Audiology

Binaural squelch and head shadow effects in children with unilateral cochlear implants and contralateral hearing aids

Gli effetti squelch binaurale e ombra nei bambini con impianto cocleare monolaterale e protesi acustica controlaterale

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SUMMARY

The aim of this study was to investigate the amount of binaural squelch effect (BSE) and head shadow effect (HSE) in children who use unilateral cochlear implants (CI) and contralateral hearing aids (HA). The study group consisted of 19 CI recipient children who consistently wore a contralateral HA. Speech sounds were used to evaluate speech perception performance in noise. Testing was performed in three listening conditions: (1) bimodal listening with noise source on HA side; (2) CI only with noise source contralaterally (HA off); (3) CI only with noise source on the CI side. Statistical analysis revealed a significant difference between the three listening conditions and post hoc tests indicated significant differences for all pairwise comparisons (p < 0.001). The average BSE and HSE were 11.8% and 17.1% respectively. The majority of bimodal CI users showed BSE and HSE with significant speech perception improvement in the presence of noise.

KEY WORDS: Cochlear implants • Children • Bimodal benefit • Binaural squelch effect • Head shadow effect

RIASSUNTO

Lo scopo di questo studio è stato quello di indagare il grado di effetto squelch binaurale (BSE) e di effetto ombra (HSE) nei bambini che fanno uso di impianto cocleare (CI) e protesi acustica controlaterale (HA). Sono stati arruolati 19 bambini con CI che indossavano regolarmente una HA. Per valutare la performance vocale in presenza di rumore è stato utilizzato un test di identificazione vocalica. Il test è stato eseguito in tre condizioni di ascolto: (1) ascolto bimodale con sorgente di rumore sul lato HA; (2) ascolto con CI con sorgente di rumore sul lato HA; (3) ascolto con CI con sorgente di rumore sul lato CI. I valori medi di BSE e di HSE osservati sono 11.8% e 17.1% rispettivamente. L'analisi statistica condotta ha evidenziato una differenza significativa sia nel confronto tra le tre condizioni di ascolto che per l'analisi post-hoc (p < 0.001). In conclusione, la maggioranza dei bambini con CI hanno mostrato BSE ed HSE con un miglioramento significativo nella percezione vocale in presenza di rumore.

PAROLE CHIAVE: *Impianto cocleare • Bambini • Beneficio bimodale • Effetto squelch • Effetto ombra*

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Introduction

It is well known that binaural hearing provides important benefits over monaural hearing, especially under challenging listening conditions [1 2]. Two basic effects that involve advantages for binaural hearing are binaural squelch effect (BSE) and head shadow effect (HSE). BSE refers to the capacity of the central auditory system to process the stimuli received from each ear and to reproduce it with a higher signal-to-noise ratio (SNR) by comparing interaural time and intensity differences. On the other hand, HSE results from the physical placement of the head which acts as an acoustic barrier and leads to an increase in SNR in the ear far from the noise when signal and noise are spatially separate. Research in normal hearing subjects indicated a 3 dB improvement in BSE for the binaural speech recognition threshold and an average increase of 3 dB SNR for HSE which is more dominant for attenuation of high frequencies and can cause even 8 to 10 dB of improvement [3].

One main advantage of binaural hearing is the improvement in speech perception in the presence of noise, which is a common downfall with cochlear implant (CI) recipients. Current CI technology offers good opportunities for formal and informal language acquisition in deaf children [4 5] as well as good speech understanding in quiet environments in postlingually deafened adults [6], but it still remains insufficient to provide fine acoustic information especially in the low frequency (LF) domain that may contribute to better speech perception in noise [7].

Over the past years, the trend in cochlear implantation has been the extension of indications to severe as opposed to uniquely profound hearing losses. On the other hand, cochlear implantation is still performed unilaterally in several countries due to economic reasons. Therefore, an increasing number of CI recipients wear a hearing aid (HA) to make use of LF residual hearing on the contralateral side. Hence, contralateral HA use offers an alternative to bilateral cochlear implantation in that unilateral CI recipients benefit from the LF cues provided through acoustic signals from contralateral HA in addition to electrical signals from the CI. This has been termed as "bimodal benefit" [8].

Bimodal benefit in CI recipients has recently received much attention, and previous studies have shown its significant positive effect on speech recognition in noise and on functional performance in daily life as well as on the improvement of localisation and music perception skills [3 9-11]. However, these studies have been mostly carried out among adult users and there are relatively limited results in children [12-14] due to difficulties in testing young children under challenging listening conditions and obtaining robust outcomes: e.g. Beijen et al. [13] and Mok et al. [15] studied the bimodal benefit in children using a word recognition test in quiet and/or in noise, where both reflected significantly better outcomes under bimodal rather than CI alone listening conditions. However, in both studies the difficulty of the test task did not enable recruitment of children younger than 6 years.

On the other hand, some studies revealed findings for CI recipient adults showing, more specifically, BSE and HSE with significant improvement in speech perception in noise [16-18]. However, to our knowledge, so far there are only two studies that have investigated HSE in bimodal CI recipient children, with discordant outcomes. Ching et al. [19] indicated a significant HSE for sentence recognition in noise where speech and noise were presented separately at ± 60º azimuth, whereas Mok et al. [15] did not find any significant HSE for word recognition outcomes when noise was presented ipsilaterally to CI or from 0° azimuth. Similarly, specific outcomes for BSE in children were very limited. Ching et al. [20] reported limited access to binaural squelch due to the deficient capacity of current CI technology to represent timing information and limitations of CI users to make use of interaural time difference cues.

The aim of the present study was to investigate the amount of BSE and HSE in children who used unilateral CI and contralateral HA as well as study the potential predictors of outcomes such as unaided/aided audiological outcomes, duration of CI experience and duration of HA experience prior to cochlear implantation. This study used the Auditory Speech Sounds Evaluation (A§E) test [21] that presented some speech sounds in the presence of noise in order to compare speech perception skills under bimodal and unilateral listening conditions.

Materials and methods

Participants

The study group consisted of 19 children (11 female and 8 male) with congenital, bilateral severe-to-profound sensorineural hearing loss. They did not have any additional disabilities. All had been full-time CI users (10-12 hrs/day) for at least 4 months (mean 20 months, range 4-51 months, SD 11.7) as well as being full-time contralateral HA wearers postoperatively and being consistent bilateral HA users preoperatively. Their ages varied from 3 to 14 years (mean age 9, SD 2.9). The mean age at implantation was 6.5 years (SD 3.1). The 12 children were implanted with an Advanced Bionics HiRes90K implant and fitted with HiRes-S sound coding strategy, whilst 6 children used Cochlear Freedom System fitted with ACE and 1 child the Med-El Combi40+ System fitted with CIS strategies. Demographic information for each subject including gender, age, aetiology of deafness, age at implantation, CI model, sound coding strategy, duration of CI experience, age at HA fitting and HA model is shown in Table I.

This study was approved by the local Ethics Committee and parents' consent was given freely.

Procedures

CI maps for individual recipients were controlled prior to testing. Following a regular CI fitting session, their most comfortable levels were verified in live-speech when listening together with HA in order to avoid any discomfort due to a loudness summation effect. All children were asked to visit their HA providers shortly before their appointment in our centre, after which existing HA programs fitted by their providers were used during testing. Unaided contralateral hearing thresholds were measured via an Interacoustics AC40 audiometer and TDH39 headphones in a sound treated room at frequencies between 125-6000 Hz using a warble tone, as were aided thresholds in free field through a loudspeaker placed at 0º azimuth at 1 m distance from the subject. Unaided as well as aided hearing thresholds for individual subjects are given in Table I.

BSE and HSE were evaluated using A§E software that was installed under NOAH onto a PC that was connected to an Aurical audiometer and 2 portable loudspeakers. The phonemes /a-i-u/, which were part of the A§E identification test onomatopoeia section, were selected as speech stimuli since they could offer a better reflection of the LF gain provided via the HA, whereas speech noise was presented as the noise stimulus. The details

Table I. Demographic information and audiological outcomes in individual CI recipients.

P	Age	Gender	Aetiology	CI Ear	CI Age	CI Exp.	CI Model / Sound Coding Strategy	HA Fitting Age	HA Model	Speech Signal Intensity at A§E Test (dB HL)	PTA (dB HL)		
											Unaided	HA	CI
1	5;6	F	Unknown	R	4;9	0;8	HiRes Bionic Ear / HiRes-S	0;8	Widex SENSO	60	98	57	25
2	9;7	M	Unknown	R	5;10	3;8	HiRes Bionic Ear / HiRes-S	2	Unitron US 80 PP	61	113	55	29
3	10;10	F	Connexin26	R	9;2	1;7	HiRes Bionic Ear / HiRes-S	1	Oticon 390PL	63	113	65	38
4	4;6	M	Unknown	R	2;10	1;7	HiRes Bionic Ear / HiRes-S	1;6	Starkey A675 SEQUEL	63	103	83	35
5	11;4	F	Unknown	L	9;7	1;8	HiRes Bionic Ear / HiRes-S	2;0	Eurion SWISS	63	120	82	40
6	14;1	F	Unknown	R	13;8	0;4	Freedom / ACE	0;8	Eurion SWISS	57	113	47	36
7	8;6	M	Unknown	R	5;7	2;10	Freedom / ACE	2;6	Phonak PPCL 4+	57	113	62	39
8	10;10	F	Unknown	R	9;5	1;4	Freedom / ACE	1;3	Widex SENSO	63	112	55	30
9	9;9	M	Connexin26	R	8;5	1;3	Freedom / ACE	1;6	Phonak SUPERO 412	65	107	42	25
10	5;9	F	Unknown	R	4;4	1;4	HiRes Bionic Ear / HiRes-S	2;6	Bernafon AF120	63	112	55	34
11	11;7	F	Unknown	R	10;2	1;4	HiRes Bionic Ear / HiRes-S	0;8	Starkey A675 SEQUEL	60	107	48	25
12	11;1	M	Unknown	R	6;9	4;3	COMBI40+ / CIS	2;6	Phonak PPCL 4+	58	100	62	29
13	8;6	M	Unknown	R	6;11	1;6	HiRes Bionic Ear / HiRes-S	0;11	Phonak PPCL 4+	72	112	65	31
14	6;6	F	Unknown	L	5	1;5	HiRes Bionic Ear / HiRes-S	1;6	Phonak PPCL 4+	60	110	62	26
15	6;10	F	Unknown	R	5;3	1;6	Freedom / ACE	0;4	Phonak PPCL 4+	60	110	62	34
16	5;10	M	Unknown	R	3;9	2	HiRes Bionic Ear / HiRes-S	1	Rionet HB-53P	68	105	53	31
17	4;3	M	Unknown	R	2;7	1;7	HiRes Bionic Ear / HiRes-S	0;8	Hansaton HP-AGC	65	105	62	33
18	10;2	F	Unknown	R	9;4	0;9	Freedom / ACE	0;11	Widex SENSO	56	115	57	25
19	3;10	F	Unknown	L	2;11	0;10	HiRes Bionic Ear / HiRes-S	2;9	Phonak SUPERO 412	70	115	55	33

P: Participant; F: Female; M: Male; R: Right; L: Left; CI: Cochlear Implant; HA: Hearing Aid; Exp.: Experience; PTA: Pure Tone Average.

of the A§E identification test are described by Govaerts et al. [21].

A§E was started in training mode in order to familiarise the child with the test and to minimise learning effects. Each child was explained her/his task regarding speech sound identification with a picture-pointing response. All phonemes and their corresponding pictures were introduced to the child one by one. Once the child was able to associate each phoneme with the corresponding picture under quiet listening conditions (phonemes administered at 75 dB and 70 dB HL respectively), test mode was initiated. During the test, each phoneme was administered four times in a random order by the software. Scoring was done by selecting the phoneme to which the child pointed. When the child was not able to respond due to being inattentive, the signal was repeated once again and if she/he was still unable to identify the phoneme, it was scored as negative. The test was ended when all phonemes had been scored.

Testing was performed under three listening conditions (conditions B, C and A respectively as illustrated in Figure 1): in condition B, both CI and HA were switched on. Loudspeaker 1 where the speech signal was presented was located at 0º azimuth and Loudspeaker 2 which was assigned to the speech noise was positioned to the HA side (± 90º). Both loudspeakers were placed at 1 m distance from the subject's head; in condition C, HA was switched off and the test was repeated; in condition A, loudspeaker 2 was moved to the CI side (± 90º) and the test was repeated. The speech noise was administered at a fixed intensity of 65 dB SPL, whereas the speech signal was used at various intensities depending on the performance of the child to avoid ceiling and floor effects. The

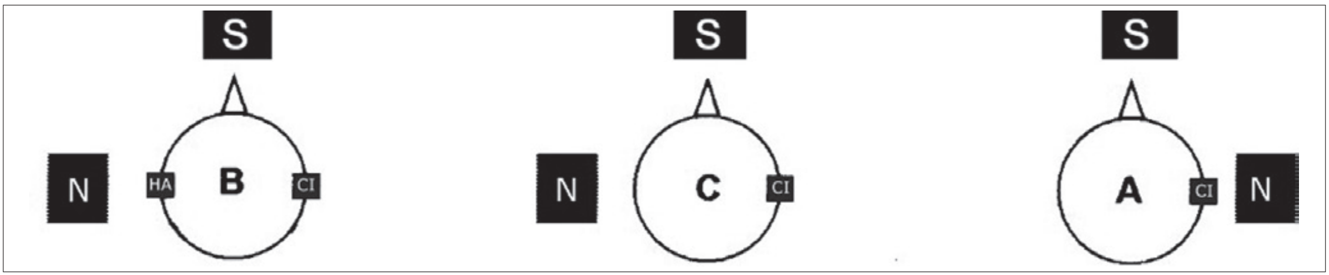

Fig. 1. Illustration of the three listening conditions: (B) bimodal listening with noise source on HA side; (C) CI only listening with noise source on HA side; (A) CI only listening with noise source on CI side. S: Speech; N: Noise; CI: Cochlear Implant; HA: Hearing Aid.

initial speech signal was administered at 70 dB HL in condition B and if the child's score was ≤ 58%, the test was repeated by increasing signal intensity by 3 dB, whereas if the score was > 92% the test was restarted by decreasing signal intensity by 5 dB. When the child scored between 59-92%, the test was carried out at the same speech signal intensity as conditions C and A, respectively.

Data analysis

Statistical analysis was carried out using Statistical Package for Social Sciences (SPSS) version 19.0 (Chicago, IL, USA). The percentage of correct scores for speech perception outcomes in each listening condition (B, C and A) was calculated by dividing the number of correct responses by the maximum score (3 phonemes x 4 repetitions = 12). For each subject, BSE was calculated by subtracting the percentage of correct scores for condition C from that for condition B, and HSE was calculated by subtracting the percentage of correct scores for condition A from that for condition C. Differences between outcomes in listening conditions were investigated by using repeated-measures analysis of variance, and post hoc tests were performed by using paired t-test procedures with Bonferroni correction for multiple comparison (comparison-wise alpha = 0.017). Pearson correlations were computed to investigate the correlations between the duration of CI experience, duration of HA experience prior to implantation, unaided/aided hearing thresholds, the intensity at which A§E speech signal was presented, listening conditions, BSE and HSE.

Results

The mean raw scores for listening conditions B, C and A, respectively, were 9.84 (range 8 to 11, SD 0.96), 8.42 (range 5 to 11, SD 1.92) and 6.37 (range 2 to 10, SD 2.06). Statistical analysis revealed a significant difference between the three conditions ($p < 0.001$) and post hoc tests indicated significant differences for all pairwise comparisons ($p < 0.001$).

Figure 2 shows the percentage of correct scores for all

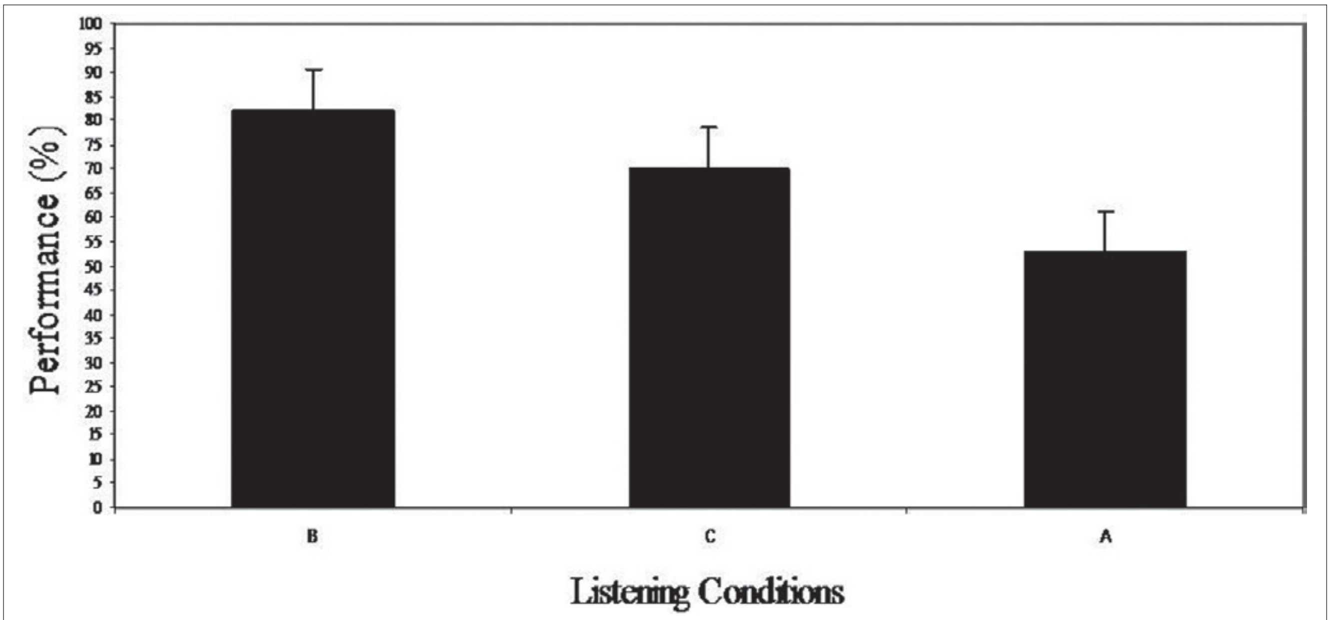

Fig. 2. The average percentage of correct scores for each listening condition: (B) bimodal listening with noise source on HA side; (C) CI only listening with noise source on HA side; (A) CI only listening with noise source on CI side.

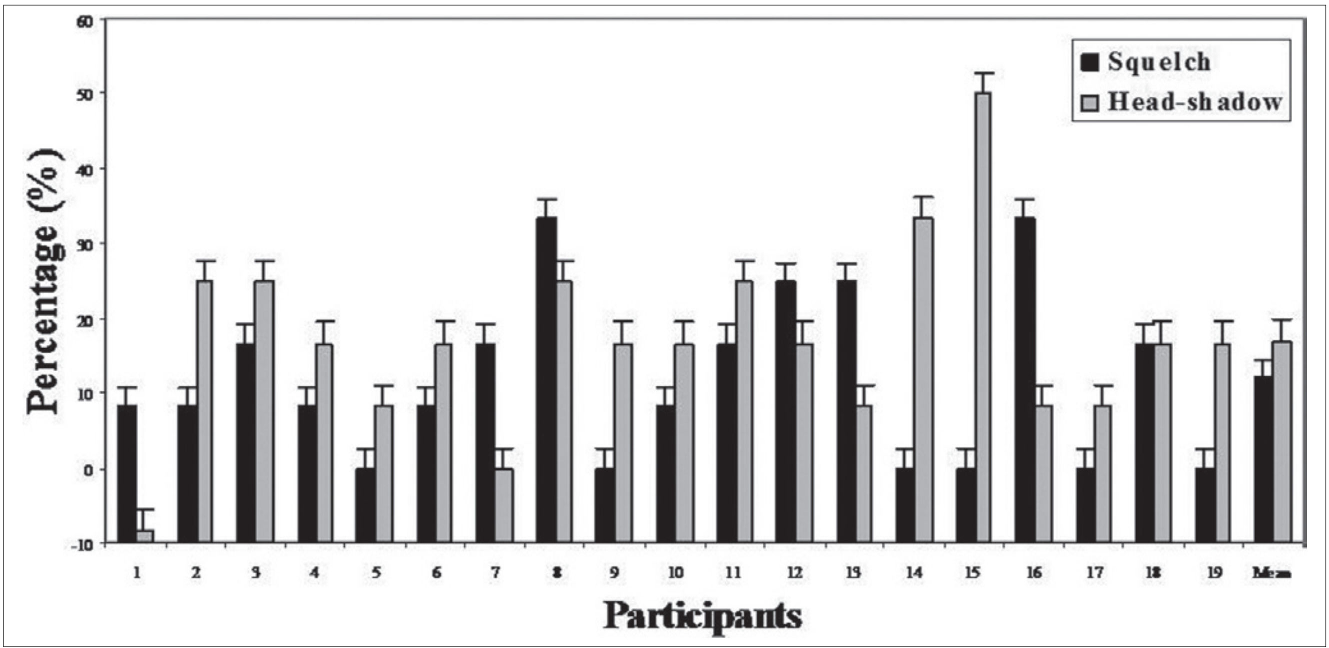

Fig. 3. Binaural squelch and head shadow effects for each subject and their average.

listening conditions. The average scores were 82% (range 67 to 92, SD 7.9), 70.2% (range 42 to 92, SD 16.0) and 53.1% (range 17 to 83, SD 17.2) for conditions B, C and A, respectively.

Figure 3 illustrates outcomes for BSE and HSE for individual subjects as well as their average. 13 of 19 children benefited for BSE, whereas 17 children showed performance improvement due to HSE. The average BSE and HSE were found to be 11.8% (range 0 to 33, SD 11.2) and 17.1% (range -8 to 50, SD 12.6), respectively. The largest performance difference was seen between B and A listening conditions: 29% in average.

The audiological outcomes such as unaided pure tone average, aided free field audiometry and speech presentation intensity in relation to 65 dB SPL noise level are shown in Table I. The correlations between the duration of CI experience, duration of HA experience prior to implantation, unaided pure tone average, aided free field audiometry, the speech signal intensity, the three listening conditions, BSE and HSE were not statistically significant ($p > 0.05$).

Discussion

The present study investigated bimodal benefits in CI recipient children. Outcomes suggested that children who use cochlear implants and contralateral hearing aids had considerable bimodal benefit and therefore, their speech perception performance in the presence of noise improved. All children showed at least one binaural advantage, although the amount of benefit reflected inter-subject variability: 13 of 19 children benefited from BSE, whereas 17 children showed improvement in performance due to HSE. BSE findings in the majority of children pointed out that they were able to integrate poor representation of CI with better timing information of HA and to make use of interaural time difference cues. On the other hand, HSE findings were in line with Ching et al. [19] and not Mok et al. [15] who did not find any significant HSE. These discrepancies can be due to the small CI sample size of these studies or due to different study settings such as positioning of speech and noise sources. Mok et al. [15] positioned the noise source at 0º azimuth, whereas in our study it was placed contralaterally at ± 90º azimuth. HSE previously was shown to be largest when the noise source was at 90º azimuth to the opposite side [22]. Furthermore, the largest difference in performance was seen between B and A listening conditions, which indicated CI only listening with the noise source on CI side as the most difficult condition. Previous studies had discrepancies for correlations between bimodal benefit and audiological outcomes such as unaided pure tone average and aided free field audiometry as well as the duration of CI experience and the duration of HA experience prior to cochlear implantation. There were studies showing the positive effect of degree of LF residual hearing [3] or longer duration of HA experience prior to implantation [23] on bimodal benefit. Some studies even found an adverse effect of better hearing thresholds at mid-to-high frequencies [8 15]. However, our results were in line with the majority of previous outcomes [13 19] and did not reveal any significant correlations between these variables. Such findings are promising for unilateral CI recipients with profound hearing loss and with no LF residual hearing especially in countries where bilateral implantation is still not reimbursed. On the other hand, in countries without any financial restrictions, the decision depends more on evaluation of the amount of benefit that a second CI or a contralateral HA can provide for individual subjects by taking into consideration better time-based cues that HA can convey to an ear with LF residual hearing in comparison to CI [24 25]. Therefore, there is an increasing need for audiological tests that are clinically applicable to young children and that can be used in the decisional process between bimodal versus bilateral CI use, which is more effective when implantation is done simultaneously or with the shortest possible time interval sequentially [26]. For this purpose, a test based on the identification task, which is a closed set condition, in our opinion is useful for testing young, even preverbal children older than 2.5 years of age [27], and the use of phonemes instead of words is less influenced by cognitive bias [21]. Moreover, our selection of test phonemes has the advantage of being less time consuming when considering the limited duration of attention in children, and these phonemes are identified at earlier stages in young children [27]. However, the limitation of the present study was mainly the small sample size. The outcomes based on this test in larger CI populations could provide better insight into the amount of bimodal benefit as well as the effect of CI and HA fitting parameters in young children. Additionally, the test procedure could be improved by introducing optimisation strategies in bimodal fitting. Bimodal fitting optimisation is still not a common clinical practice in many CI centres, and some CI users continue to receive independent fitting service from their HA providers. Previously, Ching et al. [11] have described a fitting procedure to adjust CI and HA together in adults, whilst Mok et al. [15] performed loudness balancing in children older than 9 years. Optimising bimodal fitting can be more challenging and may need special attention in young children, especially for loudness-balancing between the two devices taking into consideration that children have difficulties in judging loudness levels. However, as a minimum principle in order to optimise performance, real-ear measurements should be used to verify the achievement of prescriptive targets, the HA frequency response should be maximised for speech understanding, the HA should amplify sounds to comfortable loudness for low, medium and high input levels and loudness summation effects should be compensated for both acoustic and electric stimulation [3 19]. Background noise is inevitable in real life environments such as streets, parks, kindergartens, schools and classrooms where children spend considerable time. Therefore, bimodal listening may help children's incidental learning, conversational skills and academic success by increasing the SNR and conveying better target speech cues. Moreover, it may help to prevent contralateral auditory deprivation that can be induced by the absence of auditory stimulation [26]. Therefore, contralateral HA use is recommended as a clinical standard whenever bilateral implantation is not possible. Our clinical experience showed that if children are asked to continue to wear their HA right after surgery, they spontaneously adapt to electrical and acoustical stimulation and willingly accept regular HA use on the opposite side. However, parents' attitude plays a crucial role as well. Therefore, parents certainly need to be counselled about the advantages of bimodal use to consent to their child wearing two devices instead of only one.

Conclusions

Present findings revealed that unilateral CI recipient children who used contralateral hearing aids showed considerable bimodal benefit, especially for the aspects taken into consideration by this study. Therefore, their speech perception performance in the presence of noise improved. At least one binaural advantage was present for all children and the amount of benefit reflected inter-subject variability. Audiological outcomes such as unaided pure tone average and aided free field audiometry as well as the duration of CI experience and the duration of HA experience prior to cochlear implantation did not have a significant effect on BSE and HSE.

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