VALIDATION OF HEARING AID OPTIMIZATION PROCEDURE USING LOCALIZATION FOR BIMODAL COCHLEAR IMPLANT USERS

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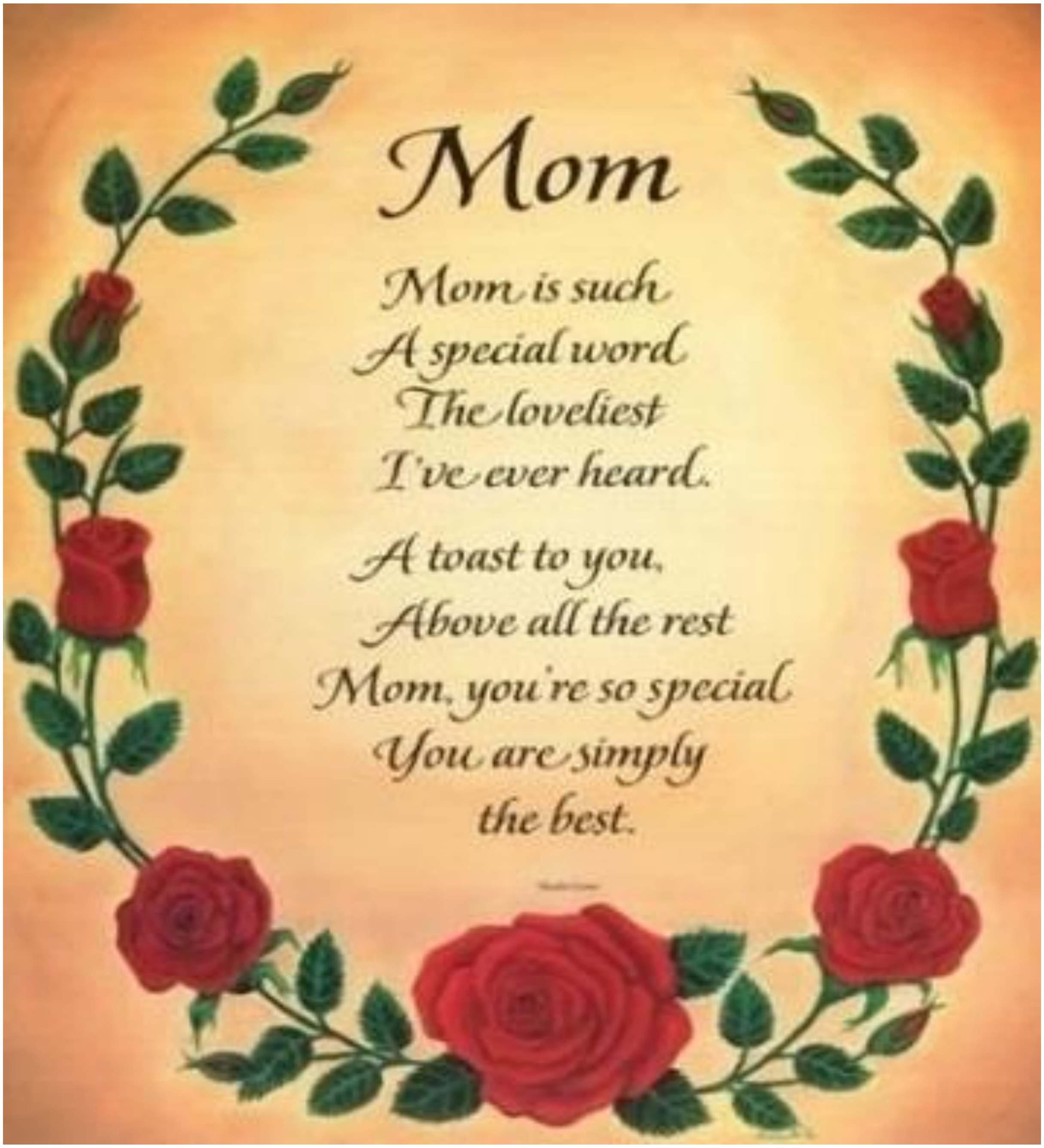
This Dissertation is submitted as part fullfillment
for the Degree of Master of Science in Audiology
University of Mysore, Mysore

MAY, 2015

DEDICATED TO MY AMMACHI…



Mom

Mom is such
A special word
The loveliest
I've ever heard.

A toast to you,
Above all the rest
Mom, you're so special
You are simply
the best.

Certificate

This is to certify that this dissertation entitled **"Validation of Hearing Aid OptimizationProcedure Using Localization for Bimodal Cochlear Implant users"** is a bonafide work in part fulfillment for the degree of Master of Science (Audiology) of the student with Registration No. 13AUD009. 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 other Diploma or Degree.

Mysore,
May 2015

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Certificate

This is to certify that this dissertation entitled **“Validation of Hearing Aid OptimizationProcedure Using Localization for Bimodal Cochlear Implant users”** has been prepared under my supervision and guidance. It is also certified this has not been submitted earlier in other University for the award of any other Diploma or Degree.

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Declaration

This dissertation entitled **"Validation of Hearing Aid OptimizationProcedure Using Localization for Bimodal Cochlear Implant users"** is the result of my own study under the guisdance of Prof. Asha Yathiraj Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Mysore, **Register No**: 13AUD009

May, 2015

Acknowledgments

The completion of my dissertation marks the end of a long and eventful journey. It is true that life is what happens, when you are completing your dissertation. I could not have succeeded without the invaluable support of several individuals. I take this opportunity to acknowledge their support along the way.

I am grateful to the God Almightyfor the good health and wellbeing that was necessary to complete this work.

*I would like to express my deepest gratitude to **Prof. S.R. Savithri**, Director, AIISH, for permitting me to carry out this dissertation.*

*I wish to express my sincere thanks to **Dr. Ajith Kumar U**, HOD, Dept of Audiology, AIISH for granting me permission to use the instruments.*

*I am indebted to **Prof. Asha Yathiraj**, for guiding me through this dissertation. 'Thank you' is just not enough ma'am. Your patient listening, guidance, support, time management are among the several virtues I have learnt from you during this period of dissertation. Thank you for developing my interest towards the field of cochlear implants and providing an excellent atmosphere for carrying out this research.*

*Above all, I would like to acknowledge the tremendous sacrifices that my **Ammachi** and **Pappa** have made to ensure that I had an excellent education; for this and much more, I am forever in their debt. It is to them that I dedicate this dissertation. **Bijikkuttan**, my brother, you are not just my reflection; you are my heart's reverberation and my soul's resonance. Thanks for being there for me Bro!*

*I deeply express my gratitude to all the Professors, Readers and lecturers in AIISH especially **Ajish Abraham sir, Sandip sir, Sujeet sir, Animesh sir, Vijay Narne sir, Manjula ma'am, Rajalakshmi ma'am, and Vasantha Lakshmi ma'am**. I have enjoyed the opportunity to watch and learn from your knowledge and experience. Their frequent insights and patience with me are always appreciated. I would also like to thank **Dr. Shijith,** library and information officer, for his advice on researching books and articles related to my study.*

I would not have completed this dissertation without the valuable help from my dear ***classmates, especially Preetha, Bebek, Tharique, Hashim, Akhil, Vinodini, Swathi, Anjali,*** *- had a fun and memorable time with you guys!!*

My sincere thanks to my **seniors** *especially* **Ruben chettan -** *you are not just my friend, but the perfect older brother who gave me bundles of advice to take on the challenges that life threw my way with girth and determination.* **Srikar sir..,** *I am not getting words to express you are like a helping hand from God almighty, you came in to a most difficult turning point of this dissertation and shown me the correct direction.* **Beena chechi,** *who were always willing to help and gave their best suggestions my appreciation for your kindness is beyond words.*

Many thanks to my ***juniors;*** *especially* **Rose Mary,** *the immature one* **Ashitha,** *the mature oneyou both are awesome….. whenever I am is in middle of tension you both helped me to come back in the real track and to face the difficulties in a sportsman mentality.* **Nadir, Basih, Gopika, Merina** *for their helps in the completion of this work. You were always supporting me and encouraging me with your best wishes.*

Finally I would like to thank all the children who participated in this research. Thanks to the parents of the participants for showing their enthusiasm and support for the research. Thanks to all my bachelor's classmates for being with me throughout my ups and downs. The journey at AIISH from bachelors to masters was just memorable and wonderful. I also place on record, my sense of gratitude to one and all, who directly or indirectly, have given their hand in this venture.

Abstract

Several studies have emphasized the benefits of cochlear implants over the standard hearing aids in cases of severe to profound hearing loss. Due to the extension in the candidacy criteria for cochlear implantation over the years, the number of individuals using bimodal implants has increased. However, to avail the maximum benefits of bimodal cues it is necessary to systematically fine tune and optimize the output of the hearing aid in relation to the cochlear implant. The present study was carried out with the aim of determining the stimuli that can be used to optimize hearing aids in individuals using bimodal cochlear implants depending on their aided performance in the non-implanted. The study also aimed to validate the optimization through a localization task.

The study comprised of 19 participants (10 children using cochlear implants on one side and hearing aid on the non-implanted ear; 9 children with normal hearing). It was carried out in two phases involving optimization of the hearing aid and validation of the optimization procedure through localization. Warble tones and Ling six sounds were used in the two phases of the study. The obtained data were analyzed and the results indicated that localization patterns of children with bimodal fitting and children with normal hearing was significantly different; the errors in the localization of high frequency sounds increased with reduction in the cut-off frequency were the hearing aid could be optimized; and there was a direct relation between the cut-off frequency and the lateralization of the Ling's speech sounds.

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Chapter 1

Introduction

It has been reported by Garg, Singh, Chadha, & Agarwal (2011) that around 7% of the population of India suffers from profound degree of hearing impairment and around one in every 1000 live birth has more than 90 dB HL hearing thresholds in the better ear . Since nearly 40,000 live births happens in the country per day, the number of children with profoundly hearing impairment are expected to go incredibly high (Reddy, Bindu, Reddy, & Rani, 2006). Across all age group a total of 63 million people with the prevalence around 6.3% have been found to suffer from significant auditory loss (Garg et al., 2011).

Individuals with severe to profound sensorineural hearing loss are noted to not benefit from standard hearing aids, but cochlear implants have been shown to be an effective means of rehabilitation (Dorman et al., 2013). The advantage of a cochlear implant is that it bypasses the external, middle ear and damaged inner ear and stimulates the nerve endings directly. Cochlear implants are recommended to be used unilaterally or bilaterally. Additionally they are recommended to be used bimodally wherein the person utilizes a cochlear implant on one side and a hearing aid on the other.

The number of individuals using bimodal cochlear implants has been noted to have increased largely (Francart & McDermott, 2013). In India the Defense Research and Development Organization (DRDO) has developed an indigenous multi-channel cochlear implants which are under human trials currently (Chaturvedi, Mohan, Mahajan, Kakkar, & Vipin, 2006). It has been reported by Garg et al. (2011) once the indigenous cochlear implants become available commercially, the candidacy criteria will be more wide and the number of implant recipients will increase drastically due to it's low cost.

According to the studies in individuals using unilateral cochlear implants, most of them have residual hearing in the contralateral ear of implantation (Gifford & Dorman, 2012; Grantham et al., 2012). Addition of acoustic stimulation along with electrical stimulation has been note to result in advantages in sound quality, bimodal release from masking, binaural redundancy, head shadow, squelches, music perception and localization of the sound source in children (Ching, van Wanrooy, Dillon, & Carter, 2011; Dorman et al., 2013; Francart & McDermott, 2012, 2013). Additionally, studies have indicated that the bimodal stimulation leads to better generative language skills in children with bimodal fitting than those using bilateral or unilateral implant (Ching et al., 2011; Nittrouer & Chapman, 2009). The studies was also revealed that children with bimodal implantation are able to avail bimodal advantages like the perception of more natural sound, improved own voice quality, usage of full communication potential available, availability of more directional sound, better localization, improved music perception, more confidence in everyday life, which is similar to children with bilateral cochlear implants or bilateral hearing aids. (Ching, Incerti, & Hill, 2004; Dunn, Tyler, & Witt, 2005, 2015; Gfeller & Woodworth, 1997; Hamzavi, Pok, & Gstoettner, 2004; Mok, Grayden, Dowell, & Lawrence, 2006; Tyler et al., 2002)

Studies have reported that there are no integrated systems or generally accepted fitting procedures for the bimodal stimulation (Cullington & Zeng, 2010; Francart, Brokx, & Wouters, 2008; Francart & McDermott, 2013; Sucher & McDermott, 2009).

Ching, Psarros, Hill, Dillon, & Incerti (2001) found that 75% of unilateral implanted individuals gets better speech perception scores when the hearing aid has the frequency response is in NAL-RP prescription ±3 dB/octave.

Different procedures for optimization of hearing aids have been recommended in literature.Ching, Psarros, Hill, Dillon, and Incerti (2001) utilised a loudness matching technique to equalized loudness of warble tones in the frequencies 500 Hz, 1000 Hz, and 2000 Hz and connected speech at 65 dB SPL. The individual was required to listen to the sound through the implant alone first and remember the loudness. This loudness was to be matched with the hearing aid alone. On an average, for balancing the loudness between ears the individual required a gain which was 6 dB above the NAL-RP prescribed gain. Such a technique was considered likely to tax memory and result in difficulty in loudness matching.

Praveen and Manjula (2012) reported of optimization of hearing aids in bimodal cochlear implant users using white noise and narrow band noise in two frequencies (500 Hz & 2000 Hz). This was done irrespective of the aided performance in the hearing aid side. However, often individuals using hearing aids in the non-implanted ear do not have any useful hearing in frequencies above 1 kHz. This makes it difficult to optimize hearing aids using the technique used by them.

It has been reported by Ching, Van Wanrooy, & Dillon (2007) that the validation of the optimization procedure is very important, similar to that of systematic fine turning. They also emphasized the need to evaluate the improvement in the performance of an individual.

The ability to localize sound source correctly is considered an important feature of the auditory system that is helpful in difficult listening situations. It is found to be directly linked to the ability of the auditory system to extract information of sound such as inter-aural time difference, inter-aural level difference, and inter-aural phase difference binaurally. Localization studies done in unilaterally implanted children (Ching et al., 2001; Hill et al., 2005) and adults (Ching, Incerti, & Hill, 2004; Tyler et al., 2002) have revealed that localization ability is comparatively poor for unilateral cochlear implant users, and the localization ability has been seen to improved when a hearing aid is worn in the contralateral side. It has been reported that this advantages may be due to the binaural interaction that occurs with the combination of electrical stimuli from the implant and acoustical stimuli from the hearing aid. According to Dorman et al. (2013), localization is particularly important for cochlear implant users as they have difficulty in using other cues for speaker identity, such as voice pitch and intonation are diminished. Localization experimenters have been reported to use different experimental set-ups with 11 loudspeakers that cover an arc of 180°(Ching, Incerti, & Hill, 2004; Ching et al., 2001) and with an array of 5 loudspeakers which covers an arc of 150°(Ching, Hill, et al., 2005).

1.1. Need for the study

For achieving optimum binaural performance in individuals with bimodal cochlear implants, the gain of the hearing aid needs to be adjusted to enable the individual to get the benefits of listening through both ears. The criteria for selecting individuals for cochlear implants have changed over the years, such that there now exists several clients with a fair amount of residual hearing in the non-implanted ear but with poor speech identification abilities. There also exist clients with residual hearing only in the lower frequencies in the non-implanted side. It would be erroneous to use the same procedure for hearing aid optimization in these individuals having varying amount of residual hearing in the non-implanted ear. Hence, there is a need to have a protocol that is flexible, that requires optimization only in those frequencies that are required. This would depend on the available residual hearing in the contra lateral ear of implantation. There is no universally accepted procedure for the optimization of the hearing aids. Hence, there is a need to develop and validate a hearing aid optimization procedure in bimodal cochlear implant users.

1.2. Aim of the study

The aim of the study would was to determine the stimuli that need to be used to optimize hearing aids in individuals using bimodal cochlear implants, depending on their aided performance in the non-implanted and to validate the optimization through a localization task.

1.3. Objectives

1) To optimize the hearing aid in bimodal cochlear implant users using different frequency stimuli,

2) To validate the optimization using a localization procedure using warble tones and Ling’s six sound test.
3) To find the relation between the aided thresholds in the hearing aid side and the localization in the bimodal condition.
4) To find the difference in the localization ability in different azimuth in the bimodal stimulation.
5) Compare the difference between localization abilities in children using bimodal cochlear implants with normal hearing children.

Chapter 2

Literature Review

It has been reported that listening with two ears helps us perceive the direction and location of a source of the sound, along with segregation and selective attention to different sound sources. The pre-requisites for binaural benefits, as noted in literature are the audibility of sounds in both ears and the ability of listener to compare the time differences and level differences of acoustic signals reaching at the two ears (Ching, Incerti, Hill, & Wanrooy, 2006; Ching, Van Wanrooy, Hill, & Incerti, 2006). It has been demonstrated that bilateral amplification in individuals with bilateral severe to profound hearing loss leads to superior speech intelligibility (Bronkhorst, 2000), localization (Noble, Byrne, and Lepage 1994) and everyday functioning (Ching, Psarros, Hill, Dillon, & Incerti, 2001; Ching, Incerti, & Hill, 2004). Bilateral fitting is considered essential for binaural processing, but not sufficient for assuring effective use of binaural cues by children with hearing impairment. Studies had reported that with the binaural amplification some individuals received binaural benefits whereas others did not (Ching, 2005; Tyler et al., 2002). Binaural hearing is also observed to avoid neural degeneration and auditory deprivation (Gelfand & Silman, 1993).

2.1 Bimodal fitting and binaural benefits

The use of a hearing aid in the ear opposite of an ear implanted with a cochlear implant (CI) is considered a non-invasive alternative to binaural hearing and is referred to as bimodal stimulation. This helps those who have usable residual hearing in the non-implanted ear. The binaural benefits of speech intelligibility are found to mainly arise from a combination of increased redundancy, head shadow effect and squelch effect, which are available through either bimodal stimulation or bilateral implantation. The additional advantage of bimodal fitting over bilateral electrical stimulation is the added advantage of complementarity i.e, the use of acoustic low-frequency cues to complement the electric high-frequency stimulation (Ching et al., 2007).

Head movement has been found to help the human auditory system extract variations in binaural information for localization of the source of interest Munhall, Jones, Callan, Takaki, & Bateson (2004). The combination of visual cues, such as lip reading, to auditory information has been found to significantly improve speech understanding abilities (Grant & Greenberg, 2001). In the multitalker situations, knowledge about the position of the sound source has been observed to improve speech recognition (Kidd, Mason, Brughera, & Hartmann, 2005). There are studies which shown that head movements help normal hearing listeners to differentiate between sounds coming from front and rear positions (Bronkhorst, 1995; Perrettand & Noble, 1997; Wallach, 1940; Wenzel, Arruda, & Weidhtman, 1993). The interaural time differences and level differences are reported to be similar for sounds coming from the front and the back (Wightman & Kistler, 1999). In such situations, the only cued available for making this distinction has been found to stem from the spectral filtering introduced by the shape of the outer ear. These pinna cues are of little use for CI due to the position of the microphones and the limited frequencies processed by CI. However, the head movements are noted to provide significant advantages in resolving front–back confusion even in normal hearing individuals (Perrettand & Noble, 1997). Individuals with hearing impairment, who use conventional amplification, have been found to have better speech perception and localization abilities with two hearing aids than with one (Byrne & Noble, 1992).

Individuals wearing a single cochlear implant are known to miss binaural hearing advantages. However, it is reported that it is possible to restore these advantages by the use of a hearing aid in the contralateral ears which also preserves the residual hearing in the non-implanted ear by providing auditory stimulation (Gatehouse, 1992; Gelfand & Silman, 1993; Palmer, Jiang, & McAlpine, 1999). Although there are solid evidence on binaural benefits achieved by adult bimodal cochlear implant users (Ching, Incerti, & Hill, 2004; Tyler et al., 2002) there is not much evidences for children.

Jerger, Lew, & Chmiel (1993) studied the effect of contralateral hearing aid in six cochlear implanted children by comparing speech perception and speech production in binaural and monaural condition. The pure-tone average in the non-implanted ear of the children was 105 dB HL. In quiet, three out of six children perceived speech better in the bimodal condition than with a cochlear implant alone in one ear. There was no significant difference in speech production between amplification conditions.

Studies by Ching et al. (2001) and Ching, Incerti, Hill, and Brew (2004) showed that children with bimodal stimulation perform significantly better after systematic hearing aid fine-tuning and also bimodal performance with loudness fine-tuned hearing aids was superior to CI performance Thus, it was concluded that it was not reasonable to expect children to achieve good results only by fitting a hearing aid into the non-implanted ear. To achieve that, fine tuning of the hearing aid with respect to the loudness perception of the individual was required.

With the extension of cochlear implant candidacy criteria, Dowell (2005) noted that the number of unilaterally implanted children with usable residual hearing in the opposite ear has increased over the years. The majority of these children were reported to get benefit from the conventional amplification. However, earlier Byrne and Noble (1992) speculated that the addition of acoustic hearing would interfere with the perception of electrical hearing in the contralateral ear. It has been indicated by Ching (2005) that when the four-frequency-pure tone average shows moderate to severe degrees of hearing loss, bilateral fittings have a significant advantage over unilateral fittings.

Ching et al. (2001) and Ching, Wanrooy, Hill, and Dillon (2005) assessed the horizontal localization ability of children with a cochlear implant in one ear and a hearing aid in the contralateral ear. They used a custom made procedure to optimize the frequency response of the hearing aid to balance the loudness between the hearing aids and the cochlear implants. This was done by adjusting the gain settings of the hearing aids to complement the cochlear implants.

It has been have investigated the speech intelligibility of adults (Mok et al., 2006) and children (Mok, Galvin, Dowell, & Mckay, 2010) in cochlear implants alone condition and in bimodal condition in this most studies show binaural advantages (Tyler et al., 2002) whereas a few did not (Schafer, Amlani, Paiva, Nozari, & Verret, 2011). Ching et al. (2004) opined that the difference in finding may be due to the different methodology, subject characteristics, and device characteristics used across the studies.

The improvement in speech intelligibility due to binaural hearing was ascribed by Ching et al. (2007) to the combined effect of head shadow, binaural squelch, and binaural redundancy. They noted that due to a head shadow effect the signal-to-noise ratio at one ear was superior to the other when the signal and noise were spatially separated. Ching, Van Wanrooy, Hill, and Incerti (2006) demonstrated that when one ear is closer to the talker of interest, and the other ear is closer to the noise source, the brain can selectively attend to the ear with a better signal-to-noise ratio. This resulted in an average improvement of 3 dB in speech intelligibility. They concluded that the result was not only due to the head shadow effect but also the brain's ability to combine the signal and noise arriving at the both ears and to partially reduce the impact of noise with the help of time or phase differences between the ears. They made this conclusion based on the findings of the study by Ching et al. (2005) who found that due to binaural squelch an advantage of 1 to 2 dB was obtained. According to Ching et al. (2001, 2005) the situations in which the signal-to-noise ratios are equal between ears, receiving two inputs through the two ears rather than one, gives an advantage of about 1 to 2 dB and this is often referred to as 'binaural redundancy. The effect of binaural squelch has been evaluated in a study by (Ching, 2005) in normal, bilateral hearing aids and adults and children fitted bimodally. In this study the speech and uncorrelated noise were presented to both ears of normally hearing children through earphones, and through the direct audio input sockets of amplification devices for children with hearing impairment. The advantage due to binaural squelch was quantified by comparing the performance in the condition were no interaural time delay occurred between the ears, and with a delay of

700 microseconds in one ear. The children with normal hearing and those with moderate hearing impairment who wore bilateral hearing aids obtained an average advantage of about 3 dB in the condition with 700 microsecond interaural delay. There was advantage observed for adults but not children with bimodal fitting. It has been reported that these results are probably due to the inherent limitation of the cochlear implant to preserve fine timing information and the head shadow effect that is usually assessed by presenting speech and noise from specially separated sources. It has been indicated by Ching (2005) that the bimodal stimulation ensures that the subject is getting the binaural advantages due to binaural redundancy and head shadow effects even with a severe hearing loss in the non-implanted ear. Ching (2005) also has been said that if there are no clear contraindications for fitting a hearing aid to the non-implanted ear, the bimodal fitting should be routine for all recipients of unilateral cochlear implants who have some amount residual hearing in the contralateral ear.

2.2 Binaural vs Bimodal Fittings

It is well established that the bilateral amplification results in better performance compared to unilateral amplification in individuals with bilaterally hearing impairment. (Ching, Massie, & Wanrooy, 2009; Dawes, Munro, Kalluri, & Edwards, 2013; Dawes & Munro, 2014; Neher & Jin, 2009; Schleich, Nopp, & Haese, 2004). To enable cochlear implant users to have access to binaural hearing, either binaural cochlear implants are recommended or bimodal fitting is recommended where the user wears a cochlear implant on one side and a hearing aid on the other side. In an international consensus on bilateral cochlear implantation and bimodal stimulation the experts in the field compared the advantages and dis-advantages of both bilateral implantation and bimodal stimulation (Offeciers et al., 2005). They listed the advantages of bilateral implantation as it makes sure that the better ear is always implanted as it is difficult to predict preoperatively which ear will result in better speech perception for the electrical stimulation and it helps to provide same type of bilateral cortical stimulation. The disadvantages of bilateral implantation includes the higher costs for the two implants and surgery and the difficulty to impose the future advances in the technologies. The consensus concluded that the bilateral implantation should be recommended for the individuals having poor benefit from the existing unilateral implant, in cases with meningitis otherwise the full insertion of electrodes become impossible due to cochlear ossification, those who needed same type of binaural hearing as a professional requirement. The same international consensus listed the advantages of bimodal stimulation as it is a cost effective method with no further surgery has required provide binaural benefits in individuals who have residual hearing in the non-implanted ear.

A cost-effective analyses done by Summerfield et al. (2006) indicated that the second implantation had a small and inconsistent effect on improving the quality of life of the individual in post-lingually deafened adults. The same study also has indicated that almost half the subjects who had no history of tinnitus before the second implantation become worsen. It was reported by Summerfield, Marshall, Barton, & Bloor (2002) that an individual can achieve more quality of life per expenditure in unilateral cochlear implant than a bilateral situation.

Barton, Bloor, Marshall, & Summerfield (2004) observed that a mismatch in the electrode insertion depths makes it difficult to fine tune the two implants to give a single fused percept of stimuli from both the ears in bilateral CI users. Li, Corrales, Edge, and Heller (2004); McDermott, Sucher, & Simpson (2009) and Moore (2001) reported that although bilateral amplification and bilateral implantation have superior benefits over any other form existing technology, the prognosis with bilateral implant system varies based on the amount of the auditory neuron survival, functional performance of the individual and the residual capacity in the central auditory system to make the maximal use of binaural cues.

Ching et al (2007) observed that the benefits of bilateral cochlear implantation is condition specific and it cannot be generalized to all conditions. It was also found that the fitting schemes used and the technology of the implant system also had a major role in the success of the bilateral implants. Recommendation was made to adjust the bilateral implants individually and it depends on the use of independent speech processors. It was seen that there may be tempory uncoordinated stimulation to the two ears because of the time difference between signals arriving at the two ears.

It has been reported by (Li et al., 2004) that in the context of advancement of technology such as gene therapy, hair-cell regeneration, stem cells, and other possible future treatments for hearing loss we must think twice before the bilateral cochlear implantation in children who have significant useful residual hearing in the contralateral side. It has been indicated by Jerger et al. (1993) in some rare but not least situations the bilateral hearing aid user have problem in binaural processing and better speech perception scores are obtained with a unilateral device than with bilateral devices. It may be because of asymmetrical distortion in the two cochlear stimulation and distortion or delay in the inter-hemispheric transmission through the corpus callosum as reported by Ching et al (2007). Thus, it was inferred that this is likely to be a problem for some people who receive bilateral implants.

According to the cross-sectional survey conducted by Ching et al. (2007), bilaterally implanted children achieved auditory abilities and academic improvements similar to hearing aid using children with unaided thresholds of 80 to 104 dB HL. It has been supported by a study of Stacey, Fortnum, Barton, and Summerfield (2006). In a similar study by Ching et al. (2007) and Hill (2007) for bimodal children whose preimplantation hearing levels were greater than 110 dB HL, the functional performance were almost equivalent to bilaterally aided children with moderate to severe hearing loss. From the above mentioned studies it can be concluded that children with bimodal stimulation performs equal or better than the bilaterally implanted children. Similar to the report by Offeciers et al. (2005) all the above discussed evidence are increasing the support of bimodal fittings over bilateral implantation for the recipients of unilateral cochlear implants who have useful residual hearing in the contralateral ear.

2.3 Procedure of Bimodal Fittings

The major aim of bimodal fitting is that both the electrical and acoustical stimulation should provide audible outputs to the user in a comfortable way across the wide range of input levels. In bilateral hearing aid users and bilateral cochlear implants users there are standardized procedures to achieve this goal (Dillon, 1999). It was reported by Blamey, Dooley, James, and Parisi (2000) that application of the usual hearing-aid fitting procedures or cochlear implant mapping procedures in bimodal condition can often result in loudness mismatch between ears due to the differences in the dynamic range of acoustic and electric hearing. There are studies which report loudness perception problems or mismatch between ears even after the adjustments in the gain settings of the amplification devices in the bimodal condition (Dunn et al., 2005; Mok et al., 2006; Morera et al., 2005). There have also been reports of irritation and discomfort in a bimodal condition owing to the lag in the sound from the implant compared to that of the hearing aid (Ching, Incerti, & Hill, 2004).

Tyler et al. (2002) reported that after allowing clients to adjust the volume control of hearing aid in a bimodal condition, half of them demonstrated a significant binaural advantage for localization and speech perception in noise. Ching et al. (2007) reported that the localization ability of the individual improved from chance level in the monaural condition to 85% correct after an individualized fine tuning of the contralateral hearing aid in the bimodal condition. Ching, Incerti, and Hill (2004) and Ching et al.(2001) have provided evidence regarding the importance of systematic fine-tuning and loudness balancing of contralateral hearing aid in the bimodal condition for the achievement of better speech perception and localization.

According to Ching, Incerti, and Hill (2004), the recommended bimodal fitting procedure involves the prescription and verification of hearing aid characteristics based on the NAL hearing aid standard as reported by Byrne and Dillon (1986) and Chmiel, Jerger, Murphy, and Tooley-Young (1997), followed by fine-tuning the hearing aid according to the individual preferences based on intelligibility judgments, and finally balancing the loudness and gain of the hearing aid with the cochlear implant in a systematic way..

It has been reported by Ching et al. (2007) that an ideal bimodal fitting scheme should allow to establish comfortable level balances between acoustic and electric inputs in a single procedure with simultaneous adjustment of the implant and hearing aid for both ears rather than the current existing procedure which adjusts the hearing aid gain after the map of the cochlear implant is stabilized. It was also reported that the systematic fine-tuning procedure must be implemented for each individual separately which will ensure that the information of the speech signal are presented to the most effective part of the hearing range in each ear of the individual. As reported by Ching et al (2001), Mok et al (2006) and Moore (2001), usually the residual acoustic hearing is good in the low frequencies. Taking full advantage of this by acoustic hearing was considered to allow the user to extract salient pitch cues that complemented the mid frequency and high-frequency cues provided by electric hearing. On the other had increasing the gain settings in the high frequencies where hearing loss is severe was thought to prove detrimental speech perception performance.

Dooley (1993) studied the outcome of speech perception test using a single speech processor for delivering the inputs to a hearing aid for acoustical stimulation and a cochlear implant for electrical stimulation in the opposite ear simultaneously. However, this method was not proven to be superior to the use of a conventional way of fitting independent hearing aid and cochlear implant. It was assumed to be due to the loss of cues in localization and binaural squelch due to the single microphone setup used in the bimodal system.

Blamey and Peter (2005) and Blamey(2005) designed an adaptive dynamic range optimization processor especially for bimodal stimulation. However, the binaural advantage of this fitting method was not well proven according to Ching et al. (2007).

Praveen & Manjula (2012) reported of optimization of hearing aids in bimodal cochlear implant users using white noise and narrow band noise in two frequencies (500 Hz & 2000 Hz). This was done irrespective of the aided performance in the hearing aid side.

2.4. Methods of validation of optimization procedures

Ching, Incerti, and Hill (2004) and Ching et al. (2007) noted that bimodal benefits such as localization, speech perception, music perception, spatial release from masking and complementarity improve significantly with systematic fine turning. The above mentioned studies indirectly indicate that the bimodal advantages can be a potential option for the validation of the systematic fine turning or the optimization procedure.

2.4.1. Localization

It has been reported by Ching et al (2007) that individuals with severe to profound hearing impaired unilateral amplification may lateralize or discriminate the side or direction of the sound source by utilizing the knowledge that the louder sounds are more likely to come from the side of hearing aid or cochlear implant. For the exact localization of the source of sounds, it is essential to make use of the interaural difference in time, level and phase of the sound reaching both the ears.

Ching et al. (2001) reported that the interaural time differences vary directly as a function of the direction of the sound source with respect to the midline of the head on a horizontal plane. Due to this binaural hearing aids, bimodal stimulation or bilateral implantation certainly are of superior position in localization ability than a unilaterally amplified condition. There are a number of factors were recommended to be adjusted for accurate utilization of interaural difference in time, level and phase. Ability to provide accurate interaural time difference information to the individual was found to depend on the ability of amplification devices to preserve and the fine timing details effectively while processing the signal. The study by Dillon, Keidser, Brien, and Silberstein (2003) indicates that a delay that occurs in hearing aids generally will not exceeds 500 micro seconds, and timing information is almost well preserved in the hearing aids. It has been reported by Byrne & Noble (1992) that there are research evidence that proves that individuals fitted with bilateral hearing aids are able to localize accurately because of the accurate use of interaural time differences in the amplified sounds, especially in the low frequencies. The experimental evidences by Byrne and Noble (1992), Perrettand and Noble (1997) and Byrne (1998) indicate that horizontal localization decreased significantly when the low-frequency hearing loss exceeded 50 dB HL and the vertical localization disappeared when there was high frequency hearing loss.

It was noted by Ching et al. (2007), that existing speech processing strategies used in the cochlear implant, other than the analog-based strategies do not give much emphasis to the temporal fine structure cues which in turn will affect the availability of interaural time difference cues. Investigations by Ching et al. (2005, 2007) on the importance of interaural time difference cues indicated that users of CI alone were not able to use interaural time difference cues to improve speech perception in noise. According to Lawson, Brill, Wolford, Wilson, & Schatzer (2000) the main reason for the variation in the interaural time difference in the absence of fine structure information is the variation that occurs in the interaural time difference detection thresholds between electrodes and the absence of synchronization between the two implants in bilateral cochlear implant. The other reasons for the affected interaural time difference is the discrepancies that occur in the insertion depth of the individual electrode array in the same individual which leads to differences in the place and rate of stimulation of the low frequencies, as reported by Ching et al. (2007). Ching et al (2007) also reported that in the central auditory system the low frequency cues preserve the time difference between the ears, because neural impulses are phase-locked to the low frequency stimulus. The combination of low-frequency fine-tuning information from hearing aid with high-frequency information from the cochlear implant on the contralateral side makes bimodal fitting more efficient in obtaining the interaural fine time.

According to Ching et al. (2005) the interaural level difference is one of the other major cues which helps in the accurate localization and it depends on the preservation of the physical differences in level between ears. It has been reported by Schleich et al. (2004) that the main reason behind the interaural level difference is the head shadow effect, which causes the signal-to-noise ratio at the near ear to be superior than the contra lateral one, giving rise to interaural difference in level.

Ching et al. (2001) postulated that the interaural level differences are marked at the high frequencies because the size of the head is larger than the wavelength of sound at high frequencies. It has been reported by Ching et al (2007) that without fine turning in the bimodal condition these interaural cues may be deaminized or distorted and it can result in errors in localization. They reported the possible reason for the above mentioned is because the implant and hearing aid have two separate signal processing techniques and independent gain control circuitry along with the mismatched compression characteristics between the devices. So it can be concluded from this that careful optimization of the hearing aid performance in the bimodal situation has major role in improving the localization performance.

2.4.2. Speech Perception

It has been reported by Litovsky, Fligor, and Tramo (2002) that the speech perception in noise is better through two ears than through one ear because of the binaural advantage with two ears. This is due to the combined effects of binaural redundancy, head diffraction and binaural squelch effects. Due to binaural redundancy because of complex crossover pathways and the ability of the two ears to work together and combine inputs from both the ears, it is found to reduce the effect of noise on understanding of speech. The binaural redundancy was noted to an average improvement of about 1 to 2 dB in situations which have no directional separation between the speech and nose source (Bronkhorst, 1988; Cox, Dechicchis, & Wark, 1981).

Ching, Incerti, and Hill (2004) and Ching et al., (2001) had investigated the effect of redundancy by presenting speech and noise from a loudspeaker located at 0° azimuth and the listeners obtained an average of 1 dB advantage when they were fitted bimodally than when they used a CI alone for perceiving sentences in noise. The bimodal fitting also received 11% to 14% more voicing information and manner information for consonant perception compared to using a CI alone condition (Ching, Incerti, & Hill, 2004; Ching et al., 2001). Diffraction due to head was found to there will be difference in the levels of the signals across the head and difference in the signal to noise ratio between the ears based on the position of the sound source with respect to the listeners head. In this case individuals can selectively listen to the ear with better SNR with the help of combined action of the two ears. The head diffraction will give an average the advantage of 3 dB (Bronkhorst & Plomp, 1992). Binaural release of masking is the feature of our auditory system which can improve speech intelligibility by up to 12 dB in situations which had speech and noise arising from different directions. Litovsky et al. (2002) had found that on an average, the advantage due to binaural squelch is about 2 dB. According to Bronkhorst (1988) theoretically the binaural advantage due to these effects is applicable to both bimodal stimulation and bilateral implantation as long as sounds are above the aided thresholds of the ears. But Hoesel & J (2004) Senn, Kompis, Vischer, & Haeuseler (2005) reported that the interaural time difference cues will get distorted in bilateral implantation case because of the in ability of electrical stimulation to carry much of temporal information,, and because of independent speech processors or processing strategies which lack synchrony in offsets that may be well in excess of any natural head-induced delays. According to Hoesel, Ramsden, & Driscoll (2002) the advantage due to head diffraction and binaural redundancy will benefit users of bimodal stimulation and bilateral implantation in a similar manner.

2.4.3. *Complementarity*

It has been reported by Ching et al (2007) that the combination of low-frequency acoustic information delivered through hearing aid and high-frequency electrical information delivered through cochlear implant leads to an additional potential advantage because both of these information complement each other.

Assmann and Summerfield (1989) as well as Brokx and Nooteboom (1982) have reported that, low frequency component of speech has information about the fundamental frequencies of the voice of the talker and even at poor SNRs these cues improve speech perception. These authors also reported that voice pitch information enhances the linguistically significant distinctions in the segmental and supra segmental aspects. The segmental aspects included voice onset time that played an important role in differentiating between voiced and voiceless sounds. According to Miller & Nicely (1955) the supra-segmental aspects included variations that occur in pitch that carry lexical information in tonal languages and information regarding stress and intonation patterns in tonal as well as non-tonal languages. The high frequency component of speech has information related to manner of articulation and place of articulation of consonants as reported by Grabe, Rosner, García-Albea, & Zhou (2003). Research by Ching, Incerti, & Hill, (2004), Kong, Cruz, Rachel, Jones, & Zeng (2004) Miller & Nicely (1955) shows that importance of complementarity. They reported that, using the CI along with contra lateral hearing aid resulted in superior perception of speech. According to Ching et al (2007) the reason for this was due to low frequency acoustic amplification where residual hearing is usually better. The low frequency acoustic amplification complemented the mid and high-frequency information provided by the cochlear implant as reported in turn enhancing speech intelligibility.

There are studies that examined the combined effect of head shadow, redundancy and complementarity (Ching, Incerti, & Hill, 2004; Ching, Wanrooy, et al., 2005). In the context of speech perception Mok et al (2006) reported that, the addition of low frequency information through hearing aid significantly improved the word identification in quite. In the review of the recent literature comparing unilateral implants with either bimodal fitting or bilateral implants in adults and children Ching et al., (2007) found that, the size of binaural speech intelligibility advantages due to redundancy and head shadow was very similar for the two bilateral conditions. On the other hand, the benefit from complementarity was present only in bimodal fitting. This was proven by Ching, Incerti, & Hill (2004) who examined segregation of voices in consonant confusions, Kong et al (2004) for masking release and Kong, Stickney, & Zeng (2005) for music perception. Further, Ching et al. (2004, 2001) indicated an average of 1 dB advantage with bimodal fitting than with a CI alone for perceiving sentences in noise. Ching et al., (2001) also found 11 to 14 percent better perception of voicing and manner information for consonant perception when using bimodal condition than compared to CI alone condition.

2.4.4. Spatial Release from Masking (SRM)

It has been reported by Litovsky(2005) that the spatial release from masking (SRM) is the improvement in speech intelligibility that occurs with a separation in the sources of target speech and competing noise. As reported by Phillips, Vigneault-MacLean, Boehnke, and Hall (2003) even though this phenomenon has been well studied in normal-hearing children, the knowledge about SRM in children with hearing impairment is sparse. Litovsky (2005) reported that children who have little or no spatial release from masking experienced greater difficulties in perception of speech in noisy environments such as classrooms.

Further, Ching et al (2007, 2005) indicated that even though few of the earlier studies showed that spatial release from masking was absent in children who used either bimodal fitting or bilateral implants, evidence to support the fitting of bilateral hearing aid as the standard option was also present. They also reported that, systematic quantification and fine turning is necessary for availing the benefits of spatial release from masking in bimodal condition. Hence, Ching et al, stressed on the importance of measuring the spatial release from masking to systematically fine-tune the hearing aid gain and other features in order to reduce the problem in listening in noise and to validate the fitting.

Chapter 3

Method

The present study was undertaken to validate the procedure being used to optimize hearing aids in bimodal cochlear implant users having varied aided performance in their non-implanted ear. Validation of the optimization was undertaken using a localization task.

3.1. Participants

A total of 19 children participated in the study. The participants were divided into two groups. The first group consists of ten children using a cochlear implant in one ear and a hearing aid in the non-implanted side. The second group consisted of nine age and gender matched normal hearing peers. The age and gender of both the groups are given in Table 1.

Table 3.1: *Age and gender of the bimodal cochlear implant users and normal hearing peers*

Groups	Gender		Age range (Years)	Mean age (Years)	Median age (Years)
	M	F			
Bimodal CI users	5	5	4.6 - 17	8.3	7.8
Normal hearing peers	4	5	5.6 - 12	8.3	7.8

The bimodal cochlear implant users had severe to profound bilateral sensori-neural hearing loss. In the non-implanted ear, the aided thresholds ranged from 15 dB HL to 55 dB HL and in the implanted ear the aided thresholds varied from 30 dB HL to 110 dB HL. Details of the cochlear implants used by the children are provided in the Table 3.2.

Table 3.2: *Cochlear implants used by the children with bimodal fitting.*

Subjects	Cochlear implant
Subject 1	CI -24
Subject 2	CI-24
Subject 3	Nucleus freedom
Subject 4	CI- 24
Subject 5	Nucleus freedom
Subject 6	I Enjoy Sound
Subject 7	Nucleus freedom
Subject 8	Nucleus freedom
Subject 9	CI- 24
Subject 10	Nucleus freedom

The aided performance with the latest cochlear implant map and hearing aids are provided in Table 3. The thresholds are provided for 10 frequencies (250 Hz, 500 Hz, 750 Hz, 1 kHz, 1.5 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz, 8 kHz).

Table 3.3: *Aided performance with separately with cochlear implant and hearing aid*

		Aided thresholds									
Participants	**Device**	**250 Hz**	**500 Hz**	**750 Hz**	**1 kHz**	**1.5 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
Subject 1	CI	30	20	30	30	35	35	30	30	35	40
	HA		40		45		75		110		
Subject 2	CI	30	25	30	20	20	25	30	25	30	40
	HA		25		30		35		40		
Subject 3	CI	15	25	20	20	20	20	25	30	20	20
	HA		50		40		55		55		
Subject 4	CI	30	20	25	25	25	30	25	30	30	55
	HA		35		40		45		60		
Subject 5	CI	35	35	35	40	40	40	45	35	40	45
	HA		40		45		40		45		
Subject 6	CI	15	20	35	30	30	40	40	40	45	50
	HA		30		45		45		50		
Subject 7	CI	40	35	35	35	40	40	40	40	40	30
	HA		40		45		70		100		
Subject 8	CI	25	25	30	30	35	30	35	35	30	35
	HA		30		40		40		50		
Subject 9	CI	20	30	30	30	25	25	30	30	20	25
	HA		30		40		40		50		
Subject 10	CI	20	20	20	20	25	25	35	35	40	45
	HA		40		45		50		50		

As can been seen from Table 3.2, the aided thresholds of side fitted with the cochlear implants were within the speech spectrum across the frequencies 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz 2000 Hz, 3000 Hz, 4000Hz 6000 Hz, and 8000 Hz and in the frequencies 250 Hz and 500 Hz in the ear fitted with hearing aids. The p of a conductive loss was ruled out by the presence of ‘A’ type tympanogram. The participants used digital multichannel behind-the-ear hearing aids with the gain ranging from 60 to 75 dB to suit their degree of hearing loss. All used custom-made soft ear moulds. Prior to their cochlear implant surgery they wore digital behind-the-ear hearing aids bilaterally for a period of at least 6 months. Only those who used cochlear implants for at least one year and had stable maps for at least six months were selected for the study. It was also made sure that the participants of the study had adequate language and normal IQ to understand the instructions.

The normal hearing group, who were age and gender matched with the children with hearing impairment, had no significant history of speech language and hearing problems.

3.2. Instrumentation

A calibrated two channel Grason Stadler - 61 clinical audiometer with loud speakers was used to assess the unaided and aided performance of the children with hearing impairment. A calibrated middle ear analyzer (GSI tympstar) was used to evaluate the middle ear status and an Oto acoustic emission analyzer (ILO Version 6) to confirm the presence of a hearing impairment. Via a HiPro the personal hearing aids of the children were programmed using a computer loaded with NOAH 4 programing software along with the specific company software. For the hearing aid optimization and localization task, a Hewlett-Packerd workstation loaded with Cuebase software along with Lynx Aurora 16 sound card and signal router was utilized. Adobe Audition (Version 3) software loaded in the workstation was made use of to generate warble tones and to play the test stimuli. Eight calibrated Galvanic 8020B loudspeakers connected to the workstation were used to deliver stimuli during the localization task. The loud speakers were placed at -135°,-90°,-45°, 0°, 45°, 90°, 135°, and 180° azimuths (Figure 1), at a distance of 1 meter from the head of the child. All the speakers output were calibrated with the help of a sound level meter (Larson-Davis system 824, model number 2540) with a half inch free field microphone.

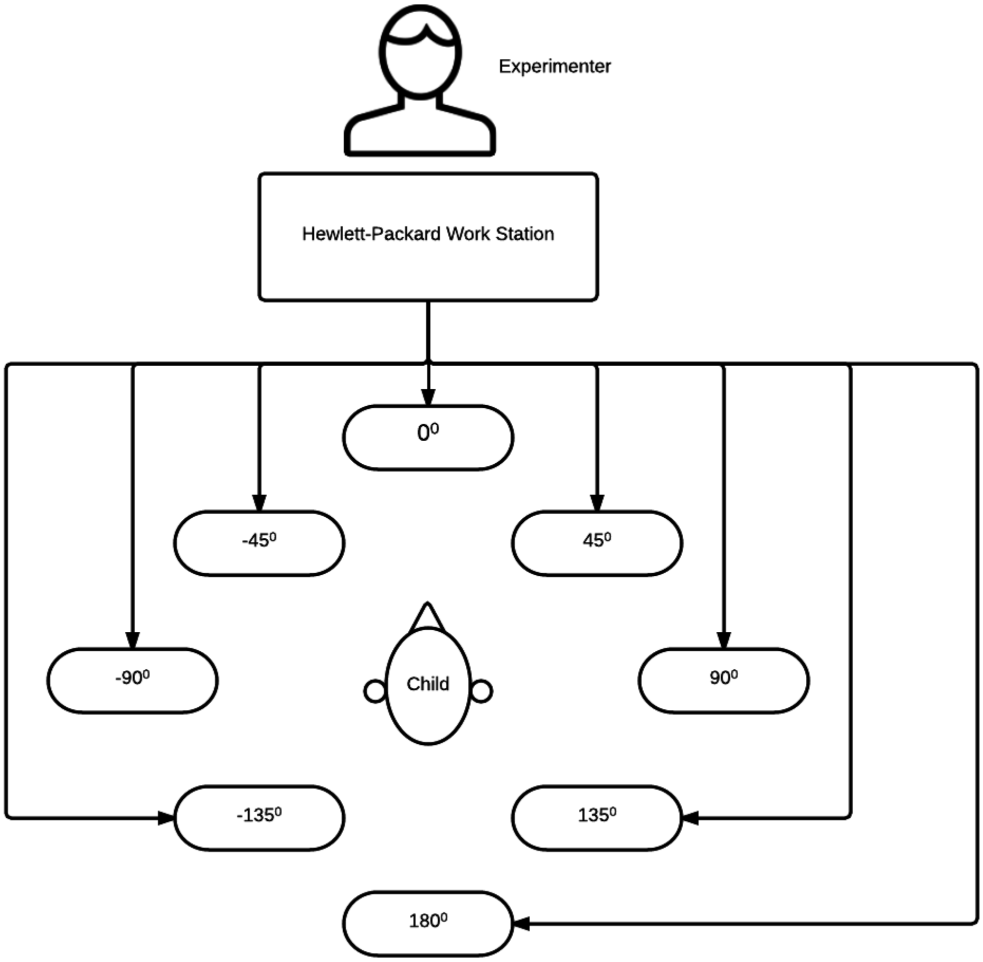

Figure3:1: *The localization setup*

3.3. Material

Warble tones (250 Hz, 500 Hz, 1000 Hz, 2000 Hz, & 4000 Hz) and Ling's six sounds (/a/, /i/, /u/, /s/, /sh/, /m/) were used to optimize the hearing aids as well as measure localization abilities of the children. The recorded version of the Ling's six sound test, having the voice of a female with a neutral accent, was used.

3.4. Environment

The initial aided performance was evaluated in a sound treated two-room situation with facility to carryout sound field testing. Two sound field speakers were placed at 45^o at a distance of 1 meter from the ear of the child. Hearing aid optimization and the localization was carried out in a semi-sounded treated room. The participants were seated in the chair which was placed equidistant from the loud speakers. The loudspeakers were placed 1 meter away from the child at -135^o, -90^o, -45^o, 0^o, 45^o, 90^o, 135^o, and 180^o azimuths.

3.5. Procedure

Initially the aided performance for pure tone thresholds and Ling sound identification of the individual was established for each ear independently. The performance of the cochlear implant was tested with a stable map that the child has used for at least one month.

The performance with the prescribed hearing aid was checked in the settings that were originally recommended by a qualified audiologist. Reprogramming of the hearing aid was done if the aided audiogram was out of the speech spectrum and there was provision to provide more gain either by increasing the gain of the child's existing hearing aid or by using a higher gain hearing aid.

To obtain the aided audiogram, warble tones and monitored live voice were presented from a calibrated audiometer through sound-field speakers. Each ear was tested with the signals presented through loud speakers placed on the same side. The lowest level that the child responded was noted. Only those children who had aided audiograms within the speech spectrum in the frequencies 250 Hz to 8000 Hz in the cochlear implant side and at least in 250 and 500 Hz in the hearing aid side, was recruited for further testing

Prior to evaluating the localization abilities of each child, the hearing aid output was optimized so that the loudness levels from the two devices (hearing aid & cochlear implant) were matched.

3.5.1. *Optimization of hearing aids*

To check the optimization of the hearing aids, the children were tested using warble tones and the Ling's six sound test. The stimuli were presented from the loudspeaker located at 0^o azimuth at 50 dB HL or the comfortable level of the child. The child was instructed to point to the ear / ears that the signals were heard. The following three forms of responses were considered to indicate that the loudness of the two devices were equal and that the sound was localized to the midline: Child points to both ears; Child points to the center of the head; or child reports that he/she cannot make out from which side the signal occurred. In case a child did not give any of the above responses, his / her hearing aid was manipulated. In case a child localized sounds mainly to the hearing aid side, the gain of the hearing aid was reduced. However, if the child mainly localized to the cochlear implant side, the gain of the hearing was increased, provided there was headroom to increase it. The protocol and the recording form developed by Yathiraj and Megha (2013) was used to record the responses (Appendix A).

3.5.2. *Localization*

The same stimuli that were used for optimization were utilized in the localization experiment. Each stimulus was presented three times through each of the loud speakers. These stimuli were randomly presented through the eight loudspeakers that were also randomly selected. The child was instructed to point to the loudspeaker from which he/she heard the signal. The responses was noted on a response sheet. The children were given breaks if they showed any sign of fatigue. The localization was tested in most of the children in 4 to 5 sessions that were spread over a week.

3.6. Analyses

The data were analyzed to find the RMS degree of errors and statistical analysis software SPSS (Statistical Package for Social Sciences (Version 17.0) for analyzing the localization trend of experimental and control groups and the effect of optimization on localization performance. Shapiro-Wilk tests was used to check for normality of the data. Besides that Friedman test and Wilcoxon sign rank were also administered.

Chapter 4

Results and Discussion

The present investigation aimed at determining the stimuli needed to optimize hearing aids in individuals using bimodal cochlear implants, depending on their aided performance in the non-implanted. Additionally, the study aimed to validate the optimization technique through a localization task. A total of nineteen children were assessed, 10 who were bimodal cochlear implant users and 9 who were age and gender matched normal hearing peers.

Statistical analyses were done using the statistical analysis software SPSS (Statistical Package for Social Sciences (Version 17.0). Besides descriptive statistics, inferential statistics was done. The data were analysed using Shapiro-Wilk to check for normality of the data; Friedman test for analysing the localization performance across different loudspeakers kept at different azimuth for a particular stimulus as well as to compare the performance across the stimuli for a particular loudspeaker azimuth; Wilcoxon sign rank test for finding the pairs of stimuli / loudspeakers having significant difference in the parameters that had a significant difference in the Friedman's test.

The findings of the study are provided under the following headings:

4.1 Comparison of localization abilities across loudspeaker azimuth for each stimulus

4.2 Comparison across stimuli for each loudspeaker azimuth

4.3 Relationship between optimization (cut-off frequency up to which the CI and hearing aid could be optimized) and localization performance.

4.4 Comparison of cut-off frequency (frequency up to which the CI and hearing aid could be optimized) and performance on Ling's sound test.

4.5 Comparison of localization performance between children using bimodal fitting and normal hearing children.

Prior to analyses of the data, Shapiro-Wilk test was administered to assess the normality of the data. The results indicated that there was normality only in few of localization scores of the children with bimodal fitting and normality was absent in the age and gender matched normal hearing control group. Hence, the data were subjected to non-parametric analyses.

The localization error for the two groups of children was calculated by finding the difference in angle between the loudspeaker through which the stimulus was presented and the loudspeaker which the participant localized. The root mean square of the degree of errors for each of the stimuli, that was presented 24 time (3 presentations per loudspeaker x 8 loudspeakers), was calculated after noting the responses on a spread sheet.

4.1 Comparison of localization abilities across loudspeaker azimuth per stimulus

The error in localizing each stimulus was calculated by obtaining the average localization response for each of the 11 sounds from the 8 different loudspeakers. From Table 4.1 it can be noticed that the localization error was similar across the stimuli within each of participant groups. In the participants using bimodal CI, the localization error was maximum for the 4000 Hz warble tone and minimum for /m/. In the normal hearing children, the error was maximum for the 1000 Hz tone and minimum for /m/.

Table 4.1: *Error in localization of each stimulus*

	Mean RMS degree of error	
Stimuli	**Children with bimodal fitting**	**Normal hearing children**
250 Hz	76.13^{o}	6.88^{o}
500 Hz	72^{o}	5.21^{o}
1000 Hz	76.88^{o}	12.08^{o}
2000 Hz	74.06^{o}	9.34^{o}
4000 Hz	77.81^{o}	7.08^{o}
/a/	75.30^{o}	5.21^{o}
/i/	72.75^{o}	6.04^{o}
/u/	77.06^{o}	7.92^{o}
/m/	71.63^{o}	3.75^{o}
/s/	74.06^{o}	8.13^{o}
/sh/	73.88^{o}	8.75^{o}

Friedman test was administered to compare the mean degree of errors in localizing the 11 different stimuli that were evaluated in the study. No significant difference in overall localization errors of stimuli emerging from the 8 different loudspeakers ($p > 0.05$). This was observed for most of the 11 stimuli in the children using bimodal cochlear implants as well the children having normal hearing ($p > 0.05$). An exception to this was the 4000 Hz warble tone that resulted in significant difference in the children with bimodal fitting ($p = 0.012$) and for /Sh/ in the normal hearing children ($p = 0.047$).

For the stimuli that had a significant effect on the Friedman's test, further analysis was done (ie 4000 Hz for the bimodal CI users & /sh/ for the normal hearing listeners). Wilcoxon sign rank test was done to determine the azimuth of the pairs of loudspeakers that resulted in an overall significant difference in localization. For the 4000 Hz stimulus, in the bimodal CI users, , there was a significant difference in the following pairs of loudspeakers placed different azimuth: 90° and 0° ($p = 0.011$), 180° and 0° (p = 0. 020); -45° and 0° (p = 0. 009); 90° and 45° (p = 0. 048); -45° and 45° ($p = 0.048$); -135° and 90° ($p = 0.026$); -90° and 90° ($p = 0.045$). Likewise, for /sh/ in the normal hearing children, the Wilcoxon sign rank test revealed that none of the pairs of angles were significantly different ($p < 0.05$).

These results indicate that both normal hearing and those with hearing impairment are able to localize stimuli that vary in frequency in a similar way. This occurred immaterial whether the stimuli were speech or non-speech. The children using bimodal CI had significantly more difficulty in localizing 4000 Hz warble tones compared to all other stimuli. This probably occurred since several of the participants had aided audiograms out of the speech spectrum in the non-implanted ear, thus making it more difficult for them to localize.

4.2 Comparison across stimuli per loudspeaker azimuth

The localization error for each loudspeaker placed at a particular azimuth was calculated by obtaining the average localization response for the 11 stimuli presented from each loudspeaker. The comparison of the participants being able to locate different stimuli for each of the loudspeakers was initially analysed using Friedman test. No significant difference across stimuli was observed in both groups of children (bimodal CI users & normal hearing children) for most of the 11 stimuli that were used ($p > 0.05$). The exception to this was for stimuli presented through the 45^o azimuth loudspeaker ($p = 0.04$) and the -45^o azimuth loudspeaker ($p = 0.00$) for the normal hearing children. Likewise, in the children using bimodal CI fitting, there was a significant difference at the -45^o azimuth loudspeaker ($p = 0.00$).

For the loudspeakers azimuths where a significant difference in Friedman's test was observed, further analysis was carried out using Wilcoxon signed rank test. This was done to identify the pairs of stimuli that were significantly different from each other. The Wilcoxon test indicated that there was significant difference in the following pairs: 2000 Hz and 250 Hz ($p = 0.03$); /m/ and 2000 Hz ($p = 0.04$) at 45^o azimuth for the normal hearing children. Further, in the same group at -45^o there was a significant difference for the pairs 500 Hz and 250 Hz ($p = 0.04$); /a/ and 250 Hz ($p = 0.04$); /sh/ and 250 Hz ($p = 0.46$). For the bimodal CI users, at -45^o azimuth there was a significant difference in the pairs 4000 Hz and 2000 Hz ($p = 0.05$); /a/ and 4000 Hz ($p = 0.04$).

It can be construed from the findings that children are able to localize sounds in a similar way, irrespective of the direction from where they originate. This is true both for children wearing bimodal CI as well as for normal hearing children. However, they tended to have more difficulty in localizing sounds that emerged from $\pm 45^o$ azimuth.

It has been demonstrated by Ching, Incerti, and Hill (2004) and Ching et al.(2001) that when hearing aids are fine tuned to enable proper optimization, children wearing bimodal devices should be able to localize sounds. In the current study despite optimization being done, the participants had fairly large localization errors. This indicates that probably factors other than fine tuning of their hearing aids play a role in them localizing sounds.

4.3 Relation between optimization (cut-off frequency) and the localization performance.

The optimization data obtained on children using bimodal CI was compared with their localization abilities. The frequencies up to which each child was able to centralize stimuli while listening through their hearing aid and CI was noted and termed as the 'cut-off frequency' of optimization. It was found that 2 children had a cut-off frequency of 1000 Hz, 3 had a cut-off frequency of 2000 Hz, and 5 had a cut-off frequency of 4000 Hz. The median of the degree azimuth errors in localization of children with different cut-off frequencies was compared with the localization ability of each stimulus (11 stimuli) and azimuth (8 azimuths).

The mean RMS of the degree of error in localization of the 11 stimuli for each azimuth for participants with different cut-off frequencies (1000 Hz, 2000 Hz & 4000 Hz) is provided in Table 4.2. It can be observed that in general as the cut-off frequency increased, the error in localization decreased. This was more evident in those whose cut-off was at 4000 Hz, especially at 45^o, 90^o, 180^o, and -90^o azimuth. The average localization errors (average for the 11 stimuli & 8 loudspeakers) shown in Table 4.3, substantiates that as the cut-off frequency increased, the localization errors decreased. In the present study, it was observed that fine-tuning the hearing aids of the children using bimodal CI, enabled the children to lateralize sounds to the midline. In spite of this, these children demonstrated considerable localization errors when tested with signals originating from different directions. The findings of the study indicate that localization errors was depended on the frequencies that could be optimized. A reduction in localization errors occurred when higher the frequency that could be optimized. Thus, it can be inferred that children who are able to obtain hearing aid optimization in limited frequencies are likely to have more difficulty in localizing signals.

Table 4.2: *Mean RMS degree of error in localization of stimuli across different azimuth for children with different cut-off optimization frequencies (1000 Hz, 2000 Hz & 4000 Hz).*

	Mean RMS degree of error		
Azimuth	**1000 Hz cut-off**	**2000 Hz cut-off**	**4000 Hz cut-off**
0	120	75	105
45	97.5	90	75
90	60	90	45
135	75	60	75
180	97.5	90	45
-135	75	120	75
-90	120	105	75
-45	90	75	75

Note. The localization error at each azimuth is the average value for the 11 stimuli used.

Table 4.3: *Relation between the cut-off frequency and mean error of localization.*

Cut-of frequency	**Mean RMS error of localization**	**Median RMS error of localization**	**SD of RMS error of localization**
1000 Hz	77.73	79.38	11.28
2000 Hz	76.12	75	8.10
4000 Hz	72.26	70.73	4.71

Note. The localization error provided is the average value for the 11 stimuli and 8 speakers

4.4 Comparison of cut-off frequency (frequency up to which the CI and hearing aid could be optimized) and optimization of Ling's sound test

The performance of the cut-off frequency at which the bimodal CI users could optimized (i.e. perceive the warble tones presented at 0^o in the centre of the head) was compared with their identification of the Ling's 6 sound test, with the use of cross tabulation (Table 4.4). As mentioned earlier, the children obtained 3 different cut-off frequencies. On the Ling's six sound test they could either optimize 4 of the low to mid frequency sounds (/a/, /i/, /u/, & /m/) or all sounds from low to high frequency (/a/, /i/, /u/, /m/, /sh/, & /m/).

Table 4.4: *Cross tabulation of cut-off frequency for warble tones and the Ling's sound optimization [4 sound optimization (/a/, /i/, /u/, & /m/) or 6 sound optimization (/a/, /i/, /u/, /m/, /sh/, & /m/)]*

		Ling sounds perceived		Total
		(/a/, /i/, /u/, & /m/	*/a/, /i/, /u/, /m/, /sh/, & /m/)*	
Cut-off frequency	1000 Hz	2	0	2
	2000 Hz	2	1	3
	4000 Hz	1	4	5
Total		5	5	10

From the Table 4.4 it can be observed that both the children who had a cut-off frequency of 1000 Hz and 2 of the 3 children with a cut-off frequency of 2000 Hz, could optimize the low to mid frequency Ling sounds /a/, /i/, /u/, /m/. On the other hand, those who had a cut off frequency of 4000 Hz could optimize all 6 Ling sounds.

Further, the aided warble tone thresholds in the non-implanted ear was compared with the cut-off frequency at which they could optimise the warble tones and the Lings sounds. It was noted that those who could optimize up to 1000 Hz, had aided thresholds well within the speech spectrum till 1000 Hz, and all other thresholds were well out of the speech spectrum. Likewise, those who could optimize till 2000 Hz also had warble tone thresholds within the speech spectrum till 2000 Hz. They were unable to optimize 4000 Hz warble tones although their aided thresholds were just out of the speech spectrum. On a similar line, those who could optimize till 4000 Hz, had aided thresholds well within the speech spectrum across all frequencies.

The findings of the study indicate that the cut-off frequency where lateralization to the centre for warble tones occurred was linked with lateralization of Ling's speech sounds. Those who could optimize warble tones till 4000 Hz were also able to lateralize centrally all the Ling's sounds. However, in those whom optimization took place below 4000 Hz, their midline lateralization was limited to the low frequency and mid frequency speech sounds. Thus, it can be construed that in difficult to test children who do not corporate for complete testing, optimization could be restricted to either warble tones or only to the Ling's sounds.

4.5 Comparison of localization performance between children using bimodal fitting and normal hearing children.

The localization abilities of the children using bimodal CI and that of the normal hearing children were compared to see the difference in performance. As can be seen in Table 4.1, the localization errors of the children with hearing impairment were considerably higher than the normal hearing counterparts. This difference was present for all 11 stimuli on which they were compared. To confirm whether this difference was statistically different, a Mann Whitney U test was performed. The comparison between the 2 groups of participants was done for the 11 stimuli that were used in the study, with the information of the 8 loudspeaker azimuths averaged. From Tables 4.5 it can be clearly seen that the normal hearing children performed significantly better than those with a hearing impairment for all 11 stimuli.

Table 4.5: Significance of difference between the performance of the children using bimodal CI and normal hearing children

Stimuli	**Z**	**p**
250 Hz	-3.68	.00
500 Hz	-3.67	.00
1000 Hz	-3.68	.00
2000 Hz	-3.68	.00
4000 Hz	-3.68	.00
/a/	-3.68	.00
/i/	-3.68	.00
/u/	-3.69	.00
/m/	-3.72	.00
/s/	-3.65	.00
/sh/	-3.68	.00

The above findings indicate that although children wearing bimodal CI follow a similar trend as that of their normal hearing peers in terms of the variations in localizing different stimuli and different locations. Despite following a similar trend, it was observed that children using bimodal CI functioned way poorer than normal hearing children on a localization task. It is reported in literature that children using bimodal CI are able localize better than those using a single CI (Ching, Massie, & Wanrooy, 2009; Dawes, Munro, Kalluri, & Edwards, 2013; Dawes & Munro, 2014; Neher & Jin, 2009; Schleich, Nopp, & Haese, 2004). It is possible the children using bimodal CI would have performed worse than what they have, had they utilized a single cochlear implant. Hence, despite the bimodal CI users performing poorer than normal hearing children, it is recommended that they continue to use a hearing aid that is optimized to obtain at least some localization cues. Further, from the findings of the study it can be deduced that optimization of a hearing aid in the non-implanted ear does enable bimodal cochlear implant users to localize sounds, though not to the same extent as normal hearing children.

From the findings of the study the following can be observed:

- There was no significant difference in localization errors of most of the stimuli except for 4000 Hz for the bimodal CI users and /sh/ for the normal hearing listeners
- There was no significant difference across stimuli in both groups of children (bimodal CI users & normal hearing children) for most of the 11 stimuli that were used

- Difficulty in localizing was seen mainly for loudspeakers placed at ± 45^o azimuth.
- As the cut-off frequency (frequency up to which the CI and hearing aid could be optimized) increased, the error in localization decreased.
- Among the bimodal CI users, those who had a cut-off frequency of 1000 Hz or 2000 Hz, could optimize the low to mid frequency Ling sounds (/a/, /i/, /u/, /m/). Those who had a cut off frequency of 4000 Hz could optimize all 6 Ling sounds.
- There was a one-to-one correspondence between the aided thresholds in the non-implanted ear and the optimization frequency.
- The normal hearing children had significantly less localization errors than those with a hearing impairment for all 11 stimuli that were evaluated.

Chapter 6

Summary and Conclusion

With the advancements in the field of audiology, the line of management for individuals with a severe to profound loss is changing from standard hearing aids to cochlear implants. This is attributed to the limited benefit from the use of standard hearing aids in these individuals. Studies also report a trend where a large increase in the number of individuals using bimodal stimulation as opposed to unilateral cochlear implants, due to the advantages in perception. However, unless the hearing aid in the non-implanted ear is fine tuned to optimize hearing through both devices, benefits seen by stimulating both ears are lost. No standard techniques are available to optimize a hearing aid in relation to a cochlear implant in individuals using bimodal stimulation.

The study current study aimed to validate an optimization procedure for children fitted with bimodal CI through a localization task in two phases. The first phase involved optimization of hearing aids and the other involved a localization experiment to verify the optimization task. A total of 19 participants (10 children with bimodal fitting and 9 children with normal hearing) participated in the study.

Warble tones (250 Hz, 500 Hz, 1000 Hz, 2000 Hz, & 4000 Hz) and the Ling's six sounds (/a/, /i/, /u/, /s/, /sh/, /m/) were used to optimize the hearing aids as well as measure localization abilities. Localization was measured through loud speakers placed at 135^{o}, -90^{o},-45 ^{o}, 0 ^{o}, 45^{o}, 90^{o}, 135^{o}, and 180 ^{o} azimuths. A total of three trials were conducted for each participant, thus making it necessary for them to localize 264 stimuli.

The results were analyzed to obtain the following information:

Comparison of localization abilities of bimodal CI users and normal hearing children across loudspeaker azimuths for different stimuli; Comparison of localization errors across stimuli at each loudspeaker azimuth; Relationship between optimization (cut-off frequency up to which the CI and hearing aid could be optimized) and localization performance; Comparison of cut-off frequency (frequency up to which the CI and hearing aid could be optimized) and performance on Ling's sound test; Comparison of localization performance between children using bimodal fitting and normal hearing children.

Based on the analyses of the data of the two groups of children, the following were inferred:

- There was no significant difference in localization errors of most of the stimuli except for 4000 Hz for the bimodal CI users and /sh/ for the normal hearing listeners
- There was no significant difference across stimuli in both groups of children (bimodal CI users & normal hearing children) for most of the 11 stimuli that were used
- Difficulty in localizing was seen mainly for loudspeakers placed at ± 45^o azimuth.
- As the cut-off frequency (frequency up to which the CI and hearing aid could be optimized) increased, the error in localization decreased.

- Among the bimodal CI users, those who had a cut-off frequency of 1000 Hz or 2000 Hz, could optimize the low to mid frequency Ling sounds (/a/, /i/, /u/, /m/). Those who had a cut off frequency of 4000 Hz could optimize all 6 Ling sounds.
- There was a one-to-one correspondence between the aided thresholds in the non-implanted ear and the optimization frequency.
- The normal hearing children had significantly less localization errors than those with a hearing impairment for all 11 stimuli that were evaluated.
- Optimization of a hearing aid in the non-implanted ear does enable bimodal cochlear implant users to localize sounds, though not to the same extent as normal hearing children.

Implications of the study

1. The study throws light on the need and importance of optimization of bimodal fitting.
2. The study gives information about the localization pattern of the children with bimodal fitting and normal hearing children.
3. The study highlights the influence of cut-off frequency on the localization ability of individuals using bimodal CI.
4. The results of the study confirm that the technique / stimuli used for optimization of a hearing aid in a bimodal CI user is valid.
5. The study provides insight regarding the stimuli that should be used depending in the aided performance in the non-implanted ear.

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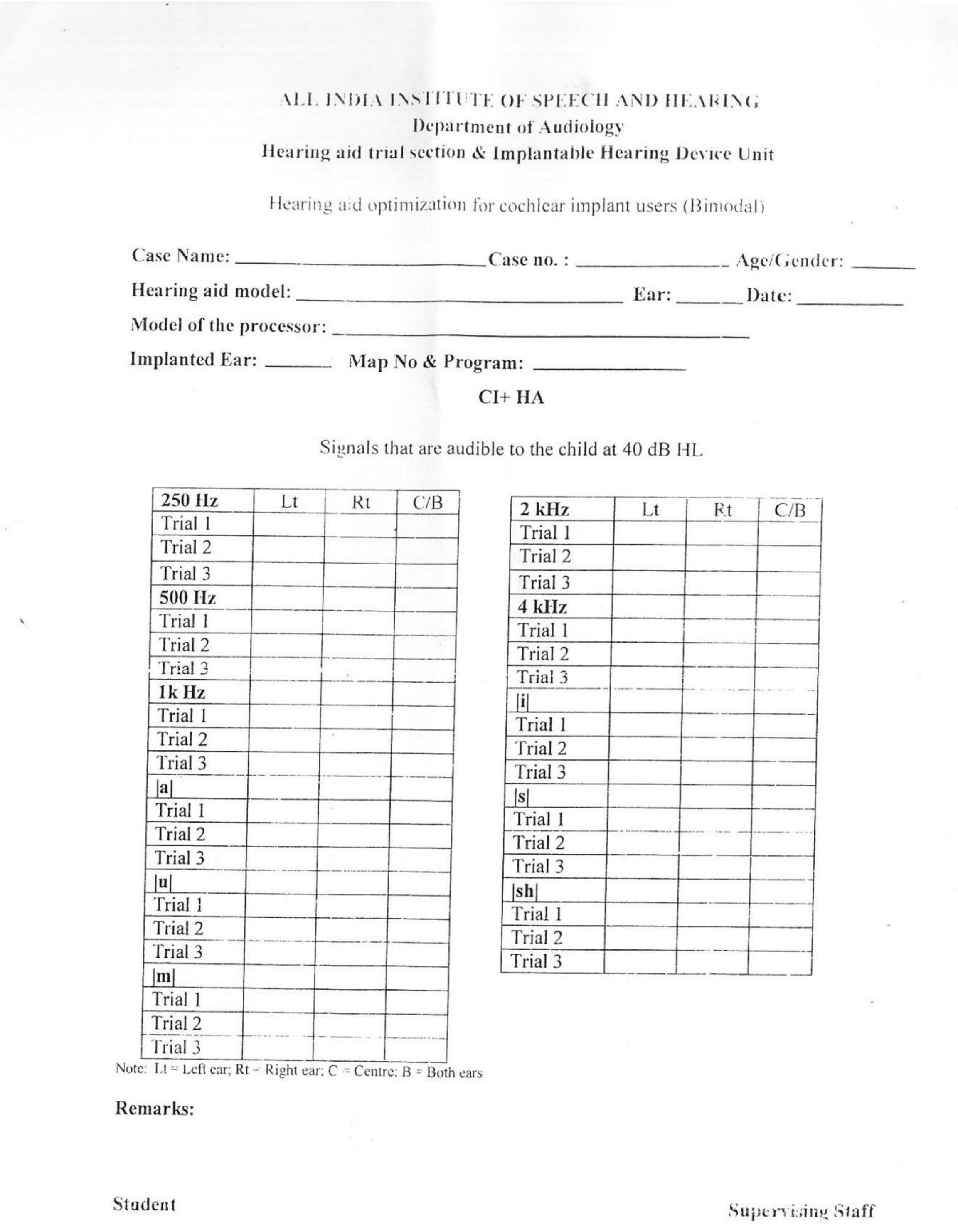
Appendix A: *Recording form developed by Yathiraj and Megha (2013)*



ALL INDIA INSTITUTE OF SPEECH AND HEARING
Department of Audiology
Hearing aid trial section & Implantable Hearing Device Unit

Hearing aid optimization for cochlear implant users (Bimodal)

Case Name: ____________________**Case no. :** ______________ **Age/Gender:** ______

Hearing aid model: ____________________________ **Ear:** _____ **Date:** __________

Model of the processor: ___________________________________

Implanted Ear: ______ **Map No & Program:** ______________

CI+ HA

Signals that are audible to the child at 40 dB HL

250 Hz	Lt	Rt	C/B
Trial 1			
Trial 2			
Trial 3			
500 Hz			
Trial 1			
Trial 2			
Trial 3			
1k Hz			
Trial 1			
Trial 2			
Trial 3			
|a|			
Trial 1			
Trial 2			
Trial 3			
|u|			
Trial 1			
Trial 2			
Trial 3			
|m|			
Trial 1			
Trial 2			
Trial 3			

2 kHz	Lt	Rt	C/B
Trial 1			
Trial 2			
Trial 3			
4 kHz			
Trial 1			
Trial 2			
Trial 3			
|i|			
Trial 1			
Trial 2			
Trial 3			
|s|			
Trial 1			
Trial 2			
Trial 3			
|sh|			
Trial 1			
Trial 2			
Trial 3			

Note: Lt = Left ear; Rt = Right ear; C = Centre; B = Both ears

Remarks:

Student

Supervising Staff