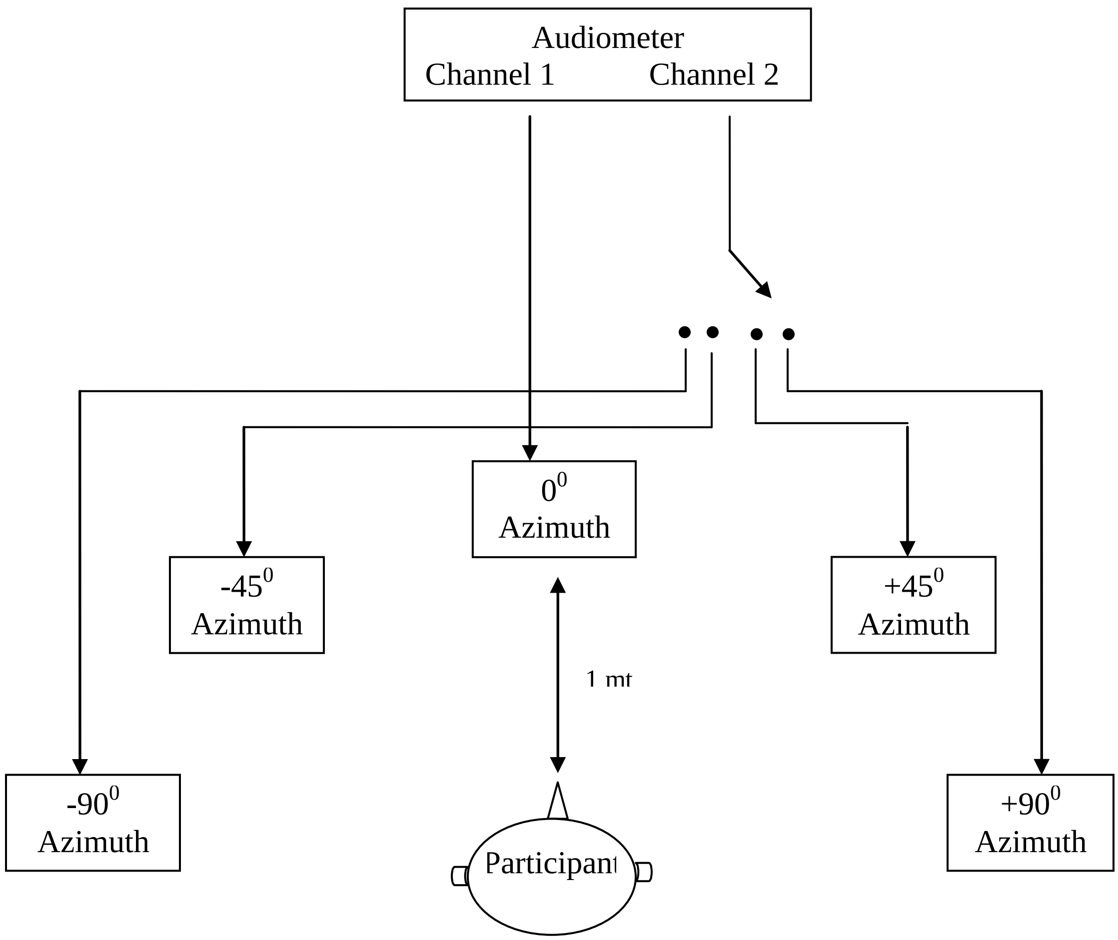


*Figure 3.1:* Block diagram of the test set-up for carrying out localization task.

A calibrated GSI Tympstar middle ear analyzer (version 2.0) was used to rule out middle ear pathology. A digitally programmable two channel and eight band behind-the-ear hearing aid with a fitting range for severe-to-profound hearing loss, coupled to a custom made soft shell ear mould was used for evaluating the aided performances. A personal computer with NOAH-3 and hearing aid specific softwares and the Hearing Instrument Programmer (HiPro) interface were used to program the digital Behind-The-Ear (BTE) hearing aids. The cochlear implant with either ear level or a body level speech processor owned by the participant, programmed with a stable map, was also used. The participants were using three models of cochlear implant from a single manufacturer. A laptop computer, installed with Adobe Audition software (version 3.0) was used to route the test stimuli through the auxiliary input of the audiometer for the localization task.

## Test environment

All the testing was done in an air-conditioned sound treated double room situation. The ambient noise levels were within permissible limits.

## Test material

The following test material was utilized in the study:

1) Phonemically balanced (PB) word list in Kannada (Vandana, 1998) was used. The test material consisted of two lists with 25 bisyllabic words in each list. This material was used to measure the Speech Identification Scores (SIS) in quiet and SNR-50 through monitored live-voice presentation.

2) A train of four white noise pulses with duration of 200 ms separated by 200 ms of silence (Tyler et al., 2002) was generated for the purpose of localization task. A calibration tone of 1000 Hz was recorded prior to the train of white noise pulses. Stimulus was generated and normalized using Adobe Audition 3.0 software. The stimulus

that was recorded on a CD which was routed through the auxiliary input of the audiometer to the loudspeakers. The presentation level of the stimulus was 45 dBHL for evaluating the localization ability of the participants.

## Procedure

Pure tone audiometric thresholds were obtained for both air-conduction (at octave frequencies from 250 Hz to 8000 Hz) and bone-conduction (at octave frequencies from 250 Hz to 4000 Hz) using modified Hughson-Westlake procedure (Carhart & Jerger, 1959). Speech audiometry was done to obtain the speech recognition thresholds and speech identification scores. Immittance evaluations were carried out to ensure normal middle ear functioning. TEOAEs were also measured to ensure dysfunction of the outer hair cells. These audiological evaluations were carried out in order to confirm the participant selection criteria.

The data were collected in three phases. They were

Phase I: Programming the hearing aid using NAL-NL1 and optimizing the hearing aid with the cochlear implant in the contralateral ear.

Phase II: Comparison of speech identification tasks in quiet and in noise in different aided conditions.

Phase III: Comparison of the localization abilities in different aided conditions.

*Phase I: Programming the hearing aid using NAL-NL1 and optimizing the hearing aid with the cochlear implant in the contralateral ear.*

In the first phase of the study, hearing aid fitting and optimization of the loudness between the ear with the cochlear implant and the ear with the hearing aid in the contralateral ear was done. Each participant was fitted with a two-channel, eight band digital behind-the-ear (BTE) hearing aid with a custom ear mould in the ear contralateral to that with cochlear implant.

The hearing aid was programmed using a personal computer and a HiPro interface unit using NOAH-3 and hearing aid softwares. The hearing aid was programmed to fit the hearing loss of the participant. NAL-NL1 fitting formula was used to prescribe the gain of the hearing aid according to the first fit with the acclimatization level set at 3, as the participants were experienced hearing aid users.

Once the individual hearing aid gain was prescribed, the aided thresholds of the participants were obtained for warble tones from 500 to 4000 Hz from a loudspeaker of the audiometer placed at $0^0$ Azimuth at a distance of one meter. The gain of the hearing aid was optimized such that the aided thresholds were within speech spectrum, from 500 to 4000 Hz, at least up to 2000 Hz.

After this step, narrow band noise centred at 500 Hz and 2000 Hz were presented at 45 dB HL. Two frequency bands were chosen since the test hearing aid had two channels. The hearing aids settings were varied based on the response of the participant. During the process of adjusting the hearing aid to approximate the loudness with that in the implanted ear for 500 Hz and 2000 Hz narrow band noises, the participant was instructed to report whether the loudness perceived with acoustical input from hearing aid in one ear and the electrical input from the cochlear implant in the contralateral ear were same or that they heard the stimuli presented at the centre of the head. In order to achieve this, the hearing aid settings were manipulated such that the signal in the ear with hearing aid matched in loudness with that in the ear with cochlear implant. The cochlear implant programming parameters were not altered while achieving equal loudness.  If the participant reported that the sound is heard louder in the ear with hearing aid, then the gain of the hearing aid was decreased. Conversely, if the participant reported that the sound heard was louder in the ear with cochlear implant, the gain of the hearing aid was increased. Once the loudness balancing was achieved with both 500 Hz and 2000 Hz narrow band noise stimuli, the same procedure was carried out using a white noise. The overall gain was systematically varied to achieve loudness balance as described earlier.

The procedure for optimizing the loudness of hearing aid was followed for each participant. Once the hearing aid was optimized in the ear contralateral to that with the cochlear implant, the data were collected in three aided conditions. The aided conditions were hearing aid alone (HA), cochlear implant alone (CI), and cochlear implant plus hearing aid (CI+HA) conditions.

*Phase II:  Comparison of speech identification tasks, in quiet and in noise, in different aided conditions.*

In this phase, data on aided speech identification in quiet and in noise were collected in three different aided conditions.

1. *Aided open set Speech Identification Scores (SIS) in quiet*:

The SIS in quiet was obtained in each test condition, for each participant in Group I, using phonemically balanced word list in Kannada for children (Vandana, 1998). This was obtained in a sound field condition through monitored live voice presentation. The presentation level (PL) of speech stimuli was fixed at 45 dBHL. The stimuli were presented through the calibrated loudspeaker of the audiometer from $0^0$ Azimuth placed at a distance of one meter from the participant. In each of the aided conditions, the SIS was obtained by presenting one complete word-list of 25 words. The SIS was obtained in three different aided conditions namely hearing aid alone (HA), cochlear implant alone (CI) and cochlear implant plus hearing aid (CI+HA) conditions.

The participant was instructed to repeat the words being presented. If the speech of the participant was unintelligible, written responses were obtained. If the participant identified the word correctly, a score of '1' was given. If not, a score of '0' was given. The maximum score was 25, as each list consists of 25 words. The total number of words correctly repeated in the list was noted for each condition. This was considered as the speech identification score of the participant for the respective aided condition. The word-list was randomized in the three aided conditions. Thus, in quiet, three speech identification scores (SIS), one for each of the aided condition (i.e., HA alone, CI alone and CI+HA conditions) were obtained. This was repeated for each participant in Group I.

2. *Aided open set Speech Identification Scores (SIS) in noise*:

To obtain the aided speech identification scores in noise, SNR-50 was measured. For the purpose of the study, SNR-50 is defined as the difference between the intensity of speech stimuli and the intensity of the competing speech-shaped noise in dB when the participant correctly repeats at least two words in a set of four words (50% of the words) being presented in the presence of competing speech noise.

The SNR-50 was measured in a sound-field condition using the words from the phonemically balanced word list in Kannada for children (Vandana, 1998). The speech stimuli were presented at a constant level of 45 dBHL through monitored live voice mode. The level of speech noise was varied to obtain the SNR-50. Both speech signal and the speech noise were presented through the loudspeaker of the audiometer located at $0^0$ Azimuth placed at a distance of one meter from the participant. As mentioned earlier, the level of the speech signal was kept constant at 45 dBHL and the level of the speech noise was varied. The initial presentation level of the noise was 30 dBHL i.e., the initial presentation level of the speech noise was kept at 15 dB below the speech signal and was varied systematically to measure the SNR-50.

The participant was instructed to repeat the words heard in the presence of the competing speech noise. The participant was presented with a set of four words taken from the phonemically balanced word list in Kannada (Vandana, 1998) at each presentation level of noise. If the participant repeated at least two words out of four words correctly, then the level of noise was increased in 2 dB steps. At each of the steps, four words were presented. If the participant failed to repeat at least two of the four words correctly, the level of noise was decreased in 4 dB steps. If the speech of the participant was unintelligible, written responses were obtained. This was continued until the highest level of speech noise that was enough for the participant to repeat at least two out of four words, was measured. At this point, the difference between the intensity of speech and the competing speech noise, in dB, was considered as the SNR-50.

Thus, the maximum level of noise at which the participant could correctly repeat at least two out of four words was measured and noted. This level was subtracted from 45 dB HL (presentation level of the speech signal) to obtain SNR-50. The SNR-50 was measured in three aided conditions, i.e., HA alone, CI alone and CI+HA conditions. Thus, for each participant, three SNR-50 values were obtained in different aided conditions and tabulated.

*Phase III: Comparison of the localization abilities in different aided conditions.*

Each participant was seated in the centre of the array of five loudspeakers connected to the audiometer as explained earlier. The loud speakers were calibrated to emit the desired stimulus at equal sound pressure level at the level of the participant's head located at a distance of one meter. A train of white noise pulses recorded on a compact disk was routed via auxiliary input to the audiometer to different loudspeakers. A set of stimuli consisting of 25 similar trains of white noise pulses, five times from each loudspeaker, were presented in each of the three different aided conditions (HA alone, CI alone and CI+HA conditions). In each of the three aided conditions, a total of 25 (5 loudspeakers*5 presentations) trains of noise pulses from the loud speakers were presented. The stimuli were presented at 45 dBHL. Before the presentation of the stimuli, the level of the presentation was monitored with the calibration tone of 1000 Hz. Six trial presentations were given to make sure that the participant had understood the instructions. During the test, the participant was instructed to maintain the designated position/orientation of the head. The order of 25 stimuli presented in each set was randomized through a ‘lottery without replacement’/ ‘simple random sampling’ method (Kalton, 1983). Thus, three different sets of the stimuli were prepared which were randomized across participants through ‘lottery without replacement’ / ‘simple random sampling’ method (Kalton, 1983). The stimulus was routed to different loudspeakers from the audiometer through a toggle switch.

The participant was instructed that he/she would be hearing to a train of noise stimuli from any one of the five speakers at a time. Each time, he or she had to report the loudspeaker from which the stimulus was heard. The response mode from the participant was through a pointing task. The location of the loudspeaker to which participants pointed was noted down in terms of Azimuth.

For the purpose of the study, degree of error (DOE) was measured for the localization task. Degree of error corresponds to the difference in degrees between the degrees of Azimuth of the loudspeaker of the actual presentation of the stimuli to the degree of Azimuth of the loudspeaker identified as the source of the stimulus by the participant. For example, if the stimulus was presented from a loudspeaker at $+45^0$ Azimuth and the participant reported the sound to be arriving from loudspeaker at $-45^0$, then the degree of error would be $90^0$ i.e., $45^0-(-45^0) = 90^0$. This DOE was obtained for 25 trials in each aided condition. Thus, in each of the three different aided conditions (HA alone, CI alone and CI+HA conditions), there was one set of degrees of errors consisting of 25 items. A single representation of degree of errors in each aided condition was done by the calculation of root mean square degree of error (rmsDOE) (Ching, Incerti, & Hill, 2004; Van Deun et al., 2009). The rmsDOE is defined as the square root of the average of squared degrees of errors in each set. Thus, each participant had three rmsDOEs, representing the localization abilities of the participants in each of the three aided conditions (HA, CI and CI+HA conditions). It is calculated using the formula (Ching, Incerti, & Hill, 2004) given below.

$$\text{rmsDOE} = \sqrt{\frac{DOE_1^2 + DOE_2^2 + DOE_3^2 + \ldots\ldots\ldots\ldots + DOE_{25}^2}{25}}$$

Where, $DOE_n$= Degree of Error of the $n^{th}$ presentation in a set; and

rmsDOE = Root mean square degree of error.

Thus from the three aided conditions (HA alone, CI alone and CI+HA), the following data were collected in each test condition from each participant:

1. SIS in quiet
2. SNR-50
3. rmsDOE for localization task.

The above data were tabulated and subjected to appropriate statistical analyses.

# Chapter- 4

## Results and discussion

The present study was conducted to compare speech perception- in quiet and in noise, and localization abilities in the three aided conditions. The aided conditions included hearing aid alone (HA alone), cochlear implant alone (CI alone), cochlear implant plus hearing aid in opposite ears (CI+HA). The data obtained from the participants in the three different conditions were subjected to statistical analyses using Predictive Analysis Software (PASW, version 18) software. The performance of the participants in three aided conditions are discussed in terms of following headings

I. Speech identification scores in quiet (SIS)
II. Speech recognition threshold in noise (SNR-50)
III. The root mean square degree of errors (rmsDOE) for a localization task

### I. Speech identification scores in quiet (SIS) in HA alone, CI alone and CI+HA conditions:

The SIS obtained for each of the participant (N=9) are as shown in the Figure 4.1. From the Figure 4.1, it can be noted that the performance on a speech identification task (SIS) was zero in HA alone condition in all the participants. All the participants scored better in the CI alone condition when compared to HA alone condition. The scores in CI+HA condition were better when compared to CI alone condition in all the participants except for the participant number six and participant number nine.

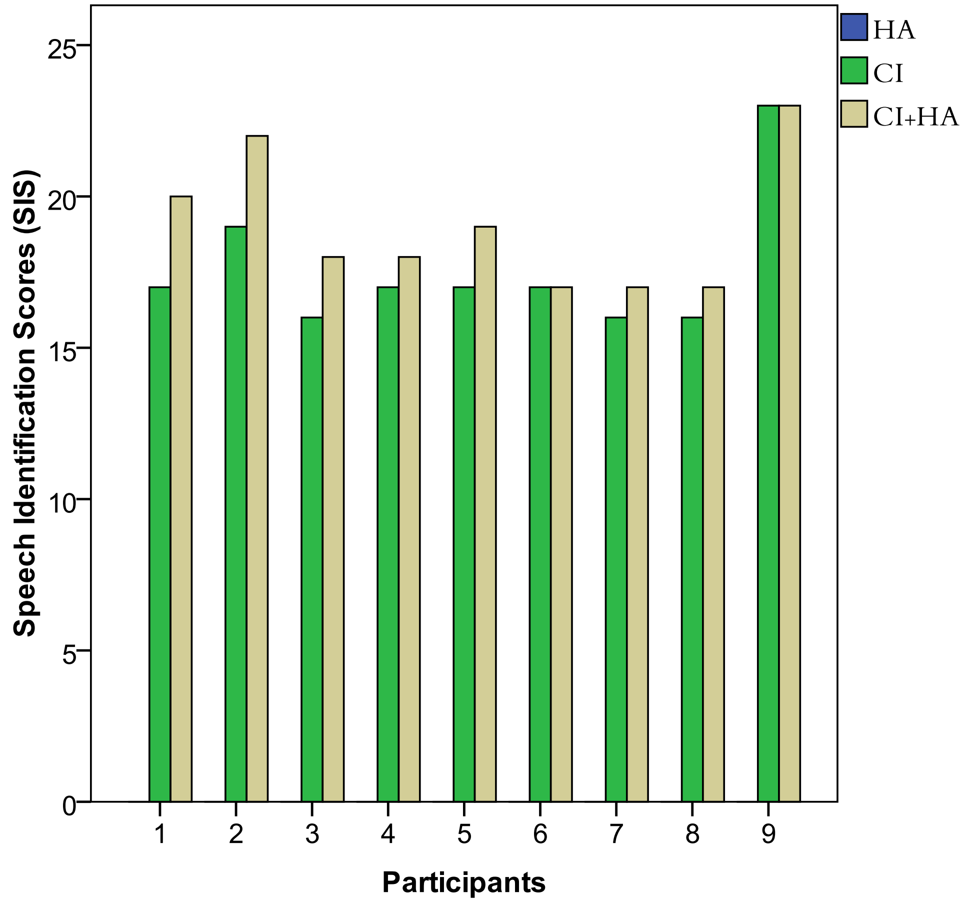


*Figure 4.1:* Speech Identification Scores (max. score=25) obtained from each of the nine participants in HA alone, CI alone and CI+HA conditions.

Table 4.1 shows the mean and standard deviation (SD) values for the SIS in the three aided conditions namely, hearing aid alone (HA), cochlear implant alone (CI) and cochlear implant plus hearing aid (CI+HA). From the Table 4.1, it can be seen that among the three aided conditions, the performance was the best in CI+HA condition followed by the performance in CI alone and then in HA alone condition. The participants did not repeat any word in the HA alone condition (i.e., SIS=0). The SIS ranged from 16 to 23 for CI alone condition, with mean score of 17.55 and SD of 2.24. The SIS for the CI+HA condition varied from 17 to 23 with mean of 19 and SD of 2.24.

Table 4.1: *Mean and standard deviation (SD) of the speech identification scores (Max. scores= 25; N=9) in quiet obtained in HA alone, CI alone and CI+HA conditions.*

| *Aided test conditions* | *SIS: Mean (SD)* |
|---|---|
| Hearing aid alone (HA) | 0 (0) |
| Cochlear implant alone (CI) | 17.55 (2.24) |
| Cochlear implant + hearing aid (CI+HA) | 19 (2.24) |

In order to find out if the differences in performance of SIS among the three different aided conditions was significant, repeated measures ANOVA was carried out. The results of the repeated measures ANOVA revealed that there was a significant difference between SIS obtained in three different aided conditions [F (2, 16) =534.388; p<0.001]. This means that there was a significant difference between the SIS obtained in any of the aided conditions. Hence, Bonferroni (post-hoc) pair-wise analysis was carried out to the find out which among the three groups differed from each other on SIS. The Bonferroni (post-hoc) pair-wise comparison revealed a significant difference in the SIS between HA alone and CI alone condition (p<0.001), between HA alone and CI+HA condition (p<0.001) and between CI alone and CI+HA condition (p<0.05). A non-parametric, Wilcoxon signed rank test was also administered to cross-check the results of the parametric tests. Wilcoxon signed rank test also revealed a significant difference in the SIS between HA alone and CI alone condition, between HA and CI+HA condition and between CI and CI+HA condition. The results of Wilcoxon Signed Rank Test are tabulated in Table 4.2.

Table 4.2: *Comparison of SIS across HA alone, CI alone and CI+HA conditions.*

| *Aided conditions* | *Z* | *Asymp. Sig. (2-tailed)* |
|---|---|---|
| HA alone vs. CI alone | -2.699 | 0.007 |
| HA alone vs. CI+HA | -2.677 | 0.007 |
| CI alone vs. CI+HA | -2.392 | 0.017 |

The results of the present study are in agreement with the results of Ching et al. (2003) who reported that the speech perception abilities in quiet were significantly better in CI+HA condition compared to CI alone condition on BKB sentence list and VCV consonant lists. Hamzavi et al. (2004) also reported similar results, where participants using a hearing aid along with cochlear implant (CI+HA) for a period of at least 12 months performed better in CI+HA condition, which was significantly better than the performance in CI alone condition on Freiburger numbers, Freiburger Monosyllables and Innsbrucker Sentence Test. Tyler et al. (2002) reported binaural advantage in only one of the three participants tested for speech recognition for word and sentences. Ceiling effect was seen in other two participants. Incerti et al. (2011) also reported a significantly better performance on VCV non-sense syllable test in CI+HA condition when compared to CI alone condition.

The results of the present study are 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. Similar finding were reported by Ching, Incerti, Hill and Brew (2004) who reported significantly better speech recognition scores on a sentence recognition task.

However, the results of study contradict the results of the study by Lim et al. (2009) who reported that there was no significant difference on speech perception score in quiet between CI alone and CI+HA condition although the hearing aid was loudness balanced with the cochlear implant in the contralateral ear. These contradicting results may be due to the language used in the study (Korean), which is a tonal language, used in the speech perception test of the study.

The benefit on bimodal condition for speech perception in quiet is reported across types of speech recognition test materials using phoneme recognition (Beijen et al., 2008), word recognition ( Tyler et al., 2002) as reported in the present study, sentence recognition tasks (Ching, Incerti, Hill & Brew, 2004), also in children and adults. The better scores observed in the bimodal (CI+HA) condition when compared to monaural conditions, either CI alone or HA alone condition, on a speech perception task in quiet may be due to access to binaural cues and binaural redundancy

**II. Speech identification scores in noise (SNR-50) in HA alone, CI alone and CI+HA conditions:**

The signal-to-noise ratio required for the 50% of correct scores on speech identification task (SNR-50) obtained for each of the nine participants are as shown in the Figure 4.2. It must be noted that since the SIS in quiet was zero in the HA alone condition, SNR-50 in HA alone condition was not measured. The aided thresholds with hearing aid in the contralateral ear were within speech spectrum at least up to 2 kHz for all the participants. Hence, the SNR-50 was carried out only in CI alone and CI+HA conditions. It is seen from the Figure 4.2 that all the participants required lesser signal-to-noise ratio to obtain 50% scores on a speech identification task (SNR-50) in CI+HA condition when compared to CI alone condition. Lesser the value of SNR-50, better is the performance in that particular aided condition. That is, the performance was good even when the difference between the speech and speech noise was lesser, in the CI+HA condition when compared to CI alone condition in all the participants.

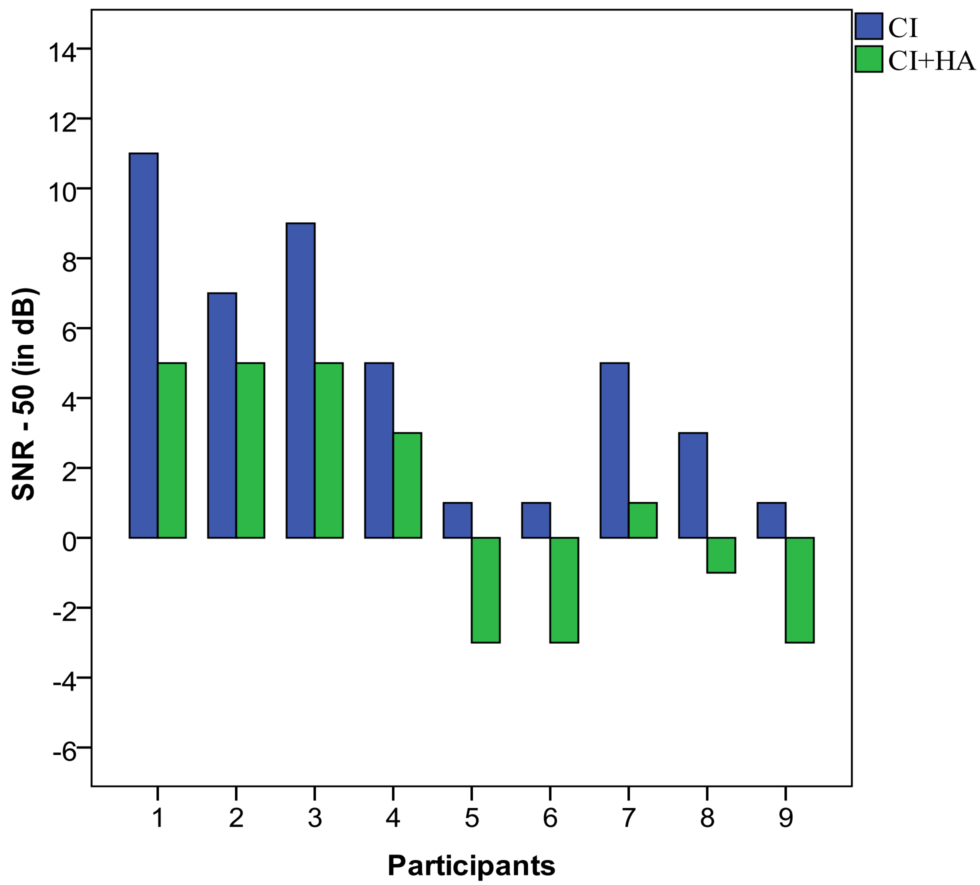


*Figure 4.2:* SNR-50 values obtained from each of the nine participants in CI alone and CI+HA conditions.

Table 4.3 shows the mean and standard deviation values for the SNR-50 of the different participants in two aided conditions namely, CI alone and CI+HA conditions.

The SNR-50 values could not be obtained in HA alone condition since the speech identification scores were zero for all the participants in HA alone condition. The SNR-50 for the CI alone condition ranged from 1 dB to 11 dB, with mean of 4.78 and SD of 3.67. The SNR-50 for the CI+HA condition varied from -3 dB to 5 dB, with a mean of 1 dB and SD of 3.60. The standard deviation reflects the variation in the duration of use of cochlear implant and age at which the participants underwent cochlear implantation.

Table 4.3: *Mean and standard deviation of the SNR-50 (N=9) obtained in CI alone and CI+HA conditions.*

| *Aided test conditions* | *SNR-50: Mean (SD)* |
|---|---|
| Cochlear implant alone (CI) | 4.78 (3.67) |
| Cochlear implant +hearing aid (CI+HA) | 1.00 (3.60) |

The mean and standard deviation given in the Table 4.3 for SNR-50, in different aided conditions, reveals that the signal-to-noise ratio required for 50% of the correct identification, is lesser in case of CI+HA condition when compared to CI alone condition. i.e., the performance in noise is better in the CI+HA condition compared to CI alone condition. The standard deviation for the SNR-50 in CI+HA was found to be more than the mean SNR-50. This may be because the SNR-50 of the individual data consisted of negative values.

In order to find out the differences in SNR-50 between CI alone and CI+HA condition, paired t-test was carried out. The results of the paired t-test revealed that there was a significant difference between SNR-50 obtained in CI alone and CI+HA conditions ($p<0.001$). A non-parametric test, Wilcoxon signed rank test, was also administered to cross-check the results of the parametric test. Wilcoxon signed rank test also revealed a significant difference in the SNR-50 between CI condition and CI+HA condition. The results of Wilcoxon Signed Rank Test are tabulated in Table 4.4.

Table 4.4: *Comparison of SNR-50 between CI alone and CI+HA conditions.*

| *Aided conditions* | *Z* | *Asymp. Sig. (2-tailed)* |
|---|---|---|
| CI alone vs. CI+HA | -2.754 | 0.006 |

These results conform to the findings reported by Tyler et al. (2002) who reported that the speech perception in noise improved with the bimodal condition when compared to that with monaural CI alone condition .In their study, the bimodal benefit was evident when the speech and noise were presented from the front when compared to speech presented from front and noise from $+90^0$ or $-90^0$, which supports the binaural squelch phenomenon. They also reported that the binaural advantage was seen for speech perception of words when compared to sentences which could be because of the linguistic redundancy present in the sentences. Berretini et al. (2010) also have reported similar results where the speech perception was better when the speech and noise were presented from the front when compared to the presentation of speech from front and noise from CI side or HA side or from the back. In their study too, the speech perception in noise was better in CI+HA condition when compared to that with CI alone condition.

Ullauri et al. (2007) also have reported the similar findings in a pilot study carried out to fit a hearing aid in the contralateral ear of the children who were using unilateral cochlear implant. Ching et al. (2007) used SNR-50 as a measure in two adults and reported that CI+HA condition led to better understanding of speech in the presence of noise when compared to CI alone condition. Although they reported that the bilateral CI (CI+CI) condition provided superior benefit for the speech perception in noise when compared to the CI+HA condition, CI+HA still remains the option of choice because of the affordability. Iwaki, Blamey, and Kubo (2008) studied speech perception in noise on adults with post-lingual hearing loss in Japanese language who used bimodal (CI+HA) implants. Japanese hearing in noise test (JHINT) was used to carry out the study. They reported that the use of ADRO technology in the bimodal devices showed better speech perception abilities in noise when compared to the use of WDRC in the hearing aid.

Keilmann et al. (2009) revealed mixed results on 17 participants, eight adults and nine children. All the participants had a stable map in the cochlear implant and the hearing aid was loudness balanced in the contralateral ear. Five of nine children scored better in the bimodal condition (CI+HA) when compared to CI alone or HA alone. One child did not reveal any difference and remaining three revealed better speech perception in noise in CI alone condition when compared to CI+HA. All the eight adults had better perception in noise in CI+HA condition when compared to CI alone condition. However, in the present study an improvement was noted among all the participants. They needed lesser SNR to obtain SNR-50 in CI+HA condition when compared to CI alone condition.

The results of the present study are in concurrence with the results of the study by Beijen et al. (2008) who reported significantly better speech perception in CI+HA condition when compared to CI alone condition on a phoneme recognition task in noise). Similar results were reported by Lim et al. (2009) in Korean language where 19 children were tested on an open set speech perception task. The scores obtained in the CI+HA condition were significantly better in CI+HA condition when compared to CI alone condition whereas the speech perception in quiet did not reveal such results.

The benefit on bimodal condition for speech perception in noise is reported across types of speech recognition test materials using phoneme recognition (Beijen et al., 2008), word recognition (Tyler et al., 2002) as reported in the present study, also in sentence recognition tasks (Ching, Incerti, Hill & Brew, 2004), also in children and adults, and in tonal languages (Lim et al., 2009).

Better perception of speech in the presence of noise are due to the fact that an individual gets to access the binaural cues which lead to binaural advantage as seen in individuals with normal hearing sensitivity. This supports the evidence that the phenomenon of binaural squelch is evident even in individuals who use different types of stimulation in each of the ears i.e., bimodal stimulation (electric+ acoustic).

**III. The root mean square degree of errors (rmsDOE) in localization in HA alone, CI alone and CI+HA aided conditions.**

The root mean square degrees of errors (rmsDOE) in localization obtained for each of the eight participants are as shown in the Figure 4.3. It can be inferred from the Figure 4.3 that all the participants had lesser rmsDOE in CI+HA condition when compared to CI alone condition followed by HA alone condition. It must be noted that the lesser the rmsDOE, better is the performance in that particular aided condition.

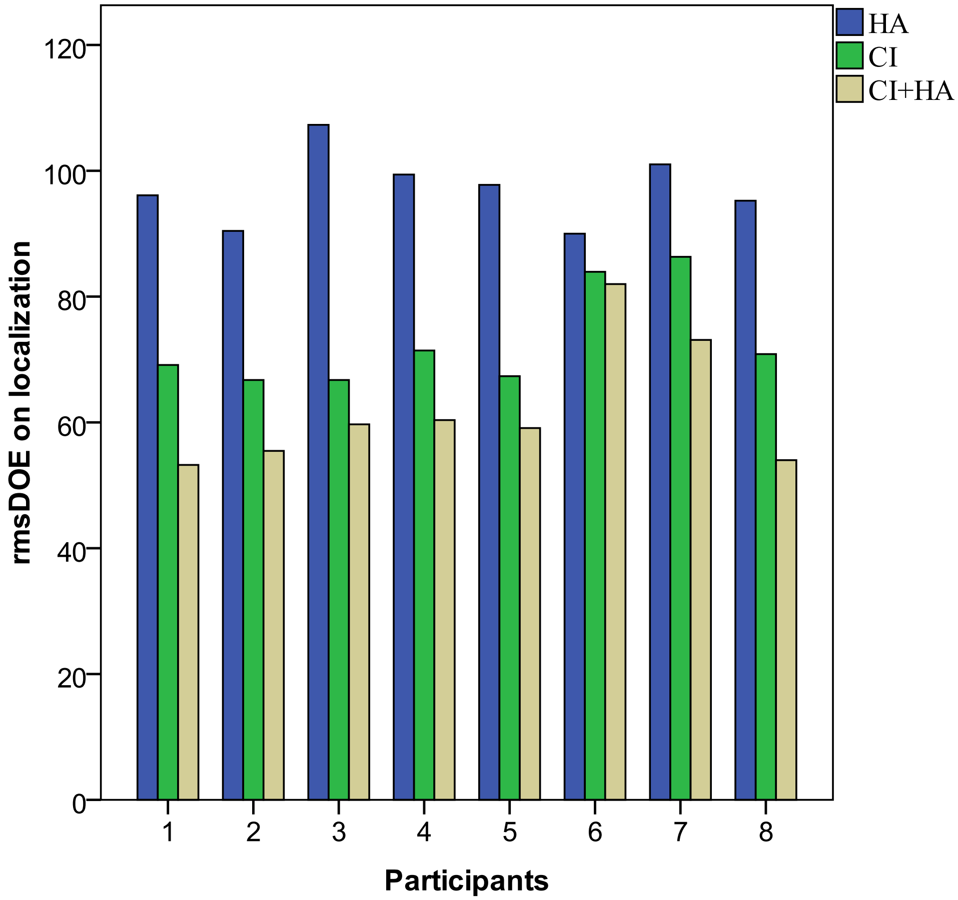


*Figure 4.3:* Root mean square degree of error (rmsDOE) on a localization task obtained from each of the eight participants in HA alone, CI alone and CI+HA conditions.

Table 4.5 shows the mean and standard deviation values for the rmsDOE in localization of the participants in three aided conditions namely, HA alone,CI alone, and CI+HA conditions. The rmsDOE for HA alone condition, CI alone condition and CI+HA condition ranged from $90^0$ to $107.3^0$, $66.74^0$ to $86.32^0$ and $54^0$ to $81.99^0$ respectively. Lesser the value of rmsDOE, better the performance. The mean and the standard deviation for the measure of rmsDOE representing the localization abilities is as shown in the Table 4.5.

Table 4.5: *Mean and standard deviation of the rmsDOE on a localization task, obtained in CI alone, HA alone and CI+HA conditions.*

| *Aided test conditions* | *rmsDOE on a localization task: Mean (SD)* |
|---|---|
| Hearing aid alone (HA) | $97.20^0$ ($5.67^0$) |
| Cochlear implant alone (CI) | $72.80^0$ ($7.83^0$) |
| Cochlear implant +hearing aid (CI+HA) | $62.10^0$ ($10.16^0$) |

On observing Table 4.5, it can be seen that the root mean square degree of error (rmsDOE) is lesser in CI+HA condition followed by CI alone and HA alone condition. This means that the errors reduce on a horizontal localization task from HA alone condition to CI alone condition and from CI alone condition to CI+HA condition. Analysis of the individual data revealed that all the participants exhibited better localization abilities in CI alone condition when compared to HA alone condition. However, one participant (participant number six) did not show much improvement on CI+HA condition when compared to CI alone.

In order to find out the differences in performance on localization task (rmsDOE) among the three different aided conditions, repeated measures ANOVA was carried out. The results of the repeated measures ANOVA revealed that there was a significant difference between the rmsDOE obtained in three different aided conditions [$F(2, 14) = 54.63$; $p<0.001$]. This means that there is a significant difference between the rmsDOE obtained between any of the three aided conditions. Hence, Bonferroni (post-hoc) pair-wise analysis was carried out to the find out which two groups differed from each other on localization task (rmsDOE). Bonferroni (post-hoc) pair-wise comparison revealed a significant difference in the rmsDOE between HA alone condition and CI alone condition ($p<0.001$), between HA alone and CI+HA condition ($p<0.001$) and between CI alone and CI+HA condition ($p<0.001$). A non-parametric, Wilcoxon signed rank test was also administered to cross-check the results of the parametric test. The Wilcoxon signed rank test also revealed a significant difference in the rmsDOE between HA alone and CI alone condition, between HA and CI+HA condition and between CI and CI+HA condition. The results of Wilcoxon Signed Rank Test are tabulated in Table 4.6.

Table 4.6: *Comparison of rmsDOE on a localization task in HA alone, CI alone and CI+HA conditions.*

| *Aided conditions* | *Z* | *Asymp. Sig.(2-tailed)* |
|---|---|---|
| HA alone vs. CI alone | -2.521 | 0.012 |
| HA alone vs. CI+HA | -2.521 | 0.012 |
| CI alone vs. CI+HA | -2.521 | 0.012 |

The results of the present study support the results of the study by Ching et al. (2003) on the six adults. They considered rmsDOE on a localization task as a measure to represent the localization ability. They reported that the errors were found to be the least in CI+HA condition followed by CI alone. The results of the present study also supports the findings by Seeber et al. (2004) who reported that the mean localization errors were found to be the lesser for CI+HA condition when compared to the CI alone condition. Similar results were reported by Tyler et al. (2002) where two out of three participants reported better localization abilities and one participant did not reveal any difference on localization scores between CI alone and CI+HA condition. However, the results cannot be generalized because of the number of participants involved in the study and consideration of percentage of correct score to represent the localization abilities due to which a ceiling effect could be seen.

The results of the present study are supported by the results of the study by Litovsky, et al. (2006) who used a measure of minimal audible angle (MAA) to represent the localization abilities in children. All the participants showed significantly better performance on MAA task on CI+HA condition compared to CI alone condition.

The objective results of the present study are in agreement with the findings by Ullauri et al. (2007) where four of the seven participants included in the study reported better localization abilities in the real-life situation. However, the parents and the teachers of all the participants reported a better localization abilities in CI+HA condition when compared to CI alone condition, through a questionnaire. Berrettinni et al. (2010) also have reported similar results where eight out of 10 participants reported better horizontal plane localization abilities with CI+HA condition when compared to CI alone condition in real-life situation.

The results of the present study are in concurrence with the findings by Ching et al. (2007) who reported lesser rmsDOE on a localization task in CI+HA condition when compared to CI alone condition. They also reported that localization abilities to be better with binaural (CI+CI) condition when compared to CI+HA condition. However, CI+CI may not be an affordable solution for many individuals when compared to bimodal (CI+HA) condition.

These results of the studies reported in the literature reveal better performance in spite of the measure used to represent horizontal localization abilities i.e., percentage of correct scores or rmsDOE or MAA. This supports the idea that the localization abilities improve whenever there is a binaural input to the human auditory system which makes use of inter-aural time differences and inter-aural level differences. The benefit of binaural hearing can even be seen in case of combination of two different types of stimulation (electric + acoustic) in two different ears.

Ching (2005) and Sammeth et al. (2011) summarized the situations where the bimodal stimulation has to be recommended, i.e., (1) Patients with residual hearing in the non-implanted ear (2) Those having good performance in the non-implanted ear with a hearing aid (3) For those who want to avail the benefit of binaural hearing (4) All young children.

The results of the present study also strongly recommend the use of hearing aid in the ear contralateral that with cochlear implant, whenever there is useful residual hearing in that ear. The CI+HA condition provides a better or an equivalent performance but is never poorer compared to CI alone or HA alone conditions. Hence, a hearing aid should be recommended whenever there is aidable hearing in the contralateral ear.

Thus, the overall results of the present study reveal that a bimodal stimulation i.e., using a hearing aid in the ear contralateral to that with cochlear implant, help to perceive speech better in quiet, in noise and also to provide better horizontal plane localization abilities in children.

# Chapter 5

## Summary and conclusion

The study aimed to optimize and evaluate the benefit of a hearing aid in the ear contralateral to that with a cochlear implant, in children. A total of 10 participants were included in the study. These participants were divided into two groups based on the task they were supposed to carry out. The participants of the Group I (N=9) were evaluated on speech perception in quiet and speech perception in noise. The participants of the Group II (N=8) were evaluated on the horizontal plane localization task. The specific objectives of the study were:

1. To validate the protocol to optimize the hearing aid in the ear contralateral to that with a cochlear implant.
2. To compare the performance of speech perception, in quiet, through the measure of speech identification scores (SIS) in the three aided conditions, namely, HA alone CI alone, and CI+HA conditions.
3. To compare the performance on speech perception, in noise, through the measure of SNR-50 (signal-to-noise ratio required for 50 % of speech identification scores) in the three aided conditions, namely HA alone, CI alone and CI+HA conditions.
4. To compare the performance on a localization task, through the measure of root mean square degree of errors (rmsDOE) in the three aided conditions, viz: namely CI alone, HA alone and CI+HA conditions.

The study was conducted in three phases:

Phase I: Programming the hearing aid using NAL-NL1 and optimizing the hearing aid with the cochlear implant in the contralateral ear.

Phase II: Comparison of the speech perception in quiet (SIS) and in noise (SNR-50) in three aided conditions, HA alone, CI alone and CI+HA conditions.

Phase III: Comparison of the horizontal plane localization abilities (rmsDOE) in three aided conditions, HA alone, CI alone and CI+HA conditions.

The results were analyzed using appropriate statistical tools such as, descriptive statistics, repeated measures ANOVA, Bonferroni (post-hoc) pair-wise comparison (if indicated), paired-t test, and Wilcoxon Signed Rank test. The important findings on the three parameters studied are given below.

1. Speech perception in quiet (SIS)

This was administered only for participants in Group I. All the participants scored zero in HA alone condition. They scored significantly better in CI alone condition when compared to HA alone condition. It was found that providing a hearing aid in the contralateral ear (i.e., CI+HA) resulted in improved speech identification scores when compared to CI alone condition. This suggests that the individuals using two different kinds of stimulation in two ear (electrical+acoustical), are still able to use the binaural redundancy cues. Thus, deriving the binaural advantage and performing better in bimodal condition.

2. Speech perception in noise (SNR-50)

This measure also was administered only to the participants of Group I. The SNR-50 could not be established in HA alone condition since the speech identification scores was zero in quiet condition for all the participants. The present study revealed that the participants performed significantly better in bimodal condition (i.e., CI+HA) when compared to CI alone condition on a speech perception in noise task ($p<0.01$), i.e., the participants needed lesser SNR in bimodal condition when compared to the CI alone condition. This suggests that the individuals using two different kinds of stimulation (electrical + acoustical) in two different ears are able to use the binaural cues deriving the binaural advantage and are able to perform better in bimodal condition. The results provide the evidence of binaural squelch phenomenon even in a bimodal stimulation. It is note worthy that the performance in bimodal condition was always better than in the CI alone condition. This is true when users have useful residual hearing in the contralateral ear.

3. Horizontal plane localization

The results of the present study revealed that the root mean square degree of errors (rmsDOE) for localization were found to be the least in CI+HA condition followed by CI alone condition and then by HA alone condition. The rmsDOE were significantly lesser in CI+HA condition when compared to CI alone condition ($p<0.001$), which in turn was significantly lesser than in HA alone condition ($p<0.001$). It must be noted that lesser the rmsDOE, better the performance. Hence, the results of the present study indicate that individuals are able to make use of the inter-aural level differences and inter-aural time differences in a bimodal condition, provided the hearing aid is optimized.

Although binaural cochlear implantation (CI+CI) provides a better benefit when compared to bimodal (CI+HA) condition, the cochlear implant and hearing aid in opposite ears deliver complementary information, especially with respect to better low frequency information through hearing aid (Ching et al., 2007). Cullington and Zeng (2011) reported that though the data revealed no significant difference between CI+HA and CI+CI conditions, the individual data showed that the CI+HA condition was better than the CI+CI condition. This supports the option of fitting the individuals with a hearing aid when compared to cochlear implant in the contralateral ear.

**Clinical implications of the study**

1. The present study throws light on the binaural benefit, that is observed in individuals with normal hearing, is also observed in individuals who use bimodal stimulation (i.e.,CI+HA). This is an important finding because majority of the children who undergo cochlear implant surgery in one ear, often do not continue to use a hearing in the contralateral ear. The findings of the present study reveal significant benefits with the use of hearing aid in the contralateral ear. Hence, a hearing aid should be optimized and used in the contralateral ear of the candidates using unilateral cochlear implant in order to avail the binaural benefit.

2. Due to the extension of the cochlear implant candidacy criteria, the number children who have useful residual hearing in the contralateral ear is increasing. Hence, optimization and fitting of hearing aid must be made mandatory in all the children

who undergo cochlear implant surgery in one ear provided there is a useful residual hearing in the contralateral ear.

3. Optimizing and use of a hearing aid in the contralateral ear would help in speech perception in quiet, in noise and in the localization. In addition, it prevents the auditory deprivation in the contralateral ear.

**Future directions for research**

1. To compare the effect of number of channels and other features in the hearing aid in order to derive binaural benefit in a bimodal stimulation.
2. To study the effect of noise on speech perception with speech presented from front and noise from different Azimuths, i.e., the phenomenon of binaural squelch.
3. To evaluate bimodal stimulation through the use of outcome measures.
4. To carry out a study on localization including more number of loudspeakers with lesser intervals between the two consecutive loudspeakers, for a better representation of the root mean square degree of errors (rmsDOE).
5. To study the effects of age of implantation and long-term usage of bimodal stimulation on speech perception and localization.
6. To carry out a detailed phoneme errors analysis / feature error analysis (place, manner and voicing) on speech perception in bimodal condition as compared to other aided conditions.

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