Directional Microphone Contralateral Routing of Signals in Cochlear Implant Users: A Within-Subjects Comparison

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Objectives: For medical or financial reasons, bilateral cochlear implantation is not always possible in bilaterally deafened patients. In such cases, a contralateral routing of signals (CROS) device could complement the monaural implant. The goal of our study was to compare the benefit of three different conditions: (1) unilateral cochlear implant (CI) alone, (2) unilateral CI complemented with a directional CROS microphone, and (3) bilateral CIs.

Design: Twelve bilateral experienced CI users were tested. Speech reception in noise and sound localization were measured in the three above-mentioned conditions. Patients evaluated which condition they presumed to be activated and the subjective benefit on a hearing scale.

Results: Compared with the unilateral CI condition, the additional CROS device provided significantly better speech intelligibility in noise when speech signals came from the front or side of the CROS microphone. Only small subjective improvement was observed. Bilateral-activated CIs further improved the hearing performance. This was the only condition where sound localization was possible. Subjective evaluation showed a clear preference for the bilateral CI treatment.

Conclusions: In bilateral deafened patients, bilateral implantation is the most preferable form of treatment. However, patients with one implant only could benefit from an additional directional microphone CROS device.

Key words: CROS, Multinoise, Sound localization, Speech reception in noise.

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INTRODUCTION

In patients with bilateral deafness, cochlear implantation on both sides offers a number of advantages compared with unilateral cochlear implant (CI) use: reduction of the negative effects of head shadow, binaural summation, spatial release from masking, sound localization, availability of a backup device, and ensuring that the better ear is implanted (Van Hoesel & Tyler 2003; Smulders et al. 2016). Over the past decade, improved speech in noise thresholds and the possibility of sound localization with bilateral CIs has been systematically demonstrated (Van Hoesel & Tyler 2003; Senn et al. 2005; Murphy & O'Donoghue 2007; Culling et al. 2012; Gaylor et al. 2013). However, bilateral implantation is not always possible due to medical or financial reasons (Chen et al. 2014). For these users, a contralateral routing of signals (CROS) device may be an alternative option because it is a less expensive alternative and does not require surgical intervention on the other side.

Only a few studies have investigated the performance of CI systems in combination with CROS devices (Verschuur et al. 2005; Arora et al. 2013; Van Loon et al. 2014; Grewal et al. 2015; Guevara et al. 2015; Taal et al. 2016; Weder et al. 2015). The results of a CROS device use are inconsistent. Speech reception in quiet environments was reported as either unchanged (Grewal et al. 2015) or improved (Arora et al. 2013; Guevara et al. 2015). Subjective ratings showed partial or overall benefits (Arora et al. 2013; Grewal et al. 2015; Guevara et al. 2015; Weder et al. 2015). Most importantly, the benefit of CROS devices for speech intelligibility in noise was shown to be situation dependent. In favorable settings, that is, speech was presented at the side of the CROS microphone, significant improvements were measured (Arora et al. 2013; Van Loon et al. 2014; Grewal et al. 2015; Guevara et al. 2015; Weder et al. 2015). In less favorable situations, with noise at the side of the CROS microphone, deterioration of speech intelligibility was reported (Arora et al. 2013; Van Loon et al. 2014; Grewal et al. 2015; Weder et al. 2015). The addition of a CROS device in CI recipients did not improve sound localization performance (Verschuur et al. 2005; Guevara et al. 2015; Weder et al. 2015).

All of the above investigations are limited to a certain extent. First, in the only published study comparing unilateral CI with CROS to bilateral CI performance, the results were obtained from different patient populations (Van Loon et al. 2014). Second, despite considerable improvements in hearing aid technology in recent years, all previous studies used CROS devices lacking directional microphones. The use of directional microphones in CI systems has been shown to provide substantial benefits in noisy surroundings (Wouters & Vanden Berghe 2001; Van der Beek et al. 2007; Dillier & Lai 2015). Hence, the goal of this study was to investigate the objective (i.e., speech in noise and sound localization) and subjective benefit of a CROS device with a directional microphone in three different treatment conditions in the same patient population: (1) unilateral CI alone (only better CI switched on), (2) unilateral CI complemented by a CROS device, and (3) bilateral CI usage. We hypothesized that bilateral deaf patients with a unilateral CI would exhibit equal or better speech reception in noise with a directional microphone CROS device in both favorable (speech at the CROS side) and unfavorable situations (noise at the CROS side).

MATERIALS AND METHODS

Ethical Considerations and Study Population

This study was designed in accordance with the Declaration of Helsinki and was approved by the local ethical committee (KEK-BE, No. 165/11). Twelve bilateral CI recipients with severe to

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profound hearing loss were included in the study. Participants gave written informed consent before undergoing the study procedure. All subjects were postlingually deafened native German speakers and experienced CI users. They were all using the same sound processor (Opus 2, Med-El, Innsbruck, Austria, 9 years of CI experience on average) and had good to excellent speech recognition performance in quiet (≥90% in Freiburg numbers at 60 dB SPL). For each participant, the better CI side was determined as the side with a higher aided speech in quiet score (Freiburg monosyllables at 60 dB SPL). For brevity, the side of the CI with the poorer speech understanding will be called "poorer CI" and the other side "better CI" throughout this text. In case of identical aided speech scores (subjects 4, 7, and 12), the participants specified their preferred ("better") CI side. A detailed summary of the participants in the study is shown in Table 1.

Processor Fitting

The subjects specified their favorite programs on their Opus 2 processors (left and right side), which were then transferred to Sonnet audio processors (Med-El). It was shown in an earlier study that transferring the programs to the Sonnet processor requires no change of the programming and no acclimatization time (Wimmer et al. 2016). The "natural" directional microphone mode was activated. This mode has a fixed directionality pattern that tries to imitate the natural pinna directionality, that is, it is omnidirectional for low frequencies and directional for high frequencies. The wind noise reduction was switched off in the transferred programs. In addition, a second program with zero current stimulation was fitted to allow the audio processor of the poorer CI side to be turned off using a remote control.

CI-CROS System

Figure 1 shows the CROS setup used in the study. A directional microphone (iLapel, Phonak, Stäfa, Switzerland) was clipped onto the audio processor of the poorer CI side. The CROS microphone was connected via cable to a wireless transmitter worn on the torso (Roger Inspiro, Phonak). A miniature wireless receiver (Roger X, Phonak) was plugged into the audio processer on the better CI side. After connection, the wireless receiver settings were set equally for each participant according to the manufacturer's guidelines ("Sonnet" option on the Inspiro) with a mixing ratio of 50% each (CI and CROS). Sound field-aided thresholds were measured using narrow-band noise (center frequencies at 0.25/0.5/1/2/3/4/6/8 kHz) with a loudspeaker placed in front of the subjects at 1 m distance. They were comparable for the bilateral CI condition (Sonnet processors), the CI-CROS condition, and former measurements (Opus 2 processors) within an uncertainty level of 5 dB. Therefore, a correct transfer was verified, and possible influences on aided hearing thresholds by the CROS microphone were excluded.

Testing Conditions

With this setup, the study participants were tested in three different CI conditions. In the unilateral condition (CI-unaided), only the CI of the better ear was active, while both the CI on the poorer ear and the CROS microphone were deactivated. In the CI-CROS condition, the poorer CI was still switched off, but the CROS microphone was activated. In the bilateral condition (CI–CI), the poorer CI was activated, and the CROS microphone was switched off. To minimize a detection bias, participants were not informed of the actual activated measurement mode (CI-unaided, CI-CROS, CI–CI): both implants and the CROS device were installed in a ready-to-use position. The investigator could switch on the activated devices in a predefined order by remote control. All experiments were performed in an acoustic chamber ($6 \times 4 \times 2$ m^3) with a reverberation time of approximately 0.2 second for frequencies between 0.25 and 10 kHz.

Speech Understanding in Noise

The speech reception thresholds (SRTs) expressed as the signal to noise ratio at 50% correct speech understanding were assessed using a standardized adaptive German matrix test (Oldenburg sentence test, Wagener et al. 1999). An approximated diffuse noise field situation was generated by presenting uncorrelated noise signals (speech babble noise) from 4 different speakers placed in front (0°), at the right side (90°), behind (180°), and at the left side (270°) of the subjects. The individual noise sources levels were 59 dB SPL summing up to an acoustic level of 65 dB SPL at the center point (i.e., at a distance of 1 m to each speaker). The long version of the test was used (i.e., 30 test sentences per

TABLE 1. Study participants

				Details for the Left Ear Side/Right Ear Side		
Subject	Sex	Age (yrs)	Better CI Side	Duration of Implant Use (yrs)	Speech Recognition With Unilateral CI* (%)	Hearing Loss PTA (dB HL)
01	F	61	L	10/10	90/60	119/119
02	F	18	R	10/11	65/100	120/120
03	M	22	L	8/15	85/75	118/119
04	F	66	R	4/2	75/75	120/85
05	F	64	L	10/11	85/65	116/120
06	F	74	L	12/12	70/65	120/120
07	M	64	R	13/12	90/90	120/103
08	F	67	L	2/2	80/60	109/120
09	M	63	L	15/14	85/85	111/111
10	F	45	L	4/6	70/60	85/106
11	F	60	R	12/5	70/90	120/120
12	M	30	L	15/8	70/70	110/105

*Monosyllables at 60 dB SPL

CI, cochlear implant; F, female; L, left; M, male; PTA, pure-tone average at 0.5/1/2/4 kHz (unaided); R, right.

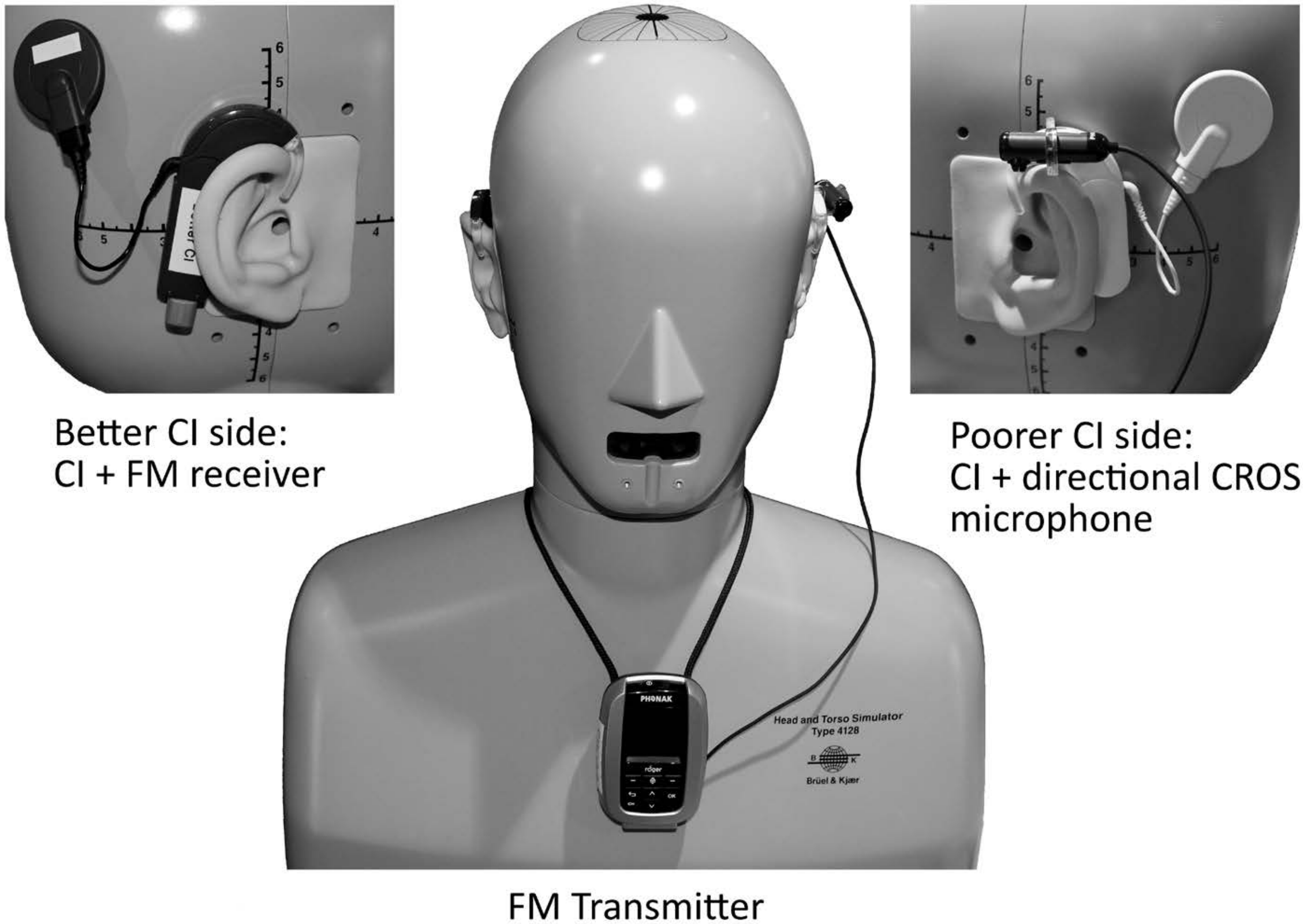

Fig. 1. Experimental setup, shown on a head and torso simulator. Note that all experiments were carried out with the subjects wearing the same experimental apparatus. The investigator could switch between the conditions (CI-unaided, CI-CROS, and CI–CI [bilateral CI]) therefore not informing the participant of the current test condition. CI indicates cochlear implant; CROS, contralateral routing of signals.

trial). The measurements started with a signal to noise ratio of 0 dB and the speech level was varied following the predetermined procedure specified by the authors (Wagener et al. 1999). The SRTs were assessed in three different spatial configurations (Fig. 2): speech material was presented from the front (S_0N_{DIFF}), from the side of the CROS microphone ($S_{CROS}N_{DIFF}$), and from the side contralateral to the CROS microphone ($S_{CI}N_{DIFF}$). Before testing, two training tests were performed and the results were discarded. To minimize training and fatigue effects, the order of the test conditions, spatial configurations, and test lists were counter-balanced.

Sound Localization

Sound localization was assessed with 12 speakers aligned in a horizontal circular setup at 1.2 m height with a radius of 1 m and an angular resolution of 30°. The head of the subject was positioned in the center of the speakers. The speakers were numbered from “1” to “12” according to a clock face (i.e., the frontal speaker was “12”). Three white noise stimuli of 200-msec duration were presented in a randomized order from each speaker at levels of 60, 65, and 70 dB SPL (totaling 36 stimuli in each test condition). The subjects were asked to verbally indicate the location (i.e., the number) of the loudspeaker that was the presumed source of the stimulus. Before testing, the subjects underwent a training session of 5-min duration. No feedback was provided during or after the test procedures. The localization error (i.e., the mean absolute error between the azimuthal positions of the stimulus speaker and the indicated speaker) and the percentage of correctly identified speakers were assessed.

Subjective Evaluation

The participants were able to test the CROS device during a short walk in the hospital area (15 min) between the audio processor fitting and the sound field measurements. Subjective evaluation was performed after each test battery. Subjects were unware of the activated measurement mode, as described in the “testing conditions” section. The subjects were instructed to identify the suspected test condition (CI-unaided, CI-CROS, or CI–CI) and to rate each condition in comparison to their normal bilateral life situation on a visual analog scale, with values ranging from −5 (much worse), to 0 (equally good), to 5 (much better) based on their subjective impressions including their speech in noise and localization performances.

Statistical Analysis

Nonparametric repeated measures analysis of variance (Friedman test) was used to test for statistically significant differences

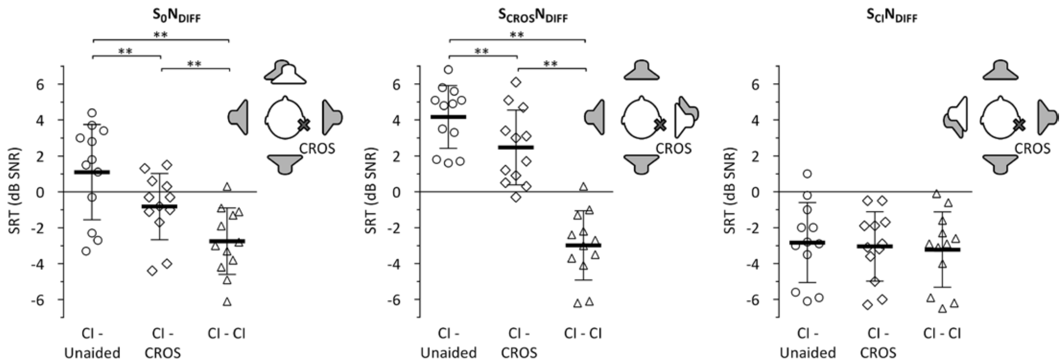

Fig. 2. SRTs measured in noise (gray speakers) for three different directions of the target speech sources (white speaker): speech from the front (S_0N_{DIFF}), from the side of the CROS microphone ($S_{CROS}N_{DIFF}$), and from the side contralateral to the CROS microphone ($S_{CI}N_{DIFF}$). SRTs were measured in three treatment conditions: unilateral CI only (CI unaided), unilateral CI with an additional CROS microphone (CI-CROS), and bilateral CI (CI–CI). Circles, diamonds, and triangles, Individual results. Horizontal lines with whiskers, mean and SD; **Significance level $p < 0.01$. CI indicates cochlear implant; CROS, contralateral routing of signals; SRT, speech reception thresholds.

($\alpha = 0.05$) among the conditions. The two-tailed Wilcoxon signed rank test with Bonferroni correction for multiple comparison was applied for post-hoc analysis. Statistical calculations were performed using the Prism 6 software package (GraphPad, Inc., La Jolla, CA).

RESULTS

Speech in Noise

Figure 2 shows the individual SRTs measured for the tested spatial configurations. The Friedman test revealed statistically significant differences for the S_0N_{DIFF} ($p < 0.001$) and $S_{CROS}N_{DIFF}$ ($p < 0.001$) test configurations. In the S_0N_{DIFF} setting, patients performed significantly better in the CI-CROS condition than in the CI-unaided condition (1.9 dB, mean difference, $p < 0.01$). Further improvements were observed in the CI–CI condition as compared with the CI-unaided condition (3.8 dB, $p < 0.01$). When speech was presented from the side of the CROS device ($S_{CROS}N_{DIFF}$), subjects in the CI-CROS (1.7 dB, $p < 0.01$) and CI–CI (7.2 dB, $p < 0.01$) conditions performed better than in the CI-unaided condition. In the $S_{CI}N_{DIFF}$ configuration, the mean SRT differences between the three hearing conditions were smaller than 0.5 dB and not statistically significant ($p = 0.39$).

Sound Localization

The average localization error was approximately at chance level (i.e., 90°) in the CI-unaided and CI-CROS conditions; larger variation was observed in the CI-CROS case (Fig. 3). As expected, the addition of the CROS microphone did not change sound localization abilities compared with the CI-unaided condition (−3°, mean difference, $p = 0.59$). Sound localization was improved for all subjects in the CI–CI condition compared with both the CI-unaided and the CI-CROS conditions (average improvement: 42°, $p < 0.01$ and 39°, $p < 0.01$). A similar general pattern was observed for the percentage of correctly indicated directions, showing negligible differences between the CI-unaided and CI-CROS conditions (1%, mean difference, $p = 0.75$), both approximately at chance level (i.e., 8.3%). Again, a statistically significant improvement was observed in the CI–CI condition compared with both the CI-unaided and the CI-CROS conditions (20%, $p < 0.01$ and 19%, $p < 0.01$). One of the participants (subject 7) was performing better than the other subjects, achieving a localization error of 15° and correctly identifying 64% of the stimulus directions (1.5 of interquartile range) in the CI–CI condition. A possible explanation would be that subject 7 benefits from high binaural integration abilities. Subject 7 showed the best results of all participants in both speech in noise and sound localization tests. Comparison of the duration of deafness, duration of implant use, and number of active electrodes with the other subjects did not reveal obvious reasons for the better performance.

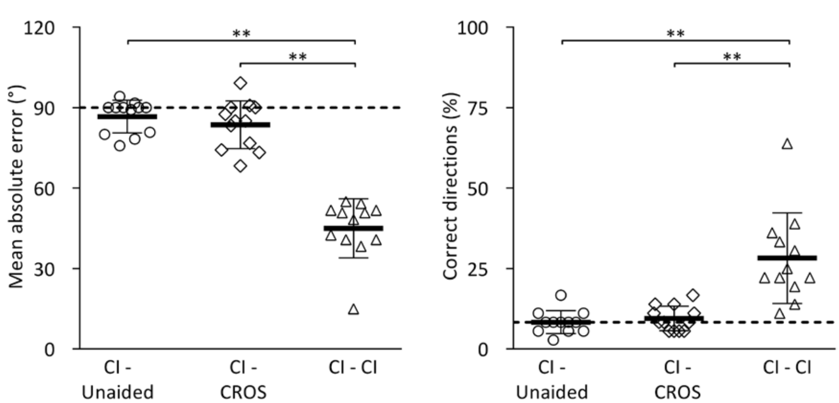

Fig. 3. Sound localization results (left) and percentage of correctly identified directions (right). Circles, diamonds, and triangles, Individual results. Horizontal lines, Mean and SD. Dashed lines, Experiment chance levels. **Significance level $p < 0.01$.

Identification and Subjective Evaluation

Figure 4 summarizes the relationship between the identification results and the subjective evaluations for the three tested conditions. All participants (n = 12) were able to correctly identify the CI-unaided condition, showing the worst subjective rating (−1.8, mean benefit). Only half of the subjects were able to identify the CI-CROS condition correctly, while 5 of these 6 presumed a unilateral situation. Compared with the CI-unaided condition, the condition with the activated CROS device was rated slightly better (−1.4). Most subjects correctly identified the CI–CI condition (n = 10). The best subjective ratings were obtained in this condition (+0.8). Despite distinct improvements between the CI-CROS and CI–CI conditions in the speech in noise tests and the sound localization performance when both implants were switched on, 1 participant (subject 5) presumed that only 1 implant was activated during the whole test setting. As a consequence, the subjective rating remained the same.

DISCUSSION

In this study, a similar pattern was observed for all results: CI-CROS was always better than or equal to CI-unaided, and the CI-CROS condition was always worse than the CI–CI condition. Statistically significant SRT improvements ($p < 0.01$) were found when the directional CROS microphone was activated in the S_0N_{DIFF} and $S_{CROS}N_{DIFF}$ configurations. When speech was presented from the side of the better CI ($S_{CI}N_{DIFF}$), negligible differences were observed between the three treatment conditions. Grewal et al. (2015) reported deteriorations in speech understanding possibly resulting from noise amplification by the CROS device. Our findings suggest that such detrimental effects could potentially be reduced by using directional instead of omnidirectional microphone technology in the CROS device.

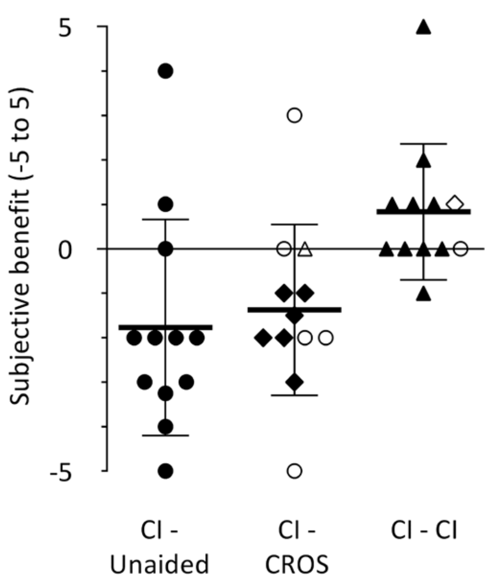

Fig. 4. The relationship between subjective rating and identification of the tested treatment condition. Subjective rating is shown on a visual analog scale in comparison to its normal bilateral situation: (−5) much worse, 0 (equally good), to 5 (much better). Horizontal lines represent mean and SD of all trials of the participants (correctly and incorrectly identified). Circles, CI unaided; diamonds, CI-CROS; triangles, CI–CI; filled symbols, correctly identified cases; open symbols, incorrectly identified cases. CI indicates cochlear implant; CROS, contralateral routing of signals.

However, a direct comparison between CROS devices with omnidirectional and directional microphones was not performed in this study and the CROS benefit could also be explained by other effects, such as an increased overall signal to noise ratio when wearing an additional CROS device. As expected, sound localization was only possible with two activated implants, whereas unilateral CI with or without the CROS device showed results at chance level, confirming previously reported findings (Weder et al. 2015).

The subjective benefit in the CI-CROS condition was only rated slightly better than that in the CI-unaided condition, although speech in noise measurements showed significant improvements. One reason for this discrepancy might be that it is difficult to identify the additional CROS microphone. Another reason would be the short evaluation time under limited experimental conditions. In general, CROS devices are not capable of providing binaural hearing and should not be the dominant support in difficult situations. This is also reflected by the lack of correct identification of the additional CROS device: the CI-CROS condition was only correctly identified by 50% of the participants, whereas correct identification of the CI–CI and the CI-unaided conditions was achieved by 83 and 100% of the participants, respectively. In addition, the CI-CROS condition was often identified as CI-unaided (n = 5), showing that patients were not aware of the CROS microphone being activated. Subjectively, the CI–CI condition was clearly preferred. It must be noted that the subjective evaluation was only surveyed after performing the speech in noise tests. The unnatural acoustical environment and short testing time only allowed a limited estimation of the subjective benefit, which might be different in everyday life situations. For a detailed evaluation, bilaterally deaf patients would have to be recruited in the time between their first and second CI surgery, with a sufficient adaption period of several months in each condition. Such a study design was not feasible, because of limited patient availability in our institution.

Van Loon et al. (2014) reported that a contralateral microphone in unilateral CI users is not an alternative to bilateral implantation. We agree with this argument; nevertheless, the findings of our study suggest that bilateral deaf patients with unilateral CI benefit from an additional CROS device on speech understanding. Such a device would have to integrate the technology of modern hearing aids (i.e., directional microphone mode and noise suppression algorithms) and be wirelessly connected to the CI. In addition, a CROS device could be temporarily administered as an auxiliary apparatus for bilateral deaf patients with a prolonged interval between the first and second cochlear implantation. The CROS device could help in everyday life situations (e.g., by bypassing the head shadow) until patients receive the second implant. The system does not require surgical intervention and can be easily installed.

All the subjects performed better in the $S_{CI}N_{DIFF}$ situation than in the S_0N_{DIFF} situation in the CI-unaided condition. We therefore expect a higher overall sensitivity to the ipsilateral side than to the front in the "natural" directionality mode of the CI audio processor. The "natural" directionality mode imitates the directionality of the human pinna by providing an omnidirectional pattern for frequencies <2 kHz and directional pattern to the front for frequencies ≥2 kHz measured in the free-field (see File #1 in Supplemental Digital Content 1, http://links.lww.com/EANDH/A331). When placed on the head, this would lead to sensitivity maxima between 45° and 90°, which is in accordance with data obtained from natural subjects (Fortune 1997). At the time of the study it was not possible to record the front-end output of the CI audio processor (no hardware support) for an objective evaluation of the microphone directionality patterns in our experimental setup.

A combination of commercially available devices was used in this study. As a consequence, CI-CROS devices can be offered to patients immediately. Nevertheless, the tested solution was not optimized with respect to aesthetics and usability. For everyday use, the presented CI-CROS solution should at least be adapted for wearing comfort. To this end, modern connectivity solutions of CI systems already provide the means to establish wireless connections between auxiliary microphones and audio processors.

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