Advantages of bimodal stimulation compared to unilateral cochlear implant use in children with hearing loss

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Introduction
Children with a cochlear implant (CI) in one ear and have usable residual hearing in the contralateral ear are candidates for bimodal hearing. By using a hearing aid (HA) in the nonimplanted ear, children can benefit from binaural hearing advantages and auditory deprivation is prevented. The present study aimed to determine the bimodal stimulation advantages in children, especially its effect on speech recognition ability and discover the effect of some factors on bimodal hearing.

Materials and methods
In this study, the participants were 42 CI children age ranged from 5 to 12 years old who used a HA in their contralateral nonimplanted ear for 6 months at least. The parents of the children signed the informed consent.
Early speech perception in Arabic (ESP) test, the developed Arabic word in noise test and Aided audiometry were compared in bimodal fitting condition and CI condition.

Results and discussion
There was a great improvement in both ESP test scores and word in noise test scores in case of bimodal condition over CI alone condition. While on aided sound field audiometry test, there was no statistically significant improvement in the aided tonal threshold between bimodal and CI alone aided threshold.
Factors such as implant age, regularity of HA usage, and amount of residual hearing in the contralateral ear were not affect benefits of bimodal hearing.

Conclusion
Bimodal hearing improves speech perception for children more than monaural hearing with a CI.

Keywords:
bimodal fitting, cochlear implant, hearing loss

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Background

Many children with bilateral hearing loss cannot use bilateral cochlear implants (CIs) because of the high cost. So, unilateral CI is used and if there is residual hearing in the nonimplanted ear, a contralateral hearing aid (HA) is used which called bimodal hearing. bimodal hearing activates the neural pathway and the central processing of binaural hearing [1] Binaural hearing has many advantages as improving speech understanding, especially in noisy environment, sound localization, and decreases listening efforts. Bimodal hearing allows transmission of the lower frequencies acoustically by the HA and transmission of the higher frequencies electrically by the CI. So, CI and HA work complementarily. The combination of low-frequency acoustic information with the signal from the CI also can result in improved sound quality [2] Bimodal fitting improves voice pitch perception which can help to separate different auditory sources. The mechanism by which the BF improves voice pitch perception is that the HA could provide important information since it conveys the low frequencies containing the speaker's fundamental frequency (F0) and first formants (F1), which are not well transmitted by the CI. Low-frequency information is important for both musical and voice pitch perception [3].

Materials and methods

The proposal was reviewed by the IRB of the faculty of medicine, Assiut University and approval by the ethics committee was obtained number (17100977). All data were confidential and not used except for research purposes.

Subjects

Forty-two children with an age range from 5 to 12 years with unilateral CI were included in this study. All of them have residual hearing in the non-implanted

ear and used a HA in the contralateral ear. The children had prelingual sensorineural hearing loss had severe to profound hearing loss in their contralateral non-implanted ear. The parents of the children had signed the informed consent.

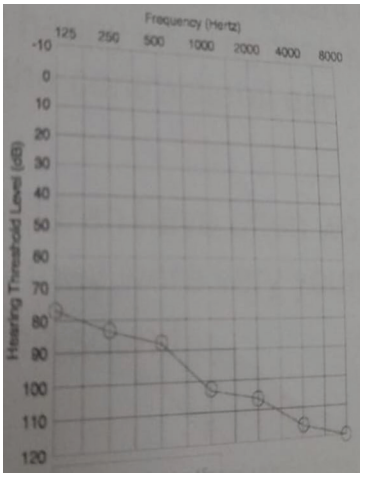
Inclusion criteria:
(1) children with CI in one ear.
(2) Residual hearing in the nonimplanted ear.
(3) Using a HA in the nonimplanted ear for 6 months or more.

Exclusion criteria:
(1) Middle ear effusion.

Equipments
(1) Otoscope using Welch Allyn device.
(2) Tympanometry (Interacoustics AT235, dennmark).
(3) Double wall sound treated booth ('IAC' model 1602).
(4) Pure tone audiometer Madsen model Orbiter 922.
(5) Arabic words in noise (WIN) test: Three lists containing Arabic phonetically balanced words For Kindergarten.
(6) Early speech perception test (ESPT) in Arabic: full color picture cards and a words menu were used.

Methods
(1) A complete history was collected about hearing loss including rehabilitation history about the CI and HA devices using detecting; the age of cochlear implantation, duration of usage, duration and regularity of HA wearing.
(2) Otoscopic examination.
(3) Basic audiological evaluation: included tympanometry to exclude children with middle ear effusion and audiometry.
(4) Unaided pure tone audiometry (PTA) thresholds were done as shown in (Fig. 1) and the threshold average of the three frequencies 500, 1000, and 2000 Hz of the non implanted ear was measured.
(5) Adjustment of the digital HAs of the children according to the pure tone audiometry of the non implanted ears. All of the HAs were with four channels or more.
(6) To balance the loudness between HA and CI. Speech stimuli (65 dB hearing level) were delivered from a speaker opposite to the patient (at the azimuth angle of zero) and the patient was asked to specify the direction of the voice. Then, the loudness in the HA was finally adjusted in a way that the voice was heard from the middle line. The CI mapping was not changed as they all were mapped at the desired auditory levels.

Figure 1



An audiogram of severe to profound sensorineural hearing loss represents the residual hearing of the non implanted ear.

(7) ESP test in Arabic was done to test the abilities of speech perception in bimodal fitting users [4]. The ESP test was designed to assess two main abilities, namely pattern perception and identification of words, whether monosyllabic or trochee words (words formed from two syllables with stress on the first one).
Test subsets were 12 words for Pattern Perception, 12 words for Trochee Identification, and 12 words for Monosyllabic Identification. For each subset, there is a picture card. Every card consisted of 12 pictures. The words were presented to the child by live voice at an intensity level of 60 dB hearing level (HL) and he was asked to point to the picture of the word he heard within the picture cards. According to the number of correct responses the score of the test was obtained. To calculate the score of Pattern Perception subtest, if the child pointed to the correct picture, a score of "2" was given. If the child pointed to a wrong picture but within the same syllable pattern, a score of '1' was given. If the child pointed to a wrong picture and not had the same syllable pattern of the word, a score of "0" was given. for Trochee and Monosyllabic Identification the correct word scored "2" and the wrong word scored "0" [4]
(8) The developed Arabic word in noise (WIN) test was used to investigate speech perception in noise [5]. The children sat at 1 meter from the loudspeaker and they were looking forward during the test. The target speech coming from the speaker at 45° azimuth and noise from the contralateral speaker (noise was presented from the side ipsilateral to the CI). Three lists of 25 monosyllabic Arabic Phonetically Balanced words For Kindergarten [6]. Words were presented at an average of 65 dB HL and the noise level was

at 50 dB HL. WIN test score were calculated as the percentage of right repeated words.

(9) Aided thresholds at speech frequencies 0.5 Hz, 1 kHz, 2 kHz, and 4 kHz were determined in CI alone and bimodal condition in sound-treated rooms ("IAC" model 1602). The threshold was detected by asking the child to raise his hand or by play audiometry method in the aided sound field. Warble tones were used by Calibrated two channels Madsen model Orbiter 922.

Every participant was tested by the three tests: ESP test, WIN test, and aided audiogram by CI only and then by both CI and HA at least after 6 m of use.

Statistical analysis

Categorical variables were described by number and percent (N, %), whereas continuous variables were described by the mean and standard deviation (Mean, SD). Chi-square test is used to compare categorical variables and compare continuous variables by Independent sample t-test. A two-tailed $P < 0.05$ was considered statistically significant. Spearman's rank correlation coefficients were used to determine the statistical correlations between two variables. All analyses were performed with the IBM SPSS 21.0 software.

Results

This study was conducted on 42 children with unilateral CI (5–12 years) with a mean age of 7.09 ± 2.3 SD, 21 males (50%) and 21 females (50%).The HA was fitted in the contralateral ear with residual hearing for 6 months or more. Among 42 children with residual hearing in the non-implanted ear, only 2 children did not attend the follow-up and so their results by bimodal hearing could not be collected. So, we compared the results of 40 children in case of CI alone and then in case of bimodal fitting.

Early speech perception test

Comparison of mean ESPT scores between unilateral CI condition and bimodal fitting condition in pattern perception words, trochee identification, and monosyllabic identification is depicted in Fig. 2.

It can be observed in Fig. 1 that among all the test subsets of ESP are higher in case of bimodal fitting than the case of CI only. There was a highly statistically significant improvement ($P < 0.01$) in the ESPT scores in bimodal fitting ($P = 0.004$ for Pattern perception, 0.008 for Trochee identification, and 0.001 for Monosyllabic identification) as shown in (Table 1).

Word in noise test

Results of comparison of mean WIN score between CI alone condition and bimodal condition in Fig. 3. It can be observed from Fig. 3 that the speech perception in noise in case of bimodal fitting is better than in the case of CI alone.

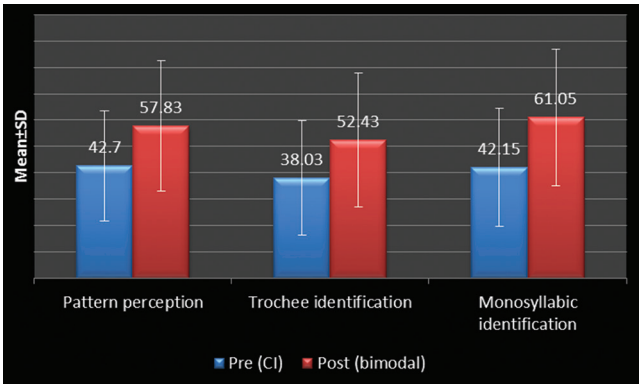
There was a statically significant improvement in WIN score after using bimodal hearing in (Table 2).

Aided audiometry test

A comparison of the mean aided threshold between fitting of CI alone and bimodal fitting at octave frequencies is presented in Fig. 4. There is no statistically significant improvement at any frequency as the *P* value is more than 0.05 of all tested frequencies.

We noted that among 40 studied participants, 14 children (35%) showed decreased threshold in bimodal fitting by 5 to10 dB at 500 Hz and 4000 Hz. While 15 children (37.5%) showed decreased threshold at 1000 Hz and 11 children (27.5%) at 2000 Hz.

Figure 2



Mean ESPT score of CI only condition and bimodal condition.

Table 1 Comparison of mean ESPT scores between CI alone condition and bimodal condition in pattern perception words, trochee identification and monosyllabic identification

Early speech perception test	CI Mean±SD	Bimodal Mean±SD	*P*
Pattern perception	42.7±20.9	57.83±24.71	0.004**
Trochee identification	38.03±21.73	52.43±25.31	0.008**
Monosyllabic identification	42.15±22.33	61.05±25.98	0.001**

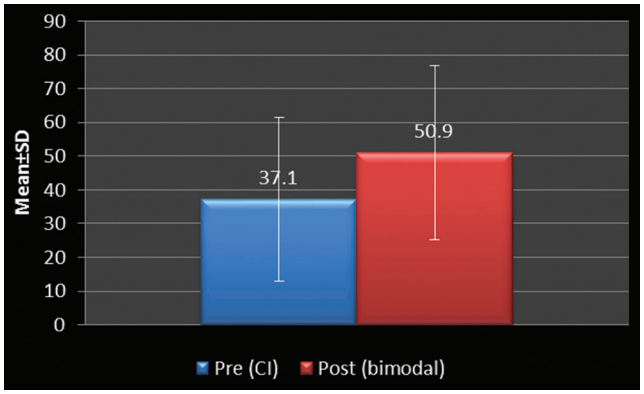
Independent samples *T* Test, *Statistically significant difference ($P<0.05$), **Highly statistically significant difference ($P<0.01$)

Table 2 Comparison of mean WIN score between CI alone condition and bimodal condition

	Cochlear implant Mean±SD	Bimodal Mean±SD	*P*
WIN	37.1±24.24	50.9±25.83	0.016*

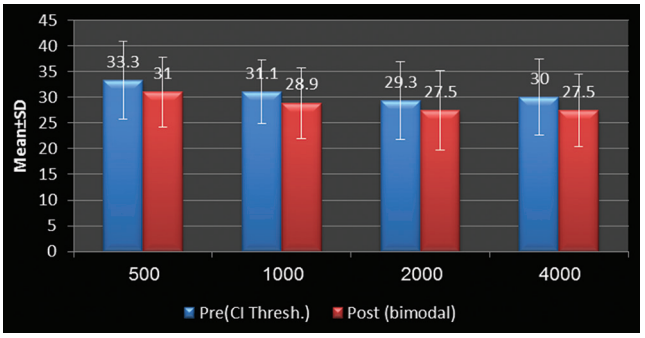
Independent samples *T* Test, *Statistically significant difference ($P<0.05$), **Highly statistically significant difference ($P<0.01$)

Figure 3



Mean WIN score between CI alone condition and bimodal condition.

Figure 4



Mean aided threshold between CI alone condition and bimodal condition at octave frequencies.

Variables that may affect the bimodal fitting outcome

(1) Age of CI ation fitting
There was no statistically significant correlation between the regularity of HA usage and the results of both the ESPT and WIN test.

(2) The regularity of HA usage on the contralateral ear:
There was no statistically significant correlation between the regularity of HA usage and the results of both ESP and WIN tests.

(3) Correlation between average pure tone audiometry thresholds of the non-implanted ear and bimodal benefit:

There was no statistically significant correlation between the average PTA of non-implanted ears and the results of both ESPT and WIN tests.

Discussion

The current study aimed to determine the advantages of bimodal stimulation in 42 children. They fitted with a CI in one ear and a HA in the contralateral ear. The children were evaluated in case of CI alone and in case of bimodal fitting after 6 months of regular use.

(1) Our results of ESP Test showed a highly statistically significant improvement ($P < 0.01$) in case of bimodal fitting in pattern, trochee, and Monosyllabic identification as shown in [Table 1]. These results are in accordance with that of Nilakantan *et al.* [7].
The current study also agreed with a comparative study by Belsare *et al.* (2020) where comparing between CI alone conditions and bimodal stimulation by (ESP) test in Marathi [8].
The better results in case of bimodal hearing may be due to adding the low frequency cues by the HA that not be provided completely by the CI. Also, HA allows children to benefit from all advantages of binaural hearing. Additionally, in our study, it was noted that the improvement in the mean score of monosyllabic and the mean score of pattern perception was more than that of trochee identification. The improvement in the mean score of monosyllabic words may be due to the familiarity with the monosyllabic words used in the Arabic (ESP) test.

(2) The results of the current study showed statistically significant improvement in WIN test scores in bimodal hearing ($P = 0.016$) as shown in [Table 2]. This is similar to the results of a studies conducted by Jang *et al.* [9], Morera *et al.* [10] and the recent study by Lotfi *et al.* [11].
The significant improvement of words perception in noise is mostly due to the improvement of the three major advantages of binaural hearing which are the head shadow effect, binaural release from masking and binaural redundancy which enhances hearing in noise by increasing the signal to noise ratio (SNR) in one ear than the other [11]

(3) In the current study, we compared the aided threshold by using a CI alone and after at least 6 months of bimodal by comparing aided threshold of speech frequencies of 500, 1000, 2000, and 4000 Hz. in Fig. 4, we found that the mean improvement in aided threshold is statistically non-significant at all frequencies.
This result is different from the study done by Belsare *et al.* where results showed significant improvement in case of bimodal hearing for aided thresholds at 1000, 2000, and 4000 Hz ($P < 0.05$) [8].
We noted that among 40 studied participants, there was decrease in the aided threshold by 5 to 10 dB at 500 Hz and 4000 Hz in 14 children (35%). While there was decrease in the aided threshold by 5 to 10 dB at 1000 Hz in 15 children (37.5%) and 11 children (27.5%) at 2000 Hz. Present results were near to the previous study of Belsare *et al.* [8] where the improvement of the aided threshold was in about 50% of the participant, but this

improvement is also statistically non-significant. A Possible explanation for the less improvement of aided threshold in bimodal hearing than CI alone threshold is that decreasing the amount of residual hearing in the non-implanted ear of some children, so the maximum gain of the HAs was not enough to improve the aided threshold than CI alone.

(4) Three clinical variables: the duration of using CI, an average of unaided PTA thresholds, and the regularity of using the HA were collected and studied for all children. These factors were expected to affect the variability in speech perception in noise and quiet. This study found that these factors have no correlation between these factors and the results of both ESP and WIN tests.
Belsare *et al.* as well as Ching *et al.* also found the same results as there was no association between the age of CI fitting or duration of HA usage and the improvement of speech perception [8,12]. However, present results are not agreed with that of Armstrong *et al.*, who stated that the duration of HA usage affects the benefit from binaural hearing [13].
   (a) Unaided pure tone audiometry (PTA) thresholds of the non-implanted ear were done and the average of unaided threshold in decibels was measured at the frequencies of 500, 1000, and 2000 Hz was used.

The current study found that there was a weak correlation between unaided pure tone averages of 500, 1000, and 2000 Hz and the scores of ESP and WIN tests scores. Blamey *et al.* states that the unaided PTA is not an predictor of the improvement by bimodal fitting [14].

Also, there was a nonsignificant correlation between bimodal benefit and unaided thresholds in the study of Liu *et al.* on Mandarin-speaking Chinese children with bimodal fitting [15].

Conclusion

According to the results, adding a HA to unilateral CI children with residual hearing in the non-implanted ear provided an obvious improvement in speech intelligibility in quiet by improving ESP test scores and speech perception in noise by improving WIN Test scores versus CI alone. Factors such as implant age, regularity of HA usage, and amount of residual hearing in the contralateral ear were not significantly associated with bimodal benefit.

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Conflicts of interest
None declared.

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