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Benefits of Bimodal Stimulation in Children with Cochlear Implant: Role of Contralateral Residual Acoustic Hearing and Auditory Experience with Bimodal Stimulation

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ABSTRACT

There is a continuing growth in the number of cochlear implant (CI) recipients who have some amount of usable residual acoustic hearing in at least one ear. Many such recipients obtain perceptual benefits from the use of hearing aid (HA) in the contralateral ear. The present study aimed to assess the benefits of bimodal stimulation (i.e. CI in one ear and HA in the contralateral ear) in children as a function of the level of contralateral residual acoustic hearing and auditory experience with bimodal stimulation. Speech recognition performance was evaluated in quiet and noisy environments under monaural CI alone and bimodal CI+HA listening conditions. The results revealed that there was a significant effect of noise on speech recognition performance. There was a significant reduction ($p<0.05$) in speech recognition performance under monaural CI alone listening condition in noisy environment. However, the effect of noise on speech recognition performance was minimized under bimodal CI+HA listening conditions as compared to monaural CI alone listening condition. The subjects obtained significantly higher ($p<0.05$) speech recognition performance under bimodal CI+HA listening condition as compared to monaural CI alone listening condition especially in noisy environments. It was further observed that the subjects obtained similar bimodal benefit irrespective of differences in the level of contralateral residual acoustic hearing. However, subjects with longer duration of auditory experience with bimodal stimulation could only achieve significant bimodal benefits compared to the subjects with less auditory experience with bimodal stimulation. Hence, children who receive a monaural cochlear implant and cannot opt for bilateral cochlear implantation for whatever reasons should be encouraged to use a hearing aid in the opposite ear irrespective of the level of residual acoustic hearing in that ear. However, sufficient auditory experience with bimodal stimulation is needed to achieve this bimodal benefit.

Keywords: Cochlear Implant, Bimodal Stimulation, Speech Recognition Performance, Contralateral Residual Acoustic Hearing, Auditory Experience with Bimodal Stimulation

INTRODUCTION

Cochlear implants have considerably changed the outcomes of children with severe-to-profound hearing loss by providing with auditory information that is not obtainable through conventional hearing aid technology. Cochlear implants make available with several benefits in children, which may include overall improvements in auditory skills [1], improvements in speech production [2], enhanced speech intelligibility [3], and improvements in reading skills [4]. In addition, cochlear implants are known to offer considerable positive effect on the psychosocial behaviour and quality-of-life factors such as physical, mental and emotional health, self-esteem, relationships with family and friends, and performance at school [5].

However, the presence of background noise continues to considerably degrade speech understanding even for the best CI performers [6-10]. This is because the electrical stimulation used in the electrode array has several limitations as compared to acoustic hearing provided by hearing aid. The poor representation of low-frequency pitch information and limited frequency resolution provided by the electrode array account for the poor perception of speech under adverse listening conditions by CI users [8-9]. Moreover, while binaural stimulation has been conventionally considered in hearing aid fitting, monaural stimulation is commonly associated with cochlear implant [11]. Hence, children who receive cochlear implants in the ear will not get the advantages of binaural hearing resulting in poor perception of speech in adverse listening conditions and poor localization abilities [7].

Binaural hearing for these children can be provided by bilateral cochlear implantation and/or bimodal stimulation. Although bilateral cochlear implantation is becoming a more common recommendation, it cannot be an option or may not be recommended for all recipients due to several reasons. This is particularly true with reference to a developing country like India. In India most of the children with CI are limited to monaural stimulation due to financial barriers [12]. Finance being the major issue of bilateral cochlear implantation in developing countries, bimodal stimulation, i.e. Cochlear implant in one ear and hearing aid (HA) in the opposite ear is a least-expensive and noninvasive alternative procedure to provide some of the benefits of binaural hearing.

When cochlear implantation was first introduced, the individuals with post-lingual bilateral profound hearing loss and getting little or no benefit from conventional HAs were only considered for cochlear implantation. However, with time, the selection criteria for cochlear implantation were progressively relaxed to include individuals with some usable residual hearing [7, 13-14]. Hence, there is a range of low-frequency residual hearing that fall within the approved audiometric criteria for cochlear implantation for children as well as adults [15]. The expanded candidacy criteria have resulted in an increase in number of CI recipients and it is expected that the total number of CI recipients worldwide will exceed 200,000 [16]. Hence, it is likely that the typical CI recipient both adults and children will have some amount of usable low-frequency residual hearing in at least one ear who can benefit through wearing a hearing aid in non-implanted ear (bimodal stimulation). The number of adults and children who can benefit through bimodal stimulation will not only continue to grow, but will grow at an increasing rate [16].

The “Rajiv Aarogyasri Scheme”, a unique community health insurance plan being implemented in Andhra Pradesh, a state in India from 2007, bears the expenditure of cochlear implantation program including surgery and post-operative rehabilitation for children placed below the poverty line. This scheme is a social experiment that has no parallel in any other state in India. Recognizing this, the other states in India such as Kerala, Ahmadabad, Madhya Pradesh, Tamilnadu and Jharkhand have also implemented a similar health insurance plan. The apex bodies in the ENT surgery such as Asia Pacific Congress on Deafness and the International Federation of Otolaryngological Societies have given special credit to the “Rajiv Aarogyasri Scheme” and adopted it as a role model for other developing countries. So far, more than 700 children have benefited from this scheme, making Andhra Pradesh, the only state in India with one of the largest CI population [17].

Thus, the expanded candidacy criteria for cochlear implantation and inclusion of CI surgery as a part of Health Insurance Plans in India have not only resulted in an increase in number of children with CI, but also have caused a large variability among these children in terms of the level of residual hearing in the contralateral ear and auditory experience with bimodal stimulation. This is a relatively new and challenging population of rehabilitation professionals in the CI centers than has been studied in the past. Hence, there is a need for a comprehensive study on bimodal stimulation, which may help the CI rehabilitation professionals to understand bimodal hearing better which, in turn, will lead to create awareness among parents of children with CI. The present study aimed to assess the benefits bimodal stimulation in children with CI as a function of contralateral residual hearing and auditory experience with bimodal stimulation.

MATERIALS AND METHODS

Participants

A total of fifty-six Telugu speaking (Telugu, a South Central Dravidian language that is the state language of Andhra Pradesh, India) pre-lingual hearing-impaired children, who received monaural CI, were initially considered for the present study. Although, initially fifty-six subjects participated in this repeated-measure experimental design, some of the children did not continue for the follow-up experiment and some not able to perform speech recognition testing. The complete data were collected from forty-eight subjects under all listening conditions, i.e. monaural CI alone and bimodal CI+HA listening conditions in both quiet and noisy environments. Hence, the database of forty-eight subjects were only considered for assessing the benefits of bimodal stimulation as a function of the level of contralateral residual hearing, the auditory experience with bimodal stimulation, and the type of signal processing strategy used in the HA.

The age of the participants ranged between 8.4 and 11.11 years with a mean age of 9.11 years. The mean low-frequency pure-tone average (averaged over 250 Hz, 500 Hz and 1000 Hz) in the non-implanted ear of children ranged between 86.66 dB HL and 103.33 dB HL with a mean threshold of 95.59 dB HL. The subjects had a minimum auditory experience (including pre-implant bilateral HA usage) of 6 years, which includes a minimum of 4 years of post-implant hearing. The auditory experience with pre-implant HA usage of the participants ranged between 2.1 and 4.3 years with a mean duration of 2.7 years. The auditory experience with post-implant ranged between 4.1 and 6.1 years with a mean duration of 4.9 years. The auditory experience with bimodal stimulation ranged between 8 and 33 months with a mean bimodal auditory experience of 15.8 months.

Sixteen of the subjects were implanted with Nucleus CI 24 RE (CA) implant with freedom speech processor; fourteen were implanted with Nucleus CI 24 RST implant with the Sprint speech processor; ten were implanted with Nucleus CI 24 RST with freedom speech processor; and eight were implanted with MED-E1 Pulsar Combi + 40 with the Opus speech processor. The children with Nucleus implant were using ACE speech processing strategy and remaining with FSP speech processing strategy. The variables such as the type of implant, speech processor and speech processing strategies were not considered in the study. The subjects were using high-power four-to-six channels, digital HA in their non-implanted ears. The HA was fitted to each child by programming the HA using NAL-RP fitting formula as recommended by [18]. The optimization of HAs in the bimodal fitting was done to maximize the audibility of sounds, including speech sounds, while maintaining listening comfort. This was accomplished by fine tuning of HA using loudness balancing and paired comparison methods as reported by [15].

Procedure

The word recognition score (WRS) testing was administered to each subject in a sound-treated audiometric room under free-field condition where the ambient noise levels were within permissible limits. WRS testing was administered to each subject under two monaural and two bimodal listening conditions such as: (1) CI alone in a quiet environment (2) CI+HA in a quiet environment (3) CI alone in noisy environments (4) CI+HA in noisy environment. A battery for assessing speech recognition performance by children in Telugu developed by [19] was used as test stimuli. This battery consists of two word lists with each list consisting of 25 disyllabic words in CVCV structure. Each list was randomized twice to form a total four word lists such as List 1 and List 2 (i.e. random 1 and random 2 of list 1), and List 3, and List 4 (i.e. random 1, random 2 of list 2). This was done to avoid the order and practice effect, as there is a need to administer WRS testing under four six listening conditions. A different list was presented at each listening condition. List 1 and List 3 were used under CI alone and CI+HA listening conditions, respectively in a quiet environment, and List 2 and List 4 were used under CI alone and CI+HA listening conditions respectively in noisy environment. The stimulus was presented at 65 dB SPL in quiet and +10 dB SNR in noisy listening conditions. The noise was a four-talker babble presented at 55 dB SPL and mixed with the speech material. The stimulus was played on a CD player, which was routed through a Digital Diagnostic Clinical Audiometer and delivered through a single loudspeaker placed in front of the child at a distance of one meter and at an angle of 0^0 azimuth.

RESULTS AND DISCUSSION

Results

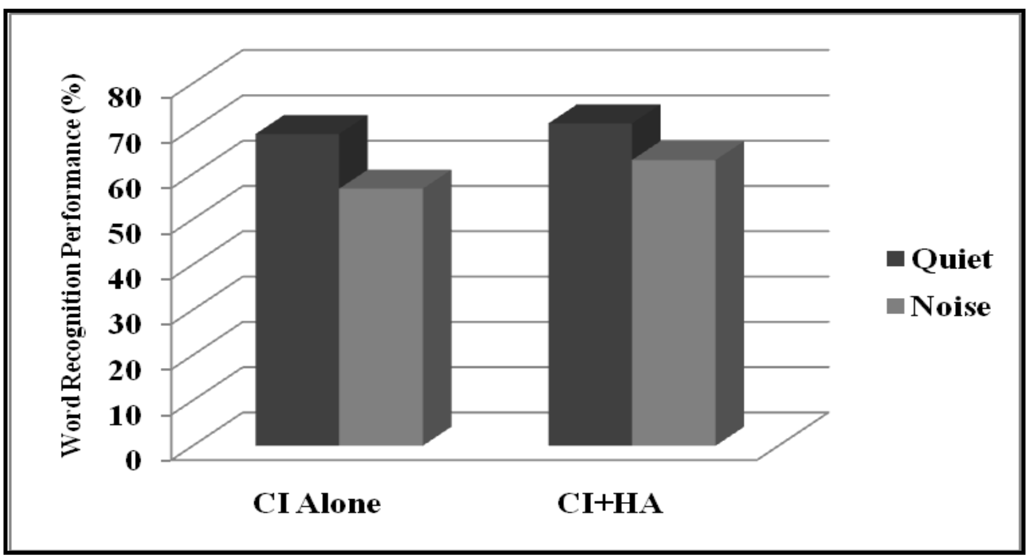
The mean and standard deviation values of WRS obtained by the subjects under CI alone and CI+HA in a quiet environment, and CI alone and CI+HA in noisy environment were calculated and then analyzed accordingly. The results are discussed under the following headings: 1) overall benefits of bimodal stimulation, 2) benefits as a function of contralateral residual hearing, and 3) benefits as a function of auditory experience with bimodal stimulation.

Overall benefits of bimodal stimulation

Table 1 and Graph 1 shows the mean values of WRS obtained by the subjects under monaural CI alone and bimodal CI+HA listening conditions in quiet and noisy environments. The subjects produced the mean WRS of 68.83%, 56.75%, 71.16% and 63.08% under CI alone in quiet, CI alone in a noisy, CI+HA in quiet and CI+HA in noisy environments respectively. The data were subjected to one-way ANOVA and LSD post-hoc analysis, and the results revealed that there was a statistically significant effect ($p<0.05$) of noise and bimodal listening condition on word recognition performance.

Table 1: Mean values of word recognition score in different listening conditions

Listening Condition	Word Recognition Score (%)				Significance value
	Quiet		Noise		
	Mean	SD	Mean	SD	
Monaural CI Alone	68.83	11.25	56.75	9.68	p<0.05
Bimodal CI+HA	71.16	10.75	63.08	11.87	



Graph 1: Mean values of word recognition score in different listening conditions

The subjects obtained a significantly lower ($p<0.05$) word recognition performance in noisy environments as compared to the quiet environment under both monaural CI alone and bimodal CI+HA listening conditions. However, the effect of noise on word recognition performance was minimized under bimodal CI+HA listening conditions as compared to monaural CI alone listening condition. The subjects obtained significantly higher ($p<0.05$) word recognition performance under bimodal CI+HA listening condition as compared monaural CI alone listening condition especially in noisy environments.

Benefits as a function of contralateral residual hearing

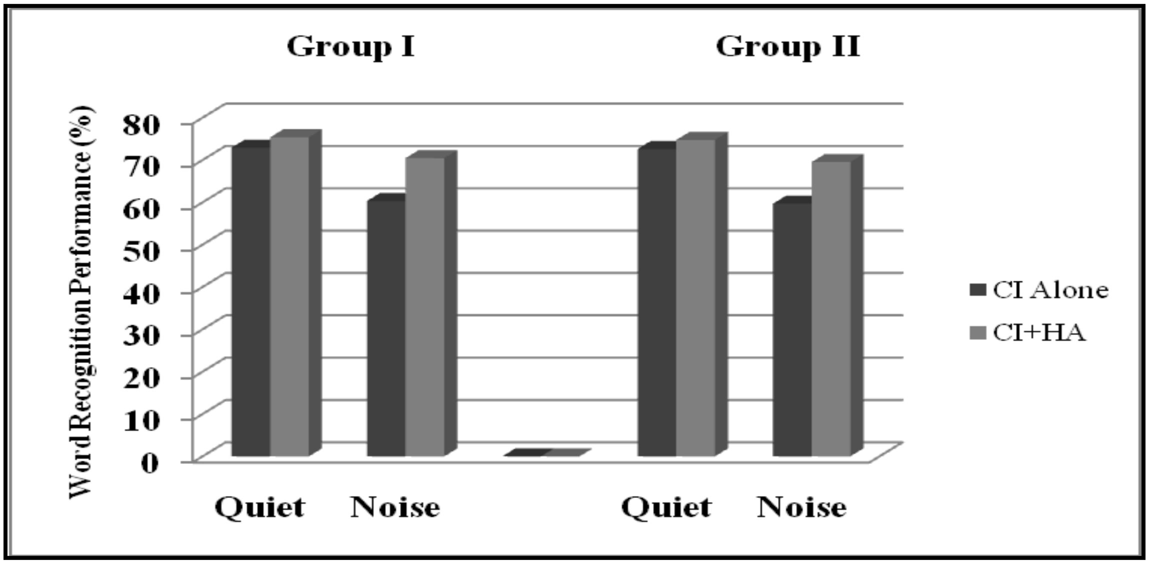
In order to assess the benefits of bimodal stimulation as a function of the contralateral residual hearing, the subjects were divided into two groups based on the mean PTA thresholds in the non-implanted ear. Group I consisted of subjects with PTA thresholds of $\leq$ 95 dB HL in the non-implanted ear, and Group II consisted of subjects with PTA thresholds of > 95 dB HL in the non-implanted ear. The subjects of each group were further inspected in order to ensure that both the groups are matched in terms of their WRS under CI alone in quiet and noisy environments. This was achieved by selecting the only subjects from each group who had similar WRS under CI alone in quiet and noisy environments. This has resulted in the formation of two equally divided groups which are matched in terms of mean WRS under CI alone in quiet and noisy environments.

The group I consisted of 13 subjects with a mean PTA threshold of 91.5 dB HL. They had a mean WRS of 72.92% and 60.32% % in quiet and noisy environments. Group II consisted of 13 subjects with a mean PTA threshold of 101.2 dB HL. They had a mean WRS of 72.61% and 59.69% in quiet and noisy environments. The mean WRS of the subjects of two groups was subjected to independent t test in order to assess the homogeneity between the groups. The results revealed that there was no statistically significant ($p>0.05$) between the subjects of two groups in terms of WRS in both quiet and noisy environments. Hence it can be considered that the two groups are considered as homogeneous under CI alone listening conditions.

Table 2 and Graph 2 show the mean values of WRS obtained by Group I and Group II under monaural CI alone and bimodal CI+HA listening conditions in quiet and noisy environments. The subjects of Group I yielded the mean WRS of 72.92%, 60.32%, 75.38% and 70.46% under CI alone in quiet, CI alone in a noisy, CI+HA in quiet, and CI+HA in noisy environments respectively. Similarly, the subjects of Group II yielded the mean WRS of 72.61%, 59.69%, 74.76% and 69.53% under CI alone in quiet, CI alone in a noisy, CI+HA in quiet, and CI+HA in noisy environments respectively. The data were subjected to one-way ANOVA and LSD post-hoc analysis, and the results revealed that there was a statistically significant effect ($p<0.05$) of noise on word recognition performance in both the groups.

Table 2: Mean values of word recognition score for Group I and Group II

Group	**Listening Condition**	**Word Recognition Score (%)**				**Significance Value**
		Quiet		**Noise**		
		Mean	**SD**	**Mean**	**SD**	
Group I	Monaural CI Alone	72.92	10.75	60.32	9.87	p<0.05
	Bimodal CI+HA	75.38	11.75	70.46	9.89	
Group II	Monaural CI Alone	72.61	10.86	59.69	9.65	p<0.05
	Bimodal CI+HA	74.76	11.95	69.53	9.76	



Graph 2: Comparison of mean values of word recognition score for Group I and Group II

The subjects in both the groups obtained significantly lower ($p<0.05$) word recognition performance in noisy environments as compared to the quiet environment under both monaural CI alone and bimodal CI+HA listening conditions. However, the effect of noise on word recognition performance was minimized under bimodal CI+HA listening conditions as compared to monaural CI alone listening condition in both the groups. The subjects in both the groups obtained significantly higher ($p<0.05$) word recognition performance under bimodal CI+HA listening conditions as compared monaural CI alone listening condition especially in noisy environments. It was further noticed there was no statistically significant difference ($p>0.05$) in terms word recognition performance between the groups. Thus, it can be inferred that both the groups obtained similar bimodal benefit irrespective of differences in the levels of residual hearing in the contralateral ear.

Benefits as a function of auditory experience with bimodal stimulation

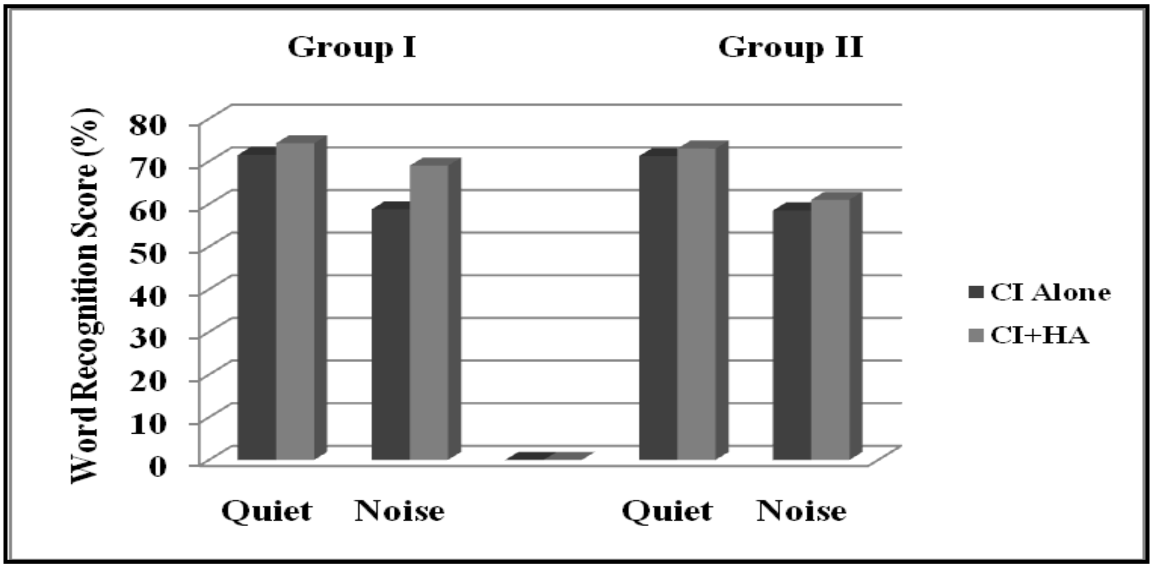
In order to assess the benefits of bimodal stimulation as a function of auditory experience, the subjects were divided into two groups based on the mean auditory experience with bimodal stimulation. Group I consisted of subjects with an auditory experience of >16 months with bimodal stimulation, and Group II consisted of subjects with an auditory experience of $\leq$16 months with bimodal stimulation. The subjects of each group were further inspected in order to ensure that both the groups are matched in terms of WRS under CI alone in quiet and noisy environments. This was achieved by selecting the only subjects from each group who had similar WRS under CI alone in quiet and noisy environments. This has resulted in the formation of two equally divided groups which are matched in terms of mean WRS under CI alone in quiet and noisy environments.

The group I consisted of 16 subjects with a mean auditory experience 21.31 months with bimodal stimulation. They had a mean WRS of 71.50% and 58.75%% under CI alone in quiet and noisy environments. Group II consisted of 16 subjects with a mean auditory experience of 10.18 months with bimodal stimulation. They had a mean WRS of 71.25% and 58.50%% under CI alone in quiet and noisy environments. The mean WRS of subjects of two groups were subjected to independent t test in order to assess the homogeneity between the groups. The results revealed that there was no statistically significant ($p>0.05$) between two groups in terms of WRS in both quiet and noisy environments. Hence it can be considered that the two groups are considered as homogenous under CI alone listening conditions.

Table 3 and Graph 3 show the mean values of WRS obtained by Group I and Group II under CI alone and CI+HA listening conditions in quiet and noisy environments. The subjects of Group I obtained mean WRS of 71.50%, 58.75%, 74.25% and 69.00% under CI alone in quiet, CI alone in noisy, CI+HA in quiet and CI+HA in noisy environments respectively. Similarly, the subjects of Group II obtained mean WRS of 71.25%, 58.50%, 73.00% and 61.00% under CI alone in quiet, CI alone in noisy, CI+HA in quiet and CI+HA in noisy environments respectively. The data were subjected to one-way ANOVA and LSD post-hoc analysis.

Table 3: Mean values of word recognition score between Group I and Group II

Listening Condition	Group	Word Recognition Score (%)				Significance Value
		Quiet		Noise		
		Mean	SD	Mean	SD	
Monaural CI alone	Group I	72.92	10.55	60.32	9.67	p>0.05
	Group II	72.61	11.45	59.69	9.79	
Bimodal CI+HA	Group I	75.38	10.66	70.46	9.75	p>0.05
	Group II	74.76	11.75	69.53	9.57	



Graph 3: Comparison of mean values of word recognition score between Group I and Group II

The subjects in both the groups obtained significantly lower ($p<0.05$) word recognition performance in noisy environment as compared to quiet environment under both monaural CI alone and bimodal CI+HA listening conditions. However, the effect of noise on word recognition performance was minimized under bimodal CI+HA listening condition as compared to monaural CI alone listening condition in both the groups. The subjects in both the groups obtained higher word recognition performance under bimodal CI+HA listening conditions as compared monaural CI alone listening condition in noisy environment. However, the subjects of Group I could only obtain significant ($p<0.05$) bimodal benefit especially in noisy environment. The subjects of Group II could not obtain significant ($p>0.05$) bimodal benefit in both quiet and noisy environments. Thus it can be inferred that the subjects with greater auditory experience with bimodal stimulation could only obtain significant bimodal benefit.

DISCUSSION

There was a significant effect of noise and bimodal listening condition on the word recognition performance. The subjects demonstrated significantly lower word recognition performance in noisy environments. In spite of significant advances within the field of CI technology related to speech coding strategies, surgical procedures to implant the electrode array, and increasingly positive outcomes [10, 20], the presence of background noise continues to considerably degrade speech understanding even for the best CI performers [6-10]. This is because the electrical stimulation used in the electrode array has several limitations as compared to acoustic hearing provided by hearing aid.

The low-frequency spectral information, which allows for the separation of voices through the use of fundamental frequency (F0) cues, is poorly transmitted through electrical stimulation [8, 21-22]. This is because the electrodes do not reach the low-frequency place because of relatively shallow insertion of electrode array in the cochlea, which severely limits the transfer of low-frequency spectral information and prevents the lower harmonics of pitch to be encoded approximately in the “right place” of the cochlea. As a result, the cochlear place of electrical stimulation is likely to be up-shifted with reference to the cochlear place of stimulation in the normal ear making unlikely this low-frequency spectral information being encoded in the auditory neuron fibers in the apical part of the cochlea [22].

The frequency resolution provided by the electrode array is limited compared with the more precise frequency resolution provided by acoustic hearing [23]. In persons with normal hearing there are 18 so-called critical bands over the frequency range 500 to 5000 Hz [24]. Although the number of critical bands in normal-hearing persons is comparable to the number of contacts in the modern multichannel CI devices, the effective number of independent channels is likely to be fewer in number in CI devices due to channel interaction and limited spatial selectivity [25]. Because of this, even the best CI performers behave as if they are getting only six-to-eight independent channels of spectral information in speech, compared to more precise spectral resolution provided by acoustic hearing [23]. Additionally, physical and physiological factors such as the electrode-nerve interface, nerve survival, and brain plasticity severely limit the actual amount of spectral information to be transmitted to the CI recipients [26].

A limited spectral resolution or little spectral information may be sufficient to understand speech in quiet environment. However, understanding speech in background noise requires spectral resolution much finer than that required for understanding speech in a quiet condition in order to separate speech from noise or to distinguish multiple talkers [27]. Hence, even though the CI users are able to obtain significantly higher levels of speech recognition performance in quiet environment, the presence of background noise continues to significantly degrade speech recognition performance for even the best CI performers [10]. Thus the poor perception of speech under background noise can be attributed to poor representation of low-frequency pitch information and limited spectral resolution provided the CI devices [8-9].

Although there was a significant effect of noise on word recognition performance under both monaural CI alone and bimodal CI+HA listening conditions, the effect of noise was minimized under bimodal CI+HA listening condition compared to monaural CI alone listening condition. The bimodal CI+HA listening condition resulted in an improved word recognition performance compared to monaural CI alone listening condition especially in noisy environment. The bimodal advantage especially in the presence of noise could have risen from combining the low-frequency acoustic information delivered through the HA with electrical information delivered via the CI.

The low-frequency residual acoustic hearing is often superior to electrically stimulated hearing. Although CI can provide good detection of low-frequency sounds, the acoustic hearing, provided by either normal hearing or HA is able to provide more accurate low- frequency information as compared to CI [8]. The F0 cues improve speech recognition in the presence of competing talker even under poor signal-to-noise ratios [28]. The low-frequency pitch information also provides information on voice onset time (VOT) cues which help to distinguish voiced and voiceless consonantal phonemes. On the other hand, the mid-and high-frequency information provided by the CI can provide important linguistic information on place and manner of articulation of consonantal phonemes. Hence, the low-frequency pitch information provided by acoustic hearing might complement the mid-and-high-frequency information provided by the electric hearing through CI to enhance speech intelligibility [7].

Another reason for the bimodal advantage could be that the acoustic stimulation provided by the HA might have provided the subjects to access the finer spectral and temporal pitch cues in the speech signal that are not well resolved by the CI [29]. The spectral resolution of residual low-frequency acoustic hearing presumably is better than that of electric hearing provided by the CI [9, 30-31]. This advantage of spectral resolution in low-frequency acoustic hearing may provide relative benefits in perceiving spectral features of speech sounds, therefore, may lead to improved speech recognition in the presence of noise [22, 32]. The low-frequency information is represented neither by the place of stimulation nor by the pattern of firing of temporal fine structure in CI [7]. As neural responses are highly synchronized to the sound waveform only for low-frequency sounds [33], it is likely that combining low-frequency fine-timing information via HA with high-frequency information via a CI would be more effective in conveying temporal cues [7].

A similar argument has been made many investigators in discussing the potential benefits of using a HA in an implanted ear with a short-electrode array (monaural-bimodal stimulation). They suggested that preserving low-frequency hearing in the implanted ear by inserting a short electrode array and stimulating the apical areas of same cochlea with acoustic information through HA together might provide listeners better spectral and temporal resolution of speech signal compared to using a long electrode array alone [29, 32].

The present study investigated the role of auditory experience with bimodal stimulation on word recognition performance. It was expected that the children with lesser degree of hearing loss in their non-implanted ear would obtain greater bimodal benefit compared to those children with greater degree of hearing loss in their non-implanted ear. However, fortunately, it was observed that the subjects in both the groups obtained significant bimodal benefit and it was further found that there was no significant difference between the groups in terms of this bimodal benefit.

The most common type of sensorineural hearing loss is a loss of hearing sensitivity that increases along with an increase in frequency. As the degree of hearing loss increases, the amount of speech information that can be extracted from an audible signal decreases. However, the degradation of speech information is less severe at low-frequencies compared to high-frequencies even when the degree of hearing loss is greater. This is consistent with the research evidence that the degradation is less severe at the lower-frequencies than at the high-frequencies even though the amount of speech information that can be extracted from an audible signal decreases with increased hearing loss. On an average, an individual with a 100-dB hearing loss at 500 Hz can extract about half the information available to a normal-hearing person from the same amount of audible signal [34].

Thus, the spectral and temporal resolutions are relatively preserved in the low-frequencies compared to the high frequencies [9, 30-31]. Although conventional hearing aids provide insufficient gain in the high-frequency region, a satisfactory access to the low-frequency information can be provided even with greater degree of hearing loss [35]. This could be the reason that the subjects with greater degree of hearing loss also obtained significant bimodal benefit as it was observed in subjects with lesser degree of hearing loss in the present study. A similar argument has been advanced by [21] regarding the potential benefits of using a HA in the non-implanted ear in CI recipients. They have suggested that although speech perception by using a HA alone is not possible, the low-frequency pitch information provided by acoustic hearing complements the mid-and high-frequency information provided by electric hearing to enhance speech intelligibility.

The present study also investigated the role of auditory experience with bimodal stimulation on word recognition performance. As expected, the subjects having a longer duration of auditory experience with bimodal stimulation could only achieve a significant bimodal benefit in the present study. This could be attributed to the reason that there are perceptual incompatibilities between electrical hearing and contralateral acoustic hearing because they differ in terms of pitch, dynamic range and shape of the iso-loudness curves [36]. As a result, the CI recipients might need sufficient auditory experience with bimodal stimulation in order to get adapt to and integrate the two distinct stimuli provided by the devices for central processing [37-38].Thus the perceptual incompatibilities because of differences in mode of stimulation did not seem to interfere with speech recognition in quiet as well as noisy environments in subjects with longer duration of auditory experience with bimodal stimulation in the present study. Although subjects with less auditory experience with bimodal stimulation could not achieve significant bimodal benefit, none of them showed any negative responses due to binaural interference.

CONCLUSIONS

- Despite the differences in the mode of auditory stimulation and perceptual incompatibilities caused by the two devices, the subjects in the present study achieved significant bimodal benefit in terms of the word recognition performance especially in the presence of noise.
- The level of residual hearing in the non-implanted ear does not seem to interfere in obtaining bimodal benefits. The subjects with greater degree of hearing loss in the non-implanted ear also have exhibited significant bimodal benefits similar to subjects with lesser degree of hearing loss.
- Hence, children who receive a unilateral CI should be encouraged to wear a hearing aid in the non-implanted ear irrespective of the level of residual hearing in that ear.
- However, auditory experience with bimodal stimulation seems to play a major role in achieving significant bimodal benefit. The subjects with longer durations of auditory experience with bimodal stimulation could only obtain significant bimodal benefit.
- Hence, children need to be provided with sufficient auditory experience with bimodal stimulation in order to get adapted to the 'incompatibilities' caused by two different stimuli for central processing before assessing the benefits of bimodal stimulation.
- Bimodal stimulation helps in preventing auditory deprivation in the non-implanted ear. Hence, especially in children, we must stimulate both the ears in order to enable them to enjoy some of the benefits of binaural hearing and also avoid an unfavorable situation in future in the ear that has not yet been implanted.
- Thus, the least-expensive and non-invasive technique of bimodal fitting approach can be considered as an effective treatment option for children who are limited to monaural CI for other reasons.

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