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Speech polar plots for different directionality settings of SONNET cochlear implant processor

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Objectives: The newest CI processor from MED-EL company, the SONNET, has two new directional microphone settings. Besides the Omnidirectional microphone mode, it has the possibility to switch to Natural or Adaptive directionality. Both new modes favour perception of sound coming from a front-facing direction compared to sounds from sources at alternate azimuths. Natural directionality mimics the pinna effect of the normal external ear.
Design: We undertook to verify the effect of these options *in vivo* by means of clinical audiological tests. Speech reception thresholds were successively measured for a variety of speech presentation azimuths while keeping the noise azimuths constant. Complete 'Speech Reception Threshold (SRT)-Polar-Plots' were obtained from these data for the Omnidirectional and Natural directionality modes of the SONNET. In addition, one 'SRT-point' was also measured in the 'Adaptive' mode for speech coming from 45° azimuth.
Study sample: A group of 13 adult CI recipients participated. Only one of these subjects had previous experience with the SONNET processor.
Results: Complete 'SRT-Polar-Plots' could be measured in Natural and Omnidirectional modes in CI recipients within an acceptable timeframe. The pinna-following directionality for Natural mode could be confirmed. Median SRT in noise for speech coming from the 45° azimuth speaker was −5.6 dB SNR for Omnidirectional, −9.1 dB SNR for Natural and −12.8 dB SNR for Adaptive microphone. Natural and Adaptive significantly improved performance compared to Omnidirectional mode at this optimal azimuth of 45° with a median improvement in SRT of 3.5 and 7.2 dB respectively.
Conclusions: A novel audiological method, 'SRT-Polar-Plot', was developed and described. Significant directionality benefits for Natural and Adaptive mode were confirmed *in vivo* using this technique.

Keywords: Cochlear implant, Directional microphone, Speech perception, Noise, Polar plot

Introduction

In everyday real-life conditions, sound reverberation and background noise can make it difficult to understand an individual speaker from a distance. As the target sound travels away from its source it reduces in intensity, while the background noise usually remains relatively constant. The ratio of the signal to noise thus decreases (Nabelek and Nabelek, 1994). The combination of reverberation, background noise, and increased distance from the speaker results in poor listening conditions. This is true for persons with normal hearing, but the impact is even greater for persons with hearing loss (Nabelek and Pickett 1974).

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Listeners with cochlear implants (CI) are known to have relatively poor speech understanding in steady noise compared to their normal hearing peers but also relative to their own good speech understanding performance in quiet (Fu et al., 1998). This discrepancy becomes larger for competing noises in real environments that are modulated or fluctuating in level (Nelson et al., 2003). Sound processing technologies such as directional microphones and noise reduction algorithms (De Ceulaer et al., 2015; Mauger et al., 2012) as well as the use of remote microphones (De Ceulaer et al., 2016; Wolfe et al., 2015) are recently being applied in CI processors as an attempt to overcome this deficit.

Directional hearing and pinna effect

Part of the selective hearing capacity of the human ear can be attributed to its differences in sensitivity for

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sounds originating from different directions or angles. Apart from the binaural information expressed in the Interaural Time Differences (ITDs) and Interaural Level Differences (ILDs), the human ear owes a monaural intrinsic directionality mainly due to the pinna of the outer ear. This directionality is often referred to as the pinna effect. The convolutions of the pinna are shaped in such a way that the external ear transmits more high-frequency components from a frontal and elevated source than from a source from the back and at ear level.

This natural frequency-dependent directional sensitivity difference of the ear can be depicted graphically in polar coordinates, the so-called Sensitivity Polar Plots. These plots illustrate how sensitive the ear (or a microphone) is to sounds arriving at different angles about its central axis. The polar pattern curve represents the collection of points that produce the same signal level output in the system (ear or microphone) as if a given sound pressure level (SPL) is generated from that point. A polar plot is represented as a circle with concentric reference lines emanating from the centre. The outer circle represents 0 dB attenuation and each inner circle typically represents 5 dB attenuation. The top represents 0° azimuths, the right is 90°, the bottom 180° and the left is 270°. An example of such a Sensitivity Polar Plot for a KEMAR open-ear response is shown in Figure 1. For the test frequencies 2 and 4 kHz the front response is shown to be a few dB less attenuated compared to that for sources from the rear (adapted from Christensen, 2013).

Directional microphones

Directional microphone technology has proven to be beneficial for speech-in-noise understanding in users wearing hearing aids (Walden et al., 2003), BAHA bone-conduction devices (Krempaska et al., 2014) and when implemented on Cochlear Implant (CI) processors (Buechner et al., 2014a; Dillier and Wai Kong., 2015; Goldsworthy, 2014; Wolfe et al., 2012). These modern microphone designs use multiple (mostly dual) microphone technology to attenuate sounds selectively depending on their source location. Sounds from the front are less attenuated compared to sounds originating from sources behind or beside the hearing-aid wearer. This is typically shown by directional Sensitivity Polar Plots.

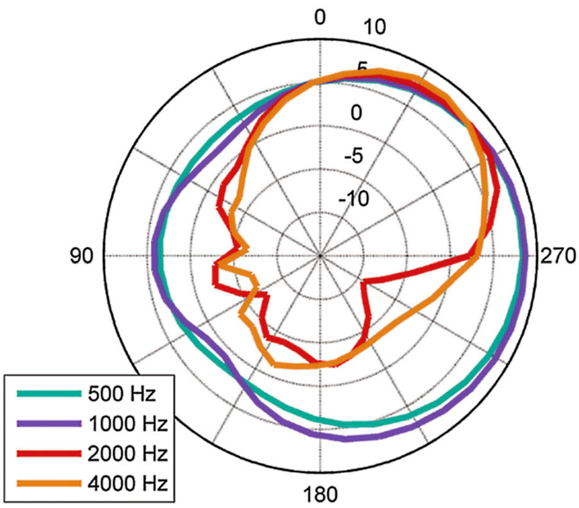


Figure 1 The KEMAR open-ear response polar plot for four frequencies. For the two lower frequencies (500 and 1000 Hz), the response is essentially omnidirectional while the higher frequencies are directional to the front (from Christensen, 2013).

The technology was re-introduced in the hearing aid industry some 15 years ago (Christensen 2013). It evolved from (1) first-order directional technology through (2) automatic switching directionality and (3) adaptive directionality to (4) the current band-split directionality technology. In this latter, the directional attenuation is not applied uniformly over the complete frequency span, but only selectively for channels above a border frequency of typically 1000 Hz. This band-split directionality tries to mimic the ear's natural directional characteristics where the pinna, together with head and torso also provide strong directionality for the frequency range of 2–7 kHz (Keidser et al., 2009).

Measuring benefit of directional microphones in recipients

The functional benefit of directional microphones for hearing aid or CI recipients is often expressed as the improvement in speech in noise perception over the omnidirectional setting when testing with spatially separated sources of speech and noise. Often, and for practical reasons, only one or two locations for speech and noise are used, which makes the results both difficult to interpret in view of daily life situations as well as difficult to compare with the Sensitivity Polar Plots of the microphones provided by the manufacturers. Usually, speech is presented from the front (S_0) and noise from a number of loudspeakers behind (N_{90}–N_{180}–N_{270}) (exceptionally also in the front hemisphere) of the subject. This results mostly in only one or two SRT values as outcome measures describing the *in vivo* benefit of directional microphones.

The current study was set up to quantify this *in vivo* directional benefit for CI recipients differently. To overcome the limitation of having only one or two speech and noise sources, we undertook to establish 'speech recognition polar plots' with speech not only coming from the front speaker (S_0) but consecutively from several speakers surrounding the listener while keeping the arrangement of noise sources constant, yielding a number of different SRTs that can be combined to form the so-called 'SRT-Polar-Plots'. They are thought to reflect more realistically and more completely the effect of directional microphone technology on a patient's performance, at least for a certain arrangement of noise sources. In that case, SRT-Polar-Plots would resemble the Sensitivity Polar Plot of the directional microphone. The SRT-Polar-Plot does not only analyse the benefit of the beam formers for speech from the front, but also effects for speech coming from other possibly less favourable directions. The study focussed mainly on SRT-Polar-Plots using the Natural Directionality mode in MED-EL SONNET CI processor.

The SONNET CI processor is equipped with two physical microphones that can be configured to three different microphone settings (Nopp, 2016). In the Omnidirectional mode, only the front microphone is used and this microphone on its own features omnidirectional equal sensitivity. In the Natural mode, the two microphones are electronically coupled in such a manner that there is only a directional attenuation of the high frequencies whereas the low frequencies are not affected much. For the high frequencies, the sensitivity pattern follows a cardioid curve. This differential directionality technique is aimed at reflecting the natural functioning of the human pinna. In the Adaptive mode, this directional sensitivity attenuation is adaptively and selectively done per frequency band in the direction of its corresponding noise source. The Sensitivity Polar Plots of these three microphone modes of the MED-EL SONNET processor measured in the free-field are shown in Figure 2 for a condition with speech from the front, and noise from 135°, 180°, and 225° azimuth.

However, when these Sensitivity Polar Plots are measured with the processor mounted on the ear of a KEMAR mannequin, these microphone directivity patterns have a different shape. Figure 3 shows the polar plot of the microphone response of the SONNET mounted on a KEMAR head for microphone in Omnidirectional and Natural (split band directional) mode (Honeder et al., 2018). The directional pattern observed with the Natural microphone mode in this figure resembles more that of the KEMAR open-ear response illustrated in Figure 1.

Previous work by Wimmer et al. (2016) with the Natural (split-directional) microphone mounted on the SONNET CI processor showed speech in noise benefits compared to the Omnidirectional microphone of up to 3.6 dB SNR for the optimal condition with speech coming from the front and noise from the back (S_0N_{180}). For less favourable signal and noise orientations, relative to the CI position, a benefit of 2.2 dB was found for the S_0N_{90} situation, 1.3 dB for S_0N_{-90} and no benefit for S_0N_0 situation. Similarly, Dorman et al. (2017) found that intelligibility in noise significantly improved by 16–19% points when changing SONNET processor microphone setting from Omnidirectional to Natural mode. This effect was shown using test set-ups mimicking a busy restaurant and a cocktail party. No significant differences were found between use of Adaptive and Natural microphone in unilateral CI users in the restaurant setting. In the cocktail party setting however, significant differences were indeed observed. Honeder et al. (2018) found speech in noise benefits of the Natural over the Omnidirectional microphone of up to 4.3 dB SNR for speech coming from the front and noise coming from two sources located at ±135° ($S_0N_{+135} + N_{-135}$). In their study, the performance with the Adaptive microphone proved 6.1 dB SNR better compared to the Omnidirectional microphone and 1.8 dB SNR better compared to the Natural microphone setting. Both differences were significant.

Methods

Study design

Thirteen adults participated in this randomized, prospective, within-subjects repeated-measures design

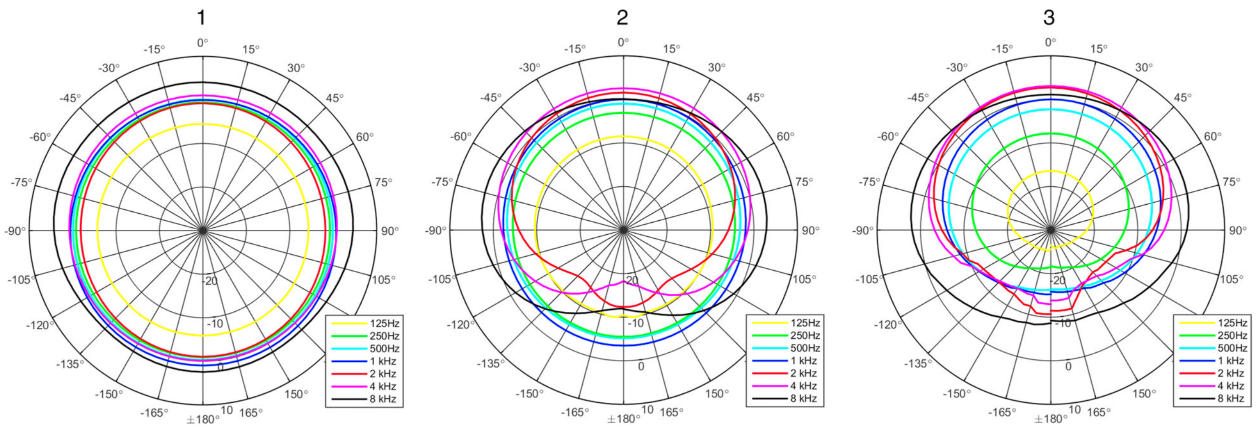


Figure 2 Sample microphone sensitivity polar plots polar plots for the 3 directionality modes for SONNET CI processor microphone within Automatic Sound Management 2.0. Sensitivity polar plots measured in free field using logarithmic sweep in anechoic chamber. (1): omnidirectional mode; (2): natural mode; (3): adaptive mode (Nopp, 2016).

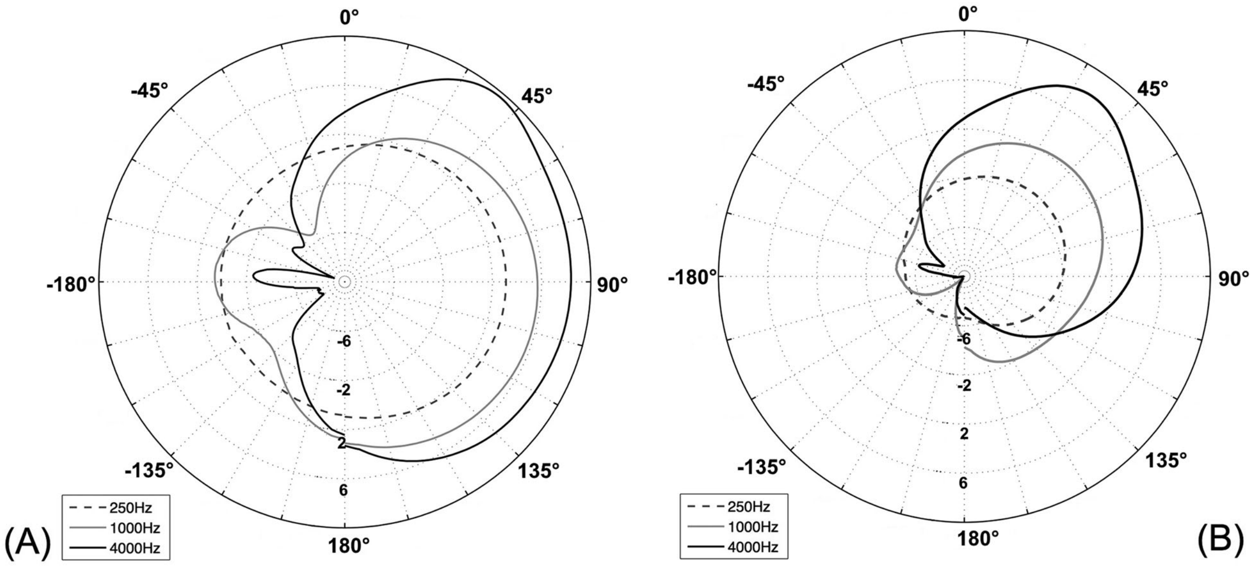


Figure 3 Microphone directivity patterns of the SONNET audio processor at different frequencies for (A) the omnidirectional setting, and (B) the Natural fixed beamformer setting measured in an anechoic chamber with the processor placed on a KEMAR mannequin. (Adapted from Honeder et al., 2018).

study. The study was approved by the Ethical Board of Jessa Hospital (Hasselt, Belgium) on October 5th, 2015, under the reference '15.90/ORL15.02'.

Participants

Thirteen post-lingual deafened adult subjects were recruited from the CI clinic at the Eargroup (Antwerp) and were assessed during one acute session. The median age of the participants was 58 years (range 23–75 years) with a median duration of pre-implant deafness of 1 year (range 0–15 years). The median duration of CI use was 3 years (range 0.5-12 years). Table 1 describes the participants' demographic data. All subjects were experienced users of the MED-EL cochlear implant system with at least six months of experience at the time of testing. All subjects were unilateral implant users. Two bimodal users were instructed to switch off their contralateral hearing aid during the entire test. They had no speech perception on the unaided contralateral ear. Prior to taking the tests in noise, subjects were systematically assessed with their clinical map for speech in quiet with lists of Flemish monosyllables (NVA) delivered at 70 dB SPL. Since multiple SRTs were measured in the study procedure, only CI recipients with phoneme scores in quiet higher than 60% were included in the study. The median speech perception score in quiet for the recruited participants was 82.0% (range 74–92%).

Concurrent participation in another study and difficulties additional to hearing impairment that would interfere with the study procedures were considered as exclusion criteria. Written informed consent was obtained from all subjects.

Table 1 Subject demographic data including details of the implant type

Subject ID	Age (years)	CI side	Duration of HL (yrs)	Duration CI use (yrs)	Implant type	Own Speech processor Type	Speech Coding Strategy	AGC Map Setting	Speech in quiet @70dBSPL[a]
S1	58	Right	5	6	Sonata	OPUS2	HDCIS	3:1	85
S2	62	Right	1	4	Sonata	OPUS2	FS4	3:1	92
S3	72	Right	1	3	Concerto	OPUS2	FSP	3:1	83
S4	48	Right	0	0.5	Synchrony	SONNET	FS4	2.5:1	82
S5	50	Left	8	3	Concerto	OPUS2	FSP	3:1	81
S6	75	Left	0	2	Concerto	OPUS2	FS4	3:1	79
S7	69	Left	0	3	Concerto	OPUS2	HDCIS	3:1	85
S8	40	Left	15	12	Combi 40+	OPUS2	HDCIS	3:1	74
S9	23	Right	0	6	Sonata	OPUS2	HDCIS EAS	3:1	78
S10	65	Right	0	2	Concerto	OPUS2	FS4	3:1	76
S11	58	Right	7	3	Concerto	OPUS2	FSP	3:1	86
S12	64	Right	1	3	Concerto	OPUS2	FSP	3:1	82
S13	27	Left	0	3	Concerto	OPUS2	FSP	3:1	78

[a]Phoneme score on a Flemish CVC word list (NVA).

Device fitting

All CI processors had been fitted according to the FOX target-driven, computer-assisted approach as described in Govaerts et al. (2010), Battmer et al. (2014) and Buechner et al. (2014b). For the study, each subject was furnished with a new MED-EL SONNET CI processor. None of the CI recipients, except for one (S4), had previous take-home experience with a SONNET processor. Recipient S4 had 6 months take-home experience. The subjects' everyday OPUS2 processor map settings were transferred to a SONNET map without any changes except for the microphone setting. All but one test subject used the default AGC compression ratio setting of 3:1. The wind noise reduction option (WNR) was disabled in the sound management for all three test-conditions.

Test set up

A test situation was created using 8 Fostex 6301B Personal loudspeaker (Foster Electric Company, Limited, Tokyo, Japan) placed in a circle having a radius of 1 meter, as shown in Figure 4. All of these speakers were connected to a PC using a Gigaport Soundcard (ESI Audiotechnik GmbH, Leonberg, Germany). The A§E software platform (Otoconsult nv, Antwerp, Belgium) (Govaerts et al., 2006) was used to generate and control all the sounds presented. It allowed the presentation of individual sentences on one of the 8 Speech speakers while uncorrelated Stationary Speech Noise (N) was simultaneously and continuously presented from the 3 rear speakers.

The test room was a quiet but normal, untreated, rectangular room with dimensions 6.45 m by 3.55 m × 2.57 m. The room reverberation time was measured using REW room acoustics analysis software (REW v5 software, 2015). The reverberation times (RT60) of this test room are displayed in Table 2 and classify the room as a normal reverberating room. The ambient background noise level in the room was 37 dB (A), well below the noise levels used during the speech-in-noise tests.

Outcome measures

During the test session, 10 adaptive speech-in-noise tests (see details below) were performed. For all participants, a speech-in-noise reception threshold (SRT) was obtained for each of the three conditions (Natural, Omnidirectional and Adaptive mode) for speech coming from the speaker at 45° of azimuth (relative to front and towards the side of the implant: S_{45}). This specific azimuth was chosen as this angle proved

Table 2 Reverberation times of the test room

	125	250	500	1000	2000	4000
RT60	0.52	0.48	0.40	0.42	0.46	0.42

RT60 values: Time [seconds] it takes sound in the test room to decay 60 dB in level; results are given for different frequencies from 125 to 4000 Hz (column headers).

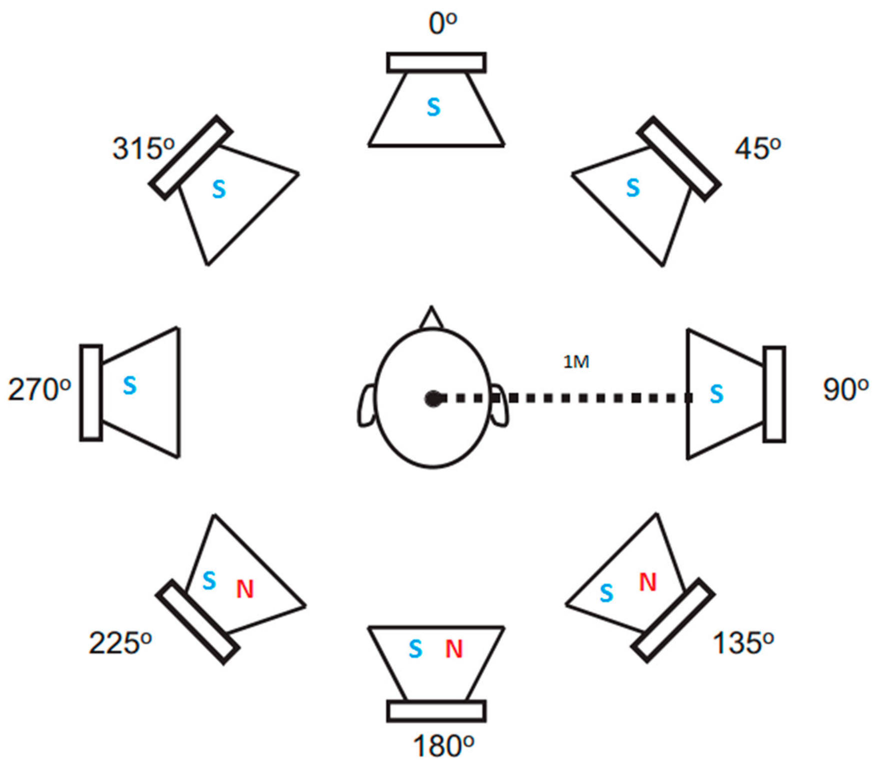


Figure 4 Schematic representation of test set-up consisting of eight loudspeakers placed in a circle having a diameter of 1meter. Speech (S) can be presented from any of the eight speakers in the presence of uncorrelated Stationary Speech Noise (N) presented simultaneously from the three rear speakers.

to yield best SRT score in a preceding pilot study. In all participants, in addition to S_{45}, a complete 'SRT-Polar-Plot' was also constructed for the Natural condition by obtaining SRTs for speech coming from the speakers at all other remaining azimuths relative to the implant side (S_0, S_{90}, S_{135}, S_{180}, S_{-135}, S_{-90} and S_{-45}). The order of these ten tests was randomized and subjects were not aware of the testing condition (single-blinded trial) and were asked to always keep their head directed to the front speaker (0°). In addition, for 4 out of the 13 CI recipients, a complete SRT polar plot (for speech coming from all 8 speakers) could also be obtained for the Omnidirectional mode. The total number of measured SRTs during the same session summed up to 17 for these participants.

Speech perception was tested using the Flemish sentences-in-noise test (Van Wieringen & Wouters, 2008). The test contains 36 lists of 10 sentences each, characterized by a varying number of target words (between two and six per sentence). Scores were recorded as the percentage of the target words correctly repeated by the listener. The presentation level of speech was fixed at 65 dB SPL. Stationary speech noise that matched the speech material used, was presented simultaneously but non-correlated through the three rear Noise speakers positioned at 135°, 180° and −135° (N_{135}, N_{180}, N_{-135}). This noise was presented adaptively at different levels with a starting level of 55 dB SPL. An adaptive SRT seeking algorithm in the A§E software used this initial signal to noise ratio of +10 dB and an initial step size of 10 dB. The subsequent step sizes were determined by the division of the initial 10 dB step by 2 raised to the power of the number of observed reversals. The minimal step size was set at 1 dB. The algorithm halted after eight reversals and the resulting SRT was calculated by averaging the SNRs from the last six reversals. The A§E-software allowed automatic data logging of the test time needed to obtain a final SRT after the required number of reversals.

Statistics

Non-parametric methods were used for descriptive and analytical statistics. The distribution of the SRT results is shown in box-and-whisker plots representing the five parameter statistics (Tukey, 1977). A Friedman ANOVA test with post-hoc Wilcoxon matched pairs tests were used for between-group differences (grouping either speech presentation azimuth data or microphone mode data). A Bonferroni adjustment for the repeated measures was applied to set an overall level of significance at 5% ($p < 0.05$). This resulted in an adjusted significance testing criterion of $p < 0.017$ for SRT scores comparing the three microphone settings at 45° of azimuth. In order not to lose statistical power, in the analysis of repeated measures for three different azimuths, statistical comparisons were done only for 8 transitions, comparing SRT for one angle to the SRT to only its ascending neighbour. This resulted in an adjusted significance testing criterion of $p < 0.006$. All analyses were conducted using Statistica software (version 9.1, Statsoft Corporation).

Results

All individual SRTs, for all the configurations, are listed in Table 3.

Table 3 Individual SRTs for each subject, in dB SNR, in each of the 3 conditions (using either omnidirectional, natural or the adaptive microphone mode) for an azimuth of 45°

	Natural								Adaptive	Omnidirectional
	S_0	S_{45}	S_{90}	S_{135}	S_{180}	S_{-135}	S_{-90}	S_{-45}	S_{45}	S_{45}
S1	−7,0	−12,1	−9,5	−4,7	3,8	2,7	2,5	−3,4	−12,8	−5,6
S2	−4,1	−9,4	−7,7	−4,5	6,0	13,3	1,5	−1,3	−14,1	−5,1
S3	−6,8	−9,2	−10,1	−4,0	2,6	−0,8	−1,1	−5,4	−12,0	−6,4
S4	−6,2	−8,8	−9,8	−7,3	−2,9	3,0	0,1	−0,8	−12,9	−8,3
S5	−6,9	−12,7	−4,7	−2,8	1,2	3,3	0,1	−1,8	−12,2	−8,1
S6	−1,9	−7,6	−4,3	−2,3	6,7	11,4	7,6	3,4	−8,1	−5,0
S7	−3,8	−9,0	−5,0	−6,2	1,2	4,5	7,1	1,6	−13,5	−9,1
S8	−5,5	−3,0	−5,7	−0,3	13,9	7,1	0,8	1,5	−11,0	−0,9
S9	−0,9	−5,9	−7,9	−4,7	0,4	−0,8	8,4	−4,3	−8,4	−0,2
S10	13,7	6,1	9,1	14,8	24,0	23,9	24,1	13,8	−0,6	11,1
S11	−7,1	−9,9	−6,5	−3,7	0,6	−2,1	−3,4	−4,2	−13,2	−11,6
S12	−7,9	−10,8	−6,7	−1,6	2,8	5,1	10,9	−2,1	−13,4	−4,2
S13	−4,4	−9,0	−4,9	−1,7	11,3	2,6	1,4	−0,7	−13,8	−5,6
				Omnidirectional						
	S_0	S_{45}	S_{90}	S_{135}	S_{180}	S_{-135}	S_{-90}	S_{-45}		
S2	−2,6	−5,1	−7,5	−7,0	−0,9	2,7	8,1	0,5		
S4	−2,4	−8,3	−8,6	−8,8	−2,9	0,8	2,4	−1,5		
S7	−1,1	−9,1	−1,5	−7,4	−4,9	4,4	1,8	2,1		
S12	−4,7	−4,2	−5,5	−6,9	2,0	7,9	3,3	5,9		

Note: For the Natural setting individual SRTs are also shown for all other angles tested. In 4 Subjects, SRTs could also be obtained for all 8 speakers in the Omnidirectional mode. A lower score indicates better performance.

Box plots representing the SRT group data obtained in the Natural microphone setting are shown in Figure 5. The best median SRT score was observed for the azimuth of 45° (SRT S_{45}: −9.1 dB SNR), confirming the selection of this optimal angle. The worst median score was observed for the azimuth of −135° (SRT S_{-135}: +3.1 dB SNR). Friedman ANOVA was highly significant ($p < 0.00001$) indicating significant differences in SRT values between group data at different angles. Post hoc Wilcoxon matched pairs tests with Bonferroni adjustment ($p = 0.006$) identified significant differences in SRT score between adjacent speech presentation angles. Five significant transitions could be identified: SRT between S_0 and S_{45} ($p = 0.003$), S_{90} and S_{135} ($p = 0.003$), S_{135} and S_{180} ($p = 0.002$), S_{-90} and S_{-45} ($p = 0.003$) and finally S_{-45} and S_0 ($p = 0.006$). When ranking all 8 SRT values, similar SRT values can be observed on both sides of the bisector axis [−135° 45°] as if it were an axis of symmetry in the polar plot.

A group SRT-Polar-Plot for the Natural Mode was constructed by plotting and connecting the group median SRT values and the 95% confidence interval of these medians (between P97.5 and P2.5 values) for all speech angles. This SRT-Polar-Plot is depicted in Figure 6 together with the median values for Omnidirectional and Adaptive mode for the S_{45} condition.

Individual SRT-Polar-Plots for both Natural and Omnidirectional microphone mode could be obtained in 4 CI recipients and are shown in Figure 7. In all these four cases, the Natural SRT-Polar-Plot is directed more frontally compared to the Omnidirectional SRT-Polar-Plot: in 22 out of the 24 amendable SRT points an improved frontal speech perception is observed.

Finally, in all test subjects, the SRT scores for speech at 45° azimuth (S_{45}) were compared for the Omnidirectional, Natural and the Adaptive microphone mode. The group distribution of the SRT results for the 3 microphone settings as well as the distribution of the within subject gain of the use of a directional microphone are shown in Figure 8. The best median SRT S_{45} score, −12.8 dB SNR, was observed for the Adaptive mode. The poorest median SRT S_{45} score, −5.6 dB SNR, was observed for the Omnidirectional microphone. Friedman ANOVA indicated highly significant ($p < 0.0001$) differences in SRT values between group data for S_{45}. Post hoc Wilcoxon matched pairs tests with Bonferroni adjustment ($p = 0.017$) identified significant differences in SRT between the three microphone modes. The SRT S_{45} score for Natural, −9.1 dB SNR, was significantly better compared to the Omnidirectional score ($p = 0.006$) and significantly worse compared to the Adaptive microphone score ($p = 0.004$). Omnidirectional and Adaptive microphone setting were found to differ highly significantly from each another ($p = 0.001$). The median within subject gain in SRT S_{45} when using the Natural microphone compared to the Omnidirectional was 3.4 dB SNR. For the Adaptive microphone, this gain in SRT S_{45} compared to the Omnidirectional was 7.2 dB SNR.

The data logging of the time frame needed to obtain an individual SRT as well as the total time needed to

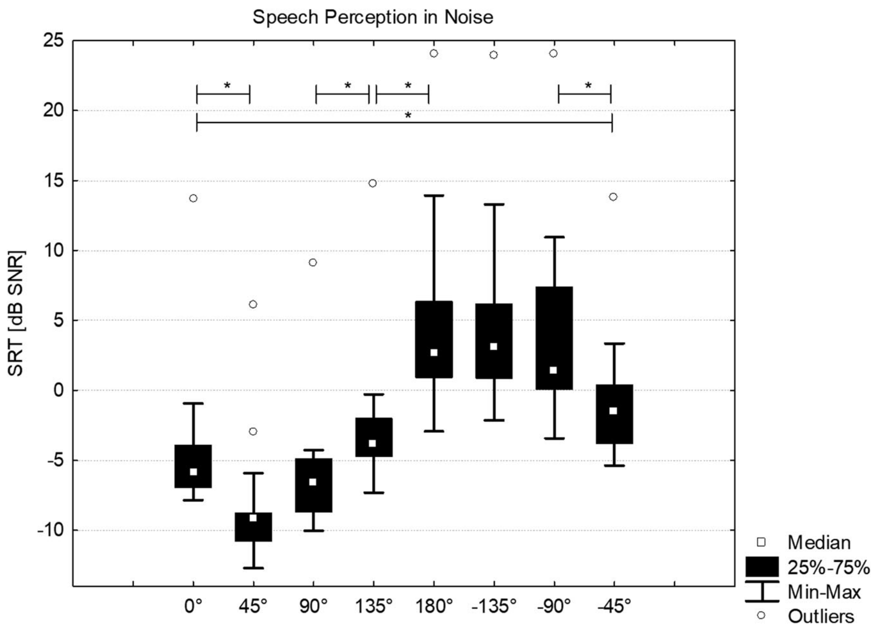


Figure 5 Box plots showing the SRT distribution (vertical axis) in Natural mode for different speech sources (horizontal axis). Median values for SRT in dB are shown, with 25% and 75% quartiles and whiskers showing the minimum and maximum values for each condition. Significant differences in speech in noise performance for adjacent angles are marked with an asterisk.

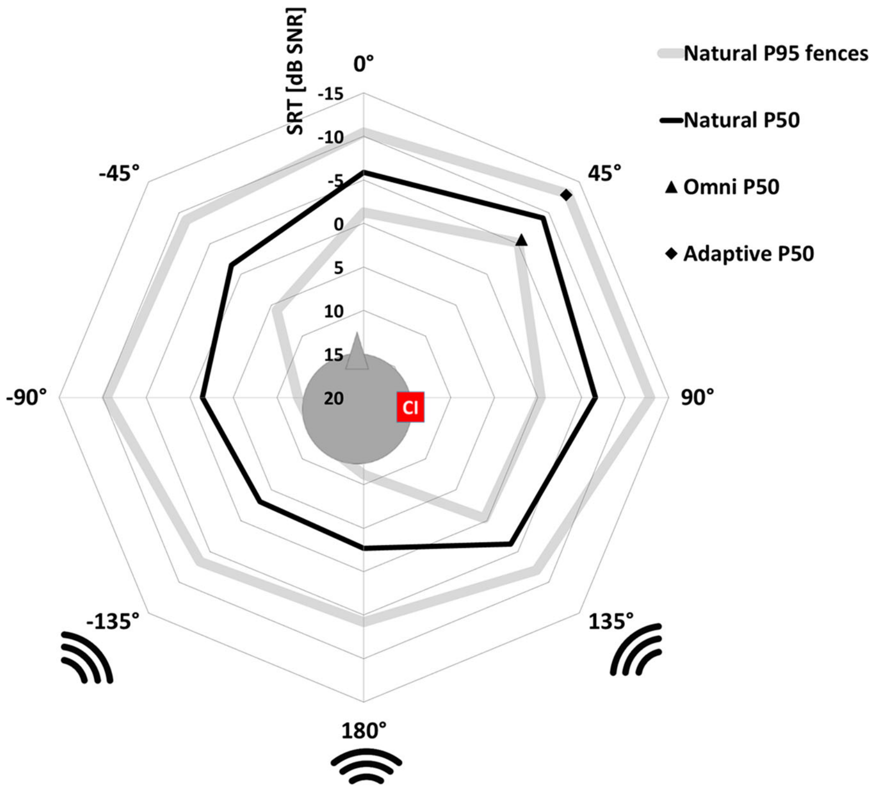


Figure 6 Median, P97,5 and P2,5 Speech SRT-polar-plots for natural mode as well as median value SRTs for azimuth of 45° for omni and adaptive setting.

measure a complete SRT plot are summarized in Table 4. The median time for a single SRT measurement was 5.5 min. The median time to measure a complete 8-point SRT polar plot (Natural) was 44 min.

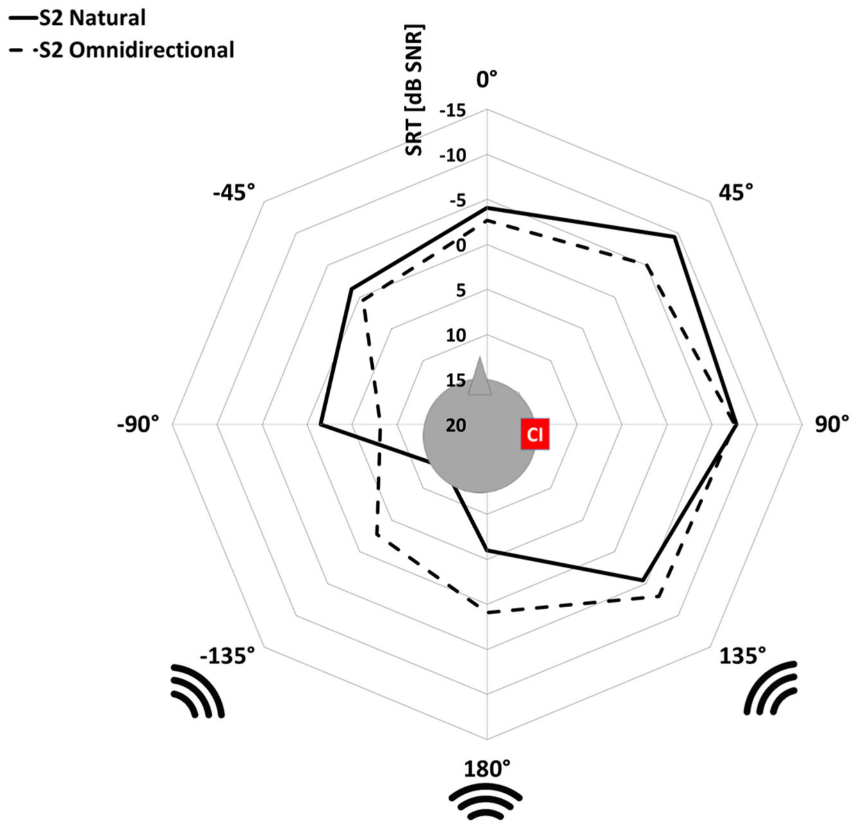
Discussion

This study shows in general that – for a certain arrangement of noise sources – it is feasible to measure and construct complete SRT-Polar-Plots in CI recipients. The time needed to measure a complete SRT-Polar-Plot is thought to be within acceptable time limits not to burden an individual hearing aid or CI user.

The SRT-Polar-Plot in Natural mode shows similarity with the Sensitivity Polar Plots of the normal open ear when looking at the transfer function for high frequencies when going from the free field to the tympanum (Figure 1). Indeed, in this mode, the best SRT scores were observed for speech from an azimuth of 45° (S_{45}) while the worst scores were observed for speech with an orientation more contralateral and more to the rear (S_{-135}). Symmetry around the bisector axis [−135° 45°] can be seen in both the Sensitivity Polar Plots as well as in the SRT-Polar-Plots. Wimmer et al. (2016) observed a maximal benefit of 3.6 dB SNR of Natural microphone in a the S_0N_{180} test situation and Honeder et al. (2018) found a similar 4.3 dB benefit for a S_0 $N_{+135} + N_{-135}$ test set-up. Both numbers are very comparable to the 3.4 dB gain found in the current study for S_{45} and noise from three combined rear speakers ($N_{-135} + N_{180} + N_{135}$).

Analysis of complete SRT-Polar-Plots for both Natural and Omnidirectional mode, obtained from four CI users, also confirms that a variable individual benefit of Natural directional microphone is measurable using this technique. It thus allows spatial assessment of real and individual functional benefit of a directional microphone in polar coordinates and can be compared to the predicted benefit as seen in KEMAR microphone Sensitivity Polar Plots.

Analysis of the group data for SRTs for speech coming from 45° of azimuth (S_{45}) for the three microphone modes shows that the Adaptive directional microphone mode outperforms the Natural directional microphone which in turn outperforms the SONNET Omnidirectional microphone. These data thus confirm the benefit provided by the directional microphone modes in the SONNET processor. The Adaptive microphone gives the best speech in noise performance for the specific test setup used in this study where the noise source has a fixed, static orientation. The same statistically significant ranking in performance of the 3 SONNET microphone settings was also observed by Honeder et al. (2018). Further research is needed to confirm whether this superiority remains valid in the case of a non-static variable orientation of this noise source. The study of Dorman et al. (2017)



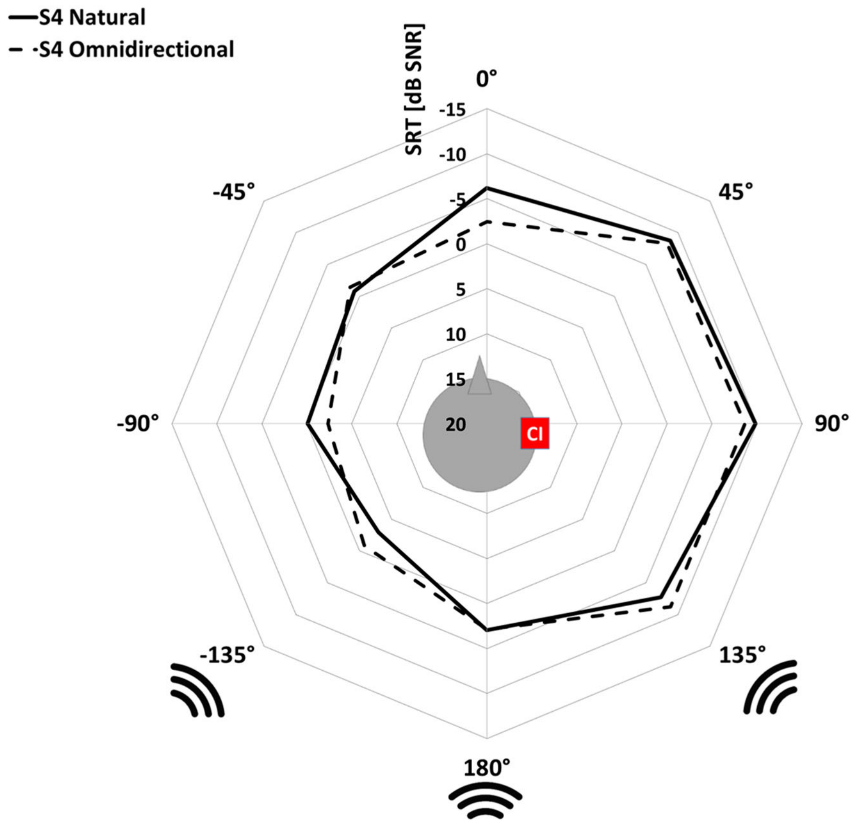


Figure 7 Complete SRT-Polar-Plots for both omnidirectional and natural mode obtained from subjects S2, S4, S7 and S12.

failed to show significant superiority of the Adaptive microphone in a restaurant environment setting could show this superiority in a cocktail party environment.

Another aspect that is highlighted from Figure 6 is that unilateral CI users are – as one would expect – more sensitive to speech sounds originating from ipsilateral sources when compared to sounds from

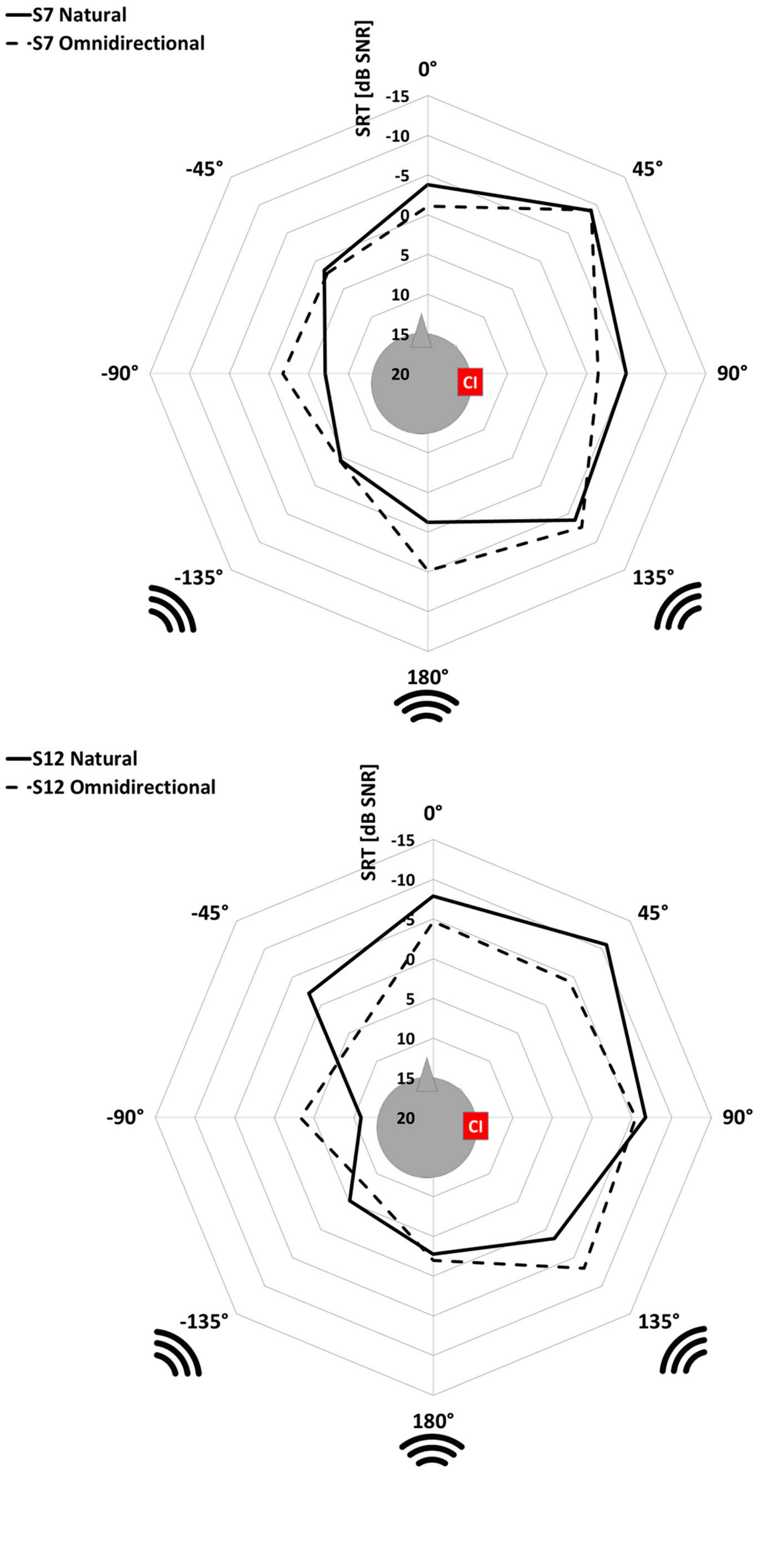


Fig. 7 ***Continued***

contralateral sources. An interesting application of the SRT-Polar-Plot could therefore be to assess, e.g. the benefit of bilateral cochlear implants by comparing the SRT-Polar-Plots for unilateral and bilateral implant use. One would expect the SRT-Polar-Plot to be more symmetrical across the midline (0–180°)

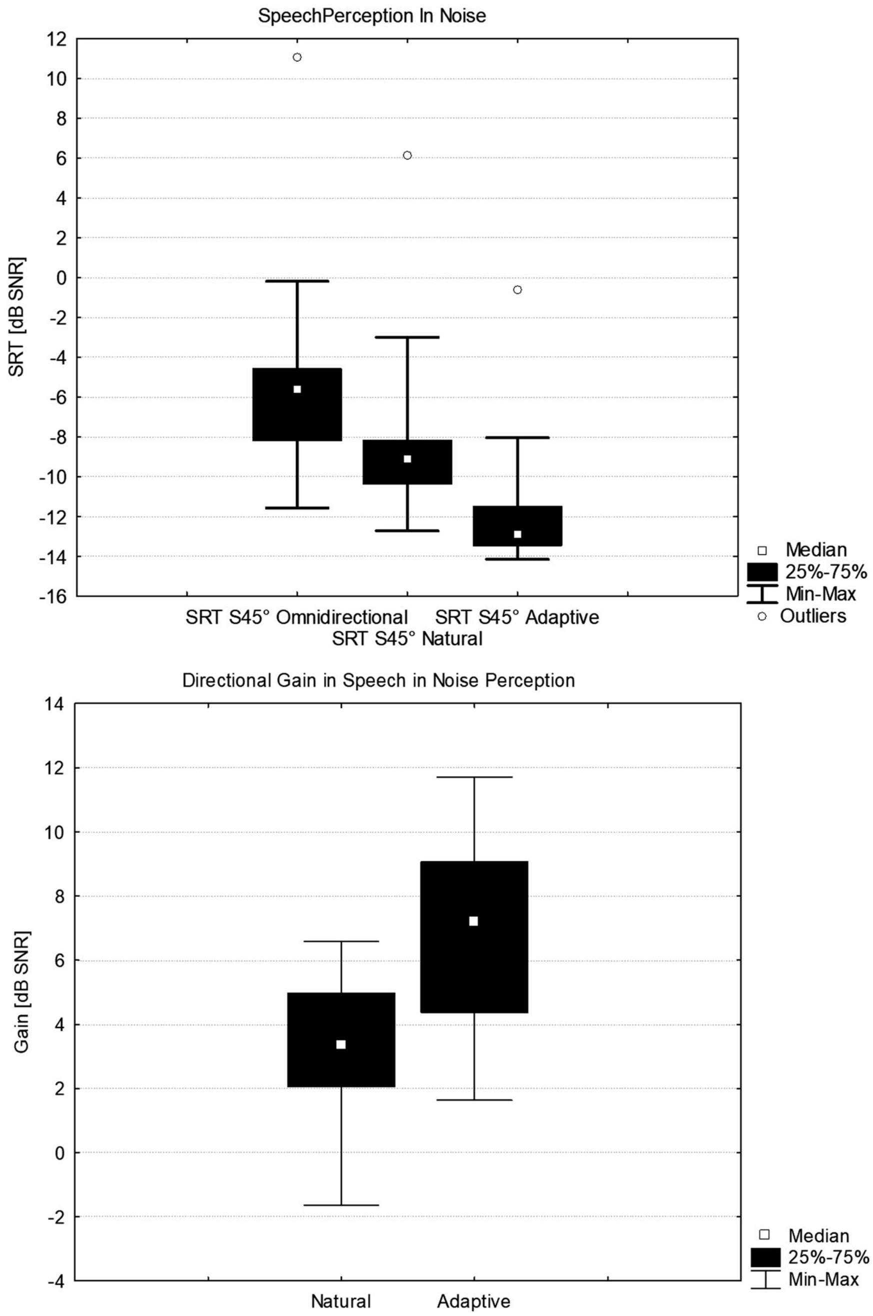


Figure 8 Upper panel: Box plots of the SRT for azimuth of 45° (SRT S_{45}) for Omnidirectional, Natural and Adaptive microphone mode. Median values for SRT in dB are shown, with 25% and 75% quartiles and whiskers showing the minimum and maximum values for each condition. Lower panel: Box Plots of Gain in SRT of Natural and Adaptive over Omnidirectional microphone setting.

for bilateral CI use. Similar methods could be applied to assess the benefit of the CI in user with single-sided deafness or asymmetric hearing loss.

Conclusions

A novel method, the 'SRT-Polar-Plot', is described as a tool to validate *in vivo* the possible benefit of the use of directional microphones for an individual hearing aid or a cochlear implant user. It was used in this study to assess the benefit of the directional microphone technology available in the SONNET CI processor. The resulting SRT-Polar-Plots found using the Natural microphone mode confirm similarity to directional sensitivity plots found in the normal ear (the pinna-mimicking-effect) as claimed by the manufacturer. Results also show the advantage of Natural microphone when compared with the Omnidirectional mode. For a static noise with a fixed orientation, the Adaptive microphone mode even outperformed the Natural mode. It remains to be verified (i) if this Adaptive directional microphone mode will also be accepted by CI recipients when moving noise sources will cause the adaptive algorithm to automatically alter the directional sensitivity and (ii) if the Adaptive

Table 4 Time [minutes] needed to measure the individual adaptive SRTs and the total time to determine a complete SRT-Polar-Plot (8 SRTs) in the Natural mode

	SRT1	SRT2	SRT3	SRT4	SRT5	SRT6	SRT7	SRT8	Complete SRT Plot
S1	8	14	5	6	5	4	5	7	54
S2	4	5	5	4	5	5	4	6	38
S3	4	6	5	6	6	5	6	11	49
S4	5	5	5	6	7	6	8	5	47
S5	5	3	7	4	6	7	18	7	57
S6	6	5	5	6	6	5	6	5	44
S7	6	6	6	6	4	14	10	8	60
S8	6	5	3	5	7	7	6	5	44
S9	9	5	4	4	4	4	5	3	38
S10	2	4	5	4	4	4	5	8	36
S11	4	4	7	4	4	4	4	4	35
S12	4	4	3	4	4	2	5	8	34
S13	4	3	4	6	4	4	5	4	34

directional microphone still outperforms the Natural when using more common, modulated noises or multi-talker babble noises in the speech-in-noise tests. Stationary noises are thought to be appropriate to assess the directionality of fixed beamformers such as the Natural microphone but are less suited in the assessment of Adaptive beamformers.

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