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**Title:** Speech perception with cochlear implants : improving the interface  
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Evaluation of the Benefit for Cochlear Implantees of Two Assistive Directional Microphone Systems in an Artificial Diffuse Noise Situation

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Objective
People with cochlear implants have severe problems with speech understanding in noisy surroundings. This study evaluates and quantifies the effect of two assistive directional microphone systems compared to the standard headpiece microphone on speech perception in quiet surroundings and in background noise, in a laboratory setting developed to reflect a situation whereby the listener is disturbed by a noise with a mainly diffuse character due to many sources in a reverberant room.

Design
Thirteen postlingually deafened patients, implanted in the Leiden University Medical Centre with the Clarion CII device, participated in the study. An experimental set-up with 8 uncorrelated steady-state noise sources was used to test speech perception on monosyllabic words. Each subject was tested with a standard headpiece microphone, and the two assistive directional microphones, TX3 Handymic by Phonak and the Linkit array microphone by Etymotic Research. Testing was done in quiet at a level of 65 dB SPL and with decreasing signal-to-noise ratios (SNR) down to –15 dB.

Results
Using the assistive directional microphones, speech recognition in background noise improved substantially and was not affected in quiet. At an SNR of 0 dB, the average CVC scores improved from 45% for the headpiece microphone to 67% and 62% for the TX3 Handymic and the Linkit respectively. Compared to the headpiece, the Speech Reception Threshold (SRT) improved by 8.2 dB SNR and 5.9 dB SNR for the TX3 Handymic and the Linkit respectively. The gain in SRT for TX3 Handymic and Linkit was neither correlated to the SRT score with headpiece nor the duration of CI-use.

Conclusion
The speech recognition test in background noise showed a clear benefit from the assistive directional microphones for cochlear implantees compared to the standard microphone. In a noisy environment, the significant benefit from these assistive device microphones may allow understanding of speech with greater ease.
Speech recognition capabilities of cochlear implantees have increased rapidly over the past years. Different studies have shown positive outcomes in identification tests for speech presented in quiet surroundings (Firszt et al., 2004; Ramsden, 2004; Rauschecker & Shannon, 2002; Parkinson et al., 2002; Anderson, Weichbold, & D’Haese, 2002; Frijns, Briaire, de Laat, & Grote, 2002). However, speech perception deteriorates rapidly when background noise is added (Spahr & Dorman, 2004; Fetterman & Domico, 2002). This deterioration can also be seen in real-life situations where patients report significant problems with speech recognition in noisy acoustical environments, such as social gatherings. In such environments, with multiple speakers present, the noise becomes diffuse and the level can easily exceed the speech reception level of listeners with impaired hearing, who use hearing aids or cochlear implants. Based on the abovementioned studies, the intelligibility scores for CVC phonemes or words for CI-users are less than 50%, resulting in poor intelligibility, while persons with normal hearing still reach good intelligibility with scores above 80% at an SNR of 0 dB (Plomp, 1977).

Many experiments are carried out to improve speech intelligibility in background noise for cochlear implant users. These approaches include increasing the number of electrodes and rates of stimulation, the use of a conditioning pulse and bilateral implants. These approaches focus mainly on processing the signal delivered to the electrode array in the cochlea. Besides these approaches, it is also possible to develop noise reduction algorithms or to use directional microphones. Knowledge of these algorithms and directional microphones is nowadays widely used for development of commercial hearing aids or assistive listening devices.

Results of experiments with persons with normal hearing and CI-users showed that a full analysis of the speech signal, spectral and temporal, is not required to understand spoken language in quiet surroundings (Shannon, Zeng, Kamath, Wygonski & Ekelid, 1995; Fu & Galvin, III, 2001). Although speech can be understood using only 4 spectral channels, extra spectral information is needed for understanding speech in background noise, and listening to music requires even more channels (Fu, Shannon, & Wang, 1998; Smith, Delgutte, & Oxenham, 2002). Experiments have shown improvement in speech recognition in background noise in CI-users with an increase in the number of active channels (Friesen, Shannon, Baskent, & Wang, 2001). The data of Friesen do show that an improvement is found of only 0.2–1.7 dB in SNR for consonants and vowels per doubling of electrodes. However, the maximum CNC word score at 0 dB is not higher than 5%. Additionally, experiments do show that the optimal number of channels for individual patients is lower than the number of electrodes available in most commercial implants as a rule (Frijns, Klop, Bonnet, & Briaire, 2003). Furthermore, speech in background noise and listening to music demands more temporal information than merely extracting the envelope of the speech signal (Smith et al., 2002). High rate stimulation showed increased speech perception in background noise (Frijns et al., 2003), and introducing stochastic resonance using a conditioning pulse was shown to be promising (Rubinstein & Hong, 2003) and is now tested in a clinical trial. The optimization of the dynamic range also shows improvements, albeit small, in speech in noise perception (James et al., 2002; Dawson, Decker, & Psarros, 2004).
Improvements in both spectrotemporal and dynamic information were achieved using electrical stimulation together with the residual hearing or bilateral implantation (Turner, Gantz, Vidal, Behrens, & Henry, 2004; Van Hoesel, Ramsden, & Odriscoll, 2002; Müller, Schön, & Helms, 2002; Laszig et al., 2004). Moreover, a two-microphone adaptive noise reduction system was used to obtain a better input-signal in noisy circumstances (Wouters & Vanden Berghe, 2001). These applications all showed improvements in understanding speech in background noise, although this was tested in typical laboratory settings, not matching real life situations.

Besides the developments in digital techniques (Wood & Lutman, 2004), directional microphones improve the signal for hearing aid users, who also suffer from a strong deterioration of speech recognition in conditions with interfering noise or sounds, by the attenuation of sounds from the rear and sides (Soede, 1993a, 1993b; Luts, Maj, Soede, & Wouters, 2004). Considerable improvement of speech perception in background noise could be achieved with those directional microphones. Luts et al. (2004) discovered improvements of 6 dB and higher in hearing aid users. However, everyday listening circumstances are different from clinical test set-ups, and these results must be seen in that perspective, which reduces the predictability of the benefit of directional microphones from straightforward clinical tests (Cord, Surr, Walden, & Dyrlund, 2004).

The purpose of the study presented in this paper was to quantify the effect of two assistive directional microphone-systems, primarily developed for use with hearing aids, on speech recognition in background noise for cochlear implantees compared to a standard omni-directional microphone of a cochlear implant system in a typical realistic situation with multiple noise sources in a reverberant situation. For this purpose, we evaluated the performance of the cochlear implantees in a set-up with 8 interfering noise sources, not just one or two noise sources.

MATERIALS AND METHODS

Experimental Diffuse Field Set-Up

Experiments were carried out in a sound-treated audiology room. Speech and noise were presented to the subject from identical self-powered loudspeakers (AV110, Conrad, Germany). Figure 1 shows a drawing of the experimental set-up. Eight loudspeakers were placed on the edges of an imaginary box (Soede, 1993b). Uncorrelated noise was played through a PC with an 8-channel sound card (Gina24, Echo Digital Audio Corp., CA) and directed to the eight loudspeakers. The ninth loudspeaker, from which the speech material was presented, was placed at 1 meter distance from the center and at 1.2 meters from the floor. This location was well within the reverberation distance of the room, which was measured to be 2 m or more for frequencies from and above 500 Hz.
For calibration and determination of the actual sound field, measurements were performed on a sphere in the center of the set-up. These measurements were felt necessary to correct for the position of each loudspeaker inside the room which could result in different sound pressure levels due to differences in distances, residual reflections of the walls, floor and ceiling (ceiling position or floor, at the edge or in the corner). The whole system was calibrated and equalized using pink noise. Equalization was done for each octave band between 250 and 8000 Hz with an equalizer program. After the calibration and equalization procedure, the measured spectrum of the front speaker and all 8 noise sources together was flat within 1 dB. Figure 2 shows the results of sound level measurements on three crossections of a sphere with a diameter of 30 cm at the position of the listener’s head (equator, meridian 45 degrees up and down) with noise coming from all 8 loudspeakers (1/3 octave band). In the 500 Hz 1/3 octave band, deviations were found with a maximum of ±3 dB. At 5000 Hz, the deviations were less than ±1 dB. Results between 1000 Hz and 4000 Hz were equal to the measurements at 5000 Hz. After calibration, and based on the measurements on the sphere, we may conclude that this set-up generates a good approximation of a diffuse noise field within the frequency range of interest.

![Fig. 1. Diffuse noise set-up with eight loudspeakers emitting background noise (N) and one loudspeaker for speech (S). The distance between the chair and the speech loudspeaker is 1.0 m. The stand for the hand-held microphone is located 0.75 m from the loudspeaker for speech. The sphere illustrates the position of the listener’s head.](image)

Speech and Noise Material
Speech and noise (stationary speech shaped) were used from the standard CVC word list on CD (prerecorded female speaker) of the Dutch Society of Audiology (Bosman & Smoorenburg, 1995). All words were balanced on a rms level, sub-lists were homogenous with regard to speech reception scores, and normative values were available (Bosman & Smoorenburg, 1995). Each list consisted of equivalent sub-lists of 11 Dutch three-phoneme monosyllables. In contrast to normal clinical use, where one list is used per condition, the results of four lists of 11 words (132 phonemes) per condition were averaged to obtain a single-data point to increase the accuracy by a factor of two. The speech-sound was played through a
compact disc player (CD720, Philips, The Netherlands) and presented by the speech loudspeaker at a fixed level of 65 dB SPL, measured at the position of the listener’s head. The soundtrack with noise from the CD was extracted to the computer. The track was split into parts and divided over the different sound channels in order to prevent any correlation between the channels.

**Microphones**

The cochlear implant users involved in the experiment were all implanted with Clarion CII (Advanced Bionics Corp., Sylmar, CA) cochlear implants. The microphone of this implant is omnidirectional and incorporated in the headpiece. The headpiece was located on the skull, approximately 4 cm behind the ear.

Two directional microphones systems were tested: the handheld FM-system TX3 Handymic (Phonak, Bubikon, Switzerland) and the Linkit array microphone system (Etymotic Research Inc., Elk Grove Village, IL), which is worn on the head. The Handymic has been designed as a wireless FM-system and can be

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**Fig. 2.** Results of sound level measurements on a sphere with a diameter of 30 centimeters. Measurements are done at 3 cross-sections of the sphere for 500 and 5000 Hz.
used in various ways, such as handheld, attached to the jacket of a speaker or it can be placed on a table (Figure 3A). The system may be of use in steady-state situations such as meetings, dining and at home in family situations. Especially when the microphone is placed near the speaker, a significant improvement of the signal to noise ratio can be obtained. The listener with impaired hearing must change the direction of the microphone manually if the source of interest moves around. The microphone can be used in an omni-directional, zoom and super-zoom mode. Based on the technical specifications, an articulation index weighted directivity index of the system, was calculated of approximately 8 dB for the microphone in super-zoom mode. Figure 3B shows the articulation index weighted polar diagram with an opening angle of approximately 130° (-6 dB point) and average noise reduction from the behind of 13 dB. During the experiment, the Handymic was placed on a one meter high stand, in front of the speech loudspeaker at 75 cm distance and in super-zoom mode. This simulated a listener holding the Handymic in his hand just in front of the body. We measured the sound level at 75 cm, with speech noise coming from the loudspeaker. Compared to a distance of 100 cm (center of the sphere), an increase was measured of the front signal of +1.5 dB. This will result in a difference in the speech-to-noise ratio of +1.5 dB compared to the center position. The Handymic’s signal was sent to the speech processor by the wireless Microlink FM-system with the FM receiver by Bruckhoff Apparatebau (Hannover, Germany, type MicroLink CI+).

The Linkit array microphone system was developed as an assistive listening device for people with hearing impairment, with hearing aids either behind the ear or in the ear (Figure 3C). Its use is mainly intended for situations with background noise such as at parties and restaurants. While wearing the Linkit on the head, the user can move freely and pick out the signal in front. A hearing aid user can use the Linkit over the ear. The microphone’s signal can be transmitted to the hearing aid wirelessly via induction. The array processing is based on the fixed sum beam forming, with three microphones inside the bar (Soede, Berkhout, & Bilsen, 1993a, Luts et al. 2004). The articulation index weighted directivity index equals 7 dB (measured on the head of KEMAR, Knowles, Itasca, IL). Figure 3D) gives the articulation index weighted polar diagram. Compared to the Handymic, the opening angle of 100° is slightly narrower while the average noise reduction from behind is 10 dB. The Linkit has an external audio output for use with the standardized Direct Audio Input (DAI) connector behind the hearing aids. This output signal of the Linkit was not yet fully adapted for use with the Clarion CII. A wire measuring 90 cm in length was used to connect the Linkit to the audio input of the speech processor for use with cochlear implants. To match the input-output sensitivity of the Linkit and the input of the processor of the cochlear implant, a 20 dB buffer-amplifier was used. During the tests, the Linkit was placed on the ear, contralaterally to the headpiece.

The output spectra of the Handymic and the Linkit were compared with each other. They were equal to each other within a margin of ±3 dB, within the frequency range of 500 and 4000 Hz.

Subjects and Test Sequence
25 Cochlear implantees who had been implanted at Leiden University Medical Centre and had more than 3 mo of experience with the implants, were invited to come to the hospital for an evaluation of the...
Fig. 3. (A) TX3 Handymic from Phonak (Bubikon, Switzerland) and (B) the AI-weighted free-field polar diagram. (C) Linkit array microphone system from Etymotic Research (Elk Grove Village, IL) and (D) the AI-weighted free-field polar diagram.
microphones in the test set-up. They would also have the chance to learn whether they could expect any benefits from the use of these microphones in their personal situations, at work or home. Thirteen people responded and were included in the test. All subjects were postlingually deafened adult users of the Clarion CII cochlear implant, having an average follow-up of 12.3 mo after implantation, ranging from 3–21 mo. The average age was 45.3 yr. All participants used a CIS (Continuous Interleaved Sampling) strategy on CII Platinum Speech Processor (PSP) worn on their bodies. Table 1 shows the patient demographics. The average phoneme score in quiet surroundings equalled 88%, with a range of 67–98%. Table 2 shows the average group results of the listening tests for quiet surroundings and SNR +10, +5, 0 and –5 dB in the standard situation with speech and noise coming from one loudspeaker which had been placed in front of the listener. These listening tests had been taken on a routine base as part of the standard clinical evaluations with speech and noise material from the standard CD. These clinical data can be used as a reference for comparison between a standard clinical test with speech and noise coming from one direction and our new set-up. Five subjects with normal hearing, aged between 22 and 25 were tested in the diffuse noise field set-up for a comparison of the performance of subjects with unimpaired hearing with our CI-patients. Each subject was seated in the imaginary center of the set-up, with the head at the same height as the loudspeaker in front of him or her. The cochlear implant users were allowed to adjust the level of the PSP to the most convenient loudness level based on running speech from the loudspeaker in front at the level used for testing (65 dB SPL) for each microphone array. There was no internal mixing of the signals of the directional microphones with the headpiece microphone. No change to the implant settings or to the position of the head was allowed during the test sequences. To minimize learning effects, the three microphones were tested in random order, based on a Latin square (ABC ACB BCA BAC CAB CBA with A = Headpiece, B = Handymic and C = Linkit). Sufficient lists of words were available, so that we did not have to repeat any list within a single session. Tests were performed in one session of 1.5 hr, with a short break. On average 53 lists were used for one subject to cover all situations.

Determination of Speech Reception Threshold

Every subject was tested at fixed noise levels: in quiet surroundings, at SNR +10 dB and SNR 0 dB with the headpiece microphone and the two directional microphones. Based on the individual results at +10 dB and 0 dB, extra tests were done for one or two extra fixed SNR ratios (e.g. +5, -5 or -10 dB) in order to obtain data points above and under a 50% phoneme-score. The estimation of the SRT for each individual can be calculated from this data by simple linear interpolation of the percentages found for the levels just above and below 50%. This elaborative procedure was chosen because it was not possible to determine the SRT with an adaptive procedure. The Dutch equivalent of the English HINT-test comprises intelligibility of sentences and thus expects 100% intelligibility.

Besides the determination of the SRT of the group, it is of interest to determine the absolute values of the phoneme scores at other SNRs. However, using the approach of score-dependent testing, we would obtain fewer data-points at SNR values of the e.g. +15, +5, -5 and -10 dB. Therefore, the data-points of each
TABLE 1. Demographics of cochlear implant users involved in this study

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age at implantation (yr)</th>
<th>Duration of severe deafness (mo)</th>
<th>CI-use (mo at moment of study)</th>
<th>Etiology</th>
<th>Phoneme score in quiet (65 dB SPL)</th>
<th>Duration of CI-use for clinical test data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23</td>
<td>0.5</td>
<td>4</td>
<td>Meningitis</td>
<td>93</td>
<td>3 mo</td>
</tr>
<tr>
<td>B</td>
<td>62</td>
<td>21</td>
<td>4</td>
<td>Hereditary progressive</td>
<td>84</td>
<td>1 yr</td>
</tr>
<tr>
<td>C</td>
<td>38</td>
<td>19</td>
<td>20</td>
<td>Aminoglycosides</td>
<td>67</td>
<td>1 yr</td>
</tr>
<tr>
<td>D</td>
<td>39</td>
<td>19</td>
<td>20</td>
<td>Left unknown, Right glomerstumor</td>
<td>98</td>
<td>1 yr</td>
</tr>
<tr>
<td>E</td>
<td>49</td>
<td>2</td>
<td>9</td>
<td>Meningitis</td>
<td>71</td>
<td>6 mo</td>
</tr>
<tr>
<td>F</td>
<td>14</td>
<td>0.2</td>
<td>12</td>
<td>Hereditary</td>
<td>87</td>
<td>1 yr</td>
</tr>
<tr>
<td>G</td>
<td>43</td>
<td>39</td>
<td>13</td>
<td>Sudden deafness</td>
<td>89</td>
<td>1 yr</td>
</tr>
<tr>
<td>H</td>
<td>59</td>
<td>1</td>
<td>10</td>
<td>Unknown</td>
<td>96</td>
<td>1 yr</td>
</tr>
<tr>
<td>I</td>
<td>52</td>
<td>23</td>
<td>14</td>
<td>Meniere's disease</td>
<td>83</td>
<td>1 yr</td>
</tr>
<tr>
<td>J</td>
<td>59</td>
<td>1</td>
<td>18</td>
<td>Unknown</td>
<td>88</td>
<td>1 yr</td>
</tr>
<tr>
<td>K</td>
<td>50</td>
<td>20</td>
<td>3</td>
<td>Progressive</td>
<td>98</td>
<td>1 yr</td>
</tr>
<tr>
<td>L</td>
<td>67</td>
<td>20</td>
<td>12</td>
<td>Meningitis</td>
<td>96</td>
<td>3 mo</td>
</tr>
<tr>
<td>M</td>
<td>49</td>
<td>15</td>
<td>12</td>
<td>Hereditary progressive</td>
<td>98</td>
<td>1 yr</td>
</tr>
</tbody>
</table>

The table gives the age at implantation, durations of severe deafness, CI-use and etiology. The last two columns give the average phoneme score in quiet surroundings obtained prior to the study, and the experience with the CI device at the time of the clinical test. All subjects were implanted with one cochlear implant. No hearing aid device was used in the contralateral ear.

subject were fitted with a psychometric curve. The group scores at SNR with fewer data points could be calculated using these psychometric curves. For the fitting, a $x^2$ function with three degrees of freedom was used as described by Schön et al. (2002). This function is equal to:

$$u(x) = u_q x x^2 [2.37 + k \times (x - x_{0.5})]$$

where $u$ is the speech reception score (in %) and $u_q$ the fitted score in quiet surroundings. The constant $k$ is proportional to the gradient of the curve at 0.5 $u_q$, $x$ is the signal-to-noise ratio, and $x_{0.5}$ is the signal-to-noise ratio at 0.5 $u_q$. The parameters $u_q$, $k$ and $x_{0.5}$ were used to fit the curve to the data.

RESULTS

Figure 4 shows the individual results (phoneme scores) for the CVC tests as obtained for all subjects with normal hearing and the cochlear implant users with the three different microphones. All cochlear

TABLE 2. Clinical results of 13 cochlear implant users, using their standard program

<table>
<thead>
<tr>
<th>Headpiece</th>
<th>Phoneme scores at SNR (%) in a standard set-up with speech and noise from one loudspeaker</th>
<th>Word scores (%) 0 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quiet                                      +10 dB</td>
<td>+5 dB</td>
</tr>
</tbody>
</table>

The mean phoneme scores on the CVC word test in a standard set-up with speech and noise from the same loudspeaker (speech at a fixed level of 65 dB SPL, free field, 11 words per data point) in quiet surroundings and in background noise with SNRs of 10, 5, 0, 5, 10 and 15 dB. The mean values are given per SNR for the results of the standard listening tests done prior to this experiment. The numbers between the brackets denote the number of cochlear implant users tested at 5 dB. The last column gives the word-score at SNR <7> 0dBsa comparison.
implant users were tested in quiet surroundings and with a signal-to-noise ratio (SNR) of +10 dB and 0 dB. Depending on the CVC scores (below or above 50% at SNR 0 or 10 dB) for each individual cochlear implant user, additional tests were carried out at an SNR of +15, +5, -5, -10 or -15 dB. Besides this, each diagram shows the average CVC score per SNR (filled dots) and the psychometric curve (open dots) fitted according to the $x^2$ function method. The averaged numbers for each SNR are also summarized in Table 3. Note that for the intermediate SNR levels (+15, +5, -5, -10 and -15 dB), the average data-points were based on the results of a subgroup of the subjects. The last 4 rows of the table show the standard deviation of the individual results. The test-retest variability over all 4 lists and conditions was satisfactory (correlation equals 0.75 for data obtained at SNR 0 dB, within subject variability at 0 dB is 9% over the 4 lists). Table 3 also shows the average results in terms of the word-score at 0 dB for comparison of this study (and set-up) with other studies.

Calculation of SRT Values and Benefit
On the basis of the individual scores, we calculated the individual SRT values by a simple linear interpolation between two levels around the SRT and we calculated each by applying the curve-fitting method. Table 4 gives the average of all individual SRT values for the group based on the linear interpolation and the values of the curve-fitting. Next to these SRT values, Table 4 also shows the gradient of the interpolation line or curve at the SRT level expressed in%/dB. Figure 5 shows the individual results expressed as benefit compared to the headpiece in dB. These values are calculated by subtracting the SRT from the linear interpolated data for the Handymic or Linkit from the SRT found for the headpiece.

Phoneme and Word Scores Dependent on SNR
Table 3 and 4 show that the normal hearing reference group had 100% phonemes correct in quiet surroundings and +10 dB SNR, and 93% phonemes correct at 0 dB SNR. The SRT equals –13.4 dB. The average gradient equals 5%/dB at the SRT. In quiet surroundings, the average phoneme score on CVC words with the headpiece microphone for the group of cochlear implant users was 87%, being equal to the average obtained in other CVC tests prior to this study (see Table 2). With the Handymic and Linkit, a score of 85% and 86% respectively was obtained. In other words, the perception in quiet surroundings, with the speech loudspeaker placed in front, was not significantly influenced by the use of the directional microphone systems ($p = 0.54$ and $p = 0.67$ respectively). Figure 4B shows a rapid decrease in CVC scores with decreasing SNR for the headpiece microphone. At SNR 10 dB the phoneme score decreased to 71%, while at 0 dB the score went down to a CVC score of 42% and a word score of 21%. The resulting SRTs equalled +2.5 dB, based on linear interpolation and +2.6 dB based on the curve-fitting. A comparison of these results for the headpiece with the results of the listening tests prior to this study (Table 2) suggests that at +10 dB and 0 dB, the phoneme scores were lower than in the previous data. However, the difference is not statistically significant ($p = 0.64$).

For the two directional microphones, Figure 4C and 4D) a small not yet significant improvement in
Fig. 4. The individual scores of each subject (gray markers and lines) and the average scores for both the group with normal hearing (A) and the group of cochlear implant users with the headpiece (B), Handymic (C) and Linkit (D) microphones.
phoneme scores over the headpiece microphone was already noticeable at 10 dB SNR: from 71% to 80% and 77% with the Handymic (p = 0.11) and the Linkit respectively (p = 0.36). At an SNR of 0 dB, the phoneme scores for the Handymic and the Linkit were 67% and 62% respectively for all subjects, the word scores were 44% and 38% respectively. At -5 and -10 dB, fewer subjects were involved. For the Handymic, the phoneme scores were 55% and 45% at -5 and -10, while the Linkit results equalled 54% and 39%.

Comparison of SRT and Benefit
The mean SRT values for the Handymic and the Linkit were significantly better than the SRT value obtained with the headpiece (p < 0.001, Students t-test). The lower average SRT value of the Handymic over the Linkit was not significant (p = 0.3). The results in Figure 5 show that the average benefit of the Handymic and Linkit over the headpiece equals 8.2 dB (SD = 2.6) and 5.9 dB (SD = 3.9) respectively. Of the subjects, 12 out of 13 received a positive benefit from listening with the Handymic or the Linkit.

However, the results of subjects C and K are considerably different in comparison to the results of the other subjects and also beyond expectations based on the technical properties of the directional microphones.

Subject C had a phoneme score in quiet surroundings of 67% prior to the testing. Her test results in quiet surroundings and in background noise with SNRs of 5 dB, 0 dB, and 10 dB are obtained with the headpiece. The word scores for the Handymic and the Linkit were 67% and 62% respectively for all subjects. The word scores for the Handymic and the Linkit were 67% and 62% respectively for all subjects, the word scores were 44% and 38% respectively. At -5 and -10 dB, fewer subjects were involved. For the Handymic, the phoneme scores were 55% and 45% at -5 and -10, while the Linkit results equalled 54% and 39%.

<table>
<thead>
<tr>
<th>Ear/Microphone</th>
<th>SRT (SD) in dB</th>
<th>Gradient %/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH/none</td>
<td>-13.4 (0.6)</td>
<td>5.0</td>
</tr>
<tr>
<td>CI/Headpiece</td>
<td>-2.5 (4.8)</td>
<td>4.6</td>
</tr>
<tr>
<td>CI/Handymic</td>
<td>-5.7 (5.2)</td>
<td>4.7</td>
</tr>
<tr>
<td>CI/Linkit</td>
<td>-3.4 (6.3)</td>
<td>3.9</td>
</tr>
</tbody>
</table>

SRT values and gradients are averaged based on each individual SRT and gradient.

**TABLE 3. Test results of normal hearing (NH) and cochlear implant users in diffuse noise set-up**

<table>
<thead>
<tr>
<th>Ear/Microphone</th>
<th>Phone-</th>
<th>SRT (SD) in dB</th>
<th>Gradient %/dB</th>
<th>Ear/Microphone</th>
<th>Phone-</th>
<th>SRT (SD) in dB</th>
<th>Gradient %/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH/none [N = 5]</td>
<td>Quiet</td>
<td>100</td>
<td>0.4</td>
<td>5.4</td>
<td>5.0</td>
<td>3.4</td>
<td>12</td>
</tr>
<tr>
<td>CI/Headpiece</td>
<td>+15 dB</td>
<td>100</td>
<td>14</td>
<td>4.6</td>
<td>5.7</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>CI/Handymic</td>
<td>+10 dB</td>
<td>71</td>
<td>15</td>
<td>4.0</td>
<td>5.0</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>CI/Linkit</td>
<td>+5 dB</td>
<td>42</td>
<td>17</td>
<td>4.4</td>
<td>5.3</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>NH/none</td>
<td>0 dB</td>
<td>67</td>
<td>15</td>
<td>4.7</td>
<td>5.3</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>CI/Headpiece</td>
<td>-5 dB</td>
<td>45</td>
<td>17</td>
<td>4.4</td>
<td>5.3</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>CI/Handymic</td>
<td>-10 dB</td>
<td>31</td>
<td>17</td>
<td>4.4</td>
<td>5.3</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>CI/Linkit</td>
<td>-15 dB</td>
<td>44</td>
<td>17</td>
<td>4.4</td>
<td>5.3</td>
<td>3.8</td>
<td></td>
</tr>
</tbody>
</table>

Implant users used their own processor with the Linkit or Handymic connected to the audio input. The mean phoneme scores on the CVC word test (65 dB SPL, free field, 44 words per data-point) in quiet surroundings and in background noise with SNRs of 5, 0, 5, 10 and 15 dB. The mean values are given per SRT for 13 subjects. The numbers between the brackets denote the number of cochlear implant users that was tested at 5, 0, 5, 10 and 15 dB. The last column gives the word score at SNR < 0 dB as a comparison.

**TABLE 4. SRT values based on linear interpolation between near points and curve fitting for whole group of data**

<table>
<thead>
<tr>
<th>Ear/Microphone</th>
<th>Linear interpolation</th>
<th>Curve fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH/none</td>
<td>SRT (SD) in dB</td>
<td>Gradient %/dB</td>
</tr>
<tr>
<td>CI/Headpiece</td>
<td>+2.5 (4.8)</td>
<td>4.6</td>
</tr>
<tr>
<td>CI/Handymic</td>
<td>-5.7 (5.2)</td>
<td>4.7</td>
</tr>
<tr>
<td>CI/Linkit</td>
<td>-3.4 (6.3)</td>
<td>3.9</td>
</tr>
</tbody>
</table>

SRT values and gradients are averaged based on each individual SRT and gradient.
psychometric curve and the test-retest variability (SD 9% at 0 dB SNR). Subject K had been using the cochlear implant at the time of the research for 3 mo. It is most probable that the results were influenced by the lack of experience with speech in noise and the order of the tests. For this particular case, the tests started with the headpiece microphone, and followed by the Linkit and the Handymic. The score of 40% at SNR +10 dB resulted in an SRT of 12.4 dB with the headpiece which was poorest result of all our subjects. Standard clinical testing at 6 mo showed a score of 81% at +10 dB. Therefore, it is most probable that the results were influenced by the short usage of the cochlear implant and order of the tests.

Other Correlations
No correlation of the SRTs (linear interpolation or curve fitting) was found with duration of deafness, CI use or phoneme scores in quiet surroundings (all \( p \)-values > 0.2). We also analyzed the correlation between the individual SRTs with the headpiece and the SRTs found with the Handymic and the Linkit. Figure 6 shows the individual data for all 13 subjects, and the calculated results with linear regression. The regression lines show a fairly strong correlation with a gradient of 0.9 for the Handymic with \( R = 0.87 \) \((p < .001)\) and 1.0 for the Linkit with \( R = 0.78 \) \((p < 0.01)\). The difference in the gradient of the Handymic and the Linkit is not significant \((p > 0.9)\).

DISCUSSION
This experiment shows the differences in speech understanding for the different microphones in an artificially built set-up with multiple noise sources. For the headpiece, results obtained in the artificially built set-up could be compared with those obtained in a clinical, single loudspeaker set-up. We expected poorer results for the headpiece in the new set-up compared to the standard tests with speech and noise coming from a single loudspeaker positioned at the front. This was based on the expectation that the location of the headpiece microphone at the back of the head would be worse than the position of the microphone of a hearing aid positioned behind the ear (BTE). For a hearing aid microphone positioned at BTE position, Soede et al. (1993b) measured a negative directivity of -1 dB with KEMAR in a cocktail party set-up. In this set-up, with speech coming from in front, the speech signal is attenuated with a small amount due to shading of the head, although the noise of the loudspeakers at the contralateral side is also partly attenuated. When data are compared at SNR +10 dB and 0 dB from Table 2, the data in the diffuse noise set-up is 3 percentage points (71% versus 74%) and 5 percentage points (42% versus 47%) lower than for a single-source set-up. Based on a gradient of 4.6%/dB around the SRT (see Table 4), this difference equals – 0.7 dB to -1.0 dB (Table 4). This difference of –1.0 dB is in line with Soede’s (1993b) measurements in a comparable set-up with a microphone positioned behind the ear. However, results are not statistically significant \((p = .5)\) due to the limited amount of tests done. Additional tests need to be done to determine the differences.
Fig. 5. Benefit of Handymic and Linkit compared to headpiece expressed in dB. Results for all subjects and the mean of the group (N = 13). The average for the Handymic and Linkit equals 8.2 dB (SD = 2.6) and 5.9 dB (SD = 3.9) respectively.

Fig. 6. Individual SRTs obtained with Handymic (A) and Linkit (B) as a function of the SRTs obtained with the headpiece microphone. The regression lines show a relatively consistent shift downwards independent of the CI–users performance level in background noise.
On average, for both the Handymic and the Linkit, an improvement of the SRT was found of 8.2 and 1.9 dB compared to the headpiece microphone (Figure 6). Luts et al. (2004) tested a prototype of the Linkit with listeners who were hearing impaired in a reverberant room and also found an average improvement of 6 dB. From this, we may conclude that cochlear implant users may receive the same benefit as hearing aid users. The improvements are large but were approximately 1 dB lower for both microphones than the values predicted on the basis of the technical specifications. For the Handymic, the articulation index weighted directivity index equals 8 dB and with an advantage in SNR due to the distance of 1.5 dB, a total improvement may be expected of 9.5 dB. For the Linkit, an articulation index weighted directivity index was equal to 7 dB based on measurements with KEMAR. The difference of 1 dB as found in this experiment appears to be comparable with results that are found by Soede et al. (1993b) and Luts et al. (2004). Soede found a difference of 1 dB between physical measurements and SRTs found with hearing impaired listeners and suggested the influence of extra noise by a small amount of reverberated speech in the room. This could also be the case for our set-up, although measurements did show that the listener was positioned within the reverberation distance of the loudspeaker. However, an additional unknown factor is the validity of weighting of the directivity index over all frequencies by the articulation index results in the case of cochlear implant users. The weights of the articulation index are based on listening tests for normal listeners and not for hearing impaired persons or electrical hearing. Future research is needed to determine the contribution of each frequency band to speech intelligibility in background noise for cochlear implant users. This is not only important for determining the effects of directional microphones but also for understanding effects of speech algorithms, the effects of pathology and spectral settings on speech intelligibility in noise.

The tests with the two subjects C and K resulted in unexpected benefits. The scores resulted in a very low benefit for the microphones for subject C and a very high benefit for subject K compared to the benefit of the whole group (Figure 5). No explanation can be found in type of cochlear implant or fitting method because they had the same implant and were fitted by the same audiologist. A possible explanation can be found in the fact that they started with a lower phoneme score of approximately 70% in quiet surroundings. Adding background noise resulted immediately in a drop of the intelligibility scores around the threshold level of 50%. Subject C was able to perform around threshold level for +10 dB SNR as well as 0 dB. This resulted in flat psychometric curves for the Headpiece and the Linkit and therefore, results can be influenced by the within subject test-retest variability which was found to be around 8% for the CVC scores. Subject K performed relatively poorly at a +10 dB SNR with the headpiece microphone. From these results, it can be concluded that the method of testing using CVC words at fixed signal-to-noise ratios, although 4 lists of 11 words were used, still may result in individual results beyond expectations based on the technical properties of the directional microphones. Future research is needed to refine the tests and test sequences. For the daily routine of clinical practice, it is now important to note that evaluation of the extra benefits of directional microphones, FM-systems or special noise programs requires repeated tests at various SNR levels before conclusions may be drawn.

The benefit of a directional microphone as experienced by our subjects depends on the SNR in daily
practical situations. The use of a microphone array does not cause any decrement in speech perception scores in quiet or at high SNRs relative to scores with the headpiece microphone. The listening tests show an improvement of 8.2 dB and 5.9 dB based on the SRT for the Handymic and the Linkit respectively. This average improvement is higher than improvements of 1–2 dB found in other studies with more electrodes, higher rates or bilateral implantation (Friesen et al., 2001; Frijns et al. 2003; Turner 2004). The absolute word score at 0 dB reaches now 44% for the Handymic and 38% for the Linkit. These values are higher than the average value of 5% found by Friesen et al. (2001).

The improvement may be experienced by all Clusers and does, based on the regression analysis of the data (Figure 5), not depend on the personal SRT. From the results in Table 4, it may be concluded that for the cochlear implant users, the average gradient of the psychometric function, based on the curvefitting, equals 4.9%/dB. This means that a typical cochlear implant user, in a listening situation with SNRs just around the SRT, may expect a large average improvement of the phoneme score. For example, in a typical cocktail party or restaurant, SNR values of 0 dB and worse may be expected. The results of the listening tests in the diffuse noise set-up show that in situations with such an SNR, the intelligibility increases from poor (group average 42% in this test) to fair with a level above 62% (CVC score 67% for the Handymic and 62% for the Linkit). This change from below to above 50% might be of significant help to understand what is said and to ease conversation. However, we must not forget that this is still lower than the 5 listeners with normal hearing who can understand more than 90% of what is said, at this same SNR.

The trend of an extra benefit of 2.3 dB of the Handymic over the Linkit as found in this study can partly be explained by the closer positioning of the Handymic to the speech loudspeaker. This resulted in a better SNR in the position of the Handymic of +1.5 dB. This difference will also exist in real life and can be significantly more when the Handymic is held nearer to the mouth of the speaker. However, it must be kept in mind that the Handymic and the Linkit are designed for different applications and use. The choice of which device to use should be made on required improvement, the daily situation and personal appreciation. This was also found in our group. This study was initiated by the question as to whether our patients could benefit from directional microphone systems in practical situations in daily life. Only two subjects showed interest in evaluating the systems in daily practice. Both of them experienced severe problems in their daily work and welcomed any improvement in being able to focus on their tasks instead of having to be constantly engaged with communication only. Other subjects showed less interest, although they could expect a significant benefit. It is most likely that they manage to communicate in noisy social settings by the combined use of their cochlear implants and many years of experience of lip-reading.
CONCLUSION

With the current technical status, speech recognition using cochlear implants is good in quiet surroundings and there is even room left for speech recognition in background noise. With the use of directional microphone systems, this speech recognition in background noise can be substantially improved. Compared to an average speech reception threshold of +2.5 dB found with the standard headpiece microphone of the CII cochlear implant, the Handymic resulted in a benefit of 8.2 dB and the Linkit array microphone system in a benefit of 5.9 dB. When both directional microphone systems were tested, the CI subjects were able to recognize more than 62% of the phonemes presented at 0 dB SNR. This might be of great importance in situations such as restaurant or cocktail party settings. The improvement could make a difference in the way communication can be carried out. Instead of guessing the line of conversation by listening and lip-reading, this benefit could result in a fair intelligibility and so be of significant help in understanding what is said and in easing conversation.

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