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Benefit of directional microphones for unilateral, bilateral and bimodal cochlear implant users

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Objective: To compare the standard T-Mic setting to UltraZoom and StereoZoom in 10 unilateral cochlear implant (CI) users, 10 bimodal device users and 10 bilateral CI users as well as a normal hearing (NH) reference group ($n = 10$).
Method: Speech reception thresholds were measured using the Oldenburg sentence test in noise. Speech was presented from the front at 0°, noise was presented from five loudspeakers spaced at ±60°, ±120°, 180° (setup A) or from four loudspeakers in the front hemisphere at ±30°, ±60° and one at 180° (setup B).
Results: There was a significant advantage for UltraZoom and StereoZoom for all groups in both setups. The largest advantage was for StereoZoom in the bilateral group (setup A, 5.2 dB, $P < 0.001$ and B, 3.4 dB, $P < 0.001$) There was a significant advantage for StereoZoom over UltraZoom in the bimodal group (setup A, $P < 0.01$ and B, $P < 0.05$) and in the bilateral group ($P < 0.01$, setup B only). The bilateral group performed as well as the normally hearing group in both setups and the bimodal group performed as well in setup A. There was a significant benefit of 1.8 dB for ClearVoice over UltraZoom alone for the unilateral group.
Conclusions: UltraZoom and StereoZoom provided a clinically and statistically significant benefit over the T-Mic condition. The largest gain was shown for StereoZoom in the bimodal and bilateral groups. The use of StereoZoom enabled the bilateral group to perform as well as the normally hearing group in both the challenging speaker setups. However, real life environments might provide an even greater challenge than the conditions tested here.

Keywords: Directional microphones, StereoZoom, UltraZoom, Bimodal, Bilateral, Speech performance

Introduction

Cochlear implant (CI) recipients perform well in quiet, with some achieving scores on speech perception tests similar to those of normally hearing listeners (Gifford *et al.*, 2008). However, in noisy and reverberant environments performance begins to deteriorate. This is true for all listeners, but it is particularly problematic for hearing impaired individuals (Nabelek and Nabelek, 1994; Nabelek and Pickett, 1974). CI recipients require significantly higher Signal-to-noise ratios (SNR) than their normally hearing counterparts to achieve equivalent performance (Firszt *et al.*, 2004; Schafer *et al.*, 2012; Spahr and Dorman, 2004). The simplest way to address this problem is by improving the SNR before the signal enters the CI or hearing aid (HA) processing pathway. This can be done in two different ways; Frequency modulation and directional microphones. Frequency modulation (FM) systems can provide a large improvement in the SNR but are not practical in many situations as they require the cooperation of the speaker, as well as the listener, and need additional equipment (Lewis *et al.*, 2004). Directional microphones offer an alternative solution which is integral to most modern hearing devices and is entirely controlled by the user.

Directional microphones are not equally sensitive to sound arriving from all directions (omnidirectional) but have reduced sensitivity to sound arriving from a specified location Usually this is attenuating sound from behind the listener which is often noise. The process by which the microphone directionality is created is called beamforming. This process uses time and phase differences between the signals arriving at two or more spatially separated microphones. By manipulating the directional response characteristics of the microphone, an unlimited variety of sensitivity patterns can be produced. These can be either static, where the

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point of maximum attenuation or null is fixed, or adaptive, where the null dynamically follows the direction of noise (Kates, 1993; Kompis and Dillier, 2001; Saunders and Kates, 1997; Valente *et al.*, 1995).

Beamformers have been incorporated successfully into HAs since the 1990s and benefits in speech understanding could be shown in previous studies (Ricketts and Dhar, 1999; Ricketts and Henry, 2002). Two systematic reviews identified weak to moderate evidence of their effectiveness in improving speech perception in noise (Bentler, 2005; McCreery *et al.*, 2012; Ricketts and Dhar, 1999; Ricketts and Henry, 2002). However, the first beamforming algorithms integrated into CI sound processors were not commercially introduced until 2005 (Spriet *et al.,* 2007). All the major manufacturers now offer beamforming in their sound processors, each with a different marketing name. Test setups vary widely in the studies assessing the performance of these adaptive and fixed monaural beamformers. However, studies with multiple noise sources reported improvements in the speech reception threshold (SRT) which ranged from 4 to 6.5 dB (Brockmeyer and Potts, 2011; Hersbach *et al.*, 2012; Honeder *et al.*, 2018; Geißler *et al.*, 2015; Gifford and Revit, 2010; Spriet *et al.*, 2007).

UltraZoom is a monaural adaptive beamformer available in the Advanced Bionics Naida CI sound processor range. A previous study by Geißler *et al.* (2015) investigated UltraZoom in a speaker arrangement designed to reflect real world settings. Speech-shaped noise was presented from a selection of speakers positioned at 0°, ±45°, ±70°, ±90°, ±135°, and 180° azimuth. Subjects' performance with UltraZoom was compared to their performance with the T-Mic, an omnidirectional microphone placed at the opening of the external auditory canal. Results showed that the SRT improved by 5.5 dB with both fixed and roving noise. Mosnier *et al.* (2017) also showed a 3.6 dB improvement in speech perception with UltraZoom with speech in front of the subject and speech-shaped noise presented at a fixed level of 65 dB SPL at ± 90° and 180°. They also showed a significant improvement in subjective benefit using the APHAB (Cox and Alexander, 1995). Speech in noise is improved in bilateral CI users when monaural beamforming is used on both processors independently, compared to its use in only one processor (Weissgerber *et al.*, 2015). Devocht *et al.* (2016) reported that, in their sample of 12 bimodal CI users (CI in one ear and HA in the other), using the monaural UltraZoom beamfomer in both devices almost doubled the SRT advantage compared to using UltraZoom in just the implanted ear. The beamformers currently used in CIs consist of two omnidirectional microphones situated on a single sound processor, creating a first-order directional characteristic. To improve the effectiveness of any directional system the spacing between microphones can be increased, or additional microphones added, to create a superdirective array (Kates, 1993; Saunders and Kates, 1997). The limitations imposed by the small size of hearing-device casings make the application of this technology impractical in a single-hearing instrument. However, when HAs or CI sound processors are fit binaurally, four microphones are available for use across the two systems. This makes it possible to implement binaural beamforming. There are only a couple of studies which have looked at binaural beamforming in CI users. Kokkinakis *et al.* (2012) reported a significant benefit in speech intelligibility using a four-microphone binaural algorithm compared to two interaurally independent, two-microphone beamformers. Buechner *et al.* (2014) reported an 8 dB improvement in SRT compared to the omnidirectional condition. There was also a 2 dB improvement over UltraZoom in a fixed, semi diffuse noise condition using an Advanced Bionics Harmony sound processor connected to an Phonak Ambra HA.

In the Naida CI sound processor, a third order binaural beamformer called StereoZoom is available. It uses the four microphones available across the two hearing devices to produce a very narrow fixed target beam. The polar plot in Fig. 1 shows how StereoZoom compares to the monaural UltraZoom on a KEMAR dummy. It can be implemented either across two CI sound processors or across a CI and Phonak HA. For the first time, this provides the opportunity to assess binaural beamforming in a commercially available CI device.

The aims of this study were (1) to compare UltraZoom to the standard clinical setting in a unilateral, bimodal and bilateral group of CI recipients. (2) To compare StereoZoom to the standard clinical setting and UltraZoom in the same three groups. (3) To investigate the impact on UltraZoom of

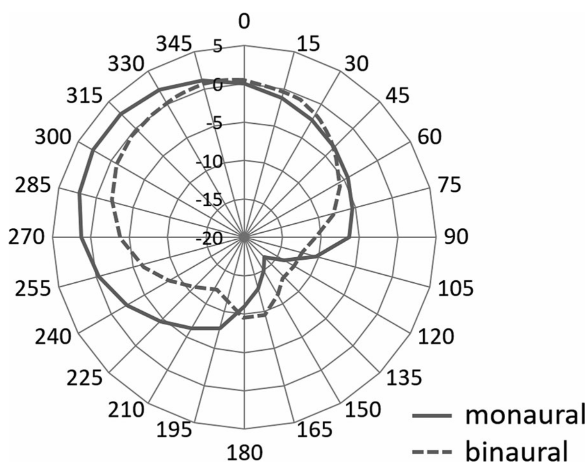

Figure 1 Polar plot showing the microphone response for both monaural and binaural beamformers on a KEMAR dummy. Circles indicate the gain in dB relative to the 0^0 response

ClearVoice (CV), a single-microphone noise reduction algorithm implemented in the Advanced Bionics sound processors (Buechner *et al.*, 2010).

Method

Subject groups

A total of 30 CI users participated in the study, split into three groups: (1) unilateral, equipped with only one CI on one side, (2) bilateral, equipped with two CIs, (3) bimodal, equipped with one CI and a HA contralateral. Ten normal hearing listeners (according to ISO norm, hearing thresholds in Table 1(d) serve as a reference group. Subject details are listed in Table 1. All subjects had German language proficiency and had a minimum speech perception of 50% correct in the Freiburg monosyllabic test as an inclusion criterion. Residual hearing in the unimplanted ear in the bimodal group is shown in Fig. 2.

Study design

Each of the three CI user groups participated in two to three appointments, with each group following a slightly different study protocol (Table 2). As all subjects elected to use the T-Mic, this was the baseline condition. For the bimodal subjects, real-ear-sound (RES) was used on the HA, imitating the T-Mic effect of the CI side. Performance with the adaptive directional microphone UltraZoom, and binaural directional microphone StereoZoom (not available for unilateral CI users) was compared to the baseline. Two different loudspeaker setups were used for this evaluation: A and B (Fig. 3, detailed description in section speech testing).

For the unilateral users, the CV noise reduction algorithm was also tested in combination with the beamforming. This was done in test setup A during appointment two. At appointment three, the beamforming was tested alone in speaker setup B. For the bilateral and bimodal users, performance of the beamformers was tested without CV. Testing was done in speaker setup A and B with T-Mic, UltraZoom and StereoZoom. For the bimodal subjects the baseline condition was T-Mic in the implanted ear and RES in the aided ear.

For reference, the normal hearing group was measured in the same two loudspeaker setups.

The interval between appointments was between one night and one month. During this interval subjects used their own sound processor with their regular clinical programing.

Device fitting

Unilateral, bilateral CI

Programs on the Naida CI sound processor were fit using the SoundWave 3.0 clinical fitting software, following standard fitting guidelines and procedures, and based on the subject's previous clinical program.

For the study measurements, a loaner Naida CI sound processor was provided. During the take-home phases, the subject's own clinical processor was used with their original programing from the clinical routine.

Bimodal

All subjects were fit with a Phonak Naida Link HA, either as UltraPower (UP) or as a receiver-in-the-canal (RIC) device. Phonak Target 4.3 software was used to program the HA. This software enables the Hearing Instrument Body Area Network (HIBAN) link between the CI processor and the HA to access the bimodal front-end features such as StereoZoom. The fitting was done according to the clinical routine of the center using the Adaptive Phonak Digital Bimodal fitting prescription, which aligns the two Naida devices in terms of e.g. automatic gain control (AGC) and loudness growth behavior (Veugen *et al.*, 2015, 2016). For convenience, QuickSync was activated in both devices. This allowed subjects to change programs on both devices at the same time by pressing one button on either the CI or HA side.

Loudness balancing was performed to align the HA and CI processor. The HA gain was adjusted to the most comfortable level with the CI, a medium loud level, based on the feedback of the subject.

Speech testing

Speech intelligibility was tested in two loudspeaker setups (Fig. 3). The speech signal was always presented from the front at 0°. Noise was presented either from five loudspeakers evenly spaced in 60° distances (±60°, ±120°, 180°) or from four loudspeakers in the front hemisphere (±30°, ±60°) and one in the back (180°). These setups were chosen based on the fact that the beamformers have a directivity towards the front, i.e. noise from around is attenuated to improve speech perception for signals from the front. In setup A noise from around the subject is respected. As StereoZoom provides a narrower beam to the front than UltraZoom, setup B was chosen to investigate the differences between the two beamformers.

Speech intelligibility in speech-shaped noise was measured via the Oldenburg sentence test (OlSa) (Wagener *et al.*, 1999). The speech level was adapted to yield the SRT, the speech level required for 50% correct word understanding, while the noise level was kept constant at 65 dB SPL. Two OlSa lists (20 sentences each) were used for each processing condition and the SRT averaged across both lists. Prior to testing, at least two practice lists were presented to minimize training effects during the test. The number of practice lists was increased if the subject was not familiar with the OlSa material.

Table 1 Demographical data of study participants

(a)		Cochlear implant side					
ID	Age [yrs]	Side	Etiology	Device	Duration of device use [yrs]	Duration of hearing impairment [yrs]	Duration of profound hearing loss [yrs]
uni 01	64.82	left	acute HL	Naida CI	1.17	12.21	5.21
uni 02	59.98	left	acute HL	Naida CI	0.81	9.23	1.23
uni 03	63.24	right	acute HL	Naida CI	2.54	37.29	11.27
uni 04	37.75	left	acute HL	Naida CI	5.80	6.42	6.42
uni 05	78.30	right	unknown	Naida CI	0.85	19.75	19.75
uni 06	48.83	left	morb. men.	Naida CI	3.22	31.56	
uni 07	75.82	right	acute HL	Naida CI	0.85	1.51	1.51
uni 08	62.39	left	fracture PB	Naida CI	1.86	6.95	5.61
uni 09	66.56	left	morb. men.	Harmony	6.02	22.79	7.78
uni 10	74.99	right	genetic	Naida CI	1.23	27.89	17.89

(b)			First cochlear implant side					Second cochlear implant side			
ID	Age [yrs]	Device (both sides)	Side	Etiology	Duration of device use [yrs]	Duration of hearing impairment [yrs]	Duration of profound hearing loss [yrs]	Etiology	Duration of device use [yrs]	Duration of hearing impairment [yrs]	Duration of profound hearing loss [yrs]
bil 01	83.35	Naida CI	left	acute HL	7.38	24.25		ac. neurinoma	5.59	26.25	
bil 02	74.13	Naida CI	right	genetic	2.09	36.26	2.24	genetic	0.54	36.26	2.24
bil 03	70.97	Naida CI	right	otosclerosis	12.06	39.28	9.26	otosclerosis	5.50	39.28	17.27
bil 04	77.66	Naida CI	right	noise	12.41	47.38	27.37	noise	11.05	47.38	27.37
bil 05	54.80	Naida CI	right	otitis media	10.56	47.39	12.36	otitis media	5.80	47.39	12.36
bil 06	67.03	Naida CI	right	ac. neurinoma	17.04	37.55	27.55	acute HL	7.33	37.55	27.55
bil 07	55.89	Naida CI	left	mult. infections	10.36	52.74	24.72	mult. infections	1.44	52.74	24.72
bil 08	55.42	Naida CI	left	morb. men.	1.04	10.73	2.72	ac. trauma	0.81	47.75	2.72
bil 09	70.35	Naida CI	left	scarlet des.	0.82	7.89	1.89	scarlet des.	0.82	70.35	70.35
bil 10	30.63	Naida CI	right	since birth	11.01	31.19	18.18	since birth	4.83	31.19	18.18

(c)

				Cochlear implant side					Hearing aid side	
ID	Age [yrs]	Side	Etiology	Device	Duration of device use [yrs]	Duration of hearing impairment [yrs]	Duration of profound hearing loss [yrs]	Device	Duration of device use [yrs]	Duration of hearing impairment [yrs]
bim 01	50.84	left	otosclerosis	Naida CI	1.18	27.59	25.59	Audio Service Mezzo 4 HP	4.25	27.59
bim 02	76.99	left	acute HL	Naida CI	1.39	34.70	4.68	Phonak Naida Q90 SP	21.69	34.70
bim 03	72.01	right	surgery	Naida CI	0.92		25.72	Phonak Bolero Q90-*P*	4.70	4.70
bim 04	82.78	right	noise	Harmony	4.45	20.37	8.36	Phonak Naida V UP	19.37	20.37
bim 05	66.96	right	acute HL	Naida CI	0.64	16.97	1.38	Phonak Naida Link UP	10.05	11.14
bim 06	77.73	left	unknown	Naida CI	1.84	20.61	3.60	Novasense Geneve	6.60	20.61
bim 07	83.57	left	unknown	Naida CI	3.19	6.67	10.67	Series Starkey	6.67	10.67
bim 08	70.48	right	acute HL	Naida CI	1.91	16.63	2.79	Oticon Chili SPS	10.55	16.63
bim 09	66.64	left	acute HL	Naida CI	1.33	7.62	5.62	Phonak Naida RIC	1.29	5.62
bim 10	61.44	right	acute HL	Naida CI	3.27	3.67	3.67	Phonak Audeo	3.67	39.69

(d)

		Hearing thresholds left ear [dB] for various frequencies [kHz]									Hearing thresholds right ear [dB] for various frequencies [kHz]								
ID	Age [yrs]	0.125	0.25	0.5	0.75	1.0	1.5	2.0	4.0	8.0	0.125	0.25	0.5	0.75	1.0	1.5	2.0	4.0	8.0
NH 01	41	5	0	0	0	0	5	−5	5	5	5	0	0	0	0	0	0	0	0
NH 02	36	−5	−5	0	0	0	5	−5	0	−5	0	0	0	0	5	0	0	5	−10
NH 03	57	5	0	0	5	5	0	0	0	10	5	5	5	5	5	5	0	5	10
NH 04	58	10	0	5	5	5	10	5	5	15	15	5	10	10	10	10	0	20	20
NH 05	65	15	15	20	20	25	25	30	20	30	10	10	15	15	20	20	20	15	10
NH 06	65	15	5	0	10	5	15	10	20	35	15	5	5	5	5	15	10	30	20
NH 07	65	5	5	5	5	10	20	20	15	30	5	10	10	10	10	15	20	20	20
NH 08	68	15	10	15	10	5	15	10	15	0	10	15	15	10	10	15	20	15	10
NH 09	76	10	10	5	5	10	5	15	15	15	10	10	10	15	15	10	10	20	5
NH 10	76	5	10	10	5	5	15	5	30	25	5	5	5	5	5	5	5	15	15

HL = hearing loss, CI = cochlear implant, HA = hearing aid, yrs = years, uni = unilateral, bil = bilateral, bim = bimodal, NH = normal hearing, morb. men. = morbus Meniere, PB = petrous bone. (a) unilateral CI user group, (b) bilateral CI user group, (c) bimodal CI user group, (d) normal hearing reference group.

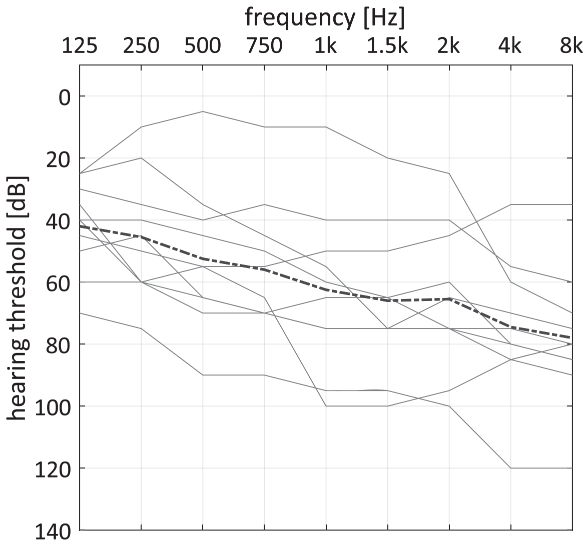

Figure 2 **Residual hearing profiles in dB HL in the contralateral ear for the bimodal group. Mean performance is shown with the dotted line**

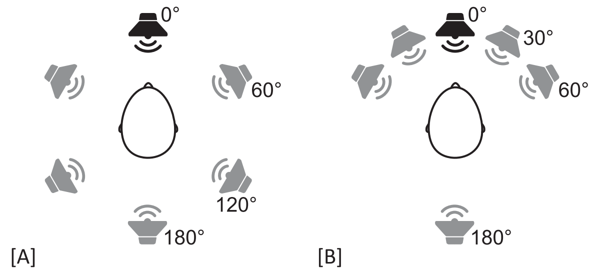

Figure 3 **Test setup A (on the left) with speakers arranged at 60^0 intervals all around the subject and setup B (on the right) with speakers clustered towards the front of the subject. Speech was always presented from the front speaker at 0^0 (in bold) and noise from the other speakers**

The subjects chair was equipped with a head rest to keep the head static during the measurements. In addition, subjects were reminded to avoid movements of the head during the tests.

Technical recordings

Measurements were made in each loudspeaker arrangement to establish the expected SNR gain using a KEMAR dummy, two CI processors and a streaming interface. The signal (speech-shaped noise as used in speech perception test) was first presented from the front. Recordings were made with the T-Mic, UltraZoom and StereoZoom settings. Secondly, the same signal was presented from the five surrounding loudspeakers in each setup and the resulting output recorded with T-Mic, UltraZoom and StereoZoom settings. Subtracting the beamformer recording (UZ or SZ) from the T-Mic recording gave the expected advantage. To compare the technical recordings to the actual measurements in subjects, measurements were performed in an acoustically treated room with low reverberation time of 0.2 s (same room as for subjects testings).

Table 2 **Outline of study protocol for the three groups tested**

Appointment	Test condition	Noise reduction	Test setup
Unilateral CI user group			
I	T-Mic UltraZoom	off	setup A
II	T-Mic UltraZoom	on	setup A
III	T-Mic UltraZoom	off	setup B
Bilateral CI user group			
I	T-Mic UltraZoom StereoZoom	off	setup A
II	T-Mic UltraZoom StereoZoom	off	setup B
Bimodal CI user group			
I	T-Mic / RES UltraZoom StereoZoom	off	setup A
II	T-Mic / RES UltraZoom StereoZoom	off	setup B

Statistics

A Factorial ANOVA (ANalysis Of VAriance) was performed to analyze higher-order interactive effects of multiple categorical independent variables. Post-hoc analysis was performed using a *t*-test for dependent samples across conditions or a *t*-test for independent samples to compare groups.

Results

Technical measurements

The SNR gains over the T-Mic setting, recorded using the KEMAR dummy, were: 4.4 dB (setup A), 1.9 dB (setup B) for UltraZoom and 6.5 dB (setup A), 3.9 dB (setup B) for StereoZoom.

Unilateral group

The results of the ANOVA showed that there was a significant difference for microphone setting (F (1) = 17, $P < 0.001$), and CV (F (1) = 4, $P = 0.05$) but not for the speaker setup. There was no interaction between groups.

Post-hoc testing using a paired t test revealed that there was a statistically significant advantage for UltraZoom over the T-Mic without CV in test setup A of 3.4 ± 2.0 dB (df = 9, $t = 6$, $P < 0.001$) and in test setup B of 1.6 dB ± 0.9 dB (df = 9, $t = 6$, $P <$ 0.001) (Fig. 4).

There was a significant advantage in setup A for CV 'on' in both T-Mic (1.7 ± 1.9 dB, df = 9, $t = 3$, $P =$ 0.02) and UltraZoom (1.7 ± 2.2 dB, df = 9, $t = 2$, $P = 0.04$) conditions (Fig. 4, indicated by dashed starred lines).

Bilateral group

The results of the ANOVA showed that there was a significant difference for microphone setting (F (2) = 28, $P < 0.001$), but not for the speaker setup. Post-hoc

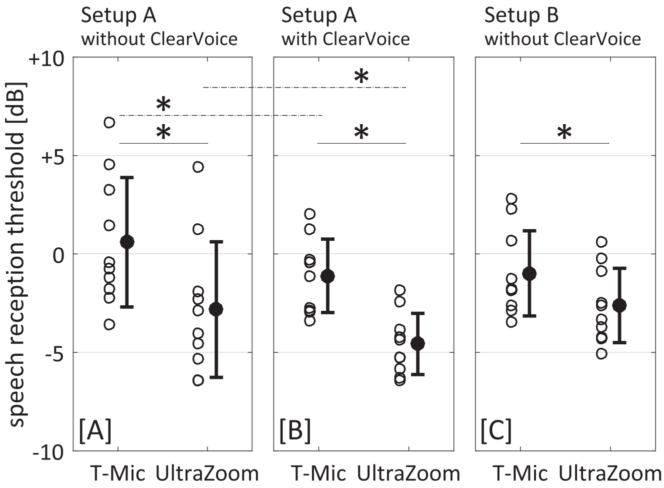

Figure 4 **Mean speech reception thresholds for the unilateral group. Speaker setup A is shown on the left as well as in the middle and setup B on the right. Measures with ClearVoice are shown in the middle and without ClearVoice on the left as well as on the right. Mean values are given with one standard deviation. Circles indicate individual scores. Starred lines show where averages were significantly different from each other**

testing using a paired *t*-test revealed that there was a statistically significant advantage for UltraZoom over the T-Mic without CV in test setup A of 4.3 ± 0.6 dB (df = 9 t = 22, $P < 0.001$) and in test setup B of 2.0 ± 1.1 dB (df = 9, t = 6, $P = 0.001$).

There was also a statistically significant advantage for StereoZoom over the T-Mic in test setup A of 5.2 ± 1.2 dB (df = 9, $t = 14$, $P < 0.001$) and in test setup B of 3.4 ± 1.1 dB (df = 9, $t = 10$, $P < 0.001$).

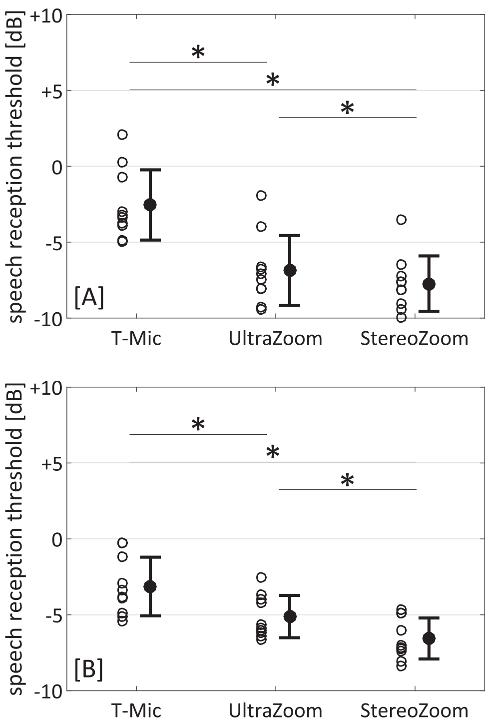

Figure 5 **Mean speech reception thresholds for the bilateral group. Speaker setup A is shown on the left and setup B on the right. In setup B only nine subjects were measured. Mean values are given with one standard deviation. Circles indicate individual scores. Starred lines show where averages were significantly different from each other**

There was an advantage for StereoZoom over UltraZoom in test setup A of 0.9 ± 1.1 dB (df = 9, $t = 2$, $P = 0.03$) and in test setup B there was a 1.4 ± 0.9 dB (df = 9, $t = 5$, $P = 0.001$), advantage (Fig. 5).

Bimodal group

The results of the ANOVA showed that there was a significant difference for microphone setting (F (2) = 22, $P < 0.001$), but not for the speaker setup. Post-hoc testing using a paired *t*-test revealed that there was a statistically significant advantage for UltraZoom over the T-Mic without CV in test setup A of 3.4 ± 1.8 dB (df = 9, $t = 6$, $P < 0.001$) and test setup B of 1.4 ± 0.9 dB (df = 9, $t = 5$, $P = 0.001$).

There was also a statistically significant advantage for StereoZoom over the T-Mic without CV in test setup A of 4.6 ± 2.1 dB (df = 9, $t = 7$, $P < 0.001$) and in test setup B of 2.6 ± 1.2 dB (df = 9, $t = 7$, $P <$ 0.001).

There was an advantage for StereoZoom over UltraZoom in setup A of 1.3 ± 0.8 dB (df = 9, $t = 5$, $P = 0.001$) and in setup B there was a 1.2 ± 1.5 dB (df = 9, $t = 2$, $P = 0.04$) advantage (Fig. 6).

A summary of the advantages gained in each test setup are provided in Table 3.

Comparison across subject groups

The best aided condition (UltraZoom for the unilaterals and StereoZoom for the bimodal and bilaterals) was compared across groups. A series of t tests with Bonferroni correction showed that in test setup A, the bilateral group was better than the unilateral group (df = 18, $t = 4$, $P = 0.001$), as was the bimodal group (df = 18, $t = 3$, $P = 0.02$). The normally hearing group was better than the unilateral group (df = 18, $t = 4$, $P < 0.001$) but no different from the

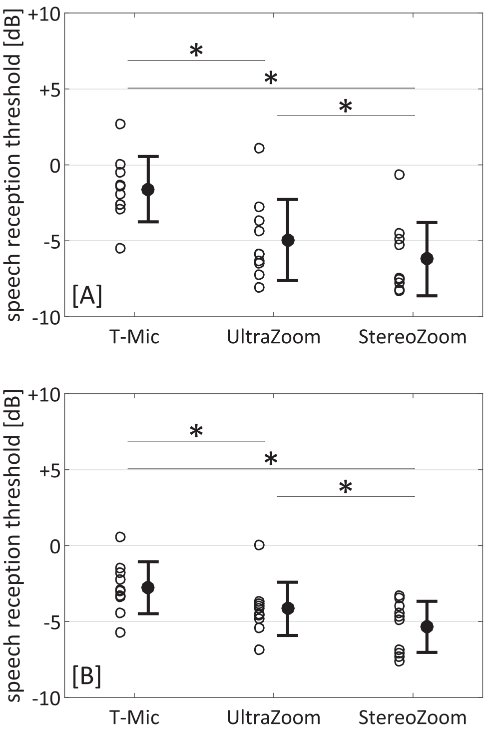

Figure 6 Mean speech reception thresholds for the bimodal group. Speaker setup A is shown on the left and setup B on the right. Mean values are given with one standard deviation. Circles indicate individual scores. Starred lines show where averages were significantly different from each other

bimodal or bilateral groups. There was no difference between the bilateral and bimodal groups.

In setup B, the bilateral group was again significantly better than the unilateral group (df = 18, t = 5, $P < 0.001$) as was the bimodal group (df = 18, t = 3, $P = 0.003$). The normally hearing group was better than both the unilateral group (df = 18, t = 7, $P < 0.001$) and the bimodal group (df = 18, t = 3, $P = 0.005$) but not the bilateral group. There was no difference between bilateral and bimodal groups (Fig. 7).

Discussion

The results of the study confirmed the significant benefit of the UltraZoom monaural beamformer over the T-Mic setting shown in previous studies (Buechner *et al.*, 2014; Geißler *et al.*, 2015; Mosnier *et al.*, 2017). In the first loudspeaker arrangement, the UltraZoom advantage over the T-Mic setting ranged from 4.3 dB in the bilateral group to 3.4 dB in the unilateral and bimodal groups. This represents a large clinical benefit to the patient and provides a noticeable improvement in performance when listening to speech in noise. In the second and harder setup, gains in speech reception threshold were smaller and ranged from 1.8 to 1.6 dB but were still large enough to be clinically significant. Discrimination functions in normally hearing adults for the OlSa show that a 1 dB change in the steepest part of the slope is equivalent to 17%. Therefore a 1.5 dB change in SNR could still provide a useful benefit to the patient (Wagener *et al.*, 1999). The improvements recorded in speech reception threshold were within the range of the those reported for other adaptive beamformers in similar conditions. Gains in speech reception threshold ranged from 6.5 dB to 3.9 dB depending on the specifications of the test setup used (Brockmeyer and Potts, 2011; Geißler *et al.*, 2015; Gifford and Revit, 2010; Hersbach *et al.*, 2012; Mosnier *et al.*, 2017; Spriet *et al.*, 2007). The speech reception threshold advantage over the T-Mic reported for the unilateral group was slightly lower than the 5.5 dB reported by Geißler *et al.* (2015) in a similar six speaker test setup and noise, but in line with the 3.6 dB advantage over the T-Mic reported by Mosnier *et al.* (2017).

The biggest UltraZoom advantage over the T-Mic was shown for the bilateral group in both speaker setups. This is most likely to be due to the activation of UltraZoom in both ears. Devocht *et al.*, (2016) previously showed that, in a group of bimodal users, symmetrical fitting of UltraZoom on both devices produced a 1 dB advantage over unilateral fitting of UltraZoom to the CI ear alone. We showed a similar 1 dB increase in the UltraZoom advantage for the bilateral group compared to the unilateral CI group. However, this advantage was not shown for the bimodal group. Although the two studies used a similar speaker setup, the Devocht group used a more sensitive within-subjects design in contrast to the two independent samples compared here, which may account for the different results. Having said this, statistical analysis did not show any differences in the beamforming advantage between the bilateral and bimodal groups in any of the conditions tested,

Table 3 Summary of the significant speech SRT advantage over the T-Mic setting in dBs provided by UltraZoom and StereoZoom in each test setup and in the technical testing

	Setup A		Setup B	
	UltraZoom Advantage	StereoZoom Advantage	UltraZoom Advantage	StereoZoom Advantage
Unilateral	3.4 dB		1.6 dB	
Bimodal	3.4 dB	4.6 dB	1.4 dB	2.6 dB
Bilateral	4.3 dB	5.2 dB	1.8 dB	3.4 dB
KEMAR	4.4 dB	6.5 dB	1.9 dB	3.9 dB

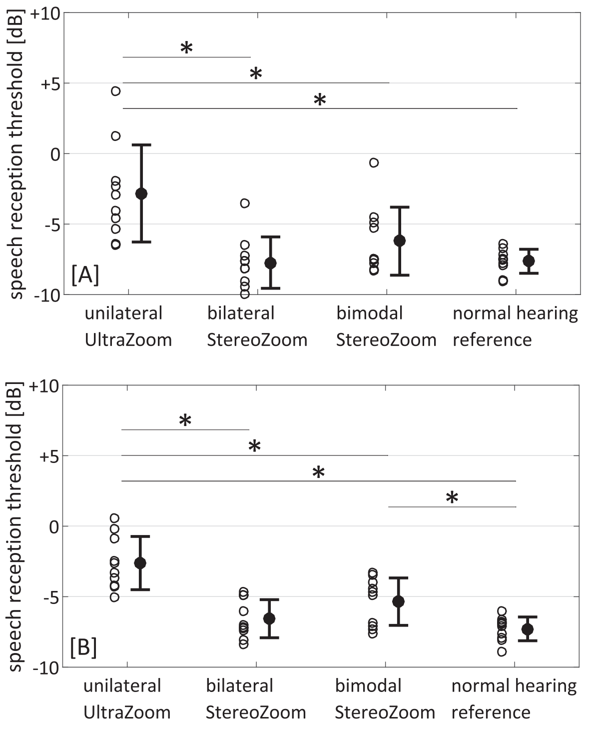

Figure 7 Mean speech reception thresholds for the best aided condition for each group and the normally hearing control group. Speaker setup A is shown on the left and setup B on the right. Mean values are given with one standard deviation. Circles indicate individual scores. Starred lines show where averages were significantly different from each other

indicating that the bimodal group did not get less benefit than the bilateral group. However, larger sample sizes may have produced a different result. There was a significant additive benefit of 1.8 dB for CV over UltraZoom alone, which was similar in size to the gain associated with CV reported elsewhere (Dyballa *et al.*, 2015; Geißler *et al.*, 2015; Holden *et al.*, 2013). The data recorded here shows that the expected benefit of CV is not affected by the addition of the beamforming.

The KEMAR result showed that under optimum conditions StereoZoom (a third order beamformer) produced a more focused microphone response and provided a significant SNR advantage in both speaker setups. When the StereoZoom setting was used by the bimodal and bilateral subjects, a small additional advantage over the monaural UltraZoom setting could be found. The size of the StereoZoom advantage over UltraZoom ranged between 1 and 2 dB across conditions and groups. The results were in line with the advantages reported by Buechner *et al.* (2014), in a fixed, semi diffuse noise condition, similar to setup A, using an Advanced Bionics Harmony sound processor connected to a Phonak Ambra HA.

The performance of beamformers is heavily dependent on the direction of the noise and the degree of separation between the noise and source signal. Greater noise reduction is achieved when the noise and signal are distinct and well separated. In diffuse environments, with lots of reverberation, the two signals become merged and the beamforming algorithms less effective (Greenberg and Zurek, 1992; Kompis and Dillier, 2001). In real life, noise can come from the front as well as behind. Condition B was designed to mimic this environment, with the noise speakers positioned in an arc in front of the subject and the target and noise less separated. In these challenging conditions, both beamformers continued to provide a significant benefit, although it was roughly half of the gain seen in the easier test condition. However, the advantage of StereoZoom over UltraZoom was more apparent in this more difficult condition, with a StereoZoom advantage over UltraZoom for both bilateral and bimodal groups in both setups. By using the microphones across both devices, the StereoZoom beamforming algorithm was able to separate out the speech from the noise more effectively than UltraZoom and provide a more robust response when the signal and noise were merged.

In the bilateral group the speech reception threshold improvements were in line with the technical measurements made with the KEMAR dummy in three out of the four conditions. For the other groups the speech reception threshold improvement was slightly lower than expected. However, the KEMAR has the advantage of remaining in a fixed position, thus allowing the beamformer algorithm to function optimally. Real participants are subject to head movements, which can reduce the effectiveness of the beamformer. Subjects were told to keep their head still, but this can be hard, especially during a long test session.

The bilateral and bimodal groups were able to use their binaural input to improve their overall speech perception in noise. They performed significantly better than the unilaterally implanted group, regardless of any signal enhancement strategies (Blamey *et al.*, 2015; Smulders *et al.*, 2016). With StereoZoom active both the bilateral and bimodal groups performed as well as the normal group in the easier speaker setup. To put this into a clinical context, at a −5 dB SNR, eight out of nine bilateral users were still scoring greater than 50% correct on the sentence test. Even in the harder setup, the bilateral group continued to perform as well as the normal group. This demonstrates that, in controlled conditions, StereoZoom gave a large enough improvement in SNR to provide near normal performance for the bilateral users and eliminated some of the difficulties for hearing speech in noise caused by hearing loss. However, in real life conditions, with moving rather than static noise sources and higher levels of reverberation, it is likely that even the bilateral CI recipients will still find it harder to hear speech in noise than normally hearing listeners.

This study did not assess real world use of either beamformer and their successful application depends on the recipient having a good understanding of the correct situations in which to use the setting. Future research should concentrate on the application of the technology in real world scenarios. This research would test the robustness of the algorithms under a variety of conditions as well as the ability of the recipients to use them appropriately.

Conclusions

UltraZoom and StereoZoom provided a clinically and statistically significant improvement in hearing in noise over the T-Mic condition, even in the most challenging listening conditions with noise in front of the recipient as well as behind. The largest clinically significant gain over the T-Mic of 2.6 dB (setup B) to 5.2 dB (setup A) was shown for the use of the StereoZoom binaural beamformer in the bimodal and bilateral groups and it provided more benefit than UltraZoom. The use of StereoZoom enabled the bilateral group to perform as well as the normally hearing group in both of the challenging speaker setups. However, real life environments include moving rather than static noise sources and higher levels of reverberation, which will provide an even greater challenge than the conditions tested here.

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Conflicts of interest We would highlight the fact that the third author is employee of Advanced Bionics, the manufacturer of the device under investigation in this report.

Ethics approval Approval was given by the Charité Medical University Berlin (Universitätsmedizin Berlin) ethics committee. Approval: EA1/124/15.

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