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# A COMPARATIVE STUDY OF FOUR DIRECTIONAL MICROPHONES AND DIRECTIVITY STEERING FOR BIMODAL COCHLEAR IMPLANT USERS

**H. Christiaan Stronks**[1,2*] **Nienke C. Langerak**[1] **Annemarie J. Schrijver**[1]
**Raphael Koning**[3] **Jeroen J. Briaire**[1] **Johan H. M. Frijns**[1,2,4]
[1] Otorhinolaryngology and HNS, Leiden University Medical Center, Leiden, the Netherlands
[2] Leiden Institute for Brain and Cognition, Leiden, the Netherlands
[3] Advanced Bionics, Hanover, Germany
[4] Department of Bioelectronics, Delft University of Technology, Delft, the Netherlands

## ABSTRACT

**Background**: Cochlear implant users (CI) experience degraded speech intelligibility (SI) in noise. A contralateral hearing aid (HA) benefits listening in noise, and directional microphones and directivity steering can further enhance SI.
**Objectives**: Four directional microphones were evaluated for bimodal listeners, including a monaural and binaural broadband front-facing beamformer ($BF_M$ and $BF_B$) and a novel monaural and binaural narrowband side-beamformer ($BF_{MS}$, $BF_{BS}$). Broadband directivity steering (DS) was also evaluated.
**Methods**: $BF_M$, $BF_B$, and DS were tested in diffuse noise with speech administered frontally or to the HA side ($S_0N_{dif}$ and $S_{HA}N_{dif}$). $BF_{MS}$ and $BF_{BS}$ were tested with speech presented on the CI side and noise on the HA side or *vice versa* ($S_{CI}N_{HA}$, $S_{HA}N_{CI}$). SI was assessed by determining speech reception thresholds (SRTs).
**Results**: In the $S_0N_{dif}$ condition, $BF_B$ significantly improved SI by 2.9 dB SNR and $BF_M$ by 1.3 dB SNR, but not significantly. In the $S_{HA}N_{dif}$ condition, $BF_M$ and $BF_B$ did not benefit SI, but DS improved SI by 3.6 dB. $BF_{BS}$ significantly improved SI by 1.1 dB SNR, but $BF_{MS}$ was ineffective.
**Conclusion**: Binaural beamformers outperform their monaural counterparts. The novel $BF_{BS}$ is a promising technique for bimodal listeners.

**Keywords:** *sensorineural hearing loss; cochlear implants; hearing aids; speech in noise; asymmetric hearing loss*

*Corresponding author: h.c.stronks@lumc.nl


## 1. INTRODUCTION

Unilaterally implanted cochlear implant (CI) users with contralateral residual hearing may benefit from wearing a hearing aid (HA) in the non-implanted ear, called bimodal hearing. Residual hearing in the other ear offers advantages over electrical hearing alone, including better speech understanding in quiet and noise [1-3]. The bimodal system from Advanced Bionics (Naída Link™) was developed specifically for this population. It features various speech enhancement strategies, including two noise-reduction algorithms based on monaural and binaural directional microphones called 'beamformers' ($BF_M$ and $BF_B$, respectively). Beamformers are spatial filters that pass on sound from certain angles (usually from the front) while attenuating noise at angles outside of the beam. $BF_M$ (UltraZoom™) is an adaptive beamformer that operates independently on both the CI and the HA and steers its null to the point of the lowest SNR. By contrast, $BF_B$ (StereoZoom™) is a fixed beamformer that combines the input from the CI and HA through wireless voice streaming technology to focus the beam further [4, 5]. Polar patterns for both beamformers are compared to the omnidirectional microphone setting in Fig. 1. It is also possible to route the signal from the HA to the CI and *vice versa*, referred to as directivity steering (DS, or ZoomControl™). This technique is akin to contralateral routing of signals (CROS), overcoming the head shadow effect by rerouting acoustic input from the HA to the typically better-hearing CI ear [5].

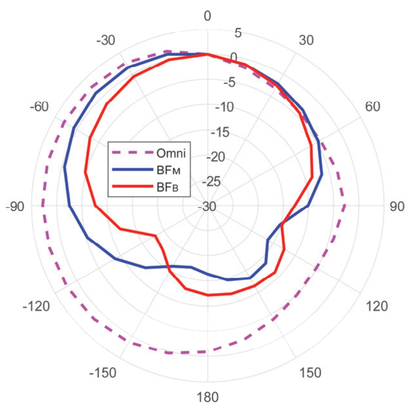


**Figure 1**. Polar patterns of the front-facing monaural ($BF_M$) and binaural beamformer ($BF_B$) and the default omnidirectional microphone setting (Omni) evaluated in experiment 1. The speech processor was mounted on the left ear of a KEMAR manikin. Reference: 0º.

Besides these clinically established broadband applications, a novel side-beamforming approach has been proposed based on artificially increasing interaural level differences (ILDs) at low frequencies [6]. This approach is especially relevant for bimodal listeners where residual acoustic hearing is typically confined to the lower frequencies [7]. ILDs are usually restricted to high frequencies, where the acoustic shadow imposed by the head decreases the sound level of a signal in the contralateral ear [8]. By introducing a narrow-band, side-facing beamformer active only at low frequencies, ILDs can be artificially increased without affecting the physiological ILDs at high frequencies. This technique is especially efficient when speech is present on one ear (e.g., the HA side) and noise on the other (CI side). The introduction of a side-facing beamformer on both ears in this scenario will thus increase the signal-to-noise ratio (SNR) on the HA side, where the speech is presented at the expense of the CI ear, where noise is presented. When the attention is focused on the better side (HA in this example), speech intelligibility (SI) will be enhanced. The advantage of this approach over the classical wide-band CROS or DS application is that it will benefit speech intelligibility in noise, regardless of whether the speaker is present on the CI or the HA side. Benefits can also be expected when speech comes from the front and noise from the sides [6]. As such, these side-beamformers are more versatile and may require less user intervention or rely less on automatic scene analysis than CROS or DS applications. Here, we evaluated two side-facing beamformers. One operated monaurally, i.e., on both ears individually ($BF_{MS}$), whereas the other operated binaurally ($BF_{BS}$) by combining the signals from both ears by subtracting the contralateral signal from the ipsilateral side to increase the artificial, low-frequency ILDs further. Polar patterns are shown in Fig. 2.

We performed two experiments. In the first, we evaluated the clinically established broadband, front-facing beamformers ($BF_M$ and $BF_B$) and DS. In the second, we assessed the effectiveness of the two experimental narrow-band, side-facing beamformers. $BF_M$, $BF_B$, and DS were tested in a diffuse field of stationary noise with speech administered frontally ($BF_M$ and $BF_B$) or to the HA side (DS, $BF_M$, $BF_B$). $BF_{MS}$ and $BF_{BS}$ were tested in a less challenging noise setup for a proof-of-principle approach, with speech and noise presented from a single loudspeaker on either side of the head.

## 2. METHODS

### 2.1 Participants

Experiment 1 evaluated the broadband beamformers ($BF_M$, $BF_B$) and DS in a population of 12 participants unilaterally implanted with an Advanced Bionics HiRes 90K™ device (9 biological females) with a mean age of 64 years (range: 50 – 85). Inclusion criteria were 1) pure-tone audiometric thresholds of at least 80 dB at 125, 250, and 500 Hz in the non-implanted ear; 2) a CI-aided CVC phoneme score in quiet of at least 80%, which are above-average listeners; 3) at least 6 months experience with their CI; 4) age ≥18 years. In experiment 2, the narrowband beamformers ($BF_{MS}$ and $BF_{BS}$) were evaluated in 18 participants with the same inclusion criteria. However, this population included only people who used a contralateral HA in daily life, whereas the first population also included three participants who were not active HA users and were fitted with an HA for the study. Pure-tone audiograms of the two populations are shown in Fig. 3. Written informed consent was obtained from each subject. This study was approved by the Institutional Review Board of the Leiden University Medical Center and adhered to the Declaration of Helsinki (Carlson et al., 2004).

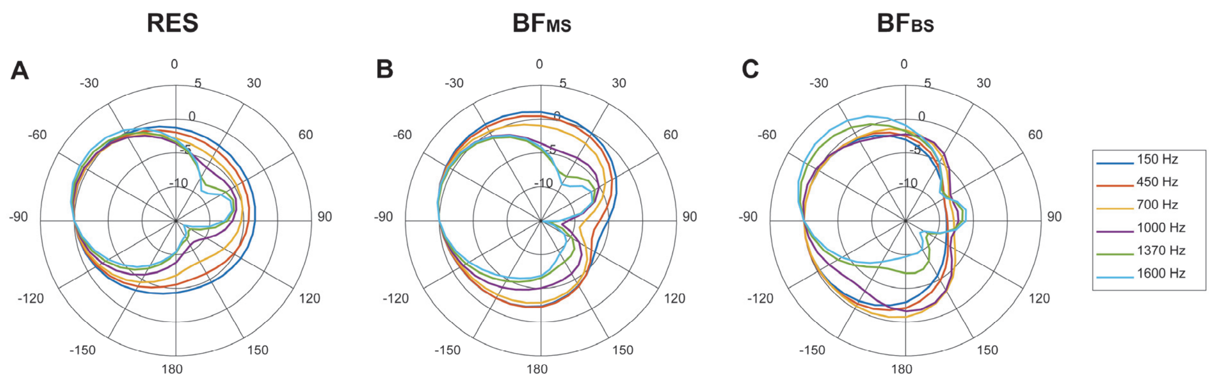


**Figure 2**. Polar patterns of the microphone settings evaluated in experiment 2. (A) Default microphone setting (Real Ear Sound™, RES). (B) Monaural side-facing beamformer ($BF_{BM}$). (C) Binaural side-facing beamformer ($BF_{BS}$). The speech processor was mounted on KEMAR's left ear. Reference: -90º.

### 2.2 CI and HA fitting

The participants in experiment 1 to evaluate $BF_M$, $BF_B$, and DS were fitted with a Q90 CI speech processor (Advanced Bionics LLC, Valencia, CA, USA) and contralaterally with a Naída S IX UP (*n* = 7) or Naída Link UP (*n* = 5) HA using PhonakTarget™ fitting software (version 3.3, Phonak, Sonova Holding AG Stäfa, Switzerland). Amplification was based on the clinical audiogram. The voice streaming technology and bimodal fitting rule are designed for the Naída Link and were fitted on the Naída S using customized fitting software (BEPSnet version 3.0.5017.18916, Advanced Bionics). The participants in experiment 1 were subsequently sent home for at least four weeks to accommodate the new fitting.

The participants in experiment 2 to evaluate $BF_{MS}$ and $BF_{BS}$ were fitted with a Harmony™ CI speech processor (Advanced Bionics) and an Audéo M90-312 HA (Phonak) contralaterally using PhonakTarget (version 6.2.5). HA fitting was based on an *in situ* audiogram (Phonak AudiogramDirect™). The experimental $BF_{MS}$ and $BF_{BS}$ algorithms could not yet be implemented on the latest generation of Advanced Bionics CI processors (Q90) available at the time of the study, and front-end processing was performed on an Audéo M90-312 HA that communicated with the Harmony CI speech processor. The pulse-width modulated HA output was converted into an analog signal suitable as auxiliary input for the Harmony CI processor using an audio transformer (Neutrik NTE1, Schaan, Liechtenstein) and a spindle potentiometer (Vishay, Malvern, PA, USA). Calibration was performed with white noise in an ACAM™ audiometry box (Acousticon Inc., Raleigh, NC, USA) using BEPSnet (version 1.14, Advanced Bionics). The HA was worn behind the ear, and the Harmony processor was clipped to the participant's clothing. A custom-made Bluetooth smartphone application (Advanced Bionics) was used to switch between microphone settings.

CI speech processors were fitted with the participant's clinical threshold and maximal comfortable stimulus levels, and HAs were fitted with the Naída bimodal fitting formula [9]. Switching off all noise-reduction algorithms other than those under investigation reduced front-end processing strategies on both devices to a minimum. The adaptive gain control remained operational.

### 2.3 Speech intelligibility testing in noise

Speech testing was performed in a sound-treated audiology booth. Experiment 1 was used to evaluate $BF_M$, $BF_B$, and DS by determining speech reception thresholds (SRTs) using the Leuven intelligibility sentence test (LIST) [10].

Speech was presented in a diffuse field of long-term speech-shaped (LTSS) noise using eight loudspeakers (Control 1, JBL Corp., Los Angeles, CA) as described previously [11].

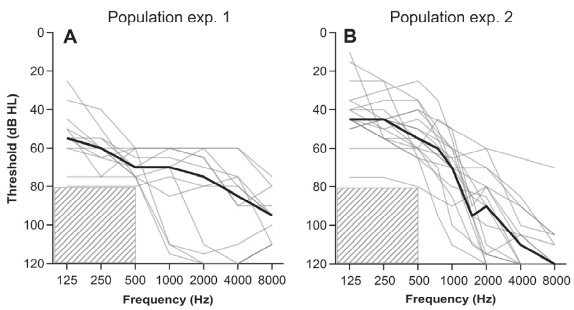


**Figure 3**. Pure-tone audiograms of the hearing aid ear. (A) Experiment (exp.) 1 evaluated the front-facing broadband beamformers (*n* = 12). Exp. 2 evaluated the side-facing narrowband beamformers (*n* = 18). Box: Exclusion criterion (>80 dB HL hearing loss at 125, 250, or 500 Hz). Thick black line: median.

Speech was administered through a MSP5A loudspeaker (Yamaha Corp., Japan) placed ~1 m from the listener at ear level calibrated at 65 dB SPL (Rion NA-28, Rion Co. Ltd., Tokyo, Japan). Speech was administered in front of the listener ($S_0N_{dif}$) or to the HA side ($S_{HA}N_{dif}$). To determine the SRT, noise levels were adaptively varied according to the LIST protocol [10]. Each listening condition was tested once. Microphone setting and speech angle were tested in a randomized block design, and LIST sentences were randomized across conditions and participants. Care was taken to deploy unique lists for each participant. Some participants found the speech testing challenging. Particularly, the $S_{HA}N_{dif}$ condition resulted in high SRTs in some participants, and we suspect that audibility, rather than noise, was the limiting factor for speech intelligibility. SRTs higher than +5 dB were excluded from the analysis. Linear mixed modeling was used for significance testing, allowing missing data to be included.

$BF_{MS}$ and $BF_{BS}$ were evaluated in experiment 2 by adaptively determining SRTs with the Dutch-Flemish Matrix test [12]. The speech was presented on the CI side and noise on the HA side ($S_{CI}N_{HA}$), or vice versa ($S_{HA}N_{CI}$), using two calibrated loudspeakers (KEF, Ci100QS, GP Acoustics, Kent, United Kingdom). Noise levels were kept constant at 60 dBA while speech was varied adaptively, according to Brand & Kollmeier [13]. The noise was a single male babble based on the ICRA noise [14] and time-reversed to eliminate any intelligible parts. Anecdotal reports from our lab indicate that some CI users can extract meaningful information from the original ICRA babble. Each listening condition was tested and re-tested, except for one participant who participated only in a single session. Performance was better overall than in experiment 1, and no data was excluded. Microphone setting and speech angle were tested in a randomized block design, and Matrix lists were randomized across conditions and participants.

### 2.4 Statistical analyses

For both experiments, linear mixed models (LMMs) were used in SPSS 29 for Windows (IBM Corp., Armonk, N.Y., USA), where SRTs were entered as the dependent variable. The microphone setting was entered as a repeated fixed variable, and the subject number was included as a random effect with a scaledID variance/covariance matrix. $BF_M$ and $BF_B$ were assessed using the $S_0N_{dif}$ configuration. $BF_M$, $BF_B$, and DS were tested in the $S_{HA}N_{dif}$ listening condition. Both listening conditions were analyzed in a separate LMM. $BF_{MS}$ and $BF_{BS}$ were evaluated using $S_{CI}N_{HA}$ and $S_{HA}N_{CI}$ and could be analyzed in a single LMM, including microphone setting, listening condition, and test/retest as repeated fixed factors. The interaction term between the microphone setting and angle was also included.

The variance/covariance matrix for the repeated factors was chosen for each LMM individually by comparing various matrix structures befitting a repeated measures design (including, but not limited to, compound symmetry, diagonal, scaledID, and Toeplitz). Different outcomes of model fit were assessed and weighed when choosing the final variance/covariance matrix, including Akaike's information criterion, distribution of the residuals (Shapiro-Wilk's normality test, histogram), the relation between actual and predicted values, and QQ-plots.

*Post hoc* multiple comparisons testing was performed on the estimated marginal (EM) means relative to the omnidirectional microphone setting in experiment 1 ($BF_M$, $BF_B$, DS) or against 'Real Ear Sound' (RES, Phonak) in experiment 2 ($BF_{MS}$ and $BF_{BS}$). Šidák's orrection was applied for multiple comparisons testing ($\alpha = 0.05$).

## 3. RESULTS

### 3.1 Experiment 1: Evaluation of broadband beamformers and directivity steering in diffuse noise

In the first setup of experiment 1, $BF_M$ and $BF_B$ were tested for their intended use when speech was administered from the front ($S_0N_{dif}$). The results are shown in Fig. 4A. The LMM revealed a significant main effect of beamforming ($F(2,9) = 6.9$, $p = 0.014$). Compared to omnidirectional microphone settings, $BF_B$ significantly improved SI by 2.9 dB SNR (standard error *SE*: 0.9; 95% confidence interval (*95%CI*): 5.6 to 0.1; degrees of freedom (*df*): 9; $p = 0.042$). The effect of $BF_{MS}$ was more moderate (1.3 dB SNR) and did not reach significance (0.6; -0.4 to 3.0; 10; $p = 0.139$).

When the speech was administered to the HA side ($S_{HA}N_{dif}$, Fig. 4B), the effect of the microphone setting was also significant ($F(3,21) = 10$, $p < 0.001$). Compared to the omnidirectional microphone setting, DS improved SI significantly by 3.6 dB SNR (*SE*: 1.2; *95%CI*: 0.2 to 7.0; *df*: 21; p = 0.032). In this listening condition, $BF_M$ and $BF_B$ deteriorated SI (EM means: -1.8 and -2.6, respectively) but not significantly (1.4; -5.8 to 2.1; 22; $p = 0.723$ and 1.4; -6.7 to 1.5; 21; $p = 0.401$, respectively).

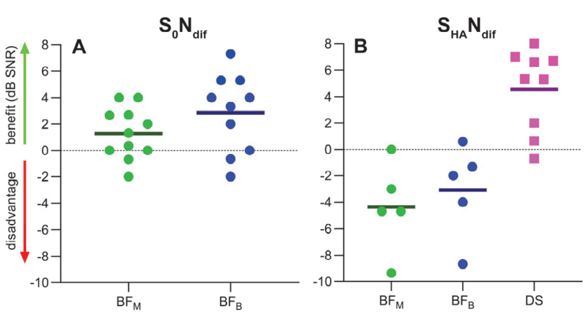


**Figure 4**. Evaluation of the clinically established broadband, front-facing monaural ($BF_M$, green symbols) and binaural beamformer ($BF_B$, blue), and directivity steering (DS, purple) in a diffuse noise field. (A) Effects of $BF_M$ and $BF_B$ when speech was administered to the front ($S_0N_{dif}$). (B) Effects of $BF_M$, $BF_B$, and DS with speech administered to the hearing aid side ($S_{HA}N_{dif}$). Dashed horizontal line: no effect (0 dB SNR difference on the speech recognition threshold). Thick colored lines: mean.

### 3.2 Experiment 2: Evaluation of side-facing narrowband beamformers

In experiment 2, two listening conditions were tested ($S_{CI}N_{HA}$ and $S_{HA}N_{CI}$), and the results are shown in Fig. 5. Microphone setting and listening condition both had a significant main effect on SRT ($F(2,29) = 5.0$, $p = 0.014$ and ($F(1,35) = 68.0$, $p < 0.001$), respectively). Their interaction was not significant ($F(2,61) = 0.2$, $p = 0.846$). Across both listening conditions, $BF_{BS}$ modestly but significantly improved SI by 1.1 dB SNR (*SE*: 0.4; *95%CI*: 0.0 to 2.1; *df*: 19; $p = 0.046$), but $BF_{MS}$ was ineffective with an EM mean difference of -0.1 dB SNR (0.3; -0.9 to 0.7; 45; $p = 0.985$).

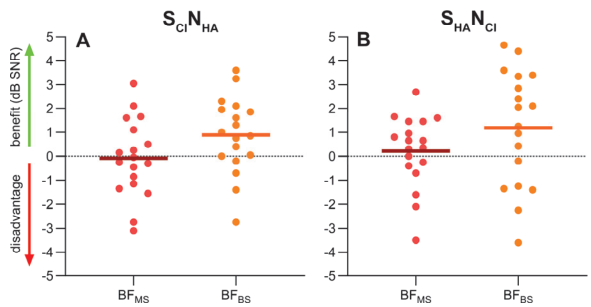


**Figure 5**. Evaluation of the experimental narrowband, side-facing monaural ($BF_{MS}$, red symbols), and binaural beamformer ($BF_{BS}$, orange) in a diffuse noise field. (A) Effects of $BF_{MS}$ and $BF_{BS}$ when speech was administered to the cochlear implant (CI) and noise to the hearing aid (HA) ($S_{CI}N_{HA}$). (B) Effects of beamforming in the $S_{HA}N_{CI}$ condition. Dashed horizontal line: no effect. Thick colored lines: mean.

To investigate the influence of the amount of residual hearing, we performed a correlation analysis by regressing the benefit of $BF_{BS}$ against the average pure-tone threshold across 500, 1000 and 2000 Hz ($PTA_{500\text{-}2000}$) in the HA ear (Fig. 6). For the $S_{HA}N_{CI}$ condition, the correlation was significant ($F(1,16) = 6.1$, $p = 0.0252$, $r^2 = 0.28$), but not for the $S_{CI}N_{HA}$ condition ($F(1,16) = 0.0$, $p = 0.869$, $r^2 = 0.0$). This correlation was not significant for $BF_{MS}$ in both listening conditions ($F(1,16) = 0.4$, $p = 0.550$, $r^2 = 0.0$ and $F(1,16) = 0.6$, $p = 0.451$, $r^2 = 0.0$, respectively).

## 4. DISCUSSION

Experiment 1 evaluated two directional microphones and directivity steering in bimodal listeners in diffuse stationary noise. The clinically established, front-facing, wideband beamformer $BF_B$ improved SI significantly by 2.9 dB SNR, whereas $BF_M$ resulted in a more modest and statistically insignificant benefit of 1.3 dB SNR. A previous study from our lab evaluated the same directional microphones for bimodal users in a diffuse noise field [4]. The authors report an average benefit of $BF_B$ that matches the current data (2.9 dB SNR), although $BF_M$ performed substantially better in that study (2.6 dB SNR). A recent study investigating $BF_B$ for bimodal listeners in an $S_0N_{dif}$ measurement setup found a comparable benefit of 2.3 dB SNR [15]. Another study compared $BF_M$ and $BF_B$ for unilateral CI users with a CROS device in the contralateral ear, again in a diffuse noise field [5]. The reported benefit of $BF_B$ was more modest than in the current study (1.4 dB SNR), whereas the benefit of $BF_M$ was not significant (0.7 dB SNR). The reduced performance in the CROS configuration can be explained by the fact that $BF_M$ and $BF_B$ are implemented as a lighter version in the CROS device to increase battery life [5]. Other studies have investigated these two directional microphones for bimodal listeners and CI users.

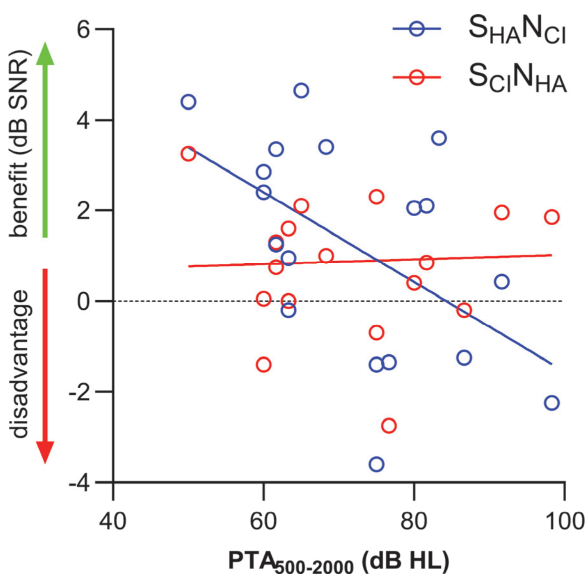


**Figure 6**. Correlation between the effect of binaural side-beamforming ($BF_{BS}$) and average pure-tone thresholds at 500, 1000, and 2000 Hz ($PTA_{500\text{-}2000}$) when speech was administered to the cochlear implant (CI) and noise to the hearing aid (HA) ($S_{CI}N_{HA}$, red symbols and line) and *vice versa* ($S_{HA}N_{CI}$, blue). The regression was significant for $S_{HA}N_{CI}$. Dashed horizontal line: no effect.

As discussed elsewhere [5], the configuration of the noise sources (loudspeaker arrangement) can dramatically affect study outcomes. Front-facing beamformers attenuate noise most effectively when administered to the sides or the back. By contrast, noise sources from the front are passed through unattenuated (Fig. 1). These spatial characteristics make comparing with other studies challenging. Ernst et al. [16] used a diffuse noise setup similar to ours by implementing a ring of loudspeakers and reported benefits of 3.4 ($BF_M$) and 4.6 dB SNR ($BF_M$) for bimodal listeners. These relatively large benefits can be explained by the absence of noise from the frontal loudspeaker in their setup, which favors beamforming. By contrast, the authors report substantially reduced benefits of 1.4 ($BF_M$) and 2.6 dB SNR ($BF_B$) when a semicircle of loudspeakers was deployed in front of the listeners, again emphasizing the impact of noise administered from the front. Another study that assessed these beamformers for unilateral CI users reports benefits of 5.3 ($BF_M$) and 7.1 dB SNR ($BF_B$) [17]. In this study, noise predominantly came from the sides and the back, favoring beamforming effectivity.

Prediction of the benefits of directional microphones as based on polar patterns or manikin (KEMAR) recordings is challenging because of the adaptive behavior of $BF_M$ and the potential overestimation of the SI benefit based on SNR effects alone [5], underscoring the importance of clinical tests for CI users.

When the speech was administered to the HA side, $BF_M$ and $BF_B$ did not significantly affect SI, but DS substantially and significantly improved SRTs by an average of 3.6 dB. This benefit can be attributed to reducing the head shadow effect, assuming that the CI ear was the better hearing side. The theoretical benefit of CROS with speech presented to the ear contralateral to the CI in diffuse noise equals the head shadow effect, i.e., approximately 7 dB [18]. The fact that our reported DS benefit is only about half of this can be explained by residual hearing in the HA ear that mitigates the CROS effect [19]. Further, DS is technically not CROS because attenuation is applied to the HA ear when DS is switched on, which will somewhat reduce hearing performance in that ear. When noise is administered to the side steered to the better-hearing ear (here, the HA ear), DS will degrade SI. Further, any ILD cues between the devices are lost because of its broadband CROS steering characteristic. Therefore, we advise manual control of this feature and counseling of the end user to explain when to activate DS and when to avoid it. In the future, the automation of DS based on auditory scene analysis can be helpful.

In experiment 2, we assessed two novel, experimental directional microphones that work differently than usual beamformers by increasing low-frequency ILDs while preserving physiological ILDs at frequencies above 1500 Hz. The binaural variant $BF_{BS}$ significantly improved SRTs by 1.1 dB, whereas $BF_{MS}$ did not significantly improve SI. The benefit of $BF_{BS}$ correlated significantly with residual hearing when speech was administered to the HA ear and noise to the other. Modeling studies with an algorithm very similar to $BF_{BS,}$ as used in the current study, showed that the benefit of such an approach could be expected to be up to 16 dB for bimodal listeners when speech is administered frontally, and noise is presented to the CI side, and up to 8 dB when noise is presented to the HA side. With speech also being administered to the side, the effect can be expected to be even higher [18]. One reason for the much smaller benefit found in the present study may be the amount of residual hearing. The previous modeling study simulated hearing loss in a group of typical hearing listeners through a filtering procedure. This resulted in a ski slope audiogram with normal hearing up to 500 Hz and a steeply sloping audiogram at higher frequencies. In our study population, however, the median residual hearing loss was 40 – 50 dB HL between 125-500 Hz.

Another reason for $BF_{BS}$'s more subtle benefit is that we used the current default microphone setting of Advanced Bionics (RES) as the reference, whereas the simulation study deployed an omnidirectional microphone. RES is also a beamformer that partially mimics, and thus mitigates, the effects of $BF_{BS}$.

Theoretically, the artificial inflation of low-frequency ILDs is beneficial when speech is administered to the side, regardless of whether it is the CI or the HA ear. However, it will be relevant to verify whether BFBS degrades SI in certain situations and whether it can always be switched on regardless of the auditory scene.

**Conclusion**

The clinically established binaural beamformer $BF_B$ and the experimental side-facing beamformer $BF_{BS}$ significantly improved SI. Given the insignificant benefits of the monaural counterparts $BF_M$ and $BF_{MS}$, we recommend using binaural beamforming whenever feasible. DS had a significant advantage when speech was presented to the HA ear; this can also be a helpful technique when speech is administered to the lesser hearing side.

## 5. ACKNOWLEDGMENTS

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