EFFECT OF HEARING AID BANDWIDTH
ON CORTICAL EVOKED RESPONSES
IN BIMODAL COCHLEAR IMPLANT USERS

DURGA S

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CERTIFICATE

This is to certify that this dissertation entitled '**Effect of hearing aid band width on cortical evoked response in bimodal cochlear implant users'** is the bonafide work submitted in partfulfilment for the degree of Master of Science (Audiology) of the student Registration Number: 17AUD015. This has been carried out under the guidance of the faculty of the institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Mysore

May, 2019

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CERTIFICATE

This is to certify that this dissertation entitled **‘Effect of hearing aid band width on cortical evoked response in bimodal cochlear implant users’** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **‘Effect of hearing aid band width on cortical evoked response in bimodal cochlear implant users’** is the result of my own study under the guidance of Dr. Manjula P., Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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Abstract

Individuals with unilateral CI are recommended to use a second device in the contralateral ear for binaural benefit such as speech perception in noise, localization, and music perception. Since bilateral cochlear implant (CI) is an expensive option, most of the children use a hearing aid (HA) in the ear contralateral to the cochlear implant. Hence, a coordinated fitting between the cochlear implant and hearing aid is important. The frequency range of the hearing aid that needs to be amplified in bimodal stimulation is not quite clear. The aim of the present study was to determine the effect of hearing aid bandwidth on cortical evoked responses in a group of 12 children using bimodal stimulation.

Three different frequency bandwidths were stored in three different memories/programs of the hearing aid, i.e., wideband amplification in Program 1, low pass with a cut-off set to 2 kHz in Program 2, and low pass with a cut-off set to 1 kHz in Program 3. The late latency responses (LLR) were considered as a tool to measure the effect of bandwidth of hearing aid. The LLR were recorded in four aided conditions i.e., CI alone condition, CI + HA with wideband amplification (CI+WB HA), CI + HA with low pass cut-off at 2 kHz (CI+2k HA), CI + HA with low pass cut-off at 1 kHz (CI+1k HA).

According to statistically analyses, bandwidth of hearing aid had no effect on morphology of LLR. However, amplitude and latency were slightly better in bimodal condition compared to CI alone. On determining the effect of bandwidth of hearing aid on LLR, there were significant differences across aided conditions. According to Wilcoxon Signed Rank test, the LLR had shorter latency in CI+ 1k HA condition and had larger amplitude in CI+ 2k HA condition. There was no particular trend observed in the findings. From the present study, it could be inferred that the presence of LLR gives information regarding functional auditory pathway, but information about the bandwidth which gave the best bimodal performance was not available. Since cortical potentials had high variation in morphology, amplitude, and latency, it could not be taken as a tool to determine effect of bandwidth of hearing aid.

Key words: bimodal, cochlear implant, hearing aid, LLR, morphology, amplitude, and latency.

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Chapter 1

INTRODUCTION

In India, about 7% of population suffers from profound degree of hearing impairment (Garg, Singh, Chadha, & Agarwal, (2011). Reddy, HemaL, Reddy, & Usha (2006) have reported that there are 40,000 live births per day in our country, with the number of children with profound hearing impairment increasing. Hearing impairment leads to difficulty in communication, especially when the hearing loss is congenital; this in turn leads to poor educational achievement and social interaction.

Individuals with severe to profound sensorineural hearing impairment are rehabilitated with amplification devices. Individuals, who do not have advantage from conventional hearing aids, benefit from cochlear implants (Dorman, Spahr, Loiselle, Zhang, Cook, Brown, & Yost, 2013). The cochlear implant bypasses the external, middle, and inner ear. It directly stimulates the auditory nerve by electrical stimulation. CI can be implanted to one ear or to the both ears. Generally, the implant is done unilaterally due to its expensive nature. Hearing aid could be used in the contra lateral ear in such individuals with unilateral implantation, i.e., bimodal stimulation.

According to the studies, individuals who have unilateral CI have residual hearing in the contralateral ear (Gifford & Dorman, 2012; Grantham, Ashmead, Haynes, Hornsby, Labadie, & Ricketts, 2012). Using a hearing aid in the opposite ear would be thus beneficial. The performance of the individual using bimodal device show better in sound quality, binaural release of masking, binaural redundancy, head shadow effect, squelch, music perception, and localization while adding up with acoustic stimulation to electrical stimulation of the CI (Ching, Wanrooy, Dillon, & Carter, 2011; Dorman et al., 2013; Francart & McDermott, 2012,2013).

Utilizing hearing aid in the contralateral ear in individuals with unilateral cochlear implant (CI) provides additional benefits like improvement in speech understanding, better localization, and improved functional performance (Tyler et al., 2002; Ching, Incerti,& Hill, 2004). A retrospective cohort study done on seven adults with post-lingual hearing loss showed that speech perception scores were better in CI alone compared to hearing aid (HA) alone condition, but bimodal condition (CI + HA) was superior to the CI alone (Hamzavi, Gstoettner, & Baumgartne, 2004). In children, also there was a significant improvement in speech recognition scores in noise in bimodal condition compared to cochlear implant or hearing aid alone conditions (Mok et al., 2010).

The studies have also revealed that the children with bimodal stimulation are able to avail the bimodal advantages like the perception of more natural sound, improved own voice quality, usage of full communication potential available, availability of more directional sounds, better localization, improved music perception, more confidence in everyday life, which is similar to bilateral cochlear implant and bilateral hearing aids (Ching, Incerti, & Hill, 2004; Dunn, Tyler, & Witt, 2005; Gfeller & Woodworth, 1997; Hamzavi, Pok, & Gstoettner, 2004; Mok, Grayden, Dowell, & Lawrence, 2006; Tyler et al., 2002).

Since there are an increased number of bimodal users in the recent years, the need for a coordinated fitting between the CI and the hearing aid has become more relevant. Certain studies imply that amplification of only low frequencies is sufficient to improve speech perception when hearing aid is used in combination with a cochlear implant (Buchner, Schussle, &Battmer, 2009; Zhang, Dorman, & Spahr, 2010; Sheffield &Zeng, 2012). These studies were carried out primarily on listeners with steeply sloping hearing loss with relatively good hearing in low frequencies. It is unclear whether these findings can be generalized to bimodal users who have poorer low-frequency residual hearing, but who have a usable residual hearing over a relatively wide frequency range. Mok et al. (2006) reported that bimodal users with poorer aided thresholds at 1 kHz and 2 kHz obtained greater bimodal benefit than users with better aided thresholds. In addition, listeners whose hearing aid did not provide amplification at 4 kHz (due to the severity of hearing loss) obtained more benefit than those who did. These results have been interpreted as indicating possible negative interactions between the acoustically amplified signal at mid- and high- frequencies and the electrical signal from the cochlear implant.

Studies by Ching et al. (2001, 2004) suggest that, on an average, for the hearing aid in the opposite side, the frequency response prescribed using the NAL prescriptive procedure will be appropriate. In a few research studies, frequency overlap between the CI and HA were studied using combined acoustic and electric stimulation (EAS). From these studies the prescribed frequency distribution varied from no frequency overlapping to some degree of overlapping across different fitting procedures, research methods. Zhang, Spahr, and Dorman (2010b) studied the benefit of frequency overlap of acoustic and electric signal in individuals with bimodal stimulation. The participants were tested using electric and acoustic signal alone and also in the condition where the low pass (LP) and high pass (HP) conditions were paired (i.e., unfiltered acoustic along with unfiltered CI or widest, 250 LP acoustic with 250 HP CI, 500 LP acoustic with 500 HP CI etc.).

Performance in the widest conditions was best for electric and acoustic stimulation alone as well as in the combined conditions. Thus reducing the frequency overlap for these bimodal users did not improve performance. Similar results were obtained in various studies indicating that reducing the overlap in frequency representation between acoustic and electric stimulation did not enhance speech understanding scores (Kiefer et al., 2005).

It is thus unclear whether the approach to fitting the hearing aid for bimodal hearing individuals should be modified in order to focus on providing primarily low-frequency information, or whether a wideband hearing aid fitting that would be more typical of stand-alone hearing aid use is appropriate. Research has shown that even CI users with severe-to-profound hearing loss in the contralateral ear can benefit from amplification (Ching et al.,2001; Ching et al., 2004; Mok et al., 2006; Potts et al., 2009), but the amount of benefit contributed specifically by low- (below 0.5 kHz), mid- (1-2 kHz) and high-(2-6 kHz) frequency amplification to bimodal benefit has not been systematically investigated.

Neuman and Svirsky (2013), tried to find the effect of hearing aid bandwidth on bimodal speech perception. Individual with bimodal hearing who had severe-profound hearing impairment in contra lateral to the ear with cochlear implant having residual hearing enough for wideband amplification using NAL-RP prescriptive guidelines were included. In addition to that the unaided thresholds were not poorer than 95 dB HL through 2k Hz. Fourteen bimodal listeners with post-lingual hearing loss participated in the study. Speech recognition performance was measured in sound field with the CI alone and with each of four bimodal fittings implemented in a digital behind-the ear (BTE) hearing aid. The four frequency responses were differing in bandwidth and were programmed into four memories of the hearing aid. On an average, bimodal benefit was obtained when the hearing aid provided amplification at all frequencies with aidable residual hearing. Limiting the hearing aid bandwidth to only low frequency amplification (below 1 kHz) did not yield significant improvements in performance over listening with the CI alone. These data suggest the importance of providing amplification across a wide frequency region as permitted by the hearing aid used by bimodal users.

Sharma (2005) used the latency of the P1 of cortical auditory evoked potential (CAEP) to determine the developmental changes in central auditory pathway. The authors reported that the latency of P1 could be taken as a biomarker to evaluate the children who receive intervention through hearing aids and/or cochlear implants. The presence of the response gives information on normal functioning auditory pathway and to decide whether child benefit from CI followed by hearing aid. Using the same marker, developmental changes and maturation of the system could also be to monitor once electrical stimulation is initiated.

Sharma (2002) investigated the maturity and flexibility of the central auditory system in children with congenital deafness following cochlear implantation over a period of time. Late latency response was analyzed. The source of generation P1 response is from auditory thalamic and cortical sources. The P1 latency reflects the accumulated sum of delays in synaptic propagation through the peripheral and central auditory pathways. Since P1 latency varies as a function of chronological age, P1 latency was used to determine the development of auditory pathways in children fitted with an implant. Comparison of P1 latencies from 18 congenitally deaf children who were fitted with a cochlear implant by age 3.5 years and age-matched peers with normal hearing was also done. The P1 latencies of children with CI when measured after 6 months of implantation were not significantly different from their age-matched normal hearing peers, suggesting that the functional development of central pathways was age-appropriate by six months after early implantation.

Ponton et al. (2000) analyzed the latencies of the P1 of LLR in children and adults with normal hearing and cochlear implants. The children were again subdivided into those who had experienced short- (1.1 years), medium- (4.9 years), and long- (8.5 years) periods of deprivation. The investigators noticed that though the overall latencies of the P1 response were delayed in children with cochlear implants, the maturation rate of P1 latency in these children were the same as those with normal hearing. On the basis of their norms for maturation of the P 1 (i.e., 15 years), the mature latencies in individuals of 17, 20, and 25.5 years of age with implants who had short-, medium-, and long- periods of deafness were extrapolated. The same investigator reported that the average time for the maturation of P1 latencies was delayed by an additional 5 years for a group of children with implants whose mean duration of deafness was 4.5 years.

Manjula and Jaisinghani (2015) studied the benefit of cortical response in assessment of bimodal performance. Comparison of aided behavioral and cortical response in children with cochlear implant and hearing aid was done. Three children participated in the study. Aided behavioral and LLR measures were obtained for each participant across three conditions viz., CI alone, hearing aid alone and both CI and hearing aid. Under aided behavioral measures, aided audiogram, aided SIS, awareness and identification of Ling’s six sounds were measured using a calibrated audiometer, with loudspeaker kept at 0 degree azimuth and one meter distance from the participant. The aided LLR were recorded using HEAR Lab ACA for synthetic stimuli /m/, /t/ and /g/ presented at 65 dB SPL through sound field. The responses were confirmed by inspecting the p value for each recording and also by validating peaks and morphology (on a five point rating scale) by three audiologists. Aided behavioral results were compared with aided LLR across all the three conditions, for all three stimuli and for all the participants. Presence of LLR was seen in all the three participants in CI alone and CI along with hearing aid conditions. Whereas in hearing aid alone condition, two of the participants had absent LLRs with own hearing aids. The authors have opined that aided LLR is congruent with aided behavioral measure and p value, latency, and morphology can be used in assessing the benefit of hearing aid on contra lateral ear in bimodal fitting.

In the current study, cortical response, i.e., LLR was taken as a measure to determine the performance of bimodal user through hearing aid and cochlear implant. According to the literature individuals with bimodal hearing get information of low frequency as well as high frequency from cochlear implant and hearing aid. In the present study, the effect on LLR in change in hearing aid bandwidth was analyzed.

Need for the study

In countries like India, everyone cannot afford bilateral cochlear implants. For binaural benefit, hearing aid is prescribed in the opposite side. Addition of hearing aid provides benefits like better perception in noise, localization, and music perception. Not every individual benefits from the additional acoustic stimulation.

In most of the cases profound loss have been seen in implanted ear and severe to profound loss seen in contra lateral ear. The aided audiogram for the hearing aid side is out of speech spectrum, mostly in high frequency region. Fitting of hearing aid plays an important role for individual with bimodal hearing. Since they require benefit from both of the devices, the frequency response of the hearing aid should match with the cochlear implant.

Most of the studies have been performed in adults with post-lingual hearing impairment. Further study is required in children in order to examine the contribution of different frequency range amplification to speech perception and to determine the cortical response in bimodal hearing and to determine the benefit from contra lateral acoustic stimulation.

Aim of the study

The aim of the present study is to examine the effect of hearing aid bandwidth on Late Latency Response, in a group of children with severe to profound hearing loss, who use a hearing aid in the ear contra lateral to the ear with cochlear implant.

Objectives of the study

The specific objectives of the study were to evaluate the following in children with severe to profound hearing impairment who use unilateral cochlear implant and contra lateral hearing aid

1. To determine whether a bimodal benefit is seen in children fitted with cochlear implant in conjunction with hearing aid in the opposite ear by

comparing the morphology, amplitude and latency of LLR in cochlear implant alone (CI) condition and cochlear implant with hearing aid in wide band condition (CI + WB HA).

2. To determine the effect of hearing aid bandwidth on LLR in bimodal users by comparing the morphology, amplitude and latency for the following three conditions
    - CI + hearing aid (HA) in wide band condition (CI+WB HA)
    - CI + HA with low pass set to 1 kHz (CI+2k HA)
    - CI + HA with low pass set to 2 kHz (CI+1k HA)

Chapter 2

REVIEW OF LITERATURE

Lack of sensory input from birth interferes with the normal development and connectivity necessary for the formation a functional sensory system results in hearing and oral language learning defect. In individuals with hearing impairment, absence of sensory input from birth, affects normal growth and connectivity needed to form a functional sensory system- resulting in deficits in hearing and oral language learning. Hearing aids are the primary rehabilitation devices for individuals with permanent hearing loss. For those in whom hearing aids are of limited benefit, cochlear implants are considered. When there is no improvement or poor benefit from hearing aid, cochlear implant serves as a better management option for individuals with hearing impairment. Individuals with cochlear implant show better benefit than with hearing aids. Implantation of the device can be either unilateral or both sides. The performance through cochlear implant can be affected by various factors (Geers, 2002). Although bilateral cochlear implantation results in better speech perception, in developing country like India due to financial restrictions most of the children are fitted with unilateral implant and the other ear with hearing aid cannot afford for the cochlear implant for both the sides, children with severe to profound hearing impairment go for unilateral implantation. Though the speech perception is poor in non-implanted ear, children continue to wear hearing aid. Cochlear implant in one ear and hearing aid in the opposite ear is termed as bimodal stimulation. Hearing through both ears gives binaural benefit for better perception. Benefit of bimodal and bilateral stimulation varies (Cullington & Zeng, 2011).A few findings reveal that bimodal is better, and a few other findings report that bilateral cochlear implants are better. In the present study, the electrophysiological evidence for bimodal benefit is being investigated. The relevant studies in literature are being given in the following headings:

2.1 Speech perception in children with bimodal hearing
2.2 Effect of hearing aid bandwidth on the bimodal benefit
2.3 Effect of bimodal stimulation on Late Latency Response after implantation

2.1 Speech perception in children with bimodal hearing

Earlier cochlear implant was recommended for individuals with bilateral congenital severe to profound hearing impairment with poor residual hearing. Due to the improvement in technology in cochlear implant and improved speech perception through CI, since 1980s CI was been recommend to individual with severe hearing impairment. In addition to cochlear implant children continue to use hearing aid for binaural hearing. However studies comparing the speech perception in monaural hearing and binaural hearing revealing that, binaural hearing was better (Carhart, 1958; Gelfand & Silman, 1993; Freyaldenhoven, Plyler, Thelin & Burchfield, 2006). A cochlear implant in one ear and hearing aid in the other ear is termed bimodal hearing (Clark, 2003). Bimodal hearing provides a clearer and natural hearing experience. The other benefits include better localization (Kuk, Potts, Strube, Skinner & Litovsky, 2009), improvement in speech understanding, especially in noise (Balkany, 2002; Gottermeier, De Filippo, & Clark, 2016), better appreciation of music (Sucher & McDermott, 2009), and prevention of auditory deprivation by stimulating the contralateral ear.

Tyler, Parkinson, Wilson, Witt, Preece, & Noble (2002) conducted a pilot study in three adults who used cochlear implant in one ear and a hearing aid in the other ear. The authors studied speech perception and localization abilities in bimodal condition. Speech perception was measured in quiet as well as in speech-shaped noise by identification of key words in the City University of New York (CUNY) sentences (Boothroyd, Hanin, & Hnath, 1985) and with recognition of Consonant-Nucleus-Consonant monosyllabic words of NU-6. Three conditions with different noise were integrated. The noise was presented either from the front, or from 90° to the right or left. A simple localization test was devised where noise bursts were presented from a loudspeaker at 45° to the left or right of the straight-ahead (0°) position. The patients were asked to find the direction of sound source, whether from the left or the right loudspeaker. The stimuli of four bursts of speech noise with pulse duration of 200milisecond which was separated by 200 msec. of silence were incorporated. From the results the speech perception score in quiet showed improvement indicating a binaural advantage, but only for one of the three patients for words and none for sentences. When stimuli were presented from the front of the patient with speech and noise from front, two patients performed better with both devices than with either device alone. Localization ability improved with both devices for two patients. This led to the conclusion that a cochlear implant in one ear and a hearing aid in the other ear can provide some binaural advantages such as localization and speech perception ability. The patients who did not show a clear binaural advantage had the poorest performance CI alone condition which did not bring about change on addition to hearing aid.

Ching Incerti, and Hill (2004) found binaural benefits in individual with bimodal hearing. Performance in speech perception, horizontal localization, and functional performance in everyday life were measured. Eighteen children were evaluated in two conditions, i.e., cochlear implant alone (CI) and a cochlear implant with a hearing aid (CI+HA). All children were integrated with a hearing aid in the non-implanted ear with the NAL-RP prescription, and the hearing aids were fine tuned individually using a paired-comparison procedure and a loudness balancing test. Binaural advantages in localization was tested using a horizontal array of five loudspeakers spaced 30° apart (120° arc) was used. From the testing, there was an enhancement in the performance when hearing aid was added to CI. Children who received a CI younger in life derived greater benefit in localization. Functional performance in real-life was assessed with the help of a parents' questionnaire. The parents were given a copy of the questionnaire, and were asked to observe the child's functional performance in a range of situations over a period of one week and to record as many examples of the child's performance in specific situations as possible. The questionnaire consisted of eighteen questions grouped into four probe areas, i.e., usage of device(s), performance in quiet, performance in noise, and environmental awareness. The children functioned more effectively in real-life with CI+HA than with CI alone which was seen clearly in the scores obtained in parents' questionnaire. None showed any negative effects from bimodal hearing.

Luntz, Shpak, and Weiss (2005) studied the perception of speech in bimodal hearing in individuals over time. Population included were 12 bimodal hearing individuals with residual hearing in the contra lateral ear. Binaural benefit was evaluated using sentence identification test in the presence of background noise. City University of

New York (CUNY) was taken for post-lingual adults and common phrase test for pre-lingual children for the evaluation. The test was administered in the presence of environment noise and in three different conditions i.e., cochlear implant (CI) alone, hearing aid (HA) alone, and CI+HA. The procedure also included testing the participant in different period of time, as 1 to 6 months after simultaneous use of both devices and again after a further 7 to 12 months. During first testing session, the mean score in background noise was 34.9% with CI alone (range 0-90%) and 41.1% with both devices (range 0-100%). Seven patients could recognize sentences in noise with CI alone, and four of them showed further improvement with added amplification. At the second session, at which all subjects could recognize sentences in noise with the CI alone, seven showed further improvement with added amplification. The mean score was 60.6% with CI alone (range 10-99%) and 75.5% with both devices (range 52-100%).This reveals that there is improvement in speech perception in cochlear implant alone and further improvement with cochlear implant + hearing aid mode. The performance also improved over time at least for the first year of rehabilitation.

Mok, Grayden, Dowell, and Lawrence (2006) conducted a study to investigate the effect of bimodal stimulation on speech perception in two conditions.. The participants of the study were 14 adults with bimodal stimulation (75% usage of hearing aid after cochlear implantation) or with hearing loss less than 90 dB HL in the non-implanted ear for low frequencies. The study was conducted in both quiet and noisy situation mainly under 3 conditions, i.e., cochlear implant (CI) alone condition, hearing aid (HA) alone condition, and when both the devices were used in conjunction in the opposite ears (CI+HA). Speech recognition scores were found for each condition using consonant-vowel nucleus-consonant (CNC) words , City University of New York style (CUNY) sentences, and spondees. Results revealed better speech perception for open set task and closed set spondees task in six and five participants respectively. However, two of them exhibited poorer speech recognition in CI+HA condition when compared to CI alone condition. The study concluded that while most bimodal device users receive speech perception benefit from bimodal fitting, others do not. For a minority, bimodal fitting might even has an adverse effect on speech perception. Some of the individual variability on bimodal benefit could be accounted for by the differences in aided thresholds in the non-implanted ear. Individuals with poorer aided thresholds in the mid- to high-frequencies exhibited greater bimodal benefit. From the study, it can be inferred addition of a hearing device to the cochlear implant, as in bimodal stimulation, does improve speech perception.

Beijen, Mylanus, Leeuw, and Snik (2008) compared the speech perception abilities of 22 children in bimodal fitting and cochlear implant alone condition. The mean age of the children was 12 years. All the children had been using hearing aid before cochlear implantation and continued to do so in the non-implanted ear even after implantation. The mean duration of hearing aid usage was 9 years 11 months. The phoneme recognition score was determined in quiet and noise with standard phonetically balanced word lists of a Dutch monosyllabic word test presented at 65 dB SPL in two conditions, i.e., CI alone condition and bimodal condition. On the phoneme recognition in quiet test, 18 of the 22 children showed a bimodal benefit. At the group level, there was a significant advantage for the bimodal condition which could be attributed to the binaural advantage. Of the 21 children who underwent the phoneme recognition in noise test, 16 exhibited an improvement when a hearing aid was added to the cochlear implant. There was a significant difference between the group score obtained in the bimodal condition and that obtained with the cochlear implant alone. This could be because in noisy situations, binaural cues can substantially reduce the disturbing effect of background noise on speech understanding via the squelch effect and easier use of the head shadow effect. They concluded that a hearing aid should be recommended to all children with unilateral implants in order to provide them a chance to experience bimodal benefit. The advantage of bimodal fitting on speech perception in post-lingually deafened adults as seen in the study by Beijen et al. (2008) cannot simply be assumed to apply to children due to the differences in the development of their bilateral auditory system.

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

In addition, the relationship between aided thresholds in the HA ear and bimodal advantage was also studied. The results of the correlation analyses showed that the bimodal subjects, with better aided thresholds at low frequencies (0.25 and 0.5 kHz), demonstrated greater bimodal advantage. This may be due to the fact that a hearing aid provides finer low-frequency spectral information than a CI, which could complement to the signal received from an implant in the opposite ear. A previous study also showed that adult implant users could utilize the low-frequency acoustic information from a contralateral hearing aid to improve the perception of low-frequency phonemes (Mok et al., 2006).The results also indicated that the bimodal subjects with poorer aided thresholds at 4 kHz demonstrated greater bimodal advantage than those with better 4-kHz thresholds. This is similar to the results for adults, which also indicated that subjects with poorer aided thresholds at 4 kHz demonstrated greater bimodal advantage (Mok et al., 2006). There could be two possible explanations for this. One could be the mismatch of high-frequency information provided by the HA and the CI as both the devices excite two different places in cochlea through acoustic and electric stimulation respectively (Blamey et al., 1996). The other possible reason could be the amplification provided in high-frequency dead regions in the ear with hearing aid, leads to off frequency listening and eventually there may have been a masking effect which limited the bimodal benefit that was gained by subjects with better aided hearing at 4 kHz. Overall, these results suggest that individual variability in bimodal outcome could be partly accounted by the differences in aided thresholds, and that better aided thresholds do not necessarily result in greater bimodal advantage. Hence, there is always been an uncertainty whether to limit the frequency range of hearing aid or not. Thus, in the present study, the effect of frequency range of the hearing aid used in bimodal condition is being investigated.

Vroegop et al. (2018) studied technology on speech intelligibility in bimodal cochlear implant individual. They investigated the effect of a binaural beam former for bimodal cochlear implant (CI) users by measuring speech reception thresholds (SRT) in noise in a repeated-measures design that varied in listening modality for static and dynamic listening conditions. Participants of 18 post-lingual adult with hearing impairment whose age range was from 32 to 81 years were involved in the study. Every participant was a experienced bimodal user with Advance Bionics HiRes 90K implant. Speech recognition threshold was measured after 6 months for every participant. All the individuals with the CI alone had open-set speech recognition of at least 70% correct phonemes at 65 dB SPL on the clinically used Dutch consonant-vowel-consonant (CVC) word lists [Bosman & Smoorenburg, 1995]. The participants with non-implanted ear had unaided hearing thresholds of ≥80 dB HL at 250 Hz. The participants who were HA users had replaced by the Phonak Naída Link UP HA for the testing. All the participants were native Dutch speakers who signed an informed consent letter before participating in the study. A significant improvement in SRT of 4.7 dB was found with the binaural beamformer switched on in the bimodal static listening condition. No significant improvement was found in the dynamic listening condition. They concluded that there is a clear additional advantage of the binaural beamformer in bimodal CI users for predictable/static listening conditions with frontal target speech and spatially separated noise sources.

2.3 Effect of hearing aid bandwidth on the bimodal benefit

Most of the bimodal users benefit from the use of a hearing aid in the contra lateral ear as hearing aid amplifies acoustical cues for lower fundamental frequency and harmonics necessary or the fine structure information not given by CI.. But the requirements for fitting the HA to be worn in conjunction with the CI are not well understood. It may be the case that a hearing aid fitting that only amplifies low frequencies (1) may be sufficient to provide bimodal benefit (Zhang et al., 2010), (2) makes it possible to provide more hearing aid gain in the low-frequency region and (3) in some cases, may be a means of preventing interference between information provided by the HA and the CI (Mok et al., 2006).

Typically, hearing aid prescriptive procedures have the goal of providing audibility over a wide frequency range as possible. But prescriptive procedures differ in recommendations of insertion gain as a function of frequency and also differ with regard to the recommended hearing aid bandwidth The ability to make sound audible through the hearing aid at high frequencies (at and above 3 kHz) will be governed by the degree of hearing loss. Often, it is not possible to provide sufficient gain through the hearing aid to allow audibility. Furthermore, even if sounds are made audible, the ability of the listener to use information in these frequency regions may be compromised (Ching et al., 1998; Ching et al., 2001a; Hogan & Turner, 1998; Turner & Cummings, 1999; Vickers et al., 2001).Some hearing aid prescriptive procedures will take into account the ineffectiveness of trying to restore full audibility in the high frequencies for those with profound high frequency loss. These prescriptions recommend less gain in the higher frequencies and more gain in the low frequencies as the thresholds at 2000 Hz and above exceed 95 dB HL (Byrne et al., 1990; Byrne et al., 2001; Dillon, 2006; Keidser et al., 2011). Other prescriptive procedures do not modify targets for high frequency gain (Bagatto et al., 2005; Moore et al., 2010).

Providing amplification to only the lower frequencies will not improve the speech perception, majority of the research suggests only when low frequency amplification is given in combination with cochlear implantation (bimodal) there would be significant benefit in terms of speech recognition.(Büchner et al., 2009; Zhang et al., 2010; Sheffield & Zeng, 2012), and few researchers reported speech to be unintelligible when signal given is only through acoustic mode(e.g., Kong et al. 2005; Zhang et al., 2010; Cullington & Zeng, 2011).Major drawback of these studies is that most of the participants of the study had relatively better hearing at lower frequencies (steeply sloping hearing loss). One limitation of these studies is that they have focused primarily on listeners with steeply sloping hearing loss, but relatively good hearing at low frequencies.

Mok et al., (2006) reported that benefit from bimodal mode mainly depends on aided thresholds. Subjects with poorer aided thresholds performed better than subjects with better aided thresholds at 1 k and 2 kHz. In addition, listeners with limited benefit at 4 kHz from hearing aids (due to severity of hearing loss) performed better. These findings may be due to interactions between acoustic signal in mid and high frequency range from the hearing aid with the electrical signals from the cochlear implant. Zhang, Spahr, and Dorman (2010) tried to find out the minimum bandwidth that should be amplified by hearing aid to improve speech recognition in unilateral CI users to obtain bimodal benefit. The participants included nine adults with post-lingual hearing loss of steeply sloping configuration except one. The non-implanted ear had thresholds less than or equal to 60 dB HL till 0.5 kHz and greater than 60 dB HL beyond 1 kHz. To find out the speech recognition the stimuli used were Consonant Nucleus Vowel Consonant (CNC) word lists in quiet and AzBio sentence lists in noise (+10 dB SNR). The acoustic speech stimuli were unfiltered (wideband) or low pass (LP) filtered (LP cut offs of 250, 500 or 750 Hz) and amplified for each subject using the frequency/gain response targets specified according to NAL-RP prescriptive formula (Byrne, Parkinson, & Newall, 1990). The electric stimuli were unfiltered or high pass (HP) filtered (HP cut offs of250, 500 or 750 Hz). In the combined condition unfiltered acoustic stimulus was paired with unfiltered electric stimulus, and corresponding low pass and high pass stimuli were paired in other bandwidth conditions. Results revealed that the better perception was obtained in combination of unfiltered acoustic with unfiltered electric stimulus. The conclusion drawn was that in individuals with residual hearing in lower frequencies, narrowing the frequency overlap between acoustic and electric stimulation would not result in improved speech recognition

Though the study done by Zhang et al., (2010) revealed a better performance in the wideband condition of the acoustic and electric stimulation, this could not be generalized to bimodal users with poorer low frequency residual hearing. It appears likely that the ability to obtain bimodal benefit from provision of only low-frequency acoustic information may depend on the degree and configuration of hearing loss. A second factor that needs to be considered is that Zhang et al. simulated a hearing aid and presented stimuli through an earphone. The hearing aid simulation did not include the type of low frequency cut-off typical of conventional hearing aids Therefore, it is important to obtain information about the potential contribution of low-, mid-, and high- frequency acoustic information to bimodal benefit through actual hearing aids.

Neuman and Svirsky (2013) estimated the effect of hearing aid bandwidth on bimodal speech perception. The participants of the study included 14 adults with a degree of severe-profound hearing loss in non implanted ear. The unaided thresholds were not poorer than 95 dB HL till 2 kHz and the hearing aid was programmed using NAL-RP prescriptive formula. The hearing aid was programmed for four settings differing in bandwidth. Modified bandwidths included low pass with 0.5, 1 and 2 kHz cut off. Test material used to check speech recognition in quiet and noisy condition was the AzBio sentence material. Results revealed that speech recognition was best in the wideband condition. Thus limiting the hearing aid bandwidth to only low frequency amplification (below 1 kHz) did not yield significant improvements in performance over listening with the CI alone.

Thus from the studies reported in literature, it is evident that for majority of the individuals with hearing aid in the ear contra lateral to that with cochlear implant, provides additional. In very few cases it was observed that bimodal mode did not provide any additional benefit and in few other cases the speech recognition scores deteriorated. The frequency range of the hearing aid that needs to be amplified in bimodal users is quite unclear. Most of the studies quoted in literature are done in adults and older children. There is a dearth of literature on the effect hearing aid bandwidth on speech recognition in children with pre-lingual severe to profound hearing loss. When few researchers recommend to limit the hearing aid amplification till 1 kHz, few others recommend to provide amplification as wide frequency range as possible. The present research aims to see the effect of hearing aid bandwidth on speech recognition in children with severe to profound hearing loss.

To summarize, as per most of the studies, aidable residual hearing at all frequencies is essential to achieve benefit from bimodal mode. Restricting the hearing aid bandwidth to only lower (below 1 kHz) resulted in same speech perception as CI alone performance.

This implies the importance of wide frequency band amplification as per the audiometric thresholds in the hearing aid used by bimodal users. There are few studies in contradiction to this finding. According to Mok et al. (2006) mid-frequency amplification might reduce the bimodal benefit. But Potts et al states that it is crucial to provide better amplification in the mid frequency for bimodal fittings.

2.4 Effect of bimodal stimulation on Late Latency Response after implantation

Sensorineural hearing loss causes significant degeneration of auditory nerve resulting in no input to the auditory pathway. Due to the reduction in the input to the auditory brainstem, there are physiological changes in the auditory brainstem nuclei i.e., shrinkage of nerve, altered pattern of neural connectivity and changes in physiological response properties. The nature and extent of these changes depends on the hearing loss. These changes are more extensive when the onset of hearing loss is congenital or in the critical period. Chronic stimulation through cochlear implant to the auditory brainstem prevents these changes.

In the earliest study, Rapin and Grazianni (1967) utilized long latency responses (LLR) and found that a majority of their 5 to 24 months infants with severe to profound hearing impairment showed cortical response 20dB better that the unaided response. Hence, the present study evaluated the effect of bimodal stimulation on LLR as LLRs have been used to evaluate the benefit from hearing devices.

.Aided cortical evoked potential is considered to validate the hearing device fitting to show that speech stimuli across the spectrum evoked a neural response at the level of auditory cortex and therefore are likely to be perceived. If the neural responses evoked by different speech stimuli differ, as evidenced by differences in the CAEPs waveforms, this suggests that the stimuli should also be discriminated from each other. The presence of speech evoked CAEPs indicates that the speech stimuli have been detected. Differences in the aided cortical responses to different stimuli indicate that the underlying neural representation to the stimuli differs. If the neural representation of the stimuli differs at the level of the auditory cortex, the infant should be able to behaviorally discriminate the stimuli, if other abilities are intact. Among the other advantages, it has also been found that CAEP are closer to behavioral threshold typically 10 dB of behavioral hearing threshold in participants with normal and impaired hearing for stimuli at frequencies across the audiometric range.

Ponton et al. (1996) studied the maturation of human cortical auditory function. They compared between normal hearing children and children with cochlear implant. Auditory evoked cortical responses have been measured in normal hearing children and adult with cochlear implant. For normal hearing children, there is a gradual evolution of Auditory Evoked Response features that extends through the adolescence, with P1 latency becoming adult-like in the late teens. Latency changes for P1 occurs at the same rate for implanted children, but overall maturation sequence is delayed. Other features like N1 and P2 are either delayed or absent in children with cochlear implant. According to the study, the cortical potential functioning does not progress until and unless the stimulation begins. Hence addition of hearing devices stimulates auditory system as well as improves functioning of cortical potentials. Sharma, in 2002, investigated the development and plasticity of the central auditory system in congenitally deaf children following cochlear implantation over period of time. The late latency response was analyzed. The P1 response was generated by auditory thalamic and cortical sources was measured. The P1 latency reflects the accumulated sum of delays in synaptic propagation through the peripheral and central auditory pathways. Since P1 latency varies as a function of chronological age, P1 latency has been used to determine the development of auditory pathways in children fitted with an implant. Comparison of P1 latencies from 18 congenitally deaf children who were fitted with a cochlear implant by age 3.5 years and age-matched normal-hearing peers was also done. The P1 latencies of implanted children after 6 months of implant use were not significantly different from their age-matched normal hearing peers, suggesting that the functional development of central pathways was age-appropriate by 6 months after early implantation. From this study, it can be construed that earlier cochlear implantation occurs in a highly plastic system in which the effect of deprivation are overcome in a relatively short period of time. According to this study, children who were implanted before three to four years of age showed age appropriate cortical response.

Sharma (2005) examined the P1 latency of cortical potential in determining the benefit of various habilitation devices for individuals with hearing impairment. The site of generation of P1 is auditory thalamus and cortex, and also the latency of P1 decreases as the age increases. Since P1 latency changes with age, it can be used to examine the maturation of central auditory pathway. In their study, the cortical response was elicited by synthesized speech /ba/ stimulus with 90msec.duration. Klatt speech synthesizer was used to generate five formant CV syllables. The stimulus was presented at an offset to onset inter-stimulus interval of 610msec. The evaluation was done in children with hearing impairment. According to the result, child with severe to profound hearing loss showed no cortical potential at the time of evaluation. After fitting with hearing aid, positive P1 with reduced latency showed that there is auditory stimulation due to hearing device. Speech evaluation of this child showed improvement in language development. In another child, there was negative P1even though after fitting of hearing aid. Hence, the child was recommended a cochlear implant. The cortical potential was recorded at the time of implantation, one month, three month and six month of implantation. There was a decrease in the latency of P1 with large positive P1. This implies that the child was benefitting from the cochlear implant who earlier was not getting auditory stimulation in hearing aid. This states that presence of P1 indicates the presence of auditory stimulation in the pathway; hence P1 could be taken as biomarker for determining the maturation in the auditory system.

Sharma (2006) studied the central auditory development in children with bilateral cochlear implants. A retrospective study was conducted in four children who received cochlear implant before two years of age. The cortical auditory evoked response was elicited longitudinally i.e., after three months, six months, one year, and three years after implantation. Two children showed latency within normal limits by three to six months, who received sequential bilateral cochlear implant. In other two children, who received simultaneous implantation also within normal limits in a very short time frame i.e., by one month post stimulation. According to the authors, the plasticity of central auditory pathway after each bilateral implantation is very high. They also opined that LLR is a good biomarker to examine the plasticity of the auditory pathway.

Kurnazet al. (2008) studied the performance of cochlear implant individuals using middle and late latency response. They investigated whether middle and late latency responses give any clues for performance. The study was done in ten pre-lingual and six post-lingual cochlear implant individuals with average age of 6 to 48 years mean (19.7-+/-15.7). In the control group, 10 individuals with no hearing and vestibular complaint were considered. Auditory perception and linguistic development tests were done pre- and post- operatively, and MLR and LLR were done post-operatively. In auditory evoked responses, the latency and amplitude were compared with the control group and with pre- and post-lingual cochlear implant individuals. The MLR and LLR were recorded postoperatively (mean postoperative period of 22.1 & 18.23 months, min. 1.5 months, max. 70 months).The MLR and LLR latencies of those implanted within last 12 months and those implanted earlier were very close to each other, MLR and LLR amplitudes were significantly higher for those implanted earlier than 13 months. The better postoperative performance was associated with shorter latency and higher amplitude of MLR and LLR. The MLR and LLR latencies were very close to each other in patients implanted within last 12 months and those implanted earlier. The MLR and LLR amplitudes were higher in patients implanted earlier than 13 months. Based on these results, it would be reasonable to conclude that postoperative MLR and LLR might give some clues about postoperative performance of CI users. Hence, MLR and LLR could be taken into consideration in determining the improvement in performance of children with cochlear implant. In the present study, the LLR is taken to measure the performance of bimodal hearing benefit.

Cullington and Zeng, in 2011, compared bimodal and bilateral cochlear implant users. Speech recognition with competing talker, music perception, and prosody discrimination and talker identification were determined. The performance of the individuals with cochlear implant was excellent in quiet environment but they had problem in perception in noisy situation. According to the study, the bimodal user performed better than bilateral user though there was no significant statistical difference. The authors opined that in bimodal hearing, the user benefits by getting information of low-frequency as well as high-frequency. In the current study, the performance of bimodal user through hearing aid and cochlear implant is going to be evaluated using the LLR. In initial studies, the LLR have been used to determine the plasticity of auditory system. In the present study, comparison between the performance of hearing aid and cochlear implant was determined by the late response.

Though LLR has found to be more useful in assessing functioning of auditory pathway, however these responses are affected by few factors. Some of the factors that affect LLR are explained in the following heading:

3.1. Stimulus used to elicit LLR

Auditory evoked LLR could be elicited by a range of transient stimulus i.e. click, tone burst, noise burst, and speech sounds (Naatanen & Picton, 1987). Most commonly used stimuli for the clinical assessment are long duration stimulus. The long duration stimuli are processed better by hearing aids. The tonal stimuli give very limited information about the perception of speech, which is the ultimate aim of the most appropriate hearing aid. Hence, tonal stimuli are not preferred to evaluate benefit of a hearing aid. Speech stimuli have better validity for evaluating hearing aid benefit.

Cortical responses have been used extensively in studying the neural representation of speech cues. Among the various studies, very few studies have used real word speech tokens. Naturally produced speech stimuli represent highly complex time varying signals that are poorly approximated by non speech stimulus such as click, tones, and noise bands. Even in case of synthetic speech, although it allows the researchers to manipulate certain aspects of stimulus, but still there are only low dimensional approximations of natural speech. For this reason, natural speech tokens were used rather than non speech stimulus (Tremblay, Friesen, Martin & Wright, 2003).

Among some of the earlier studies, used speech stimuli, Boothroyd, Martin and Ostroff (1998) obtained P1-N1-P2 responses in eight adults with normal hearing using normally produced stimuli. Three stimuli were used, syllable /sei/, sibilant /s/ extracted from the syllable and the vowel /ei/ extracted from the syllable. Results revealed that isolated sibilant and vowel preserved the same time relationships to the sampling window as they did in the complete syllables. Response to /s/ and /ei/ both follow the classic N1-P2 pattern for the stimulus onset. The response to /ei/ also contains a clear P1 component. The investigator also noted that, N1 in response to /ei/ is offset from N1 in response to /s/ by approximately 130 ms which roughly corresponds to the onset delay to the stimulus /ei/ relative to that of /s/. P2 in the response to /ei/ is similarly offset from P2 in response to /s/ by approximately 120 ms. The investigators finally made the following conclusions (i) the complete response to the entire CV syllable /sei/ is combination of the response to the two constitute phonemes /s/ and /ei/ but it is not the sum of the responses of the two (ii) The morphology and latency of the response suggests that it is an N1-P2 potential to the acoustic change accuring at the CV transient.

Agung, Purdy, Mcmahon and Newall (2006) determined whether CAEPs, produced by the ling sounds, which together cover a broad range of frequency across the speech spectrum, could be differentiated from each other based on response latency and amplitude measure. LLRs were recorded from ten normal adults in the age range of 20 to 29 years. Naturally produced speech stimuli consisting of four vowels and three consonants were used. Two stimulus duration were used of 500 ms and 100 ms presented at 65dB SPL via loud speaker. Results revealed that all subjects showed cortical responses to all stimuli and no significant effect on duration on P1 was observed. P1 latencies were significantly earlier for shorter compared to longer duration stimuli. Shorter stimulus duration resulted in larger N1-P2 amplitudes and N1-P2 response latencies. N1-P2 response amplitudes elicited by high frequency stimuli produced significantly smaller amplitudes compared to stimuli that had dominate spectral energies in low frequencies. N1 latency decreases systematically when elicited by low frequency stimuli. Similarly P1 and P2 elicited by longer duration low frequency vowels decreases in latency in this order. Hence, it was concluded that LLR latencies ad amplitude may provide an objective indication that spectrally different speech sounds are encoded differently at the cortical level. This information can be extrapolated in determining the benefit provided by the hearing aid when evaluated using speech stimuli.

2.2. Developmental changes

Investigators had reported that there was decrease in latency and increase in amplitude as a function of age from childhood to about ten years of age (Ponton, Don, Eggermont, Waring, & Masuda, 1995, 1996).The developmental time course of CAEPs in infants have been investigated extensively (Sharma, Kraus, McGee, & Nicol, 1997). Since the cortical potentials were generated by multiple brain regions including primary auditory cortex, auditory association areas, frontal cortex and sub cortical regions

(Stapells, 2002) that matured at different rates, there are complex changes in morphology, scalp distributions, amplitude and latency of P1-N1 and P2-N2 waves with maturation (Cunningham, Nicol, Zecker, & Kraus, 2000; Ponton, Eggermont, Kwong, & Don, 2000). Investigators had reported that there was decrease in latency and increase in amplitude as a function of age from childhood to about 10 years of age (Ponton, Don, Eggermond, Waring, & Masuda, 1996; 1965). In contrast, some investigators described latency increase and amplitude decrease with advancing age (Callaway & Halliday, 1973).

P1 is a dominant waveform in school age children that can be reliably recorded using various stimulus. Ponton et al. (1996) reported exponential decrease in P1 latency to brief click trains, as the age increased from 6 to 19 years. This finding was confirmed in the subsequent study using 143 normal children from 5 to 20 years (Ponton et al., 2000). Decrease in P1 latency (Kraus, McGee, Carrell, Sharma, Micco, & Nicol, 1993; Sharma et al., 1991) and amplitude during school age years (Sharma et al., 1997) have also been shown in response to speech stimulus /ba/.

Various investigators have reported that unreliable N1 response in young children between ages 5 to 7 years (Goodin, Squires, Henderson, & Starr, 1978) that becomes progressively consisted as the age increases to 9 years (Ponton et al., 2000) or adolescences (Sharma et al., 1997). Stability of N1 response has been supported by Goodin et al. (1978). In contrast, Martin et al. (1988) described a small non significant decrease in N1 latency from 6 to 23 years in response to binaural tone pips. Still others found significant decreases in N1 latency with stable amplitude to both non speech (Ponton et al., 1997) and speech stimuli (Kraus et al., 1993) across school age years.

Developmental changes reported for the P2 responses elicited by simple stimuli have generally been minimal. In contrast, Ponton et al. (1997) reported that at birth and up to 7 years age wave P2 is absent and the response is dominated by a large late P1 response. Some researchers have reported that P2 latency increases with age (Goodin et al., 1978) whereas others have reported no maturational changes in p2 response (Barrett, Neshige, & Shibasaki, 1987)

These potentials can be used for objective validity of hearing aid fitting in young infants to ensure that the speech sounds are both detected and perceived. The assumption underlying this approach is that a hearing aid that causes CAEPs for different sounds to be present and differentiated is likely to be more useful to the child than a fitting where the responses are either absent or undifferentiated. In the present study, the objective is to evaluate the effect of bandwidth of frequency response of the hearing aid on the LLR.

Chapter 3

METHODS

The study aimed at examining the effect of hearing aid bandwidth on cortical potentials in a group of children using hearing aid in the ear contra lateral to the ear with cochlear implant. The specific objectives of the study were (a) to determine whether bimodal benefit is seen in children fitted with cochlear implant in combination with hearing aid in the opposite ear (b) to determine the way in which bandwidth of the hearing aid amplification affects late latency response (LLR). The method followed in the study is given in the following sections.

3.1 Participants

In the study, twelve children with bimodal devices were included i.e., cochlear implant in one ear and hearing aid in the contra lateral ear. Children in the age range from 3 to 8 years were selected by convenient sampling. Certain inclusion and exclusion criteria were used for the selection of participants.

3.1.1 Inclusion criteria

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

- Stable map of the cochlear implant and a minimum of three months usage of cochlear implant and hearing aid together, i.e., bimodal condition.

3.1.2 Exclusion criteria

- Children with any other associated problems like intellectual disability, autism, hyperactivity etc.
- No benefit from contralateral hearing aid
- Children not cooperating for electrophysiological testing or exhibiting inconsistent responses for aided testing.

Age of the 12 participants, duration of the cochlear implant use and duration of bimodal experience are tabulated in Table 3.1.

3.2 Equipment:

- A calibrated two-channel diagnostic audiometer with loudspeaker at 0° Azimuth to find out aided thresholds.
- A high power programmable digital behind the ear (BTE) hearing aid, programmed to give three frequency responses differing in bandwidths. The hearing aid having 12 channels with a fitting range from mild to severe degree of hearing loss and three programs.
- NOAH and hearing aid programming software installed in a personal computer, HiPro interface and programming cables to program the digital behind the ear hearing aid.

- A cortical auditory evoked potential analyzer with calibrated loud speakers to present the stimuli for recording LLR.

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

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

3.3 Test environment

Air-conditioned, single or double room sound treated test suite with electrical shielding.

3.4 Procedure

The routine audiological evaluations such as pure-tone audiometry, speech audiometry, and aided testing were carried out in order to ensure that the participants met the inclusion criteria. The mean pure-tone average (PTA) of the participants was >90dBHL. The average pure-tone thresholds of participants across frequency are tabulated in Table 3.2. The procedure followed for the purpose of the study is being given under the following sub-headings:

3.4.1. Programming of hearing aid

3.4.2. Measurement of aided thresholds

3.4.3. Optimization of hearing aid in the ear contra lateral to CI

3.4.4. Measurement of aided speech identification score (SIS)

3.4.1. Programming of hearing aid. A high power digital BTE hearing aid with three programs was used for testing all the participants. The hearing aid was connected to the computer, having hearing aid programming software, through the HiPro interface and the programming cables. The hearing aid was programmed using NOAH and hearing aid software. The hearing aid was programmed for NAL-RP prescriptive formula. The hearing aid was programmed according to the pure-tone thresholds of the ear contra lateral to the ear with cochlear implant. Three programs were stored in the hearing aid, each differing in terms of bandwidth of the frequency response, i.e.,

- Full bandwidth in program 1
- Low pass with a cut-off at 2 kHz in program 2

- Low pass with a cut-off at 1 kHz in program 3

The microphonewas set to omni-directional mode and the other features like comfort fit, frequency compressor, low frequency boost, wind barrier in the hearing aid were disabled. The volume control was also disabled. The program push button was enabled to change the programs during the testing.

The electro acoustic measurement of the hearing aid was done as per IEC6118-7 2005 standards using the hearing aid analyzer. This was done in order to confirm that the parameters set in the hearing aid and to ensure that the equivalent input noise level and total harmonic distortion were well within acceptable limits.

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

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

Table 3.2: *Mean pure-tone thresholds and aided thresholds of the participants across frequencies in dB HL.*

Frequency	**Pure-tone Thresholds**		**Aided thresholds with hearing aid in wide band response**	**Aided thresholds with cochlear implant**
	Right	Left		
250 Hz	89.58	92.92	-	21.25
500 Hz	99.17	98.33	42.08	22.92
1000Hz	106.25	105.83	45.42	23.75
2000Hz	>90	>90	52.08	23.75
4000Hz	>90	>90	74.17	24.17
6000 Hz	>90	>90	-	23.75
8000 Hz	>90	>90	-	26.25

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

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

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

3.4.4 Recording LLR. The LLRs were recorded after preparing the participant. The child was seated comfortably and the electrode sites were cleaned with Nuprep. After placing the electrodes, the acceptable impedance (of <5 kΩ) was ensured. The output and its distance from the participant from the loudspeaker were calibrated for the required levels. The electrodes were placed according to specified montage type. The child was seated comfortably on a chair and a video of a cartoon movie was played from the battery operated laptop in mute mode. The child was instructed to be relax and quiet before the testing. The stimulus was presented through loud speaker of the cortical evoked potential analyzer kept at one meter distance and at 0^o azimuth from the child. The following protocol was followed in eliciting auditory evoked potential.

Protocol for LLR

Stimulus parameters	Acquisition parameters
Type of stimulus: Synthetic speech stimulus:/m/, /t/, /g/	Filter setting: 0.1 to 100 Hz
Stimulus duration: 30ms	Time window: 100 ms pre-stimulus and 600 ms post-stimulus time
Epoch: 200ms	Electrode montage: Active electrode in Cz, reference electrode on nape of the neck, and ground electrode on the lower forehead.
Stimuli: /m/, /t/, /g/	
Intensity: 75 dB SPL	
Polarity: Alternating	
Sweeps: 200 sweeps	
Transducer: Loud speaker	
Impedance: ≤5kΩ	

The stimuli used to elicit the response were /m/ which is a low-frequency nasal sound, /g/ which is mid-frequency retroflex sound, and /t/ which is a high-frequency glottal sound. Hence in the test low-, mid-, and high- frequencies were included.

The LLR will be recorded in four conditions:

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

The P1 latency of the LLRs was computed for each aided condition for each participant. The waveforms were examined visually and *p* value was noted. The peaks P1, N1, P2 and morphology of the waveform were inspected. A *p* value of less than 0.05 was considered as LLR being present and *p* greater than 0.05 was considered as LLR absent. The morphology, latency of P1, P2, N1, and N2 were marked based on the analyses made by three experienced audiologists. The morphology of the LLR waveform was rated using five-point rating scale by three experts who marked the latency of the waveform. A five-point rating scale is given in Figure 3.1.

Figure 3.1: Five-point rating scale to rate the morphology of LLR wave forms

Aided Conditions	**No response (0)**	**Poor (1)**	**Fair (2)**	**Good (3)**	**Very good (4)**
1. CI alone					
2. CI+WB HA					
3. CI + 2k HA					
4. CI+1k HA					

3.5 Comparison of response between the conditions

The LLR recorded for three stimulus i.e., /m/, /t/, /g/ in four different aided conditions. The aided conditions included cochlear implant alone, cochlear implant with hearing aid in wide band condition (CI + WB HA), cochlear implant with hearing aid with the low pass set to 2 kHz (i.e., CI + 2k HA), and cochlear implant with hearing aid with the low pass set to 1 kHz (CI + 1k HA). The amplitude P1-N1 and N1-P2 and latencies of P1, N1, P2, and N2 were noted manually by the three expert professionals.

The data on amplitude and latencies of LLR were tabulated and compared across the four aided conditions using statistical package for social sciences (SPSS) software. Shapiro Wilk test was carried out to test the normality of data. Wilcoxon Signed Rank test was carried out to compare the effect of bandwidth in hearing aid on the LLR. Pair-wise comparison was done to compare across four conditions for three stimuli, when indicated. This was done to find out the bandwidth that gave the best perception.

Chapter 4

RESULTS

The aim of the present study was to examine the effect of frequency bandwidth of the hearing aid on the Late Latency Response (LLR) in a group of children using a hearing aid in the ear contralateral to the ear with cochlear implant (bimodal). The specific objectives included,

- To determine if bimodal mode is better than CI alone mode, using LLR.
- To compare the effect of hearing aid bandwidth in bimodal stimulation on LLR in four aided conditions.
    - CI alone
    - CI + hearing aid in wide band condition (CI+WB HA)
    - CI + HA with low pass set t o 2 kHz (CI+2k HA)
    - CI + HA with low pass set to 1 kHz (CI+1k HA)

The results of the present study are provided under the following headings:

4.1. Effect of bimodal stimulation on LLR

4.1.1 Effect of bimodal stimulation on morphology of LLR waveform

4.1.2 Effect of bimodal stimulation on amplitude of LLR peaks

4.1.3 Effect of bimodal stimulation on latency of LLR peaks

4.2. Effect of bandwidth of hearing aid on LLR in bimodal stimulations

4.2.1 Effect of bandwidth of hearing aid on morphology of LLR in bimodal stimulation

4.2.2 Effect of bandwidth of hearing aid on amplitude of LLR in bimodal stimulation

4.2.3 Effect of bandwidth of hearing aid on latency of LLR in bimodal stimulation

4.1. Effect of bimodal stimulation on LLR

The effect of bimodal stimulation on LLR was studied in 12 children. The data on morphology, amplitude, and latency of LLR in the four aided conditions were tested for normality of distribution using Shapiro Wilk test. It revealed that the data were not normally distributed ($p<0.05$). Hence, non-parametric statistics was applied after performing the descriptive statistics.

4.1.1. Effect of bimodal stimulation on morphology of LLR waveform. The morphology of the LLR waveforms was rated by three expert audiologists on a five-point rating scale. The judgments of the experts were tested for internal consistency. Reliability test was administered across the experts for each aided condition. The test revealed that there was high internal consistency (Cronbach's alpha > 0.70) and hence it could be inferred that the judgments across three experts on morphology of LLR waveforms were reliable.

The mean value of rating on morphology of LLR obtained from three experts for three stimuli /m/, /t/, and /g/ were computed and tabulated in Table 4.1. While comparing the mean value of the rating of morphology across CI alone condition and CI + WB HA bimodal condition, it was noted that there was no difference across the two aided conditions. Friedman test was conducted to find out statistical differences in ratings of morphology of LLR in the two aided conditions. The test revealed that there was no significant difference in morphology between the two aided conditions (p>0.05).

Table 4.1.*Mean value of rating on morphology of LLR in CI alone and CI + WB HA condition, as done by three experts.*

Stimuli	**Rating on morphology of LLR waveform**	
	CI alone	**CI + WB HA**
/m/	2.79	2.67
/t/	2.63	1.96
/g/	2.5	2.42

From Table 4.1, it can be noted that the mean value of the morphology rated by the experts were between 2 and 3, revealing that the overall morphology of the LLR for the three stimuli was fair.

4.1.2 Effect of bimodal stimulation on amplitude of LLR peaks. The amplitude (in µV) of P1-N1 and N1-P2 of LLR for each stimulus, in each aided condition was noted for analysis. The mean, median, and standard deviation of the amplitude of LLR for three stimuli were computed and tabulated in Table 4.2. To determine the effect of bimodal stimulation on the amplitude, LLR elicited in CI alone condition and CI + WB HA condition was compared.

Table 4.2: *Mean, median, and standard deviation of amplitude (in µV) of P1-N1 and N1-P2 for the stimuli /m/, /t/, and/g/, in four aided conditions*

Stimuli	**CI alone**			**CI + WB HA**		
	Amplitude of P1-N1					
	Mean	Median	SD	Mean	Median	SD
/m/	9.74	9.36	2.49	7.53	7.50	2.34
/t/	7.29	6.04	3.29	7.85	8.04	2.38
/g/	12.53	13.28	3.59	9.50	10.30	3.99
	Amplitude of N1-P2					
/m/	7.99	9.53	2.40	9.20	9.41	2.66
/t/	6.59	6.96	1.15	7.46	5.75	4.48
/g/	10.40	9.44	3.32	9.22	10.58	2.83

On comparison of mean and median of amplitude of P1-N1 and N1-P2, there was no difference found between CI alone condition and CI + WB HA condition. There was no specific pattern across the three stimuli.

Friedman test was done for each amplitude, for each stimulus, for all the four aided conditions, i.e., CI alone, CI +WB HA, CI +2k HA, CI + 1k HA conditions. Findings of Friedman test revealed that, there were no significant differences in P1-N1amplitude for /m/ [χ^2 (3) = 6, $p > 0.05$] and /g/ [χ^2 (3) = 1.18, $p > 0.05$] stimuli across four aided conditions. However, significant difference was seen only for the stimulus /t/ for the amplitude P1-N1 [χ^2 (3) = 9.33, $p < 0.05$]. For N1-P2 amplitude, findings of Friedman test revealed that, there was no significant difference for /m/ [χ^2 (3) = 5.8, p

>0.05], /t/ [χ^2 (3) = 3.51, p> 0.05] stimuli. Significant difference was seen only for /g/ [χ^2 (3) = 12.43, p <0.05] stimulus.

Hence, to determine the pair of conditions that had significant difference, Wilcoxon Signed Rank Test was carried out. Conditions such as CI alone with CI +WB HA, CI alone with CI + 2k HA, CI alone with CI + 1k HA, CI + WB HA with CI + 2k HA, CI + WB HA with CI + 1k HA, CI + 1k HA with CI + 2k HA were paired and compared. To determine the effect of bimodal stimulation on LLR the only CI alone condition and CI with hearing aid set at wideband (CI + WB HA) was compared.

Findings of Wilcoxon Signed Rank test revealed that, there was no significant difference in amplitude between CI alone and CI + WB HA condition for P1-N1(z=-0.9, p>0.05) as well as for N1-P2 (z =-0.25. p > 0.05). To conclude, addition of hearing aid in the contralateral ear to the cochlear implant did not show any significant change in amplitude of LLR.

4.1.3 Effect of bimodal stimulation on latency of LLR peaks. To evaluate the effect of bimodal stimulation on LLR, the latency of LLR peaks elicited with cochlear implant alone condition was compared with that of the bimodal condition. The mean, median, and standard deviation (SD) of the latency of the LLR peaks (P1, N1, P2, and N2) were tabulated across the two aided conditions in Table 4.3.

Table 4.3: *Mean, median, and standard deviation (SD) of latency (in msec.) of LLR peaks in CI alone and bimodal condition (CI + WB HA), for the stimuli /m/, /t/, and /g/.*

	LLR Latency *(in msec.)*					
LLR peaks	CI alone			CI + WB *HA*		
	Mean	Median	SD	Mean	Median	*SD*
/m/						
P1	146.45	150	32.54	134.36	144	33.22
N1	216.18	230	45.02	205.09	209	38.41
P2	285.88	300	59.24	296.29	310	68.77
N2	406	406	-	-	-	-
/t/						
P1	139.6	150	34.84	138.1	150	35.27
N1	215	225.5	45.96	211.5	220	42.89
P2	282.86	300	64.17	301.63	317	64.92
N2	406	406	-	-	-	-
/g/						
P1	141.55	150	34.55	138.55	150	31.32
N1	213.45	230	43.29	214.73	220	43.76
P2	286.75	310	60.95	301.89	310	61.43
N2	400	400	-	-	-	-

On comparison of mean and median of latency of LLR peaks elicited by the three stimuli with CI alone and CI with hearing aid set at wideband, the latency had high variations across two conditions. The mean and median did not follow any particular pattern. But there was a very slight reduction in the latency in bimodal condition.

To see if the data were normally distributed, Shapiro Wilk Test was deployed. It revealed that the data were not normally distributed ($p < 0.05$). Hence, non-parametric statistic was performed. Wilcoxon Signed rank test was done to see whether pair-wise significant difference in latency of LLR existed between the aided conditions. The statistical difference across the conditions as well as stimulus is tabulated in the Table 4.4.

Table 4.4: *Test statistic (z) and significance (p) value of latency of LLR on Wilcoxon signed rank test in CI alone and CI +WB HA for stimuli /m/, /t/, and /g/*

LLR peak latency (in msec.)	**CI alone &CI + WB HA**	
	Z	*P*
	/m/	
P_1	-0.92	0.35
N1	-1.47	0.14
P2	-1.89	0.05
	/t/	
P1	-0.17	0.85
N1	-0.66	0.50
P2	-1.36	0.17
	/g/	
P1	-0.21	0.83
N1	-0.21	0.83
P2	-0.91	0.36

While comparing the two aided conditions, there was no significant difference in the latency of peaks. Wilcoxon Signed Rank test revealed that, there was no significant difference between the latency of LLR in cochlear implant alone and cochlear implant with hearing aid set at wide band response ($p > 0.05$).

To conclude, addition of hearing aid in the contralateral ear to the cochlear implant brought about very minute change in the latency, with bimodal condition being better, though not significant.

4.2. Effect of bandwidth of hearing aid on LLR in bimodal stimulation

The effect of hearing aid bandwidth on morphology, amplitude, and latency of LLR were analyzed and given separately.

4.2.1 Effect of bandwidth of hearing aid on morphology of LLR in bimodal stimulation. The morphology of the LLR waveform elicited in four aided conditions was rated with a five-point rating scale by three expert audiologists. The mean of rating on morphology of LLR obtained from three experts across the three stimuli /m/, /t/, and /g/ was computed and tabulated in Table 4.5.While comparing the mean value of the rating of morphology across four aided conditions, it was noted that there was no difference among the values. Friedman test was conducted to find out statistical differences in morphology between the aided conditions. There was no significant difference between the three aided conditions in morphology ($p>0.05$). From the rating of morphology it could be inferred that the morphology was rated as fair and that there was no difference in morphology across different aided conditions.

Table 4.5: *Mean value of rating on morphology of LLR in four aided conditions, as done by three experts.*

	Morphology of LLR – Ratings			
Stimuli	CI alone	CI + WB HA	CI + 2k HA	CI +1k HA
/m/	2.79	2.67	2.46	2.08
/t/	2.63	1.96	2.79	2.63
/g/	2.5	2.42	2.71	2.38

From Table 4.5, the rating of morphology of LLR ranged from 2to 3 points, revealing that the morphology was fair among all the four aided conditions. According to Friedman test, there was no significant change in morphology across aided conditions.

4.2.2 Effect of bandwidth of hearing aid on amplitude of LLR in bimodal stimulation. The amplitude of P1-N1 and N1-P2 elicited by three stimuli /m/, /t/, and /g/ in four aided conditions were noted. The data were computed and tabulated. The mean, median, and standard deviation of the amplitude of LLR were tabulated in Table 4.6. The data were compared across four aided conditions to determine the effect of bandwidth on amplitude of LLR and also to find out the bandwidth that gave better amplitude.

Table 4.6: *Mean, median, and standard deviation of amplitude (in µV) of P1-N1 & N1-P2 of LLR elicited by the stimuli /m/, /t/, and/g/, in four aided conditions*

	CI alone			**CI + WB HA**			**CI +2k HA**			**CI +1k HA**		
Stimuli	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
	Amplitude of P1-N1											
/m/	9.74	9.36	2.49	7.53	7.50	2.34	9.64	9.63	3.19	9.47	9.95	3.02
/t/	7.29	6.04	3.29	7.85	8.04	2.38	8.72	8.39	2.53	10.40	10.21	5.51
/g/	12.53	13.28	3.59	9.50	10.30	3.99	12.35	12.59	4.73	10.85	11.92	2.53
	Amplitude of N1-P2											
/m/	7.99	9.53	2.40	9.20	9.41	2.66	12.78	12.78	4.05	11.88	9.88	3.45
/t/	6.59	6.96	1.15	7.46	5.75	4.48	9.87	10.49	4.08	9.35	7.75	5.06
/g/	10.40	9.44	3.32	9.22	10.58	2.83	13.26	14.59	5.87	8.62	9.18	4.36

According to Friedman test, there was no significant difference in amplitude of P1-N1between the four aided conditions, for the stimuli /m/ [χ^2 (3) = 6, p> 0.05] and /g/ [χ^2 (3) = 1.18, p> 0.05]. However, there was a significant difference only for the stimulus /t/ [χ^2 (3) = 9.33, $p < 0.05$] for P1-N1 amplitude. In case of N1-P2 amplitude, there was no significant difference for the /m/ [χ^2 (3) = 5.8, p >0.05] and /t/ [χ^2 (3) = 3.57, p >0.05], however there was a significant difference for /g/[χ^2 (3) = 12.43, $p < 0.05$] stimulus. Further, Wilcoxon Signed Rank test was carried out to determine which pair of conditions had significant differences in P1-N1 amplitude for the stimulus /t/ and also for N1-P2 amplitude for the stimulus /g/ and the findings are provided in Table 4.7.

Table 4.7.*Test statistic (z) and significance (p) values obtained from Wilcoxon Singed Rank Test for amplitude of LLR across four aided conditions, for the stimulus /t/ and /g/*

	CI alone &CI + WB HA	**CI alone & CI + 2k HA**	**CI alone & CI + 1k HA**	**CI +WB HA&CI + 2k HA**	**CI + WB HA & CI + 1k HA**	**CI + 2k HA & CI + 1k HA**
			Amplitude P1-N1 elicited by /t/			
z	-0.89	-2.49	-2.49	-1.51	-0.97	-1.34
p	0.37	0.01*	0.01*	0.13	0.33	0.18
			Amplitude N1-P2 elicited by /g/			
z	-1.24	-2.03	-1.18	-2.37	-0.17	-2.37
p	0.21	0.04*	0.24	0.02*	0.86	0.02*

On comparison of the four aided conditions, for LLR elicited by /t/ stimulus, Wilcoxon Signed Rank test revealed that, differences were seen between CI alone and CI + 2k HA, with CI + 2k HA condition having better amplitude. Significant difference was also seen between CI alone and CI + 1k HA condition, among that CI + 1k HA had better amplitude.

On analysis of N1-P2 amplitude, differences were seen only for the stimulus /g/ and differences were seen between conditions such as CI alone and CI +2k HA, CI + WB HA and CI + 2k HA, and, CI + 1k HA and CI + 2 k HA. On comparison of all the paired conditions, CI + 2k HA condition had better amplitude which was also found to be statistically significant using Wilcoxon Signed Rank test. However, there were no significant differences found among CI alone, CI + 1k HA, and CI + WB HA conditions.

4.2.3 Effect of bandwidth of hearing aid on latency of LLR in bimodal stimulation. To determine the effect of hearing aid bandwidth on the latency of LLR, each bandwidth of the hearing aid was compared with cochlear implant alone condition as well as each of the other bandwidth conditions. The mean, median, and standard deviation of latency of LLR peaks across the conditions is given in Table 4.8. While comparing CI alone condition and CI + wide band HA, the overall mean latency was shorter in CI + wide band HA condition and hence was better. On comparing CI alone condition and CI + 2k HA, CI alone condition had shorter latency. On the other hand, on comparison of the CI alone condition and CI + 1k HA condition, there was no much difference. While comparing CI + WB HA condition and CI + 1k HA, the mean latency of CI + 1k HA condition was shorter. While comparing CI + WB HA condition and CI + 2k HA, the mean latency of CI + WB HA condition was shorter. Similarly, while comparing CI + 2k HA condition and CI + 1k HA condition, the mean latency of CI + 1k HA condition was shorter. Overall, the latency in CI + 1k HA condition that is cochlear implant with hearing aid set at 1 kHz cut-off was shorter in comparison to all other conditions. The trend of increase in latency across conditions was found to be CI+1k HA < CI+WB HA< CI+ 2k HA<CI alone; with CI alone having the longest latency and CI+1k HA showing the shortest latency.

Table 4.8: *Mean, median, and standard deviation of latency (in msec.) of LLR peaks in different conditions. CI alone, CI +WB HA, CI +2k HA and CI + 1k HA, for the stimuli /m/, /t/, and /g/.*

	Latency (in msec.) of LLR											
LLR peaks	CI alone			CI + WB HA			CI + 2k HA			CI + 1k HA		
	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
/m/												
P1	146.45	150	32.54	134.36	144	33.22	137.33	146	38.37	131.29	144	48.69
N1	216.18	230	45.02	205.09	209	38.41	184	200	52.99	195.88	207.5	62.22
P2	285.88	300	59.24	296.29	310	68.77	253	300	81.41	252.33	278	83.51
N2	406	406	-	-	-	-	200	200	-	-	-	-
/t/												
P1	139.6	150	34.84	138.1	150	35.27	139.3	149	37.9	123.4	133.5	37.95
N1	215	225.5	45.96	211.5	220	42.89	204.75	204	47.95	207.5	213.5	51.29
P2	282.86	300	64.17	301.63	317	64.92	279.83	304	66.27	284.17	311	62.26
N2	406	406	-	-	-		200	200	-	-	-	-
/g/												
P1	141.55	150	34.55	138.55	150	31.32	137.6	146.5	37.14	119.9	133	34.19
N1	213.45	230	43.29	214.73	220	43.76	201.75	209	43.79	207.2	213.5	48.51
P2	286.75	310	60.95	301.89	310	61.43	279.83	304	66.27	288.5	311	63.06
N2	400	400	-	-	-		200	200	-	-	-	-

Statistical difference values of the latency across the four aided conditions have been provided in the Table 4.8. According to the Wilcoxon signed rank test, there was no significant difference between the aided conditions. While comparing CI alone and CI +

1k HA condition CI + 1k HA was better than CI alone condition. While comparing CI + 1k HA with CI + 2k HA, there was a significantly shorter mean latency for the peak P1 for /t/ stimulus for the CI + 1k HA condition. For /g/ stimulus there were significant differences across CI alone with CI + 1k HA condition, CI +WB HA with CI + 1kHA, and CI +1k HA with CI + 2k HA. Among CI alone and CI + 1k HA, CI + 1k HA condition was better. Between CI +WB HA and CI + 1kHA, CI + 1k HA were slightly better. Between CI +1k HA and CI + 2k HA, CI +1k HA was better. Overall, the latency of CI + 1k HA condition had shorter latency followed by CI+ WBHA, CI + 2k HA and CI alone.

Table 4.8: *Test statistic (z) and significance (p) values of Wilcoxon signed rank test for latency of LLR peaks, between four aided conditions, for three stimuli.*

LLR peak	CI alone & CI+WBHA		CI alone & CI +2k HA		CI alone & CI + 1k HA		CI + WB HA & CI +2kHA		CI +WB HA & CI + 1kHA		CI +1K HA & CI+ 2k HA	
	Z	*P*	z	*p*	z	*P*	Z	*p*	z	*p*	z	*P*
						/m/						
P_1	-0.92	0.36	-0.84	0.40	-1.18	0.24	-1.30	0.19	-0.31	0.75	-2.20	0.03
N1	-1.47	0.14	-1.82	0.07	-1.18	0.24	-1.46	0.14	-0.42	0.67	-0.73	0.46
P2	-1.90	0.06	-0.54	0.59	-1.60	0.11	-0.54	0.6	-1.07	0.29	-1	0.32
						/t/						
P1	-0.18	0.86	-0.15	0.88	-2.09	0.04*	-0.92	0.36	-1.78	0.08	-2.67	0.01*
N1	-0.66	0.51	-1.21	0.23	-0.56	0.58	-0.94	0.35	-1.01	0.31	-0.28	0.78
P2	-1.36	0.17	-0.32	0.75	-0.31	0.75	-0.74	0.46	-0.53	0.6	-0.82	0.41
						/g/						
P1	-0.21	0.83	-0.18	0.86	-2.67	0.01*	0	1	-2.67	0.01*	-2.67	0.01*
N1	-0.21	0.83	-1.49	0.14	-0.28	0.78	-1.52	0.13	-1.54	0.12	-0.17	0.87
P2	-0.91	0.36	-0.94	0.35	-0.11	0.92	-0.74	0.46	-1.05	0.29	-0.13	0.9

Note: *:$p<0.05$

The amplitude and latency of LLR peaks had high variation across the four aided conditions. In terms of amplitude, CI with hearing aid set at 2k cut-off had better amplitude; however latency was shorter in CI with hearing aid set at 1k Hz cut-off.

To determine the effect of bandwidth of the hearing aid in bimodal condition, the morphology, amplitude and latency were compared. The results revealed that there were no significant changes on morphology ratings made by three experts. According to amplitude, /g/ stimulus which was predominantly high- frequency stimulus had given significantly larger amplitude in CI +2k HA condition. In terms of latency, /m/ stimulus which was predominantly low-frequency stimulus had given significantly shorter latency and was better in CI + 1k HA condition.

The summary of the findings of the present study is tabulated in Table. 4.9

Table 4.9: *Brief summary of the findings of effect of hearing aid bandwidth on morphology, amplitude and latency in bimodal device users.*

Evaluation	Comparisons	Parameters	Results
Effect of bimodal stimulation on LLR	Comparison of CI alone with CI + WB HA condition	- Morphology	- No significant changes
		- Amplitude	- No significant differences were seen for P1-N1 amplitude as well as for N1-P2 amplitude.
		- Latency	- No significant changes in latency but bimodal condition had slight shorter latency compared to CI alone condition on comparison of mean and median
Effect of bandwidth of hearing aid on LLR in bimodal stimulation	Comparison of • CI alone with CI +WB HA • CI alone with CI + 2k HA • CI alone with CI + 1k HA • CI + WB HA with CI + 2k HA • CI + WB HA with CI + 1k HA, • CI + 1k HA with CI + 2k	- Morphology	- No significant changes across four aided conditions
		- Amplitude	**P1-N1:** • Differences were seen only for the stimulus /t/. • On pair-wise comparison, significant differences seen in the following pairs: 1. CI alone with CI + 2k HA 2. CI alone with CI + 1k HA. • Between CI alone with CI + 2k HA,CI + 2k HA was better • Between CI alone with CI + 1k HA**,**CI + 1k HA was better

Effect of bandwidth of hearing aid on LLR in bimodal stimulation	HA		**N1-P2 amplitude:** • Significant difference was seen only for the stimulus /g/. • On pair-wise comparison, significant differences were seen in 1. CI alone with CI + 2k HA 2. CI + WB HA with CI + 2k HA **3.** CI + 1k HA with CI + 2k HA • Among all the pairs, **CI + 2k HA had larger amplitude, followed by CI + 1k HA, CI + WB HA and CI alone.**
		Latency	• Significant difference was seen only for the latency of P1. • For the stimulus /t/, differences were seen in the following pairs: 1. CI alone and CI + 1k HA 2. CI + 1k HA and CI + 2k • For the stimulus /g/ following pairs had differences: 1. CI alone and CI + 1k HA 2. CI + WB HA and CI + 1k HA 3. CI + 1k HA and CI + 2k HA Among all the pairs, **CI + 1k HA** had shorter latency, followed by CI + WB HA, CI+ 2k HA and CI alone

Chapter 5

DISCUSSION

The objective of the study was to determine the effect of hearing aid bandwidth on cortical auditory evoked potentials in children using bimodal devices. The effect was studied by analyzing the morphology, amplitude, and latency of LLR. The data were analyzed and tabulated. The discussion of results of the present study is provided in the following headings:

5.1 . Effect of bimodal stimulation on LLR

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

To verify the objectives of the present study, the LLR were obtained in four aided conditions from 12 participants. The data were analyzed and tabulated across four aided conditions as well as three stimuli /m/, /t/, and /g/. The morphology, amplitude and latency of LLR were analyzed by three experts. The morphology of LLR was rated with a five-point rating scale by three experts in the field and compared across four aided conditions.

5.1 Effect of bimodal stimulation on LLR

The study aimed to evaluate the benefit of bimodal stimulation over CI alone using LLR. To analyze the effect on bimodal hearing, the data were compared across cochlear implant alone condition and the cochlear implant with hearing aid in wideband condition. There was no significant different across the conditions. However, slight differences were found in mean and medial latency of LLR between CI alone and CI + WB HA condition. Among these conditions CI + WB HA condition had shorter latency.

Tyler et al. (2002) in his study reported that bimodal hearing in children has binaural advantages. Binaural advantages such as speech in the presence of background noise and localization ability improved when the hearing aid was added to the ear contra lateral to the ear with cochlear implant. Some children had no improvement because they had least scores in the hearing aid alone condition. In such patients, integrity of the anatomical structures responsible for good hearing might be compromised. In the present study, when cochlear implant alone condition was compared with the bimodal condition; there was a reduction in latency in bimodal condition. Ching et al. (2004) in her study analyzed the speech perception, localization, and functional performance in bimodal hearing individuals. The authors concluded that the children had higher scores in cochlear implant with hearing aid condition. Hence, we could infer that performance is better in bimodal condition.

Iwaka et al. (2004) compared monaural verses binaural performance in an individual with bimodal hearing. The P300 was recorded in the subject in two aided conditions, that is CI alone and CI + HA. The overall latency in CI alone condition was longer compared to CI +HA condition. This individual performed better with both devices compared to CI alone. The investigators thus concluded that bimodal hearing was better. Rapin and Grazianni (1967) utilized LLR for evaluation of hearing device benefit. In the present study, LLR was used as a tool to evaluate the performance across the aided conditions. From the mean amplitude and latency of LLR across CI alone condition and CI + WB HA condition, the latency was shorter and amplitude showed no change in CI + WB HA condition. But there was no significant difference in amplitude or latency between the two aided conditions. It can be construed that addition of hearing aid to cochlear implant improves the performance. The bimodal hearing has an effect on LLR with better response when the hearing aid was added to the opposite ear, revealing that bimodal performance was better.

5.2 Effect of bandwidth of hearing aid on LLR in bimodal stimulations

To determine the effect of bandwidth on LLR, the morphology, amplitude, and latency were compared across four aided conditions. Pair-wise comparison was done to find the bandwidth of the hearing aid that gave better amplitude, latency, and morphology. On examination of morphology across four aided conditions, it was seen that there was no effect of bandwidth of hearing aid on morphology. The mean and median of the amplitude of P1-N1 and N1-P2; and latency of P1, N1, P2, and N2 revealed high variation. The finding of Wilcoxon Signed Rank test revealed that the amplitude and latency had an effect on bandwidth. From the analysis amplitude was better in CI + 2k HA condition, and the latency was shorter in CI + 1k HA condition.

Zhang, Spahr, and Dorman (2010) tried to determine the minimum bandwidth required for individuals with CI to get binaural benefit. Their study included filtered speech to determine frequency response performance. The participants included in this study were individuals with steeply sloping hearing impairment who had residual hearing in the low frequencies. Both acoustical and electrical stimulus was filtered to get frequency response. . According to the authors, by reducing the frequency overlap between acoustic and electric stimulation would not result in improved speech recognition ability in individuals with low- frequency residual hearing in the non-implanted ear. And also performance on speech recognition task was better in wide band condition.

Neuman and Svirsky (2013) determined the effect of hearing aid bandwidth in individuals with bimodal hearing. Speech perception was obtained and analyzed at different band widths of the hearing aid. The participants in the study included individuals with severe to profound hearing impairment. They had unaided response of less than 95 dB HL till 2k Hz. The speech perception was tested by making use of AzBio sentence material in quiet and noise. Hearing aid had bandwidths including low pass of 0.5 kHz, 1 kHz, and 2 kHz. The performance was better in wideband condition. According to Neuman and Svirsky (2013) and Zhang, Spahr, and Dorman (2010), individuals with bimodal hearing performed better in wideband condition on examination of behavioral speech recognition task. In the present study, electrophysiological test was carried out to find out the effect of bandwidth of hearing aid in bimodal hearing in children. The morphology, amplitude, and latency of LLR were compared .The result obtained from the current study had high variation. The LLR were elicited from the participant who werein the age range of 3 to 7 years.

The developmental time course of CAEPs in infants have been investigated extensively (Sharma, Kraus, McGee, &Nicol, 1997). Since the cortical potentials were generated by multiple brain regions including primary auditory cortex, auditory association areas, frontal cortex, and sub-cortical regions (Stapells, 2002) that matured at different rates, there are complex changes in morphology, scalp distributions, amplitude, and latency of P1-N1 and P2-N2 waves with maturation (Cunningham, Nicol, Zecker& Kraus, 2000;Ponton, Eggermont, Kwong& Don, 2000). Investigators had reported that there was decrease in latency and increase amplitude as a of function of age from childhood to about 10 years of age (Ponton, Don, Eggermont, Waring& Masuda, 1996;

1965). In contrast, some investigators described latency increase and amplitude decrease with advancing age (Callaway &Halliday, 1973).

As there were high variations in the LLR amplitude and latency, particularly in the age group of 3 to7 years, conclusion could not be reached regarding the effect of the bandwidth of hearing aid in LLR in bimodal users. The presence of LLR could throw light on the functioning of auditory pathway, but could not give information regarding the bandwidth that provided better LLR.

To conclude, the LLR - being auditory evoked cortical potential - showss high variation in latency, amplitude, and morphology especially in the age group that was included in the present study. They do not give accurate response for the present study. The presence of LLR tells us about the functioning of the auditory pathway in the higher cortical region, but do not provide information about the effect of bandwidth of hearing aid among bimodal users. The information about which hearing aid bandwidth will give the best bimodal benefit could not thus be inferred by using LLR.

Chapter 6

SUMMARY AND CONCLUSIONS

The present study aimed at determining the effect of bandwidth of hearing aid in children using bimodal stimulation.. The effects were determined by the morphology, amplitude, and latency of LLR peaks P1, N1, P2, and N2. The objectives included in the present study were (i) determining effect bimodal stimulation on LLR (ii) determining the effect of bandwidth of hearing aid in bimodal stimulation on the morphology, amplitude, and latency of LLR peaks.

The study was conducted in 12 children with severe to profound hearing impairment. The participants were users of bimodal stimulation. Each participant was selected with the inclusive and exclusive criteria. Each participant had mean unaided thresholds greater than 90dB HL in all audiometric frequencies important for speech. The mean aided thresholds in the unimplanted ear were 40 to 55 dB HL till 2k Hz and were out of spectrum at 4k Hz.

The study included high power BTE hearing aid which was programmed with the prescriptive formula NAL-RP and according to the subject specific hearing thresholds. Further manipulation was done in hearing aid to give frequency restricted responses like low pass cut-off at 1kHz, 2kHz and wideband. LLR were recorded according to the standard protocol in sound treated environment, making the subject seat comfortably. The LLR were recorded in four aided conditions that is CI alone condition, CI + wideband hearing aid condition, CI + hearing aid at 2kHz low pass cut off, and CI + hearing aid at 1kHz low pass cut-off condition.

The recorded LLR waveforms were analyzed by three experts; and latencies and amplitude were noted and tabulated. Morphology was rated with a five-point rating scale and analyzed. The data were noted and tabulated. Before statistical analysis the data were tested for normality of distribution. According to Shapiro Wilk test the data from the present study were not normally distributed having the p value less than 0.05. The results obtained can be explained in the following headings:

6.1. Effect of bimodal stimulation on LLR

- The CI alone condition and CI + WB HA condition was compared to determine the effect on bimodal stimulation.
- The finding could be explained briefly in terms of morphology, amplitude, and latency.
- There were no significant changes in morphology from the finding obtained from Friedman test.
- Wilcoxon Signed Rank test result revealed that there was no significant difference in amplitude and latencies recorded for three stimuli /m/, /t/, and /g/, between CI alone condition and CI with hearing aid at wideband condition($p>0.05$).
- Hence, from the results it could be inferred the that addition of hearing aid to unilateral cochlear implant brings about slight reduce in latency and slight increase in amplitude, but it was not statistically defined.

6.2. Effect of bandwidth on bimodal hearing

The LLR waveform morphology, peak amplitude, and peak latencies were compared across four aided conditions and analyzed elicited by the stimuli /m/,/t/,and /g/. Findings could be explained in the following headings:

6.2.1. LLR morphology. There was no significant change found across the four aided conditions in terms of morphology of LLR waveforms.

6.2.1. LLR amplitude. In terms of amplitude, amplitude of P1N1 and N1P2 were noted. According to statistical analysis following results were obtained:

i. P1N1 amplitude:

There were significant differences seen only for the stimulus /t/.On pair-wise comparison, significant differences were seen in the following pairs:

1. CI alone with CI + 2k HA
2. CI alone with CI + 1k HA.

Between CI alone with CI + 2k HA,CI + 2k HA was better. Between CI alone with CI + 1k HA**,**CI + 1k HA was better.

ii. N1-P2 amplitude:

There were significant differences found in LLR elicited by the stimulus /g/.On pair-wise comparison, significant differences were seen in the following pairs:

1. CI alone with CI + 2k HA
2. CI + WB HA with CI + 2k HA
3. CI + 1k HA with CI + 2k HA

Among all the pairs, **CI + 2k HA** had larger amplitude, followed by CI + 1k HA, CI + WB HA and CI alone.

6.2.3. LLR latency. In terms of latency, there was significant difference only for the latency of P1 which was elicited by the stimulus /t/ and /g/.

i. Stimulus /t/ had significant differences for the following pair of conditions:
    1. CI alone and CI + 1k HA
    2. CI + 1k HA and CI + 2k

ii. Stimulus /g/ had significant differences in the following pair of conditions:
    1. CI alone and CI + 1k HA
    2. CI + WB HA and CI + 1k HA
    3. CI + 1k HA and CI + 2k HA

- Among all the pairs, **CI + 1k HA** had shorter latency, followed by CI + WB HA, CI+ 2k HA and CI alone.
- The finding of the present study had high variation across the four aided conditions.
- The high variation in amplitude as well as latency may be due to high variation seen in higher cortical potentials which matures at different rate especially in the age range of 3-7 years.(Callaway &Halliday, 1973, Ponton et.al.,1965, 1996).
- From the result it can be construed that the LLR may not be useful in knowing that bandwidth of hearing aids in bimodal condition. .

To conclude, though there were significant differences across afew aided conditions, elicited by three stimuli /m/, /t/, and /g/. Thechanges were different for latency and amplitude. The cortical responses are generated by multiple brain regions including primary auditory association areas, frontal cortex and sub cortical regions (Stapells, 2002) that mature at different rates. There are complex changes in morphology, scalp distribution, amplitude and latency of P1-N1-P2 waves (Cunningham, Nicol, Zecker& Kraus, 2000; Ponton, Eggermont, Kwong& Don, 2000). Since there are high variations in LLR among children, the LLR is not a useful measure with significant changes across the conditions.

Clinical implication:

- Hearing aid is recommended to the contra lateral ear in addition to CI, hence the performance becomes better.
- The presence of LLR gives information regarding functioning auditory pathway, also it reveals the benefit of amplification device in perceiving speech.

Future Directions:

- Further, study could be on older children and adults having matured LLR, to find the effect of hearing aid.
- To compare the electrophysiological and behavioral measures in children using third upper stimulation.

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