Optimization and Evaluation of a Hearing Aid in the Ear Contralateral to that with Cochlear Implant

[1]Praveen H. R. & [2]Manjula P.

Abstract

It is well documented that the individuals with normal hearing combine information from both ears in order to understand speech better in complex listening conditions and to locate sounds. Whenever an individual has hearing loss in both ears, it is a standard procedure to fit hearing devices in both ears. These devices can be hearing aids or cochlear implants or a combination of the two. The present research aimed to evaluate the benefit of using a hearing aid in the ear contralateral to that with cochlear implant on speech perception in quiet and in noise; and horizontal localization abilities in children. The measures Speech Identification Scores (SIS), Signal-to-noise ratio-50 (SNR-50) and degree of errors on a localization task (rmsDOE) were used to quantify the performance on speech perception in quiet, speech perception in noise and horizontal localization abilities respectively. These measures were carried out in three different aided conditions namely; hearing aid alone (HA alone), cochlear implant alone (CI alone) and cochlear implant plus hearing aid (CI+HA). Results revealed that there were significant improvement in CI+HA condition on all the three measures when compared to CI clone condition followed by the performance in HA alone condition. Thus, it is research recommended that a hearing aid is to be used in the ear contralateral to that with a cochlear implant, whenever there is an aidable residual hearing in the contralateral ear, to avail the binaural benefits.

Key words: *Bimodal stimulation, SIS, SNR-50, localization.*

Introduction

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

The benefit obtained by fitting the hearing devices to children with hearing loss (Fujikawa & Owens, 1978; Haggard, Foster, & Iredale, 1981) has been well documented. These devices can be either hearing aids or cochlear implants. Traditionally, children with hearing-impairment are being fitted with hearing aids over the past many decades. However, the number of children with hearing impairment using cochlear implants has increased (Dowell, 2005).

For individuals with bilateral severe to profound hearing loss, cochlear implant provides better speech perception ability when compared to hearing aids. Although the concept of binaural cochlear implant is proposed to be beneficial in providing binaural advantage, majority of the children in India who undergo cochlear implant surgery are implanted unilaterally and they continue to use a cochlear implant in only one ear which is evident from the studies reported in literature (Desa Souza, D'Souza, Kochure, & D'Souza, 2004; Deka et al., 2010). Since cochlear implant is expensive, it is not an affordable solution to recommend bilateral cochlear implants for majority of the individuals. Hence, the concept of fitting the contralateral ear having residual hearing with a conventional amplification device is being recommended from the past few years. Using a hearing aid and a cochlear implant in the opposite ears simultaneously refers to a bimodal condition (Clark, 2003). Bimodal stimulation was initiated at the Human Communication Research Centre (HCRC) at the university of Melbourne / Bionic ear Institute in 1989 (Clark, 2003). Studies have indicated that the bimodal stimulation may help to serve the purpose of binaural benefits in individuals using unilateral cochlear implant.

Very few individuals with unilateral cochlear implant continue to use a hearing aid in the contralateral ear. The binaural advantage for perceiving speech in noise can be explained in terms of three different effects:

[1]E-mail: pheonixnash@gmail.com; [2]Professor of Audiology, E-mail: manjulap21@hotmail.com

binaural summation, head shadow, and binaural release from masking. Binaural hearing allows listeners to localize sound sources by attending to the ear with the better signal-to-noise (SNR) ratio and use of inter-aural level and inter-aural time differences (Litovsky, 2005).

The reason for understanding speech better through binaural condition than monaural condition in a noisy situation, can be explained by head shadow effect, head diffraction, binaural redundancy and binaural squelch (Ching, Incerti, Hill, & Brew, 2004). Several studies have demonstrated the binaural squelch effect in normals (Van deun, Van Wieringen & Wouters, 2010) and also in individuals with hearing-impairment using binaural hearing aids (Dillon, 2001; McCullough, & Abbas, 1992) or bilateral cochlear implants (Laske et al., 2009; Chan, Freed, Vermiglio, & Soli, 2008; Ricketts, Grantham, Ashmead, Haynes, & Labadie, 2006) or bimodal conditions (Tyler et al., 2002; Ching, Incerti, Hill, & Brew, 2004; Ching, 2005; Keilmann, Bohnert, Gospeth & Mann, 2009). Since head shadow effect is a physical phenomenon, it will occur whenever the sounds are audible to the human ears whether the stimulation is acoustic or electric or the combination of both (Ching, 2005).

Bimodal amplification and Speech perception in quiet and noisy situation: Studies conducted after optimizing the hearing aid with cochlear implant in the contralateral ear, using BKB sentence list and VCV consonant lists in the presence of noise (Ching, Incerti& Hill, 2003), Freiburger numbers, Freiburger Monosyllables and Innsbrucker Sentence Test (Hamzavi, Pok, Gstoettner& Baumgartner, 2004); phoneme recognition in quiet and in noise; consonant recognition (Incerti, Ching & Hill, 2011) in three aided conditions namely, HA alone, CI alone and CI+HA conditions, revealed significantly better speech perception abilities in CI+HA condition than CI alone condition followed by HA alone condition. The evidence of binaural squelch was also reported when the speech and noise was presented from front (0^o Azimuth) when compared to speech from front and noise from other azimuths (Tyler et al., 2002; Berritini, Passetti, Giannareli & Forli, 2010)

A two article series by Ching, Hill, Dillon, and Wanrooy (2004a, b) evaluated the fitting of hearing aid and found that the using hearing aid in-the-ear contralateral to that of cochlear implant can help to improve the quality of life of the recipient and the recipient's family. It also can eliminate the negative impact of auditory deprivation in the non-implanted ear. This may enhance the speech perception in noise and provide enhanced sound quality. Hence, they recommended that the bimodal fitting should be made mandatory, provided there is a useful residual hearing in the ear contralateral to that of cochlear implant.Lim et al., (2009) conducted a study on 19 children in Korean language who underwent unilateral cochlear implant. The results revealed that the participants benefited by fitting a hearing aid in the contralateral ear, in terms of speech perception in noise. Whereas, no significant difference was reported for speech perception in quiet between CI+HA and CI alone condition. Litovsky, Johnstone, and Godar (2006), Ching, Wanrooy, and Dillon (2007), Cullington and Zeng (2011), Sammeth, Bundy, and Miller (2011) reported that although binaural condition (CI+CI) condition revealed significantly better benefits when compared to CI+HA condition, they recommended that the use of bimodal devices (CI+HA) is more effective for the speech perception in noise, with respect to the cost and risks involved as in case of binaural cochlear implants (CI+CI).

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

Ching, Psarros, Hill, Dillon and Incerti (2001) and Tyler et al., (2002) evaluated the benefit on localization of using a hearing aid in the contralateral ear using the measures rmsDOE and percentage of correct scores respectively. They concluded that simultaneous use of cochlear implant and hearing aid in opposite ears resulted in better localization benefits when compared to CI alone condition. Seeber, Baumann and Fastl (2004) compared the localization abilities in individuals using binaural cochlear implants (CI+CI) who used bimodal stimulation (CI+HA) earlier to second cochlear implant. Although CI+CI condition resulted in better performance on a horizontal localization task when compared to CI+HA condition, CI+HA condition resulted in a significantly better performance when compared to CI alone condition. Ullauri, Crofts, Wilson and Titley (2007) collected feedback from parents and teachers and seven children, who used a hearing aid in the ear contralateral to the ear with cochlear implant for period of eight to nine weeks. Although participants reported mixed results regarding the benefit on bimodal stimulation, parents and teachers of all the participants reported better performance on localization tasks in real-life situations. Thus from the studies reported in the literature, it is evident that the use of hearing aid in the ear contralateral to that with cochlear implant, would benefit the individuals. The benefit is in terms of better speech perception in quiet, also in the presence of noise and improved localization abilities. However, there is a dearth in literature regarding the same in pediatric population. The present research is an attempt to study the benefit of bimodal stimulation in children.

Ching (2005) and Lovett, Kitterick, Hewitt, and Summerfield (2010) have proposed the main motivation for aiding the contralateral ear so as to (1) to create the potential for binaural hearing which will help to understand speech better, especially in noisy situation, and to help an individual to better localize the sounds (2) to ensure that the more responsive auditory nerve is stimulated i.e., to avoid auditory deprivation, (3) to provide a back-up in the event of device failures, and (4) to provide an opportunity for the future advances in hearing restoration.

Binaural cochlear implants may not be an affordable option for many individuals. Cochlear implants provide better high frequency cues; whereas hearing aids would provide better low frequency cues (Ching et al., 2003; Chang, Bai & Zeng, 2006). Thus, an added advantage of bimodal fitting was that the low frequency cues provided by acoustic hearing complemented the high frequency cues conveyed by the electric hearing in the perception of speech and music (Ching, Massie, Wanrooy, Rushbrooke, & Psarros, 2009; Chang et al., 2006). Hence, there is a need to establish a protocol to fit a hearing aid in the ear contralateral to the implanted ear for the individuals who may not be able to afford binaural cochlear implant.

Thus, most of the earlier studies conducted on adult population have reported better perception of speech in quiet, as well as in noise, and better localization abilities in individuals using cochlear implant and a hearing aid in opposite ears. Hence, the present research attempts to evaluate the role of binaural hearing through bimodal stimulation, in children, on speech perception in quiet, as well as in noise and localization tasks.

The objectives were to evaluate the following in children who were using cochlear implant in one ear and fitted with a hearing aid in the contralateral ear: (1) to validate a protocol in order to optimize the hearing aid in the ear contralateral to that with a cochlear implant. (2) To compare the speech identification scores (SIS) in quiet in three aided conditions, hearing aid alone (HA alone), cochlear implant alone (CI alone), and cochlear implant plus hearing aid (CI+HA) conditions. (3) To compare the performance on speech in noise, through the SNR-50 measure (i.e., signal-to-noise ratio required for 50% of identification scores) in three aided conditions, HA alone, CI alone and CI+HA conditions. (4) To compare the performance on a localization task through the measure of root mean square degree of errors (rmsDOE) in three aided conditions, viz: HA alone, CI alone and CI+HA conditions.

Method

Participants

The data were collected from a total of 10 participants who were using a unilateral cochlear implant. The participants were assigned to one of the two groups based upon the task that they were supposed to carry out. The first group (Group I) consisted of nine children, who were evaluated on speech perception in quiet and speech perception in noise (SNR 50) tasks. The degree of hearing loss in the ear with cochlear implant before the implantation was found to be severe to profound hearing loss with pure tone average ranging from 85 to 120 dBHL. In the contralateral ear, they had severe to profound degree of hearing loss with a pure tone average ranging from 88.3 to 120 dB HL. Their age ranged from 5;5 years to 17;10years, with mean age of 10 years and standard deviation of 3.8 years. They had undergone cochlear implantation in one ear and were using a stabilized map for a period of at least three months. The age at which the participants were implanted unilaterally ranged from 3.2years to 10.2 years.

The second group (Group II) who had to carry out the localization task consisted of eight children with hearing-impairment. The degree of hearing loss in the ear with cochlear implant before the implantation was found to be severe to profound hearing loss with pure tone average ranging from 90 to 120 dBHL. In the contralateral ear, they had greater than severe degree of hearing loss with a pure tone average ranging from 88.3 to 103.3 dBHL. Their age ranged from 5.5 years to 17.10 years, with a mean age of 10.5 years and a standard deviation of 7.3 years. They had undergone cochlear implantation in one ear and were using a stabilized map, for a period of at least three months. The age at which the participants were implanted ranged from 3.2 years to 10.2 years.

Instrumentation and localization set-up

A calibrated two channel diagnostic audiometer, Madsen Orbiter 922 with Madsen loud speakers were used for performing speech identification and localization tasks in different aided conditions. For carrying out the localization task, five loudspeakers were connected to the audiometer. One loud speaker each was placed at +90^{o}A, +45^{o}A, 0^{o}A, -45^{o}A, and -90^{o}A. The loudspeakers were located at a distance of one meter away from the participant, in a semicircle. One channel of the audiometer was connected to the loudspeaker placed at 0^o A. During the localization task, a toggle switch was used to route the signal of the other channel of the audiometer to any of the four speakers placed at +45^o A, +90^o A, -45^o A, or -90^o A. The loud speakers were calibrated to emit the output that would result in equal dB HL at the microphone at a distance of one metre.

The other devices used in the study included: A digitally programmable two channel and eight band behind-the-ear hearing aid with a fitting range for severe-to-profound hearing loss, coupled to a custom made soft shell ear mould was used for evaluating the aided performances, a personal computer with NOAH-3 and hearing aid specific softwares and the Hearing Instrument Programmer (HiPro) interface were used to program the digital behind-the-ear (BTE) hearing aids, cochlear implant with either ear level or a body level speech processor owned by the participant, programmed with a stable map, a laptop computer, installed with Adobe Audition software (Version 3.0) was used to route the test stimuli through the auxiliary input of the audiometer for the localization task. All the testingswere done in an air-conditioned sound treated double room situation. The ambient noise levels were within permissible limits.

Procedure

The data were collected in three phases.

Phase I

Hearing aid fitting and optimization of the loudness between the ear with the cochlear implant and the ear with the hearing aid in the contralateral ear was done. Each participant was fitted with a two-channel, eight band digital behind-the-ear (BTE) hearing aid with a custom ear mould in the ear contralateral to that with cochlear implant.The hearing aid was programmed using a personal computer and a HiPro interface unit using NOAH-3 and hearing aid softwares with the acclimatization level set at 3, as the participants were experienced hearing aid users. Once the individual hearing aid gain was prescribed, the aided thresholds of the participants were obtained for warble tones from 500 to 4000 Hz, from a loudspeaker of the audiometer, placed at 0^o Azimuth at a distance of one meter. The gain of the hearing aid was optimized such that the aided thresholds were within speech spectrum, from 500 to 4000 Hz, at least up to 2000 Hz. After this step, narrow band noise centred at 500 Hz and 2000 Hz were presented at 45 dBHL from a loudspeaker at 0^0 Azimuth. Two frequency bands were chosen since the test hearing aid had two channels. The hearing aid settings were manipulated (increase or decrease in the gain) such that the signal in the ear with hearing aid matched in loudness with that in the ear with cochlear implant. The cochlear implant programming parameters were not altered while achieving equal loudness. If the participant reported that the sound is heard louder in the ear with hearing aid, then the gain of the hearing aid was decreased. Conversely, if the participant reported that the sound heard was louder in the ear with cochlear implant, the gain of the hearing aid was increased. Once the loudness balancing was achieved with both 500 Hz and 2000 Hz narrow band noise stimuli, the same procedure was carried out using a white noise. The overall gain was systematically varied to achieve loudness balance.

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

Phase II

Data on aided speech identification in quiet and in noise were collected in three different aided conditions.

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

Aided open set Speech Identification Scores (SIS) in noise: To obtain the aided speech identification performance in noise, SNR-50 was measured.For the purpose of the study, SNR-50 is defined as the difference between the intensity of speech stimuli and the intensity of the competing speech-shaped noise in dB when the participant correctly repeats at least two words in a set of four words (50% of the words) being presented in the presence of competing speech noise. The SNR-50 was measured in a sound-field condition using the words from the phonemically balanced word list in Kannada for children (Vandana, 1998). The speech stimuli were presented at a constant level of 45 dBHL through monitored live voice mode from a loudspeaker at 0^{o} Azimuth at a distance of one meter. The level of speech noise was varied to obtain the SNR-50. Both speech signal and the speech noise were presented through the loudspeaker of the audiometer located at 0^{o} Azimuth, placed at a distance of one meter from the participant. The initial presentation level of the noise was 30 dBHL which was varied systematically to measure the SNR-50.

The participant was instructed to repeat the words heard in the presence of the competing speech noise. The participant was presented with a set of four words taken from the phonemically balanced word list in Kannada (Vandana, 1998) at each presentation level of noise. If the participant repeated at least two words out of four words correctly, then the level of noise was increased in 2 dB steps. At each of the steps, four words were presented. If the participant failed to repeat at least two of the four words correctly, the level of noise was decreased in 4 dB steps. If the speech of the participant was unintelligible, written responses were obtained. This was continued until the highest level of speech noise that was enough for the participant to repeat at least two out of four words, was measured. At this point, the difference between the intensity of speech and the competing speech noise, in dB, was considered as the SNR-50. Thus, the maximum level of noise at which the participant could correctly repeat at least two out of four words was measured and noted. This level was subtracted from 45 dB HL (presentation level of the speech signal) to obtain SNR-50. The SNR-50 was measured in three aided conditions, i.e., HA alone, CI alone and CI+HA conditions. Thus, for each participant, three SNR-50 values were obtained in different aided conditions and tabulated.

Phase III

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

The participant was instructed that he/she would be hearing to a train of noise stimuli from any one of the five speakers at a time. Each time, he or she had to report the loudspeaker from which the stimulus was heard. The response mode from the participant was through a pointing task. The location of the loudspeaker to which participants pointed was noted down in terms of Azimuth. A single representation of degree of errors in each aided condition was done by the calculation of root mean square degree of error (rmsDOE) (Ching, Incerti, & Hill, 2004; Van Deun et al., 2010). The rmsDOE is defined as the square root of the average of squared degrees of errors in each set. Thus, each participant had three rmsDOEs, representing the localization abilities of the participants in each of the three aided conditions (HA, CI and CI+HA conditions). It is calculated using the formula (Ching, 2004) given below. Thus from the three aided conditions (HA alone, CI alone and CI+HA), the following data were collected in each test condition from each participant: SIS in quiet, SNR-50 and rmsDOE for localization task. The above data were tabulated and subjected to appropriate statistical analyses.

Results and Discussion

The present study was conducted to compare speech perception- in quiet and in noise, and localization abilities in HA alone, CI alone and CI+HA conditions. The data obtained from the participants in the three different conditions were subjected to statistical analyses using Predictive Analysis Software (PASW, Version 18).

Speech identification scores in quiet (SIS) in HA alone, CI alone and CI+HA conditions: The SIS obtained for each of the participant (N=9) are as shown in the Figure 1. From the Figure 1, it can be noted that the performance on a speech identification task (SIS) was zero in HA alone condition in all the participants. All the participants scored better in the CI alone condition when compared to HA alone condition. The scores in CI+HA condition were better when compared to CI alone condition in all the participants except for the participant number six and participant number nine.

Among the three aided conditions, the performance was the best in CI+HA condition followed by the performance in CI alone and then in HA alone condition. The participants did not repeat any word in the HA alone condition (i.e., SIS=0). The SIS ranged from 16 to 23 for CI alone condition, with mean score of 17.55 and SD of 2.24. The SIS for the CI+HA condition varied from 17 to 23 with mean of 19 and SD of 2.24. Repeated measures ANOVA revealed that there was a significant difference between SIS obtained in the three different aided conditions [$F(2, 16)=534.388$; $p<0.001$]. Hence, Bonferroni (post-hoc) pair-wise analysis was carried out which revealed a significant difference in the SIS between HA alone and CI alone condition ($p<0.001$), between HA alone and CI+HA condition ($p<0.001$) and between CI alone and CI+HA condition ($p<0.05$). A non-parametric, Wilcoxon signed rank test was also administered to cross-check the results of the parametric tests which revealed a significant difference in the SIS between HA alone and CI alone condition ($p<0.01$), between HA and CI+HA condition ($p<0.01$) and between CI and CI+HA conditions ($p<0.05$).

The results of the present study are in agreement with the studies who reported that the speech perception abilities in quiet were significantly better in CI+HA condition compared to CI alone condition on BKB sentence list (Ching et al., 2003; Ching et al., 2004), VCV consonant lists (Ching, 2003) Freiburger numbers, Freiburger Monosyllables and Innsbrucker Sentence Test (Hamzavi et al., 2004) Word lists and sentence list (Tyler et al., 2002) also reported a significantly better performance on VCV non-sense

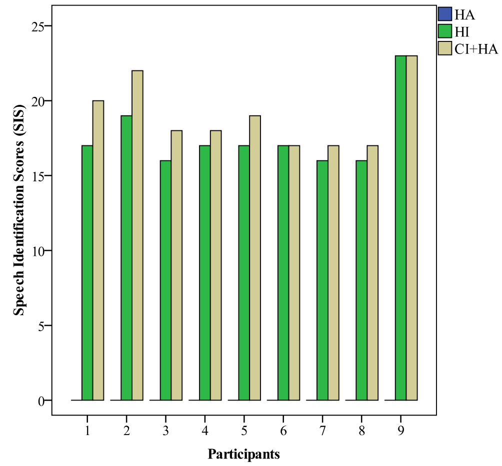

Figure 1: Speech Identification Scores (max. score=25) obtained from each of the nine participants in HA alone, CI alone and CI+HA conditions.

syllable test (Incerti et al., 2011); phoneme recognition task (Beijen, Mylanus, Leeuw & Snik, 2008). However, the results of study contradict the results of the study by Lim et al., (2009) who reported that there was no significant difference on speech perception score in quiet between CI alone and CI+HA condition although the hearing aid was loudness balanced with the cochlear implant in the contralateral ear. These contradicting results may be due to the language used in the study (Korean), which is a tonal language, used in the speech perception test of the study.

The better performance observed in the bimodal (CI+HA) condition when compared to monaural conditions, either CI alone or HA alone condition, on a speech perception task in quiet may be due to access to binaural cues and binaural redundancy.

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

The SNR-50 values could not be obtained in HA alone condition since the speech identification scores were zero for all the participants in HA alone condition. The SNR-50 for the CI alone condition ranged from 1 dB to 11 dB, with mean of 4.78 and SD of 3.67. The SNR-50 for the CI+HA condition varied from -3 dB to 5 dB, with a mean of 1 dB and SD of 3.60. The standard deviation reflects the variation in the duration of use of cochlear implant and age at which the participants underwent cochlear implantation. These results reveal that the signal-to-noise ratio required for 50% of the correct identification, is lesser in case of CI+HA condition when compared to CI alone condition. i.e., the performance in noise is better in the CI+HA condition compared to CI alone condition.

The standard deviation for the SNR-50 in CI+HA was found to be more than the mean SNR-50. This may be because the SNR-50 of the individual data consisted of negative values. The results of the paired t-test revealed that there was a significant difference between SNR-50 obtained in CI alone and CI+HA conditions ($p<0.001$). A non-parametric test, Wilcoxon signed rank test, was also administered to cross-check the results of the parametric test which revealed a significant difference in the SNR-50 between CI condition and CI+HA conditions ($p<0.01$).

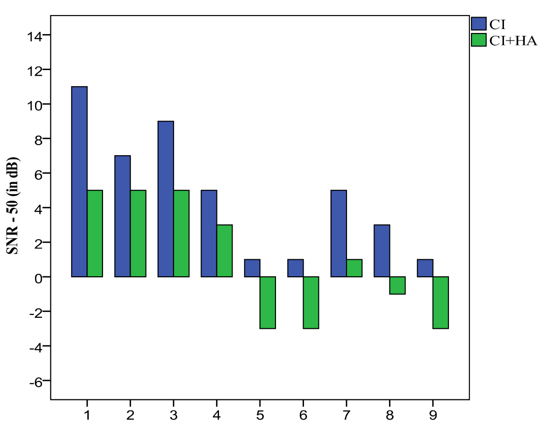

Figure 2: SNR-50 values obtained from each of the nine participants in CI alone and CI+HA conditions.

These results conform to the findings reported by Tyler et al., (2002), Berretini et al., (2010) and Ullauri (2007) who reported that the speech perception in noise improved with the bimodal condition when compared to that with monaural CI alone condition. They reported that the bimodal benefit was evident when the speech and noise were presented from the front when compared to speech presented from front and noise from +90° or-90°, which supports the binaural squelch phenomenon. Iwaki, Blamey and Kubo (2008) reported that the use of ADRO technology in the bimodal devices showed better speech perception abilities in noise when compared to the use of WDRC in the hearing aid. Ching et al., (2007) used SNR-50 as a measure in two adults and reported that CI+HA condition led to better understanding of speech in the presence of noise when compared to CI alone condition. Although they reported that the bilateral cochlear implant (CI+CI) condition provided superior benefit for the speech perception in noise when compared to the CI+HA condition, CI+HA still remains the option of choice because of the affordability. Keilmann et al., (2009) also reported an improvement among all the participants who needed lesser SNR to obtain SNR-50 in CI+HA condition when compared to CI alone condition.

The results of the present study are in concurrence with the results of the study by Beijen et al., (2008) and Lim et al., (2009), who reported significantly better speech perception in CI+HA condition when compared to CI alone condition on a phoneme recognition task in noise. Better perception of speech in the presence of noise are due to the fact that an individual gets to access the binaural cues which lead to binaural advantage as seen in individuals with normal hearing sensitivity. This supports the evidence that the phenomenon of binaural squelch is evident even in individuals who use different types of stimulation in each of the ears i.e., bimodal stimulation (electric+ acoustic).

The root mean square degree of errors (rmsDOE) in localization in HA alone, CI alone and CI+HA aided conditions: The root mean square degrees of errors (rmsDOE) in localization obtained for each of the eight participants are as shown in the Figure 3. It can be inferred from the Figure 3 that all the participants had lesser rmsDOE in CI+HA condition when compared to CI alone condition followed by HA alone condition. It must be noted that the lesser the rmsDOE, better is the performance in that particular aided condition.

The results of the repeated measures ANOVA revealed that there was a significant difference between the rmsDOE obtained in three different aided conditions [$F(2, 14)=54.63$; $p<0.001$]. Hence, Bonferroni (post-hoc) pair-wise analysis was carried out which revealed a significant difference in the rmsDOE between HA alone condition and CI alone condition ($p<0.001$), between HA alone and CI+HA condition ($p<0.001$) and between CI alone and CI+HA condition ($p<0.001$). A non-parametric, Wilcoxon signed rank test was also administered to cross-check the results of the

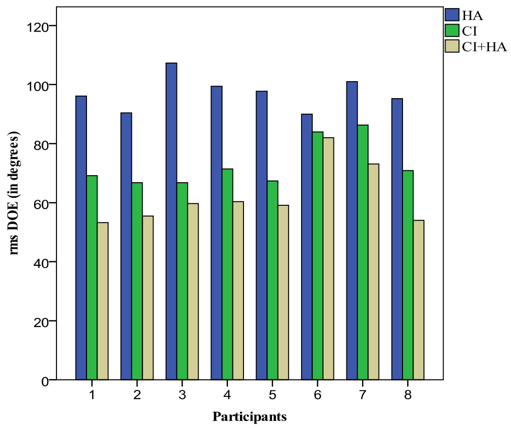

Figure 3: Root mean square degree of error (rmsDOE) on a localization task obtained from each of the eight participants in HA alone, CI alone and CI+HA conditions.

parametric test, also revealed a significant difference in the rmsDOE between HA alone and CI alone condition ($p<0.05$), between HA and CI+HA condition ($p<0.05$) and between CI and CI+HA condition ($p<0.05$).

The results of the present study support the results of the study by Ching et al., (2003) and Seeber et al., (2004) who reported that the errors were found to be the least in CI+HA condition followed by CI alone. Similar results were reported by Tyler et al., (2002) who reported an improvement on the percentage of correct scores on a localization task in two out of three participants tested. The results of the present study are supported by the results of the study by Litovsky, et al. (2006) who used a measure of minimal audible angle (MAA) to represent the localization abilities in children. All the participants showed significantly better performance on MAA task on CI+HA condition compared to CI alone condition. Although Ching et al. (2007) reported lesser rmsDOE on a localization task in CI+HA condition when compared to CI alone condition, they reported that localization abilities to be better with binaural (CI+CI) condition when compared to CI+HA condition. However, CI+CI may not be an affordable solution for many individuals when compared to bimodal (CI+HA) condition.

The results of the present study are in agreement with the findings by Ullauri et al., (2007) and Berrettinni et al., (2010) where four of the seven participants included in the study reported better localization abilities in the real-life situation. However, the parents and the teachers of all the participants reported a better localization abilities in CI+HA condition when compared to CI alone condition, through a questionnaire. Ching (2005) and Sammeth et al., (2011) summarized the situations where the bimodal stimulation has to be recommended, i.e., (1) Patients with residual hearing in the non-implanted ear (2) Those having good performance in the non-implanted ear with a hearing aid (3) For those who want to avail the benefit of binaural hearing (4) All young children.

The results of the present study also strongly recommend the use of hearing aid in the ear contralateral that with cochlear implant, whenever there is useful residual hearing in that ear. The CI+HA condition provides a better or an equivalent performance but is never poorer compared to CI alone or HA alone conditions. Hence, a hearing aid should be recommended whenever there is aidable hearing in the contralateral ear. Thus, the overall results of the present study reveal that a bimodal stimulation i.e., using a hearing aid in the ear contralateral to that with cochlear implant, help to perceive speech better in quiet, in noise and also to provide better horizontal plane localization abilities in children.

Summary and Conclusions

The study aimed to optimize and evaluate the benefit of a hearing aid in the ear contralateral to that with a cochlear implant, in children. A total of 10 participants were included in the study. These participants were divided into two groups based on the task they were supposed to carry out. The participants of the Group I (N=9) were evaluated on speech perception in quiet and speech perception in noise. The participants of the Group II (N=8) were evaluated on the horizontal plane localization task. The results were analyzed using appropriate statistical tools such as, descriptive statistics, repeated measures ANOVA, Bonferroni (post-hoc) pair-wise comparison (if indicated), paired-t test, and Wilcoxon Signed Rank test. Speech perception in quiet (SIS) administered for participants in Group I revealed a significantly better scores in CI+HA condition followed by CI alone and HA alone condition. SNR-50, administered on participants of Group I revealed that the participants needed lesser SNR in CI+HA condition followed by CI alone and HA alone, .i.e., performance was better with CI+HA condition followed by CI alone and HA alone condition. These results on speech perception in quiet and in noise reveals that individuals using a bimodal stimulation are also able to avail binaural advantage through the phenomenon of binaural redundancy and binaural squelch. Performance on a horizontal localization task revealed that the participants had lesser degrees of errors in CI+HA condition followed by CI alone and HA alone condition. Thus this study strongly recommends the use of hearing aid in the ear contra lateral to that with cochlear implant whenever there is residual hearing.

Clinical implications of the study and Future directions for research

The present study throws light on the binaural benefit and reveals significant benefit with the use of hearing aid in the contralateral ear. Due to the extension of the cochlear implant candidacy criteria, the number children who have useful residual hearing in the contralateral ear is increasing. Hence, optimization and fitting of hearing aid must be made mandatory in all the children who undergo cochlear implant surgery in one ear provided there is a useful residual hearing in the contralateral ear in order to avail the binaural benefit. Optimizing and use of a hearing aid in the contralateral ear would help in speech perception in quiet, in noise and in the localization. In addition, it prevents the auditory deprivation in the contralateral ear.

Further research could be carried out to compare the effect of number of channels and other features in the hearing aid in order to derive binaural benefit in a bimodal stimulation. The effect of noise on speech perception with speech presented from front and noise from different Azimuths, i.e., the phenomenon of binaural squelch can be evaluated. Research could be carried out with more number of loudspeakers with lesser intervals between the two consecutive loudspeakers, for a better representation of the root mean square degree of errors (rmsDOE) on a localization task. Detailed phoneme errors analysis / feature error analysis (place, manner and voicing) on speech perception in bimodal condition as compared to other aided conditions can be carried out. Also the effects of age of implantation and long-term usage of bimodal stimulation on speech perception and localization and evaluation of bimodal stimulation through the use of outcome measures can be carried-out.

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