Speech perception with combined electric acoustic stimulation (EAS) and bilateral cochlear implant in a multi source noise field

Uwe Baumann[1], Tobias Rader[1,2] and Hugo Fastl[2]

[1] *Abteilung für Audiologische Akustik am Zentrum der Hals-, Nasen- und Ohrenheilkunde, Goethe-Universität Frankfurt, Germany*

[2] *Arbeitgruppe Technische Akustik, Lehrstuhl für Mensch-Maschine-Kommunikation, Technische Universität München, Germany*

Objective: Combined electric acoustic stimulation (EAS) is a therapeutic option for patients with severe-to-profound high and mid frequency hearing loss but remaining low frequency hearing. The present study applied a multi-source noise field (MSNF), consisting of a four-loudspeaker array with independent noise sources, in combination with a closed set sentence test (Oldenburger Sentence Test, OLSA) to measure and compare speech perception in noise in EAS and bilateral cochlear implant (CI) subjects. Speech simulating noise (Fastl-Noise) as well as CCITT-noise (continuous) and OLSA-noise (pseudo continuous) served as noise sources with different temporal pattern. Speech tests were performed in two groups of patients aided in either the EAS condition (n=7) or with bilateral cochlear implant (n=10). All subjects in the EAS group were fitted with a high power hearing aid in the opposite ear. A group of 20 normal hearing listeners served as controls. Results: Speech reception thresholds (SRT) were severely compromised by modulated (Fastl)-noise in both groups of cochlear implant listeners compared to normal hearing listeners. Average EAS subject group SRTs were lower than average results of the bilateral CI group in all noise conditions. In reference to the OLSA-noise condition, the EAS group data showed better SRTs especially in the Fastl-noise condition. The overall better performance in modulated noise conditions in the EAS group might be explained by 1) "glimpsing", the enhanced ability of the residual acoustic hearing to listen into temporal gaps or 2) improved transmission of fundamental frequency cues in the lower frequency region of acoustic hearing, which might foster grouping of speech auditory objects. Furthermore, the results do indicate, that binaural interaction between EAS implanted ear and residual acoustic hearing in the opposite ear enhances speech perception in complex noise situations.

INTRODUCTION

Electric acoustic stimulation (EAS) combines acoustic hearing and perceptions elicited by electrical stimulation in an ear implanted with a cochlear implant. Introduced by von Ilberg *et al.*, 1999, EAS is a therapeutic option for patients with severe-to-profound high and mid frequency hearing loss but remaining low frequency hearing (Baumann

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and Helbig, 2009). Advances in the surgical approach as well as the introduction of electrode arrays designed for minimal trauma of the delicate structures of the inner ear do guarantee the preservation of acoustic low frequency hearing in the majority of patients after implantation (Gstoettner *et al.*, 2009). Results after rehabilitation show enhanced speech in noise perception compared to usual cochlear implant (CI) conditions (Kiefer *et al.*, 2002).

Speech perception in noise is one of the most difficult tasks for people suffering from hearing impairment. The Oldenburg Sentence Test (OLSA) is a useful tool to investigate speech intelligibility threshold in a noise environment (Wagener *et al.*, 1999). In the present study, a multi-source noise field (MSNF, Rader *et al.*, 2008), consisting of a four-loudspeaker array with independent noise sources, was combined with the OLSA. The multi source noise field (MSNF) enables the presentation of a more realistic noise environment and allows investigating the effects of binaural interaction regarding perceptual separation of signal and noise arriving from different directions.

It has been shown in previous studies, that amplitude modulated noise is extremely distractive for hearing impaired persons. Different speech-simulating fluctuating noises have been proposed to assess inter–individual variability; for example modulated CCITT-noise (so called Fastl-noise, Fastl, 1987) or ICRA-noise (Wagener *et al.*, 2006) Users of cochlear implant systems suffer extremely in non-continuous noise situations whereas normal hearing listeners are able to listen into short spectro-temporal gaps of masking noise (Fastl *et al.*, 1998). The so called effect of “glimpsing” is deteriorated or even absent in hearing aid or cochlear implant users.

The following questions are addressed in the present study:

1) How do patients fitted with EAS on one ear and hearing aid on the opposite ear perform in different noise and sound field conditions compared to bilateral CI subjects?
2) Can patients using EAS in one ear and a hearing aid in the other make use of bilateral cues to enhance speech perception in complex noise fields?
3) Do EAS patients make use of “glimpsing” in modulated noise?

MATERIAL AND METHODS

Subjects

Two groups of cochlear implant patients served as subjects in the present study (demographical data c.f. Table 1).

The EAS group consisted of seven subjects. Six subjects were implanted with a PULSAR-CI^{100} implant with a FlexEAS electrode array; one subject received a SONATA-ti^{100} implant attached with the recently introduced Flex20 electrode array (MED-EL, Innsbruck, see Baumann and Helbig, 2009 for further details on implant and electrode technology). Average age of the subjects was 66 years (median), average EAS experience was 14 months. All subjects were fitted with a DUET processor in the implanted ear. The DUET processor is a device which combines a cochlear implant speech processor and a hearing aid specially designed for amplification of the lower frequencies (Helbig *et al.*, 2008). The opposite ear was fitted with a digital high power hearing aid. Average pure tone audiogram data for the opposite ear is displayed in Fig. 1, data for the implanted ear (pre and post implantation) is displayed in Fig. 2. As visible in Fig. 2, considerable residual hearing is present up to 750 Hz, the average hearing loss at 500 Hz is 80 dB HL. However, hearing deteriorates after implantation to a certain extent: at 500 Hz. The average difference between pre- and post-implantation audiogram at 500 Hz is 35 dB, at 125 Hz 15 dB and at 250 Hz 20 dB.

group	age [years]	sex	condition left ear	condition right ear	duration of deafness [years]	experience CI [months]	System	Etiology
EAS bimodal	26	f	EAS	hearing aid		4	Med-El PULSARci100	unknown, progressive
EAS bimodal	32	f	EAS	hearing aid		14	Med-El PULSARci100	infection
EAS bimodal	69	f	hearing aid	EAS		15	Med-El PULSARci100	progredient
EAS bimodal	69	m	hearing aid	EAS		15	Med-El PULSARci100	progredient
EAS bimodal	68	m	hearing aid	EAS		>24	Med-El PULSARci100	kongenital
EAS bimodal	37	m	EAS	hearing aid		8	Med-El PULSARci100	progressive
EAS bimodal	66	f	EAS	hearing aid		3	Med-El SONATAti100	progressive, hearing loss
CI bilateral	42	m	CI	CI	9	3	Advanced Bionics HiRes90k	progressive, hearing loss
CI bilateral	52	m	CI	CI	46	>24	Med-El PULSARci100	ototoxic
CI bilateral	66	m	CI	CI	1	13	Cochlear CI24RECA	progressive
CI bilateral	41	f	CI	CI	n.a.	>24	Med-El C40+	progressive, degenerative
CI bilateral	56	m	CI	CI	6	>24	Med-El PULSARci100/C40+	hearing loss
CI bilateral	50	f	CI	CI	1	13	Cochlear CI24RECA	progressive, hearing loss
CI bilateral	57	f	CI	CI	10	>24	Cochlear CI24M/CI24RECA	hearing loss
CI bilateral	60	f	CI	CI	1	>24	Cochlear CI24RECA	progressive
CI bilateral	47	f	CI	CI	14	>24	Advanced Bionics HiRes90k	otosclerosis
CI bilateral	47	m	CI	CI	6	19	Cochlear CI24RECA	progressive

Table 1: Demographical data of participating subjects.

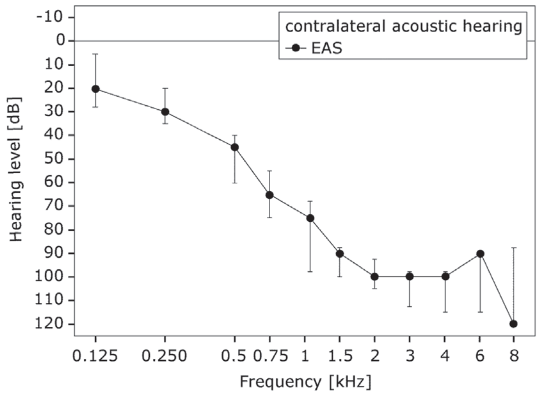

Fig. 1: EAS subject group, average pure tone audiogram of ear opposite to the cochlear implant.

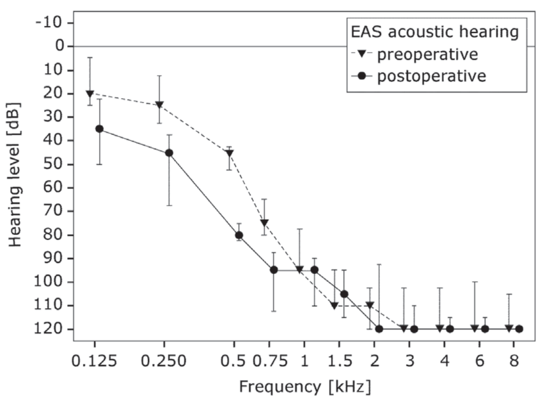

Fig. 2: EAS subject group, average pure tone audiogram of implanted ear pre- and post operatively.

The bilateral CI group consisted of 10 subjects, average age 51 (median), range 41 to 66 years. Different devices from different manufactures were present in this group of subjects (5 COCHLEAR, Melbourne, 3 MED-EL, Innsbruck, 2 Advanced Bionics, Sylmar, USA). All but one subject had bilateral experience of more than 12 months. There was no residual hearing preserved in the bilateral CI group. Monosyllable comprehension was tested prior to the study at 65 dB sound level with the German Freiburger Speech Test. Average monosyllable reception was within a range of 50% and 100% with bilateral CI (Median 87.5%).

Reference data was accomplished in a group of 20 normal hearing subjects (see Rader *et al.*, 2008 for more details).

The subjects received an allowance for their efforts. The study was approved by the local ethics committee.

Experimental set-up

Speech intelligibility experiments and data collection were conducted by means of a personal computer equipped with a high quality 24-bit 8-channel AD-DA converter (RME Digiface). The noise field was presented via a four-loudspeaker array (JBL Control One). A Matlab GUI applying a toolbox (SoundMex, HörTech GmbH, Oldenburg) simultaneously send independent noise signals to four channels of the AD-converter, which were amplified (Ecler MPA 6-80R), and feed to the loudspeaker array. Speech signal presentation was realized via an additional channel and send to a different active speaker (Tannoy VNet300) in front of the subject (S0 condition).

Loudspeaker placement

S0N0 (speech and noise presented from 0 degree azimuth): The S0N0 noise condition presents speech and noise from 0° azimuth direction with one single speaker for both speech and noise signal. It can be assumed that in this mode of signal presentation speech intelligibility performance is not influenced by auditory localization effects.

Multi-Source Noise Field (MSNF): four speakers were set up in each corner of a sound proof room. Each individual speaker was directed to the head of the subject. Subjects were placed in the centre of the room. The MSNF set-up allows the presentation of a pseudo-diffuse noise source field at the subjects' ears. It is supposed that the MSNF setup allows the subject to take advantages provided by localization cues and other binaural effects.

Noise characteristics

Three different kinds of noise were applied in the present study:

a) OL-noise: The noise signal applied in the OLSA is generated by a summation and averaging of a large number of OLSA test sentences. Therefore, OL-noise shows only very weak temporal modulation. Summation and averaging preserves that the long-term spectrum is equal to OLSA sentences. The frequency range of the noise begins at 150 Hz, cut off frequency is 12.6 kHz.

b) CCITT-noise was developed by the Comité Consultatif International Télégraphique et Téléphonique (according to ITU-T Rec. G.227 (11/88) Conventional telephone signal) and renamed in ITU Telecommunication Standardization Sector. Features of this noise are to contain almost no temporal fluctuation and to have no informational masking property. In contrast to OL-noise, the spectrum comprises frequencies up to 22 kHz.

c) Fastl-noise (Fastl, 1987): In order to represent the temporal characteristics of speech, CCITT-noise is amplitude modulated with randomized modulation frequency. The spectral distribution of the modulation source signal of Fastl-noise shows a maximum at 4 Hz, which correlates with the amplitude-modulation statistics of German language. It serves as a single competing speaker simulation without any informational masking. Fastl-noise provides the opportunity of listening into short temporal gaps (“glimpsing”).

The sound level of the noise was fixed to 75 dB SPL for the normal hearing control group and 65 dB SPL in both implanted subject groups. These noise level settings were chosen according to results of a pilot study, where the noise level was variable and speech level was fixed to 65 dB.

Each of the four channels of the MSNF was calibrated separately to 75 dB. Afterwards all pre-equalized channels were combined to the target level of 75 dB in position of the subjects’ ears. Calibration was accomplished in reference to dB SPL with a B&K 0.5 inch microphone 4155, a B&K preamplifier 2669, a B&K measuring amplifier 2690, and a NTI AL1 sound level meter.

Speech test

The Oldenburg Sentence Test (OLSA, Wagener *et al.*, 1999) was used to determine subjects’ individual speech reception threshold (SRT) with different noise conditions. Noise level was fixed and speech level was set adaptively according to the number of correctly perceived words. Speech level was increased if less than three words were correct, and decreased if more than two words were correct. Each test list comprised 20 sentences composed of first name, verb, numeral, adjective and object. The sentences are composed out of a ten-word-group for every word of the sentence. Based on the randomized selection of words, sentences are sometimes senseless or funny. This results in low memorability and predictability. The subjects’ responses were analyzed using correct word-scoring. The individual result of an OLSA test is given by a certain speech reception threshold. As the noise signal is fixed to either 65 dB (CI subject groups) or 75 dB (normal hearing control group) the signal-noise ratio (SNR) could be calculated from the individual SRT.

The OLSA was conducted in “closed set” mode. Thereby, after presentation of the test sentence the subject had the task to indicate the perceived parts of the five elements sentence on a touch screen.

RESULTS

Figure 3 displays average SRT results in different conditions by means of box plots consisting of median, inter quartile and range values. Due to inversion of the Y-axis, better performance (lower SRT) is depicted by “higher” boxes. Outliers are indicated by circles (defined as data points more than 1.5 box-lengths apart from median).

Comparison to normal group

Compared to the normal hearing group, deteriorated performance can be figured out for all noise conditions in both cochlear implant groups. The largest difference is visible in the Fastl-noise/S0N0 condition: compared to the bilateral CI group in terms of average SRT the normal hearing group is more than 10 dB ahead of the bilateral CI group. The smallest difference occurs in the OL-noise/MSNF condition: median SRT results of the EAS group are only 3 dB below median SRT of the normal hearing group.

Effect of soundfield

The largest effect of noise sound field characteristic can be observed in the Fastl-noise condition. The bilateral CI as well as the EAS subject group shows average SRT improvements of 4.4 dB and 3.4 dB respectively comparing S0N0 and MSNF sound field condition. Obviously, the ability of separation between speech and noise signal improves in both groups of subjects. Interestingly, this effect seems to be absent in the normal hearing group.

Effect of noise spectral characteristics

Noise spectrum shows a clear impact on SRT as is observable when OL-noise and CCITT-noise results are compared. Clearly, average SRT results are deteriorated in the CCITT-noise condition regardless of sound field characteristic in the bilateral CI group. SRT drops approximately 3 dB down in the S0N0 condition and nearly 6 dB down in the MSNF condition in this group of subjects. Interestingly, this effect is nearly absent in the group of EAS subjects. Normal hearing subjects do even perform better in the CCITT-noise condition either in the S0N0 or MSNF sound field.

Effect of noise modulation characteristics

Average results of normal hearing subjects do show clear improvements between unmodulated CCITT-noise and modulated Fastl-noise in both sound field conditions

(S0N0: 6.5 dB, MSNF: 3.1 dB). In contrast to the control group, a small degradation is detectable when SRT results of unmodulated and modulated noise are compared in the bilateral CI group (condition S0N0). The temporal modulation seems to distract this group of subjects in this condition more than the EAS group since average results do not differ in this group to that amount. The effect of degraded performance with modulated noise seems to be absent in the MSNF sound field condition for both groups of CI subjects.

Effect of subject group (EAS versus bilateral CI)

Interestingly, the average SRT results of the EAS subject group are lower and therefore better than the average SRT of the bilateral CI group in all conditions. The largest difference of nearly 6 dB is visible with Fastl-noise in the MSNF sound field condition; the smallest difference is 2.5 dB with OL-noise in the S0N0 sound field condition.

Comparison of ranges and inter quartiles

Ranges and inter quartiles are larger for CCITT- and Fastl-noise compared to the OL-noise condition in all subject groups. Within Fastl-noise, ranges and inter quartiles seem to be nearly equal in all groups. With MSNF condition, the best performer of the EAS-group showed SRT of -7.9 dB, the worst performer of the normal hearing group reached a SRT of -10.6 dB.

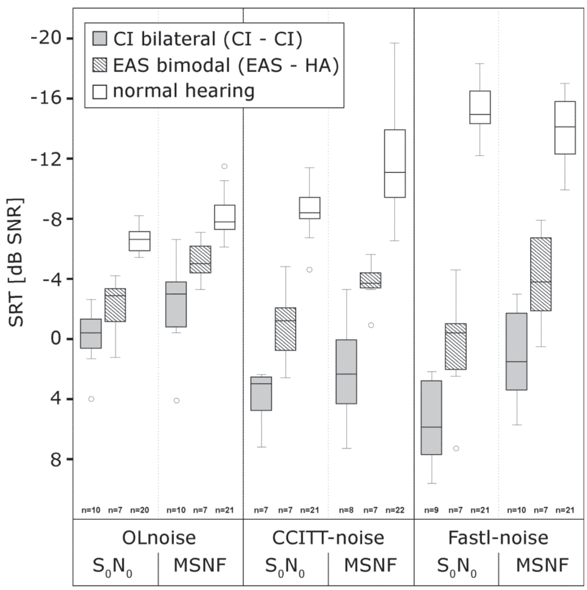

Fig. 3: Speech reception threshold (SRT) in three different subject groups (CI bilateral, EAS with additional hearing aid in the opposite ear) and a reference normal hearing group. Three different noise characteristics: OL-noise, CCITT-noise and amplitude modulated CCITT-noise according to Fastl, 1987, (Fastl-noise). Noise level fixed at 65 dB SPL for the implanted groups; and at 75 dB SPL for the reference group. Better performance of the EAS group compared to the bilateral CI group in all noise and sound field conditions. See text for discussion.

Group performance averaged over noise condition/sound field condition

In order to compare average group performance in different noise and sound field conditions, Fig. 4 shows collapsed data. As already observed in Fig. 3, the EAS group shows higher performance in terms of improved average SRT compared to the bilateral

CI group. The largest effect is demonstrated in the MSNF sound field condition (SRT difference 5.0 dB). Best performers in the EAS group do reach the range of results derived from the normal hearing reference group. However, in the MSNF condition, the SRT difference between the average of the CI bilateral/EAS and the normal hearing group is nearly 12 dB and 7 dB respectively.

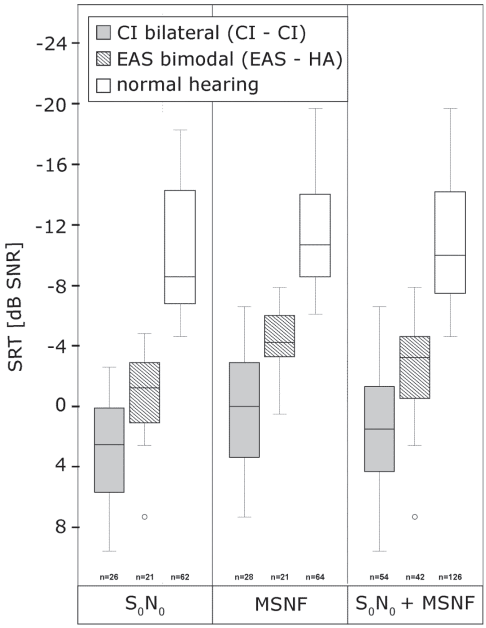

Fig. 4: SRT average of the three different noise conditions of the present study (OL-noise, CCITT-noise, Fastl-noise). Left: Collapsed data for sound field conditions S0N0 and MSNF. Right: Grand total. Better performance of the EAS Group in terms of average SRT.

DISCUSSION

Several studies have addressed the beneficial effect of combining acoustic and electric stimulation in the past. For example, recently Dorman and colleagues had investigated speech perception in noise a group of bimodal CI users and a group of unilateral CI users

(Dorman *et al.*, 2008). When acoustic information was added to the electrically stimulated information, performance increased by 17-23 percentage points on tests of word and sentence recognition in quiet and sentence recognition in a 4-talker babble noise. However, since speech and noise where presented in the S0N0 condition, the impact of additional bilateral processing effects on recognition scores was not investigated.

Gap listening

Normal hearing subjects show the ability to listen into short temporal gaps provided by temporal amplitude fluctuations in modulated noise (glimpsing) to improve speech intelligibility. The present results shows, that this effect is slightly larger in the S0N0 condition compared to the MSNF sound field condition. An explanation for this observation might be the summation of four independently modulated noise signals in the MSNF condition, which will in turn reduce overall temporal fluctuation and decrease the possibility to make use of the glimpsing effect.

In contrast to the normal hearing reference group bilateral CI subjects as well as EAS subjects are not able to make use of the glimpsing effect at all, since their average SRT results do not improve in the modulated noise condition. However, the average distorting effect of noise modulation on performance is even higher in a unilateral CI condition. The average SRT of unilateral CI patients is approximately 20 dB higher than in normal listeners, whereas the average EAS subject SRT is about 10 dB, and the average bilateral CI SRT 15.6 dB higher (Fastl *et al.*, 1998, and data not shown here).

Normalization in reference to OL-noise/S0N0

Results obtained in different groups of subjects might be influenced by different composition of etiologies, age at implantation, duration of experience, rehabilitation quality as well as many other factors. Therefore, between groups comparison might be compromised to a certain extent due to these differences. In order to minimize group effects, normalization was carried out with the OL-noise S0N0 condition serving for all groups of subject as individual reference. Box plots of normalized results are displayed in Fig. 5.

The normalized data for Fastl-noise and S0N0 sound field condition shows clearly the already observed effect, that the presence of temporal masker fluctuation deteriorates performance in both CI subject groups (bilateral CI 5 dB, EAS 3 dB), whereas the normal hearing group could improve performance dramatically. Compared to the OL-noise, average normalized SRT improves about 8 dB in the normal hearing group. Interestingly, the MSNF condition shows improved SRT in both CI subject groups compared to the S0N0 condition. This indicates that bilateral CI/EAS bimodal subjects are able to make use of localization cues. Performance in these groups of subjects increased because speech and noise sources were perceptually separated. This effect is also demonstrated in the OL-noise and CCITT-noise conditions.

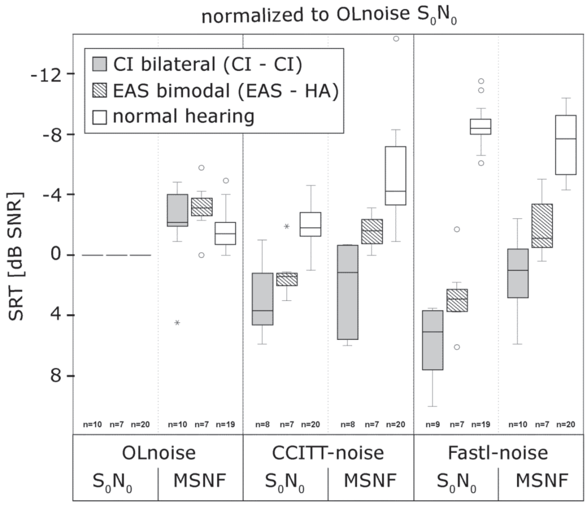

Fig. 5: Data of Fig. 3. normalized in reference to the OL-noise S0N0 condition individually for each group of subjects. Largest deterioration for modulated noise (Fastl-noise) in the S0N0 condition. See text for further discussion.

CONCLUSION

- Modulated noise shows a strong distractive effect for speech perception with cochlear implants.
- EAS combined with an additional hearing aid in the ear opposite to the implant shows better speech perception in noise performance compared to a group of bilateral cochlear implant subjects.
- The largest effect of EAS compared to bilateral CI was observed in a multi source noise field condition.
- Interaural processing between EAS implanted ear and opposite ear may account for this effect.

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