Fixed and adaptive beamforming improves speech perception in noise in cochlear implant recipients equipped with the MED-EL SONNET audio processor

Clemens Honeder¹, Rudolfs Liepins¹, Christoph Arnoldner¹, Hana Šinkovec², Alexandra Kaider², Erich Vyskocil¹, Dominik Riss¹*

¹ Department of Otorhinolaryngology, Head and Neck Surgery, Medical University of Vienna, Vienna, Austria, ² Center for Medical Statistics, Informatics and Intelligent Systems, Section for Clinical Biometrics, Medical University of Vienna, Vienna, Austria

* dominik.riss@meduniwien.ac.at

Abstract

Objective
To determine the impact of the fixed and adaptive beamforming technology of the new MED-EL SONNET cochlear implant audio processor on speech perception in noise.

Methods
The study cohort comprises 18 postlingually deafened adult cochlear implant recipients with at least six months of experience. Speech reception thresholds were measured with the Oldenburg Sentence Test in continuous, speech-shaped noise. Target sentences were presented in front of the listener, with noise sources placed at -135° and 135°, respectively. Outcome measures were the differences in speech reception threshold using omnidirectional, fixed and adaptive beamformer microphone settings.

Results
The use of directional microphones significantly improved speech reception thresholds: fixed beamformer vs. omnidirectional: 4.3 dB (95%-CI [3.1; 5.5]), p < 0.0001; adaptive beamformer vs. omnidirectional: 6.1 dB (95%-CI [4.9; 7.3]), p < 0.0001; and adaptive beamformer vs. fixed beamformer: 1.8 dB (95%-CI [0.7; 3.0]), p = 0.001.

Conclusion
This study confirms the previously reported improvements in speech perception in noise of the fixed beamformer microphone setting and is the first to report significant improvements in speech perception in noise when applying the adaptive beamformer microphone settings of the SONNET audio processor. Cochlear implant users may be able to benefit from improved hearing performance especially in difficult listening situations.
Introduction

Cochlear implants (CIs) present a safe and effective treatment for severe-to-profound hearing loss, and many CI users achieve remarkable levels of speech perception in quiet [1]. Nevertheless, speech perception in noise, mainly in unilaterally-aided subjects, still remains a major challenge due to factors such as the loss of fine spectral and temporal resolution and a relatively narrow dynamic range of electrical stimulation [2, 3]. Bilateral implantation results in improvement in challenging listening situations as well as improved coding strategies and the preservation of low frequency hearing [4–7]. Despite these innovations, CI users have inferior speech perception in noise compared to normal hearing subjects [8, 9]. Further refinements have been established to improve patient outcome in challenging environments, including algorithms optimizing input dynamic compression and range, automatic gain control, single channel and multi-channel noise reduction techniques. Another effective strategy to decrease the effects of competing noise on speech perception is the use of multiple microphones and beamforming algorithms. This concept is well-established for hearing aid users, with improved speech perception in noise reported for adults and young patients [10, 11]. Directional microphones that reduce the adverse effects of noise in spatially-separated target and interfering signals have previously been tested successfully in CI users [12–15]. Studies evaluating directional microphones with fixed directivity in CI patients reported improved speech reception thresholds (SRTs) between 5–7 dB compared to less directional sub-cardioid microphones [12, 13]. Fixed beamformers provide a particular directivity pattern regardless of the specific sound field characteristics, and can be used for instance to mimic the directivity of the human ear. The use of adaptive beamforming technology may result in even better speech perception [13] since the algorithm constantly detects the direction the noise is coming from and adapts the polar pattern to attenuate the sound coming from this direction.

The aim of this study was to evaluate both the fixed beamformer and the adaptive beamformer settings of the new MED-EL SONNET audio processor in regard to effects on speech perception in noisy environments with spatially separated sound sources.

Materials and methods

Participants

18 postlingually deafened adult CI recipients implanted with MED-EL devices participated in the study. To ensure a representative sample of the adult CI users treated at our clinic, subjects with different ear conditions and etiologies were recruited. This included 12 bimodal, two bilateral, two unilateral (bilaterally deaf) and two patients with single-sided deafness. Age ranged between 18 and 76 years (mean: 54.6), and mean implant experience was 60.3 months. Demographic details and etiology are presented in Table 1. The study protocol was approved by the Ethics Committee of the Medical University of Vienna and all subjects gave their written informed consent prior to participation.

Fitting

All subjects were tested with their individual fitting map. All the devices investigated were SONNET audio processors, therefore subjects either used their own SONNET audio processor or a SONNET audio processor provided by our clinic for the duration of testing if they were using an audio processor without microphone directionality. Microphone protectors were checked and replaced, if necessary, prior to testing. Other features of the audio processor like front-end wind noise reduction (mild) and automatic gain control (compression ratio: 3:1) were set to the same default settings for all subjects. Adaptive microphone directionality was set to...
“always directional”. Three different directional microphone settings were created: (1) “omni-directional” microphone mode (OMNI), (2) “natural” mode that mimics the directivity of the human pinna based on fixed beamforming technique (FBF), and (3) “adaptive” mode applying an adaptive beamforming scheme (ABF). The FBF generates a static directivity pattern where sounds from the rear hemisphere are attenuated. This is achieved by adding a specific delay between the microphone channels and subsequent summation of the signals. The degree of attenuation is frequency-dependent. For lower frequencies, the directivity pattern is similar to OMNI; with increasing frequency the attenuation increases, with the highest attenuation reached at an angle of 135˚. The ABF uses an adaptation algorithm to estimate the position of the noise source, which is based on the particular sound field characteristics. The direction of attenuation is then adjusted accordingly.

### Speech tests

Speech perception in noise was evaluated with the Oldenburg Sentence Test (OLSA), an adaptive, closed-set, German language sentence test [9, 16, 17]. The measured SRT quantifies speech perception in noise, with results in dB signal-to-noise ratio (SNR) at which 50% of the presented words are perceived correctly. The target sentences, presented by a male speaker, consist of five randomly selected words from a list of 10 possible choices. The noise signal (OLSA noise) consists of 30 randomly time-shifted OLSA sentences and therefore exhibits spectral characteristics similar to the short-time frequency spectrum of the target sentences [9]. The speech tests were performed in a sound-isolated chamber (3.15 × 3.10 × 2.10 m) with a reverberation time $T_{60}$ of 0.15 s at 500 Hz. Bilaterally implanted subjects were tested in their better ear and were instructed to deactivate the contralateral device; in patients with single-sided-deafness (SSD) or bimodal hearing, the contralateral ear was plugged and covered with

---

### Table 1. Demographic characteristics of the study population.

| ID | Gender | Age (years) | Ear status (left–right) | Tested side | Implant experience (months) | WRS @ 65 dB SPL (% percent) | Etiology                  |
|----|--------|-------------|--------------------------|-------------|----------------------------|----------------------------|---------------------------|
| 1  | F      | 45          | CI-NH                    | L           | 43                         | 75                         | progressive               |
| 2  | F      | 45          | CI-HA                    | L           | 7                          | 45                         | progressive               |
| 3  | M      | 62          | CI-NH                    | R           | 12                         | 40                         | Meniere’s disease         |
| 4  | F      | 49          | HA-CI                    | R           | 8                          | 80                         | progressive               |
| 5  | F      | 18          | CI-CI                    | R           | 164                        | 65                         | progressive               |
| 6  | M      | 54          | CI-HA                    | L           | 34                         | 40                         | sudden hearing loss       |
| 7  | F      | 50          | CI-HA                    | L           | 41                         | 50                         | tympanosclerosis          |
| 8  | F      | 76          | HA-CI                    | R           | 105                        | 40                         | progressive               |
| 9  | M      | 58          | HA-CI                    | R           | 139                        | 60                         | progressive               |
| 10 | F      | 52          | Deaf-CI                  | R           | 61                         | 70                         | progressive               |
| 11 | M      | 52          | HA-CI                    | R           | 73                         | 60                         | otosclerosis              |
| 12 | F      | 24          | HA-CI                    | R           | 37                         | 55                         | progressive               |
| 13 | F      | 61          | CI-CI                    | L           | 114                        | 55                         | progressive               |
| 14 | M      | 76          | CI-HA                    | L           | 83                         | 55                         | progressive               |
| 15 | M      | 67          | HA-CI                    | R           | 6                          | 60                         | progressive               |
| 16 | F      | 54          | Deaf-CI                  | R           | 105                        | 55                         | progressive               |
| 17 | F      | 76          | HA-CI                    | R           | 46                         | 35                         | progressive               |
| 18 | M      | 64          | HA-CI                    | R           | 8                          | 45                         | progressive               |

F = female; M = male; CI = cochlear implant; HA = hearing aid; NH = normal hearing; WRS = word recognition score with CI; Deaf = profoundly deaf; L = left; R = right.

[https://doi.org/10.1371/journal.pone.0190718.t001](https://doi.org/10.1371/journal.pone.0190718.t001)
earmuffs to minimize the effect of residual hearing. Measurements and signal playback were controlled with MATLAB (The MathWorks, Inc.); speech signals were presented over a WES-TRA LAB 501 loudspeaker and JBL Control 1 pro loudspeakers were used for noise playback. Speech was presented from 0° azimuth at a distance of 130 cm from the subject’s head, with noise sources placed at ±135° azimuth (Fig 1) at the same distance; all sound sources were located in the horizontal plane at ear height. Noise sources were calibrated to ensure the same output sound pressure level (SPL). In a second step, the overall noise field level was adjusted to reach a certain SPL at the listening position. The noise level was constant at 65 dB, and the speech level was adapted depending on the subject’s performance based on the adaptation scheme of the OLSA. The initial SNR was +10 dB in all subjects. Subjects were advised to avoid head movements during signal playback. The choice of the noise source locations was based on the measured directivity patterns of the SONNET audio processor, illustrated in Fig 2. It was assumed that the difference in sensitivity between OMNI and FBF would correlate with

Fig 1. Experimental setup. All loudspeakers were placed in the horizontal plane approximately at ear height. Speech (S) was presented from 0° azimuth, noise sources (N) were placed at ±135° azimuth. The distance between sound sources and the center of the listener’s head was 130 cm.

https://doi.org/10.1371/journal.pone.0190718.g001
the difference in SRT between the settings. Therefore, the noise sources were placed to expect a potentially large impact of the FBF setting. Two noise sources were chosen instead of a single noise source situation as this setup represents a more realistic scenario as well as an additional challenging situation for the ABF scheme. The average level difference due to the head shadow between ipsilateral and contralateral noise source was 4.2 dB (n = 4) at the position of the SONNET microphones.

The sensitivity pattern of the ABF structure depends on the instantaneous sound field characteristics and thus cannot be generalized by means of sensitivity measurements. However, if the spatial separation between speech source and noise sources is sufficient, a positive effect on the SRT can be expected. To ensure accurate assessment of the ABF impact, the experimental setting had to fulfill certain requirements: 1) the noise had to be continuously presented to provide sufficient adaptation time for the ABF algorithm. And 2) the noise signals had to be uncorrelated to ensure that they were treated as independent sources by the ABF algorithm. This was achieved by introducing a random phase shift between the two noise channels.

**Study design**

The experiment was conducted in a single-blinded manner in an acute setting. Prior to testing, two training lists consisting of 20 sentences were presented to the participants to allow them to familiarize themselves with the test procedure and the stimuli material. This was followed by the presentation of two more lists (20 sentences) for each testing condition, to assess SRTs. To minimize both learning and fatigue effects, sentence lists and testing order with respect to the microphone setting were randomized.

**Statistical analysis**

The SRT values from both test lists for each condition were included in an ANOVA model in regard to the fixed factor “microphone setting” and the random block factor “patient”. The Tukey-Kramer method was used to perform multiplicity-adjusted, pairwise comparisons between group means. Group differences are described by the mean difference with adjusted 95% confidence intervals (CI).

All p-values are results of two-tailed tests; a p-value of <0.05 was considered statistically significant. Statistical analysis was performed with SAS (SAS Institute Inc. (2002–2017), Cary, NC, USA).

**Results**

The SRT results for all conditions are shown in Fig 3. Analysis of variance revealed a highly significant effect (p<0.0001) of the microphone setting. Both directional microphone conditions showed statistically significant improvements in SRTs compared to the OMNI condition. With the FBF setting the SRT improved on average by: 4.3 dB (95%-CI [3.0; 5.5]), p<0.0001; for the ABF condition the improvement was 6.1 dB (95%-CI [4.9; 7.3]), p<0.0001. SRTs of ABF compared to FBF improved on average by 1.8 dB (95%-CI [0.7; 3.0]), which was also statistically significant (p = 0.001). No statistically significant learning effects between the first and second run were observed (p = 0.59). Fig 4 illustrates the data differences for the SRT (average of both runs) on an individual level. The FBF format improved speech perception in noise in all but one of the participants (Fig 4A). In the ABF setting, all patients showed improved SRTs as compared to the omnidirectional microphone setting (Fig 4B). In comparison to the FBF scheme, the ABF technique improved SRTs in 14 patients (77.8%), showed comparable results in 2 cases (11.1%) and caused deterioration in SRTs in 2 CI users (11.1%) (Fig 4C).
Discussion

The aim of this study was to evaluate the new MED-EL SONNET cochlear implant audio processor’s fixed and adaptive beamformer techniques for potential benefits to speech perception in noise. The statistically significant improvements of 4.3 dB in SRTs for the FBF scheme and 6.1 dB for the ABF technique are in the range of the benefits reported in the literature [12–15, 18, 19]. However, it should be noted that these results are difficult to compare due to inconsistencies in technical setups and applied hearing tests. Further differences between the studies include the evaluated speech processors and coding strategies, spatial conditions, spectral and temporal noise characteristics, speech testing paradigms, and subjects’ ear status. Even though no discrimination function was measured for the particular spatial setup used in our study, the benefit in speech perception provided by beamforming can be considered relevant. The slope of the discrimination function for CI users (13.6%/dB) in the co-located masker condition S0N0 was smaller than the slope of the S0N0 condition for normal hearing subjects (17.1%) [9, 20]. In other studies testing normal hearing subjects in modified setups, Rader et al. (2008) measured a slope of 14%/dB in a multi-source noise field and Wagener (2004) 11.3%/dB in quiet [21, 22]. When attempting to link the reported SRTs and the published slopes of the discrimination function, it is important to keep in mind that the discrimination function of the OLSA exhibits a high variability between CI users. It has been demonstrated that in this specific patient population the discrimination function is steeper in better performers, who also exhibit a higher test-retest reproducibility [20]. It should also be highlighted that the setting used in this study may overestimate the benefit in real life, as more reverberant environments,
different noise signal characteristics and moving noise sources potentially diminish the beneficial effect of beamforming algorithms [15, 23]. The spatial setup used in this study represents a rather straightforward situation for beamformers, since the noise sources were placed at locations where high attenuation may be expected. Furthermore, microphone aging and environmental influences like dust could decrease the beamformer performance in everyday life. CI users benefited from FBF and ABF characteristics immediately without the necessity of adaptation time. In the given setting both FBF and ABF provided a very consistent and predictable benefit. In the ABF scheme, all patients, regardless of etiology or CI experience, showed improved SRTs as compared to the omnidirectional microphone settings. Razza et al. evaluated the impact of FBF and ABF settings of the Nucleus 5 CP810 sound processor in a $S_0 \cdot N_{45}$ scenario and, in contrast to our results, did not find a significant difference [24]. Apart from the fact that the directional sensitivities of the CP810 beamformers are slightly different compared to the SONNET, this is most likely due to the different spatial setups of speech and noise sources. This illustrates a potential weakness of adaptive beamforming algorithms: depending on the listening environment, they can outperform both omnidirectional microphones and
directional microphones with fixed directivity, but they could theoretically also deteriorate the target signal in situations where noise and target signal occur at similar angles. Additionally, they might deteriorate sound localization and decrease awareness for environmental sounds such as cars. In fact, the ABF characteristics implemented in the SONNET are only intended to suppress noise sources from the rear hemisphere. An additional feature of the SONNET processor which is intended to improve speech perception in noise is the automatic switching between OMNI and ABF settings, depending on the input signal level. When activated, the ABF is applied for high-input levels only, i.e., when the listening environment is potentially difficult for the CI user. Because adaptive microphone directionality was set to “always directional”, this feature was not tested in this study.

It is worth noting that the ABF performs significantly better than the FBF in our particular test scenario with two noise sources, although a two-channel ABF is designed to attenuate only a single direction. This might be due to the attenuation of the second noise source because of the head shadow effect, which results in the selection of the ipsilateral noise source as the loudest direction.

This study evaluated the benefits of beamforming with a single CI. Since complex binaural beamforming algorithms are already established for hearing aids and such algorithms have also been successfully tested in CI users [25], the use of beamforming in bilaterally implanted patients as well as the use of even more sophisticated bilateral beamforming algorithms might further improve speech perception in noise in the near future.

**Conclusion**

CI audio processors equipped with directional microphones improve speech reception in noise substantially, given that speech and noise sources are spatially separated. In the presented scenario, the ABF algorithm of the MED-EL SONNET audio processor yielded significantly better results compared to the FBF algorithm and the omnidirectional microphone. The FBF algorithm produced significantly better results than the omnidirectional microphone setting. However, emphasis needs to be drawn to the fact that directional microphones may also decrease the awareness of sudden sound sources like approaching cars. Furthermore, adaptive beamforming may also deteriorate speech perception in certain listening situations. Future studies are needed to evaluate the benefit of the ABF algorithm in everyday life. Until then, the

---

**Fig 4. Individual differences in terms of SRT for each subject.** (A) Fixed beamformer (FBF) vs. Omnidirectional microphone (OMNI), (B) Adaptive Beamformer (ABF) vs. OMNI, and (C) ABF vs. FBF.

https://doi.org/10.1371/journal.pone.0190718.g004
FBF scheme could be the recommended standard setting for hearing in noise in CI patients, to allow them to benefit from this promising technology.

Acknowledgments

The authors want to thank Michaela Blineder, Stefan Flak and Sonja Reiss for the excellent audiological support provided during the study. Furthermore, the authors want to thank Noelani Peet and Ruth Zöhrer for medical writing and MED-EL for providing a SONNET audio processor for the duration of the study to allow suitable candidates who were still using older audio processors to be tested.

Author Contributions

Conceptualization: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Dominik Riss.

Data curation: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Hana Šinkovec, Alexandra Kaider.

Formal analysis: Clemens Honeder, Rudolfs Liepins, Hana Šinkovec, Alexandra Kaider.

Funding acquisition: Dominik Riss.

Investigation: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Erich Vyskocil.

Methodology: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Hana Šinkovec, Erich Vyskocil, Dominik Riss.

Project administration: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Dominik Riss.

Supervision: Christoph Arnoldner, Dominik Riss.

Validation: Alexandra Kaider.

Visualization: Clemens Honeder, Rudolfs Liepins, Hana Šinkovec, Alexandra Kaider.

Writing – original draft: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Hana Šinkovec, Alexandra Kaider, Dominik Riss.

Writing – review & editing: Clemens Honeder, Rudolfs Liepins, Christoph Arnoldner, Erich Vyskocil, Dominik Riss.

References

1. Gifford RH, Dorman MF, Shallop JK, Sydowksi SA. Evidence for the expansion of adult cochlear implant candidacy. Ear Hear. 2010; 31(2):186–94. https://doi.org/10.1097/AUD.0b013e3181c6b31 PMID: 20071994

2. Spahr AJ, Dorman MF, Loiselle LH. Performance of patients using different cochlear implant systems: effects of input dynamic range. Ear Hear. 2007; 28(2):260–75. https://doi.org/10.1097/AUD.0b013e3180312607 PMID: 17496675

3. Kokkinakis K, Azimi B, Hu Y, Friedland DR. Single and multiple microphone noise reduction strategies in cochlear implants. Trends in amplification. 2012; 16(2):102–16. https://doi.org/10.1177/1084713812456906 PMID: 22923425

4. Litovsky R, Parkinson A, Arcaroli J, Sammeth C. Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. Ear Hear. 2006; 27(6):714–31. https://doi.org/10.1097/01.aud.0000246816.50820.42 PMID: 17086081

5. Gifford RH, Driscol CL, Davis TJ, Fiebig P, Micco A, Dorman MF. A Within-Subject Comparison of Bimodal Hearing, Bilateral Cochlear Implantation, and Bilateral Cochlear Implantation With Bilateral Hearing Preservation: High-Performing Patients. Otol Neurotol. 2015; 36(8):1331–7. https://doi.org/10.1097/MAO.0000000000000804 PMID: 26164443
6. Vermeire K, Punte AK, Van de Heyning P. Better speech recognition in noise with the fine structure processing coding strategy. ORL J Otorhinolaryngol Relat Spec. 2010; 72(6):305–11. https://doi.org/10.1159/000319748 PMID: 20847579

7. Smulders YE, van Zon A, Stegeman I, Rinia AB, Van Zanten GA, Stokroos RJ, et al. Comparison of Bilateral and Unilateral Cochlear Implantation in Adults: A Randomized Clinical Trial. JAMA otolaryngology—head & neck surgery. 2016; 142(3):249–56.

8. Riss D, Hamzavi JS, Blinder M, Honeder C, Ehrenreich I, Kaider A, et al. FS4, FS4-p, and FSP: a 4-month crossover study of 3 fine structure sound-coding strategies. Ear Hear. 2014; 35(6):e272–81. https://doi.org/10.1097/AUD.0000000000000063 PMID: 25127325

9. Wagener K, Brand T, Kollmeier B. Development and evaluation of a German sentence test Part III: Evaluation of the Oldenburg sentence test. Z Audiol. 1999; 38(3):86–95.

10. McCreery RW, Venediktov RA, Coleman JJ, Leech HM. An evidence-based systematic review of directional microphones and digital noise reduction hearing aids in school-age children with hearing loss. Am J Audiol. 2012; 21(2):295–312. https://doi.org/10.1044/1059-0889(2012/12-0014) PMID: 22858614

11. Bentler RA. Effectiveness of directional microphones and noise reduction schemes in hearing aids: a systematic review of the evidence. J Am Acad Audiol. 2005; 16(7):473–84. PMID: 16295234

12. Wolfe J, Parkinson A, Schafer EC, Gilden J, Rehwinkel K, Mansanares J, et al. Benefit of a commercially available cochlear implant processor with dual-microphone beamforming: a multi-center study. Otol Neurotol. 2012; 33(4):553–60. https://doi.org/10.1097/MAO.0b013e1825367a5 PMID: 22588233

13. Dillier N, Lai WK. Speech Intelligibility in Various Noise Conditions with the Nucleus(R) 5 CP810 Sound Processor. Audiol Res. 2015; 5(2):132. https://doi.org/10.4081/audiore.2015.132 PMID: 26779327

14. Wimmer W, Weder S, Caversaccio M, Komps M. Speech Intelligibility in Noise With a Pinna Effect Imitating Cochlear Implant Processor. Otol Neurotol. 2016; 37(1):19–23. https://doi.org/10.1097/MAO.0000000000000866 PMID: 26427637

15. Spriet A, Van Deun L, Eftaxiadis K, Laneau J, Moonen M, van Dijk B, et al. Speech understanding in background noise with the two-microphone adaptive beamformer BEAM in the Nucleus Freedom Cochlear Implant System. Ear Hear. 2007; 28(1):62–72. https://doi.org/10.1097/01.aud.0000252470.54246.54 PMID: 17204899

16. Wagener K, Kühnel V, Kollmeier B. Development and evaluation of a German sentence test Part I: Design of the Oldenburg sentence test. Z Audiol. 1999; 38(1):4–15.

17. Wagener K, Brand T, Kollmeier B. Development and evaluation of a German sentence test Part II: Optimization of the Oldenburg sentence test. Z Audiol. 1999; 38(2):44–56.

18. Chung K, Zeng FG. Using hearing aid adaptive directional microphones to enhance cochlear implant performance. Hear Res. 2009; 250(1–2):27–37. https://doi.org/10.1016/j.heares.2009.01.005 PMID: 19450437

19. Mosnier I, Marx M, Venail F, Loundon N, Roux-Vaillard S, Sterkers O. Benefits from upgrade to the CP810 sound processor for Nucleus 24 cochlear implant recipients. Eur Arch Otorhinolaryngol. 2014; 271(1):49–57. https://doi.org/10.1007/s00405-013-2381-8 PMID: 23408020

20. Hey M, Hockte J, Hedderich J, Muller-Deile J. Investigation of a matrix sentence test in noise: reproducibility and discrimination function in cochlear implant patients. Int J Audiol. 2014; 53(12):895–902. https://doi.org/10.3109/14992027.2014.938368 PMID: 25140602

21. Rader T, Schmiegelow C, Baumann U, Fastl H. Oldenburger Satztest im “Mult-Source Noise Field” mit unterschiedlichen Modulationscharakteristika (German). 34. Deutsche Jahrestagung für Akustik; Dresden 2008.

22. Wagener K. Factors influencing sentence intelligibility in noise. Oldenburg: Bibliotheks- und Informationssystem der Carl von Ossietzky Universität Oldenburg; 2004.

23. Ricketts T. Impact of noise source configuration on directional hearing aid benefit and performance. Ear Hear. 2000; 21(3):194–205. PMID: 10980727

24. Razza S, Albanese G, Ermoii L, Zaccone M, Cristofani E. Assessment ofdirectionality performances: comparison between Freedom and CP810 sound processors. Otolaryngol Head Neck Surg. 2013; 149(4):608–13. https://doi.org/10.1177/0194599813496382 PMID: 2383307

25. Buechner A, Dyballa KH, Behrmann P, Fredelake S, Lenarz T. Advanced beamformers for cochlear implant users: acute measurement of speech perception in challenging listening conditions. PLoS One. 2014; 9(4):e95542. https://doi.org/10.1371/journal.pone.0095542 PMID: 24755864