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Binaural hearing advantages for children with bimodal fitting

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ABSTRACT

Objectives: Bimodal fitting (BF) allows children with cochlear implant to benefit from binaural hearing advantages. Three major binaural hearing advantages, which enhance hearing function of people with normal hearing, are head shadow effect (HSE), binaural squelch effect (BSQ) and binaural summation effect (BSU). This study in pediatric patients attempting to measure the auditory benefits of bimodal stimulation in children with long-standing use of a cochlear implant (CI), and residual hearing on the contralateral side.
Methods: This cross-sectional study investigated binaural advantages in 24 children of 8–12 years who had undergone cochlear implantation in a cochlear implant center in Tehran and continuously used BF. Improved score of speech perception in noise (SPiN) under BF condition, as compared to the application of cochlear implant alone, was a binaural advantage found in this study. Each binaural advantage was measured by obtaining the SPiN score under different listening and noise conditions, using relevant formulas. The measured value of each advantage reflects the improved score of SPiN, caused by that certain advantage.
Results: In this study, improved mean SPiN score caused by the HSE, BSQ and BSU was, respectively, 3.13, 1.42 and 2.04 dB, indicating greater binaural advantages and hence improved SPiN, under BF condition in comparison with cochlear implant alone.
Conclusion: Children with unilateral cochlear implant and measurable residual hearing in non-implanted ear can benefit from binaural advantages and better SPiN when hearing aid is used in the unaided ear.

1. Introduction

When bilateral cochlear implant cannot be used for patients with bilateral hearing impairment, a hearing aid can be used in their non-implanted ear with residual hearing. This is because patients with bilateral hearing loss need bilateral stimulation to develop the neural pathway required for central processing of binaural hearing [1]. In this case, the cochlear implant stimulates one ear with electrical signals and the hearing aid sends the amplified acoustical signals to the other ear. The combination of these two inputs is called bimodal fitting.

In bimodal fitting, binaural hearing results in auditory stream segregation and improved spatial hearing efficiency and affects different skills including SPiN. Various efficiency studies into BF users have reported some binaural advantages, such as localization and improved speech perception in silence and noise [1].

Although it has been presented many advantages for binaural hearing, psychoacoustic articles provide three major advantages: head shadow effect (HSE), binaural squelch effect (BSQ) and binaural summation effect (BSU), which enhance hearing performance in patients with normal hearing [2]. HSE occurs when the sources of a target signal, such as speech and an unwanted signal (noise) are spatially segregated. When the ear opposite to the noise source is blocked by the HSE, the interaural level difference (ILD) causes signal-to-noise ratio mismatch in both ears. The ear opposite to the noise side generally has a higher signal-to-noise ratio; therefore, the target signal is more understandable in this ear than the noise-side ear [3]. BSQ or Release from Masking occurs when the signal and unwanted noise are spatially separated. This release from masking in the presence of noise greatly contributes to the improvement of speech perception [4]. BSU or binaural redundancy is the result of two samples of the same signal from which meaningful information is extracted. In contrast to the BSQ, the BSU does not require spatial separation of noise and signal [5]. The BSQ needs central auditory processing and results in improved loudness perception when a signal is heard bilaterally, instead of unilaterally [3].

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To separate competitive voice sources, people with normal hearing use the speech fundamental frequency[1](F0) and information of temporal fine structure in speech.[2] This information results in enhancement of speech recognition in the presence of fluctuating and complex background noise. In fact, the gap in audible speech stream can be filled by combining additional speech information with the listener's knowledge. This function is known as a form of release from masking (RM). The cochlear implant users not only cannot use F0 differences to separate the target speech from the competing noise, but also cannot benefit from the RM [6]. This is because of limited processing strategies of cochlear implant, which transmit speech signals with low spectral resolution and without temporal fine structure. In addition, such limitations as spectral smearing, caused by the channel interaction, makes it difficult for the users to separate target signal from the background noise [7,8].

Moreover; People with unilateral cochlear implant have lower localization and spatial hearing abilities compare to their normal peers; however, this weaknesses can be overcome by using bimodal fitting as it provides them with binaural advantages and enable them to receive more speech signals, which improves the spatial segregation of signal from noise and speech perception. This is because; in BF the addition of hearing aid to cochlear implant amplifies low-frequency signals by combining them with cochlear implant signals, thereby improving the segregation process of competing voices. This process leads to signal segregation through binaural processing mechanisms [9].

The majority of studies about binaural hearing advantages have been conducted on adults and there are scant relevant studies into pediatric BF user. The literature results are also uncertain, specifically with respect to the effects of HSE, BSQ and BSU on SPiN in children. Therefore, more comprehensive studies are required and the current study is supposed to achieve this result.

2. Materials and methods

This cross-sectional study was conducted in a cochlear implant center in Tehran in 2018. In the study, 24 pre-lingually deafened children (8–12 years) with cochlear implant who continuously used bimodal fitting were enrolled. The inclusion criteria consisted: those children who receive their implant before the age of 2.5 years, the lack of middle-ear infection, general health, normative intelligence, ability to take tests, mean binaural aided thresholds of higher than 55 dBHL in speech frequencies of 0.5, 1, 2 and 4 kHz (hearing aid and cochlear implant together), Speech perception score (in quiet) of > 70%, the lack of auditory neuropathy disorder, at least six-month of using hearing aid in the non-implanted ear and taking hearing aid at least for 6 h per day.

After obtaining the informed written consent of the participants and their parents, the investigations performed in 2–3 sessions, as follows:

1. Collecting medical history and initial clinical examinations including otoscopy and tympanometry.
2. Adjusting hearing aid and ear molds: the hearing aids were adjusted according to the NAL-NL1, a recommended fitting formula for BF cases, to provide desired frequency response [10].
3. Mapping cochlear implant: since this study aimed at investigating speech perception ability of participants in daily life conditions, the patients were evaluated when their speech processors was set at the normal everyday program that they would normally use for everyday listening
4. The loudness balance between two ears: to balance the loudness between hearing aid and cochlear implant, a speech stimuli (65 dB SPL) was 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 hearing aid was finally adjusted in a way that the voice was heard from the middle line. The cochlear implant mapping was not changed as they all were mapped at the desired auditory levels [11].
5. Pure tone audiometry: to evaluate the audiometric thresholds in BF users, the pure tone audiometry was done binaurally (using hearing aid and cochlear implant together) in the free field with a speaker at 0° azimuth [12] and the mean threshold in speech frequencies of 0.5, 1, 2 and 4 kHz was determined.
6. Speech audiometry: the word reception threshold (WRT) and speech discrimination score (SDS) tests were used to investigate speech perception capacities.
7. Assessing binaural advantages using the SPiN test: a binaural advantage found in this study was the improved SPiN score in BF condition as compared to cochlear implant alone. The effects of each binaural advantage; HSE, BSQ and BSU, were assessed through SPiN measurements under different listening and noise conditions and using the findings in respective equations. The measured value of each advantage reflects the improved score of SPiN, caused by that certain advantage.

To investigate the binaural advantages, the word reception threshold test was conducted using Persian Spondaic words in both silence and four-talker babble noise, which is close to reality, under different listening conditions. The noise level was at 65dBSPL (daily noise exposure). The patients were asked to look ahead during the test and avoid moving head and neck; otherwise, the test was repeated. These assessments were done by sitting the patient on a chair while the target speech was coming from a speaker at 0° azimuth. Changes in the intensity level of the speech was applied until the word reception threshold (WRT) (the level at which the patient hears the two-syllable words 50% of the time) was obtained through using a standard list of Persian two-syllable words. In this way, the word reception threshold was investigated under different hearing and noise conditions. The noise conditions (NC) of the test were as follows:

- The target speech coming from the speaker at 0° azimuth (S0) was provided in silence: (S0)
- The target speech coming from the speaker at 0° azimuth (S0), along with the noise from the same speaker (N0): (S0N0)
- The target speech coming from the speaker at 0° azimuth (S0), along with the noise from the contralateral/Ipsilateral speaker (N-90)/(N90): (S0N-90)/(S0N90)
- The target speech coming from the speaker at 90° azimuth (S90), along with the noise from the contralateral/Ipsilateral speaker (N-90)/(N90): (S90N-90)/(S90N90)

These tests were conducted at different listening conditions (LC):

- Only cochlear implant was on,
- Only hearing aid was on,
- Both hearing aid and cochlear implant were on.

As a result, each user was evaluated in different positions. To avoid the probable order effect, different test conditions and positions were selected completely random. Then the word reception threshold was calculated as a function of listening conditions and different noise conditions [13]. Three major binaural advantages including HSE, BSQ and BSU were calculated as follows, using the obtained scores [11]. The HSE was obtained by subtracting the unilateral WRT, when the noise was coming from the opposite site, from the WRT when the noise was coming from the same side, according to equation (1).

$$\text{HS (LC)} = \text{WRT (LC, ipsi)} - \text{WRT (LC, contra)} \tag{1}$$

[1] The most basic repeatable frequency in acoustic range of speech.

[2] Rapid changes in the range of speech stimulus over time and close to the central frequency of the stimulus.

The BSQ was obtained from subtracting WRT score when both devices were used, from the WRT score when only one device was used and the noise was coming from the other side, according to equation (2).

$$\text{BSQ (NC)} = \text{WRT (contra, NC)-WRT (both, NC)} \tag{2}$$

The BSU was obtained from subtracting the WRT score when both devices were used, from the WRT score when only one device was used under S0N0 condition (when there were identical stimuli in both ears), according to equation (3).

$$\text{BSU (LC)} = \text{WRT (LC, S0N0)-WRT (Both, S0N0)} \tag{3}$$

In this study, the binaural advantages were measured with respect to the ear with cochlear implant. In other words, the term ipsilateral is used when the noise source is at the same side of cochlear implant and contralateral when the noise source is located opposite to the ear with cochlear implant. Moreover, the positive values from calculations indicate the improvement of speech perception with binaural hearing as compared to the unilateral hearing (using cochlear implant alone) [14].

It is worth to say that statistical analysis of this research was done by SPSS (version 19, SPSS Inc., Chicago, IL, USA). Average and standard deviation were used to describe the results. In order to control the independent variables, multivariate analysis were run for comparing BF vs CI alone conditions.

3. Results

In this study, 24 BF users of 8–12years (14 boys and 10 girls) with the mean age of 10.96 ± 1.04 years were enrolled. All of them were prelingually deafened patients with cochlear Nucleus processor. Being illustrated in Table 1, demographic and audiometric characteristics of the participants were sex, age, Implanted ear, type of hearing aid, age at Implant surgery (month), duration of using hearing aid contra lateral to the cochlear implant (year), mean pure tone audiometry threshold at 0.5, 1, 2 and 4 kHz in the free field at different conditions (in non-implant side, with hearing aid, with cochlear implant, with bimodal fitting), WRT score and SDS score. The audiometric characteristics of the subjects, are elucidated in multi drawing audiograms in Fig. 1.

The three major binaural advantages (HSE, BSQ and BSU) were evaluated in all participates. The mean values are provided in Table 2. The obtained values indicate the improved speech perception under bimodal condition in comparison with cochlear implant alone. In all participants, the HSE was measurable, BSQ was zero in 7 participants and BSU was measurable in all participants, except one.

BF vs CI alone conditions were compared and in order to control the independent variables, multivariate analysis were run. The results are presented in Table 3. In all conditions the BF results are better and there is significant difference between BF and CI conditions (Fig. 2).

4. Discussion

4.1. Head shadow effect (HSE)

In this study, the mean HSE was 3.13 dB (2.93 for boys and 3.40 for girls). Results from previous studies into HSE are as follows:

In literature about normal hearing subjects, the HSE was obtained between 8.9 and 10.7 dB [15,16]. For those people with hearing impairment and mean auditory thresholds of about 38 dB, the HSE was approximately 5.6–8.5 dB [15,17]. Studies into binaural advantages in patients with bilateral cochlear implants have reported HSE of 8.1, 6.8 and 6.4 dB [11,14,18]. A similar study into binaural hearing advantages in adults with BF has reported the HSE value of 6.7 dB [11].

Although HSE in the current study was lower than previous studies, it improved speech perception. The interaural level difference (ILD) results in a mismatch signal-to-noise ratio between two ears when an ear is left out of the noise source due to the effect of the head shadow. As a result, HSE is characterized by an individual's ability to detect ILD. In the present study, improved speech perception caused by HSE indicates that ILD can be maintained even when an ear is only stimulated by frequencies lower than 500 Hz [19]. Differences between our findings and some literature results can be due to several factors. For example, since the participants were children, their head size was smaller

Table 1
Participant's demographic and audiometric characteristics.

	Sex	Ear	Hearing aid (H.A)	Age (year)	Implant surgery age (month)	H.A duration (year)	PTA in nonimplanted ear	PTA with H.A	PTA with CI	PTA Bimodal	WRT Bimodal	SDS Bimodal
1	F	R	Swift120	11	26	2	105	76	44	40	45	80
2	M	L	Naida III	12	22	4	106	69	51	46	50	84
3	M	R	Naida III	10	24	7	94	45	33	32	35	92
4	M	R	Nitro 7	11	25	2	106	73	39	37	40	92
5	F	R	Swift120	12	27	3	107	78	46	42	40	88
6	M	L	Naida I	12	23	5	108	71	53	48	50	88
7	M	R	Chilli 5	11	25	8	96	47	35	34	50	92
8	F	R	Nitro 5	12	26	3	109	75	41	39	40	92
9	M	R	Chilli 5	11	22	2	100	71	40	38	45	88
10	M	L	Naida I	12	22	4	102	67	49	44	50	80
11	F	R	Naida III	10	24	7	92	43	33	32	50	92
12	F	R	Naida III	11	25	2	103	73	39	37	40	92
13	M	L	Naida I	12	23	4	108	73	55	50	45	88
14	F	R	Chilli 5	11	25	8	98	49	37	36	50	84
15	M	R	Nitro 5	12	28	4	111	77	43	41	35	92
16	M	R	Chilli 7	9	27	5	105	75	45	43	40	88
17	M	L	Naida I	12	22	4	102	67	49	44	45	88
18	F	R	Naida I	9	23	6	92	41	32	32	55	76
19	F	R	Naida III	9	25	2	102	72	38	36	50	92
20	F	R	Swift120	11	27	2	106	77	45	41	55	92
21	M	L	Naida III	12	23	4	107	70	52	47	45	80
22	M	R	Naida III	10	25	7	95	46	32	33	50	84
23	F	R	Nitro 7	11	26	2	107	74	40	38	35	92
24	M	R	Chilli 7	10	22	2	95	48	40	43	40	88
Minimum				9		2	92	41	32	32	35	76
Maximum				12		8	111	78	55	50	55	92
Mean				10.96		4.12	102.33	64.88	42.13	39.71	45.00	87.67
Std. deviation				1.042		2.071	5.746	13.039	6.886	5.271	6.079	4.851

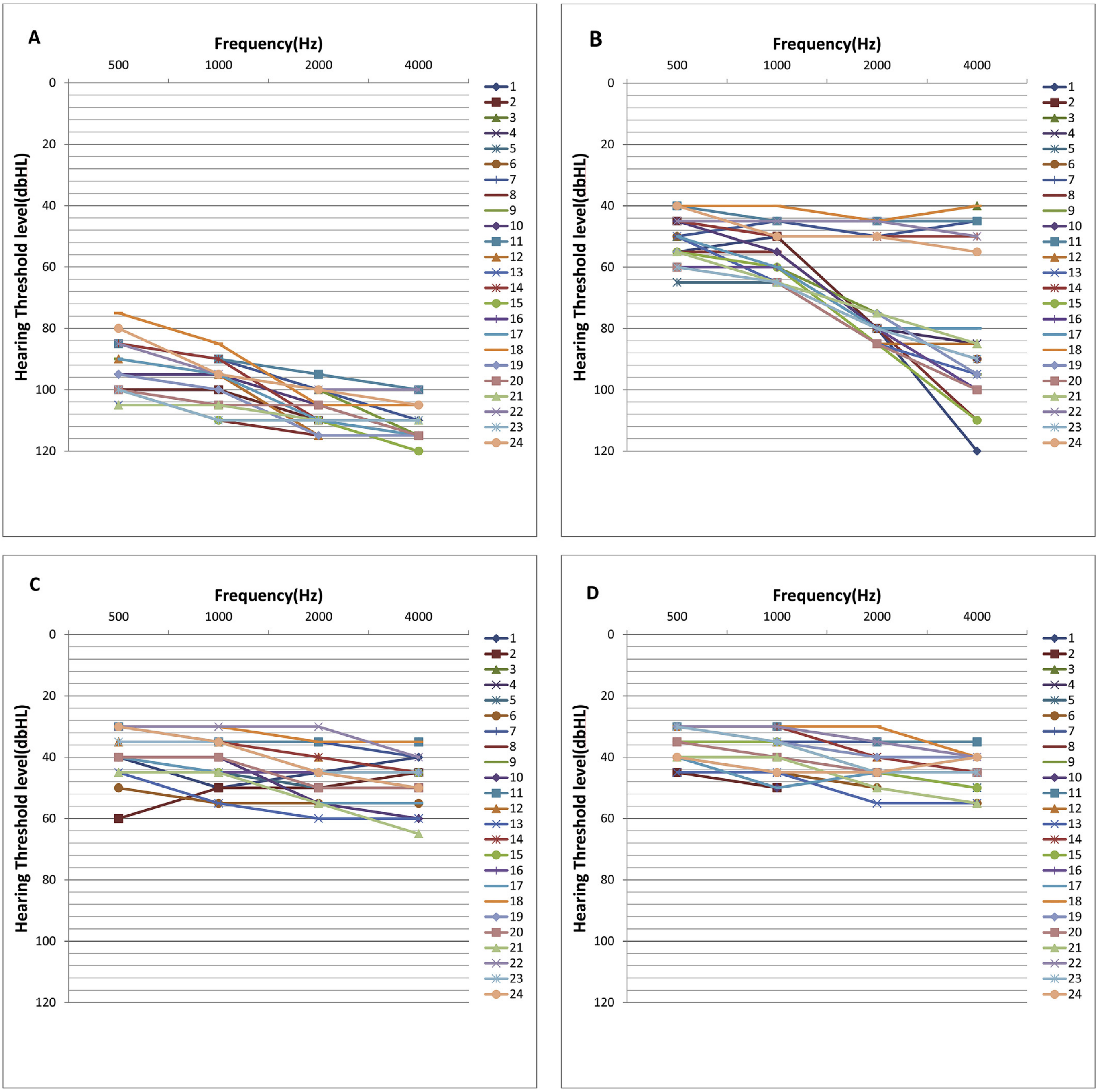

Fig. 1. Multi drawing Audiograms in different conditions: A: In nonimplanted ears with headphone. B: In free field with hearing aid. C: In free field with cochlear implant. D: In free field with bimodal fitting.

Table 2

	Sex	N	Mean	Std. Deviation
HS	Male	14	2.93	.997
	Female	10	3.40	.966
BSU	Male	14	1.93	.616
	Female	10	2.20	.632
BSQ	Male	14	1.36	1.082
	Female	10	1.50	.850

Mean value and std. deviation of Head Shadow Effect (HSE), Binaural squelch effect (BSQ), Binaural Summation effect (BSU) in male and female participants.

than the adult participants in other studies, which could affect the HSE. Moreover, the cochlear implant and hearing aid microphones are located over the auricle. Therefore, the spectral and temporal cues naturally delivered by auricle are omitted in these patients so the location of microphone can reduce binaural advantages in BF patients relative to normal hearing subjects. Furthermore, difference between the current and previous studies can be due to the difference in speech test materials employed to investigate speech perception capacity. Previous studies have used sentence perception tests; whereas, the current study used word recognition test, using two-syllable words.

4.2. Binaural squelch effect (BSQ)

In this study, the mean BSQ was 1.42 dB (1.36 for boys and 1.50 for girls). People with normal hearing had the BSQ between 2.0 and 4.9 dB

Table 3
Descriptive Statistics: WRT at different listening and noise conditions.

	Minimum	Maximum	Mean	Std. Deviation	Sig.[a]
WRT CI S0	40	58	49.38	5.882	0.000
WRT BF S0	35	55	45.00	6.079	
WRT CI S0N0	40	58	51.00	5.603	0.000
WRT BF S0N0	38	57	49.42	6.093	
WRT CI S0N90	40	60	53.58	5.785	0.032
WRT BF S0N90	39	62	52.87	5.973	
WRT CI S0N-90	40	55	49.88	5.228	0.000
WRT BF S0N-90	38	54	48.25	4.848	
WRT CI S90N90	45	60	54.29	4.982	0.000
WRT BF S90N90	42	58	51.33	4.546	
WRT CI S90N-90	42	57	50.79	4.263	0.000
WRT BF S90N-90	38	54	48.13	4.803	

[a] Multivariate measurement.

[15,16]. In people with hearing impairment and mean auditory threshold of about 38 dB, the BSQ was approximately 1.7–3 dB [15,17]. Studies into binaural hearing advantages in patients with bilateral cochlear implant have reported BSQ between 0.9 and 1.9 dB [11,14,18]. Lower BSQ in people with bilateral cochlear implant could be due to the fact that they benefit less from interaural time difference (ITD) [18,20]. A similar study into binaural hearing advantages in adults with BF has reported the BSQ of 2.9 dB [11]. The difference in results suggests further investigations into the effect of BSQ in speech perception of BF users. According to Schafer (2011), BSQ may have different effects on BF users ability, It can be very small, sometimes visible and significant and sometimes completely removed [21].The obtained results in the present study (zero effect of BSQ in 7 participants) confirm Schafer's report.

4.3. Binaural summation effect (BSU)

In this study, the mean BSU was 2.04 dB (1.93 for boys and 2.20 for girls). These findings are similar to results from people with normal hearing in whom the BSU was between 1.1 and 1.9 dB [16,22]. These findings are also consistent with results from hearing-impaired people with the auditory threshold of approximately 38 dB and BSU of 1–2 dB [15,17]. Studies into binaural advantages in patients with bilateral cochlear implant have reported that BSU varied between 1.9 and 2.5 dB; it is comparable with the findings of the current study [11,14,18]. A similar study into binaural advantages in BF adults has reported the BSU of 7.6 dB, which is significantly different from the current study [11].

Accordingly, the difference between our results and literature results can be attributed to the differences in the age group and employed speech perception tests. Although BSU requires central processing and improves loudness perception, when the same signal is listened by both ears instead of one ear [3], our findings showed that BF users can benefit, even slightly, from redundancy information from both ears. As a result, they can have better SPiN. In other words, the transfer of low-frequency acoustic signals by hearing aids can amplify high-frequency information transferred by cochlear implant [3].

4.4. BF vs CI alone conditions

The mechanism of binaural advantage in BF users depends on their ability to integrate speech redundancy information in the acoustic input with speech information in the electric input [23]. The majority of relevant studies have reported improved hearing function with BF as compared to cochlear implant alone. Results also show that at least 50% of people with residual hearing in non-implanted ear (a threshold of 90 dB and slightly better at 500 Hz) prefer using hearing aid in the non-implanted ear [24]. The results of current study as showing better scores in BF conditions in compare to CI alone, are consistent with previous investigations.

There are various reports about BF benefits for speech perception. Many studies have reported the superiority of BF over unilaterally hearing for speech perception in silence [1,25–29]. In addition to many reports on the improvement of SPiN among BF users [1,26,29–37], there are some contradictory reports. For example, Mok et al. (2006) reported poor hearing function in some people with hearing aid in one ear and cochlear implant in the other ear. Amplification of mid and high frequencies by hearing aids can interfere with cochlear implant in the other ear [38].

5. Conclusion

Regarding the findings on binaural advantages in BF users, it seems that pediatric unilateral cochlear implant users with measurable residual hearing in unaided ear can enjoy binaural advantages when they use hearing aid and a substantial benefit in SPiN is offered in BF condition vs cochlear implant alone which enhance the performance of the subjects.

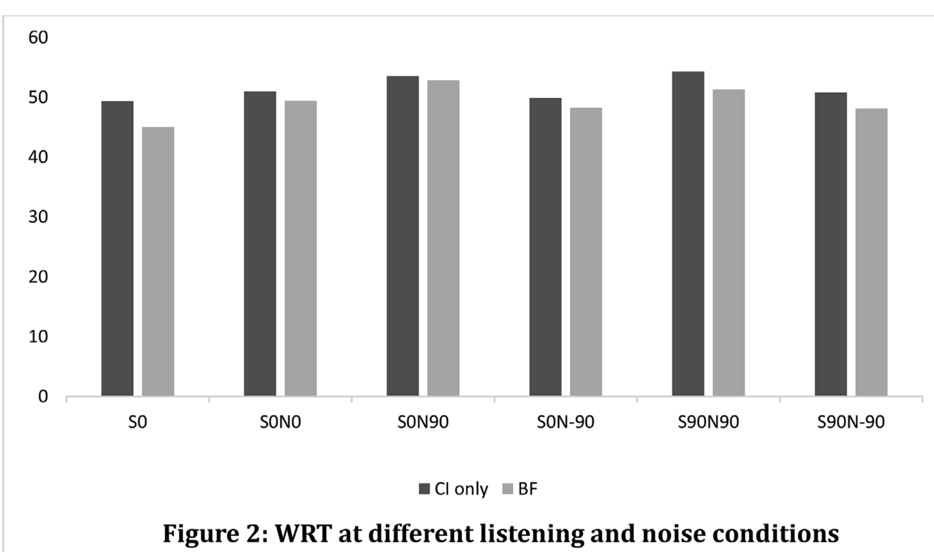

Fig. 2. WRT at different listening and noise conditions.

Declaration of interest

We have no conflict(s) of interest to declare. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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