



platform for audiological clinical testing



Report of project “Varibel: the benefit of a super-directional hearing aid for speech understanding in noise”

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Goals of the project

- Evaluation of the effect of using all four, the two anterior (positioned at the temple), or the two posterior microphones (above the pinna) per side of the Varibel hearing aid. The posterior microphones are positioned behind the ear similar to a conventional hearing aid.
- Compare speech understanding in noise with a two-sided 4-mic and 2-mic directional fitting and an asymmetric fit (4-mic in one ear and omnidirectional in the other).
- Tests will include: Speech understanding in noise and the BMLD

Subjects are 5 normal hearing subjects and 15 patients with a mild to moderate hearing loss.

Abstract

The Varibel is a strongly directional hearing aid applying an array of four microphones attached to each leg of a pair of glasses. Speech understanding in noise was tested using all four microphones (4-Mic Glasses), two anterior microphones at the temple (2-Mic Glasses) or two posterior microphones above the pinna (2-Mic BTE) per side of the device. In addition, an omnidirectional condition was added (Omni BTE) and an asymmetric fit (4-Mic Glasses on the better ear and omni on the poorer ear). Fifteen subjects with a significant speech discrimination loss were included. The Speech Reception Threshold in noise (SRT_n) was measured in a sound treated room with uncorrelated noise from 45, 135, 225 and 315°. The directional benefit (re Omni) was 6.3 dB for 4-Mic Glasses, in line with earlier studies on similar devices. The asymmetric fit showed a directional benefit of 5.3 dB, significantly better than the 2-Mic Glasses (4 dB) and 2-Mic BTE (1.4 dB) mode. The advantage of a 2-Mic array at the temple compared to a position behind the ear (2.6 dB) was significant. It was concluded that multi-microphone array enable improved understanding in noise compared to most conventional directional devices. The asymmetric fit resulted in the same directional benefit as the 4-Mic Glasses mode and possibly leads to an improved awareness of off-axis sounds in everyday situations. Anterior microphones seem to profit more from the head shadow than posterior microphones by better suppressing noise from behind.

Samenvatting

De Varibel “hoorbril” is een sterk richtinggevoelig hoortoestel dat gebruik maakt van vier microfoons die in elke poot van een bril bevestigd zijn. Het spraakverstaan in ruis werd gemeten met alle vier microfoons actief (4-Mic Glasses), twee microfoons bij de slaap (2-Mic Glasses) of twee microfoons boven de oorschelp (2-Mic BTE) aan elk oor. Bovendien werd een omnidirectionele conditie toegevoegd (Omni BTE) en een asymmetrische aanpassing (4-Mic Glasses aan het betere oor en omni op het slechtere). Vijftien proefpersonen met een aanzienlijke beperking aan het verstaan namen deel aan het onderzoek. De spraakverstaandrempel in ruis (SRT_n) werd bepaald in een echoarme ruimte met on-

gecorrleerde ruis uit 45, 135, 225 and 315°. Het directioneel voordeel (ten opzichte van Omni) was 6.3 dB voor 4-Mic Glasses, in overeenstemming met eerdere studies naar vergelijkbare toestellen. De asymmetrische aanpassing resulteerde in een directioneel voordeel van 5.3 dB, significant beter dan 2-Mic Glasses (4 dB) en 2-Mic BTE (1.4 dB). Het voordeel van een 2-Mic systeem bij de slaap ten opzichte van achter het oor (2.6 dB) was significant. De conclusie is dat de reeks van vier microfoons een verbeterd spraakverstaan in ruis mogelijk maakte dat positief afsteekt bij dat van de meeste conventionele directionele hoortoestellen. De asymmetrische aanpassing leidde tot hetzelfde directionele voordeel als de 4-Mic Glasses instelling en geeft de gebruiker mogelijk een betere waarneming van geluiden die niet van voren komen. Directionele microfoons bij de slaap lijken meer van de hoofdschaduw te profiteren dan microfoons achter het oor bij het onderdrukken van ruis van achteren.

Introduction

The Varibel is a strongly directional hearing aid applying an array of four microphones attached to each leg of a pair of glasses, recently marketed by Varibel, the Netherlands. The aid is designed to improve communication in noise beyond what is possible with conventional ear-level directional hearing aids. Laboratory measurements have shown an averaged Directivity Index (DI) of about 9 dB (or 3 dB in the optional 2-microphone “low” mode) [Berkhout and Boone, 2007]. A DI of 9 dB is about twice the DI obtained with a conventional directional hearing aid in an laboratory setting mimicking a realistic environment without reverberation [Dittberner and Bentler, 2007]. The polar plot in the free field showed a straightforward single lobed behaviour increasingly attenuating all angles deviating from 0° azimuth. Using KEMAR, a speech-weighted DI of 7.2 (or 4.4 dB at the low mode) was found [Verschuure et al., 2007].

Two clinical trials have been performed with the Varibel device. In the first, 15 hearing impaired subjects used the system for one day in different situations. Between 71% and 91% of the subjects preferred the device over their own instrument for intelligibility and comfort in real-life quiet and noisy situations [Stengs and van der Zwan, 2005]. In another study, APHAB and IOI-HA questionnaires were administered to 27 patients who had used the device from 4 to 7 months. Users reported a positive effect of the device compared to their conventional device with respect to “Ease of Communication”, listening in “Background Noise” and in “Reverberance”; no difference was found in the score on “Aversiveness”. The IOI-HA showed a significant improvement of performance in the most-relevant condition and in difficulties encountered in daily life.

Until now, no study has validated the DI measurements on the Varibel device with actual speech in noise performance. Both free field and KEMAR DI measurements have been shown to correlate well with speech-in-noise performance of normal hearing subjects in a reverberation-free diffuse noise sound field, but less so for speech-in-noise tested in noise fields created by a small number of speakers positioned at ear level, such as in a front-to-back ratio measurement [Dittberner and Bentler, 2007]. However, caution in interpreting laboratory results is summoned by the repeated finding that subjects who show a directional benefit in a controlled situation may not report benefit of the same device in their daily lives [Chung, 2004]. Nevertheless, a clinical test of the directional benefit of the Varibel device in a range of hearing impaired subjects will provide real-world evidence of the clinical efficacy not available from technical measurements. Effort will be made to test the effect of the directional technique by only comparing various directional modes of the Varibel device keeping all other amplification parameters constant, instead of, for instance, comparing performance of the Varibel and of a different hearing aid.

A possible concern for directional fittings is that users will not switch in time to a less directional mode in situations where signals come from the side or behind and possibly miss out on essential information. In addition, the directional mode of an aid may be rejected due to the unstable spatial information it provides as a function of head movements. Recently, an asymmetric fitting or “monofit” has been advocated as a means to combine the advantage of directional selectivity on one ear (the best ear, called “focus ear”) with the environmental awareness provided by an omnidirectional microphone on the other (worse) ear. In an acute test, Bentler [Bentler et al., 2004] showed that speech in noise performance was the same whether directional microphones were used on one or two ears. In a follow-up field trial, this finding was corroborated by subjective ratings [Cord et al., 2007]. The authors concluded that “an asymmetric fitting may be a viable option for patients who cannot or do not switch microphone modes”. Given the exceptional directionality of the Varibel device, performance in the asymmetric mode will be tested as an extra condition. It may be hypothesized that a profitable use of an asymmetric fitting requires good binaural processing. To test this idea, the Binaural Masking Level Difference was measured and correlated to the speech understanding in noise performance.

Subjects showing a considerable disability when tested in noise potentially are those that will benefit from a highly directional fitting more than less impaired subjects, and likely are more willing to wear un-

conventional hearing aids. Therefore, patients will be included with a significant speech discrimination loss shown in formal testing. Normal hearing subjects will also be included to assess the maximum benefit with as little inter-individual variability as possible, and to facilitate comparison with other studies.

Methods

Subjects

From the active patient database of the Audiological Centre of the Radboud University Nijmegen Medical Centre 15 hearing impaired subjects were selected. All subjects had a sensorineural hearing loss with an air-bone gap of less than 15 dB in any octave frequency 500 – 4.000 Hz. Only flat or downward sloping thresholds were included (higher frequencies less than 10 dB better than lower frequencies). The hearing loss was symmetric (asymmetry at frequencies between 500 Hz and 4 kHz within 10 dB). Thresholds at 500 Hz were at least 35 dB to limit variability between subjects and avoid subjects who can rely significantly on their unaided hearing in some or all tests. Loudness discomfort levels were at least 90 dB at 1, 2 and 4 kHz. The charts did not reveal any indications that subjects would not understand or follow the test procedures. All patients were bilateral users of a BTE aid. The best aided speech audiometric performance at a conversational level (phoneme score, Dutch NVA monosyllable lists) was between 70% and 97% in both ears. The difference of the phoneme score between ears was less than 15% for each presentation level used. The ear with the highest phoneme score was designated as the “focus” ear; if scores were equal, subjects were asked to indicate their better ear.

Subjects were informed about the project and asked for their co-operation on a voluntary basis by means of an informed consent. All subjects were willing to participate in the experiments on a completely voluntary basis. Subjects were not offered a financial reward. The local medical ethical committee has inspected the study protocol and indicated that the study did not require a formal ethical review as it was judged to impose an insignificant load on the subjects.

Procedure

Subjects were fitted with the Varibel device according to the standard fitting guidelines. The aided gain was verified using a Real Ear Measurement. If available, patients were using their own BTE earmold. However, 4 patients were using a thin tube fitting; in these cases (and in the normal hearing subjects), all tests were performed using Etymotic Research insert earphone tips. Two devices, one standard and one experimental were provided by Varibel to cover all experimental conditions, one of these fitted with a 2-mic array above the pinna (device B) and the other technically identical to the commercially available device but fitted with inoperative components similar to the additions on the first device to avoid a cosmetic difference (device A). Free-field measurements in a sound treated room showed the two glasses to produce a frequency response that was identical within 2 dB up to 6 kHz in the omnidirectional mode. The directional response of both devices in the 2-Mic mode in an anechoic room was calculated as the AI weighted Directivity Index (Boone, R. Unpublished data Delft University of Technology, August 2008). Device A showed a DI of 2,2 dB and device B of 1,9 dB.

The following microphone modes in the better and in the worse ear were compared (manual switches provided access to different modes on the same device):

1. 4-Mic Glasses. Highly directional 4-mic array (7.4 cm) in each leg of the glasses (device A).
2. 2-Mic Glasses. Directional 2-mic array (1.6 cm) in anterior portion of each leg of the glasses (device A), located at the temple of the wearer.
3. 4-Mic Glasses / Omni Front. Asymmetric fitting with the 4-mic array in the better ear and one omnidirectional microphone, placed anterior in the leg at the temple of the wearer (device A).
4. 2-Mic BTE. Directional array of 2 microphones separated by 1.6 cm at a traditional position above the pinna (device B).
5. Omni BTE. One omnidirectional microphone in each leg of the glasses, placed posterior in the leg (device A).

Device A were auto-fitted according to the Varibel prescription rule, which is based on NAL NL-1 [Dillon, 1999]. Next, the insertion gain at 50 dB input level was measured with a real ear measurement system (Aurical, GN Otometrics) using speech modulated broad-band noise. Per ear, an insertion gain was measured for each condition. The gain values reported below and shown in the figures is the average of the gains as measured at discrete test frequencies around the nominal test frequencies.

The frequency response of the device was adjusted at 250, 500, 750, 1000, 1500, 2000, 3000, 4000 and 6000 Hz to minimize deviancies from the target gain for the 4-Mic Glasses mode, but limited by feedback occurring at higher frequencies. The Varibel software allows for independent adjustment of the gain of 50 and 80 dB input signals, but equal adjustments were made for both input levels. The overall gain

was adjusted to achieve an acceptable loudness for live speech. The balance between ears was tested using live speech, and using a warble test tone at the two frequencies used for the localization experiment. In case of an imbalance, small equal adjustments with opposite signs were made in both ears. The same fitting was programmed in device B.

Speech in noise was tested using the “VU” lists [Versfeld et al., 2000] and a female speaker. Four lists were used per condition. The speech signal was presented from a frontal position (0°) and uncorrelated steady state speech shaped noise was played continuously from 4 speakers, at 45, 135, 225 and 315° at an overall level of 60 dB SPL. Half of the subjects was tested with glasses A first, and the other half with B first. The order in which conditions were tested was counterbalanced between subjects using a Latin square design (3×3 for glasses A, and 2×2 for glasses B). Each condition was tested using two lists twice in a ABCBCA design to balance for the effect of practice and fatigue.

All free field tests were performed in a sound treated room with a reverberation time of approximately 250 ms.

The Bilateral Masking Level Difference (BMLD) was tested using headphones for 500 and 2000 Hz tones. White noise was presented in phase at both ears at the Most Comfortable Level. Pure tones were fed in- or completely out of phase to each ear and adjusted in steps of 2 dB to obtain masked thresholds. The BMLD was calculated as the in-phase threshold minus the out-of-phase threshold.

Results

Real ear measurement of aided gain

Figure 1 shows the insertion gain used during testing after correcting the frequency response to approach the target gain while respecting limits set by the tolerance of the subject, feedback (mainly due to the gain >2000 kHz) and assuring an overall loudness balance between the ears for live speech and for the test frequencies used for the localization test (500 and 2000 Hz). On average, before correction the aided gain fell short of target gain but only slightly so after correction, and reached target gain for frequencies around 1000 and 4000 Hz. The between-subject variability of the difference between actual and target gain was somewhat larger at 125 Hz, probably due to the effect of the large ear mould vents in those subjects who used their own ear moulds as opposed to the insert tips used in other patients.

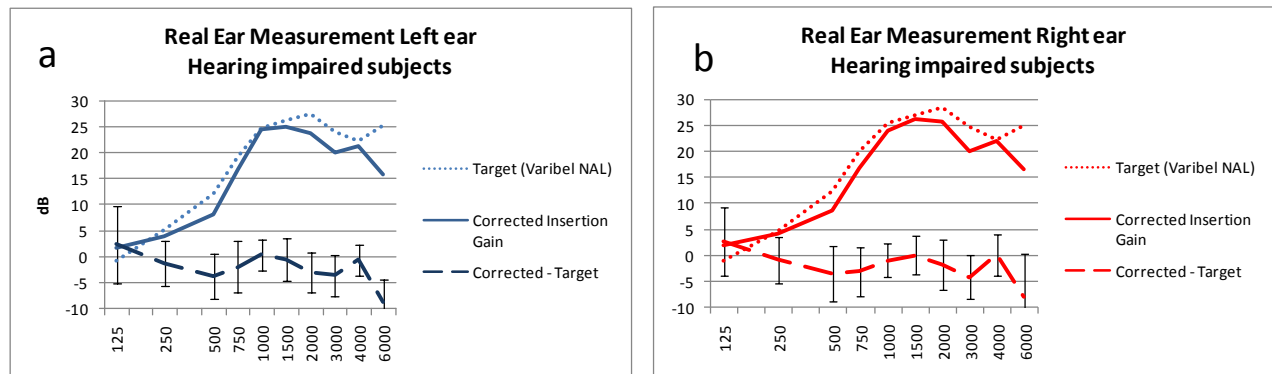


Figure 1. Real ear measurement of the aided gain (in dB) in all hearing impaired subjects (n=15). The difference between the gain used during testing (“Corrected”, omnidirectional mode) and the Varibel NAL target is also shown, with the between subject standard deviation. Figure 1a: left ear, figure 1b: right ear.

In some subjects, no conventional earmolds were available and tests were performed using foam insert tips. Real ear aided gain for conventional earmolds with standard tubing are given in Figure 2. Comparing Figure 1 and 2, it is obvious that the type of transducer did not have a larger effect on the frequency characteristic (before or after correction towards target).

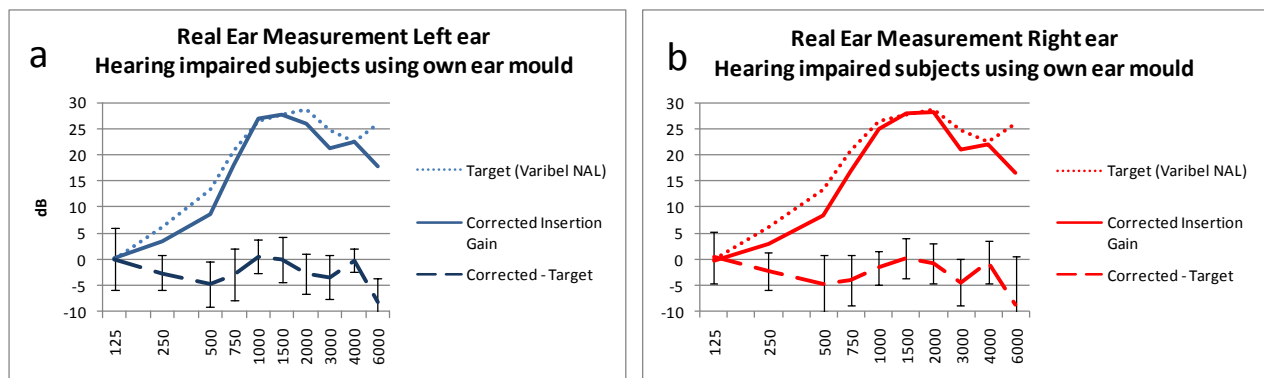


Figure 2. Real ear measurement of the aided gain in subset of hearing impaired subjects in which conventional earmolds were available for testing (n=11). Figure 2a: left ear, figure 2b: right ear. For further details, see legend of Figure 1.

Figure 3 shows the frequency response for the three modes available in the conventional device A: Omnidirectional, 2-Mic Glasses and 4-Mic Glasses. Only minor differences were found.

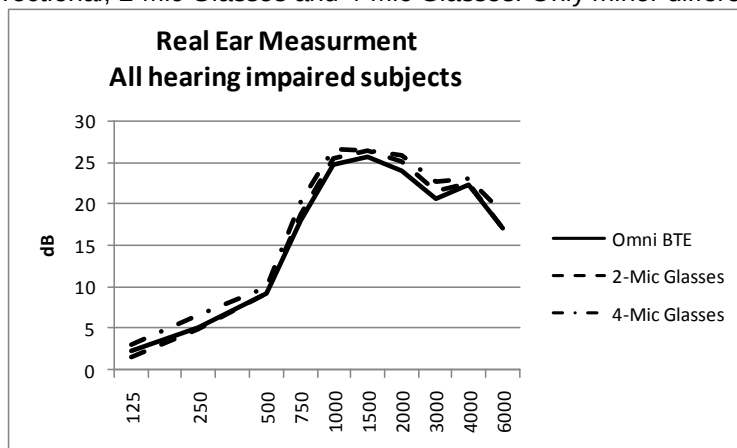


Figure 3. Insertion gain with three different microphone modes for the conventional device (n=15).

Understanding of speech in noise

Figure 4 compares the speech reception threshold in noise (SRT_n) for everyday sentences. The signal to noise ratio at threshold was positive for all conditions, indicating a poor understanding in noise by these hearing impaired subjects. As expected, the best threshold was found for condition 4-Mic Glasses; the worst for condition Omni BTE, with a directional advantage of 6.3 dB. An analysis of variance (Proc GLM, SAS Institute) was performed with Condition and Sentence List as main effects. Sentence List was treated as a random factor. Both effects were highly significant ($p < 0.0001$); the interaction was not significant. A post-hoc test (SNK grouping, alpha 5%) showed that the means of all conditions differed significantly, except those of Condition 4-Mic Glasses and 4-Mic Glasses / Omni Front).

Pearson correlations were calculated between the hearing loss averaged over .5, 1 and 2 kHz, the unaided maximum phoneme score for words in quiet, the threshold for speech in noise averaged over the 4 symmetrically fitted conditions (4-Mic Glasses, 2-Mic Glasses, 2-Mic BTE and Omni BTE) on the one hand and the directional benefit 4-Mic Glasses vs Omni BTE and High Dir / Omni Front vs Omni BTE. None of these correlations was significant ($p > 0.05$).

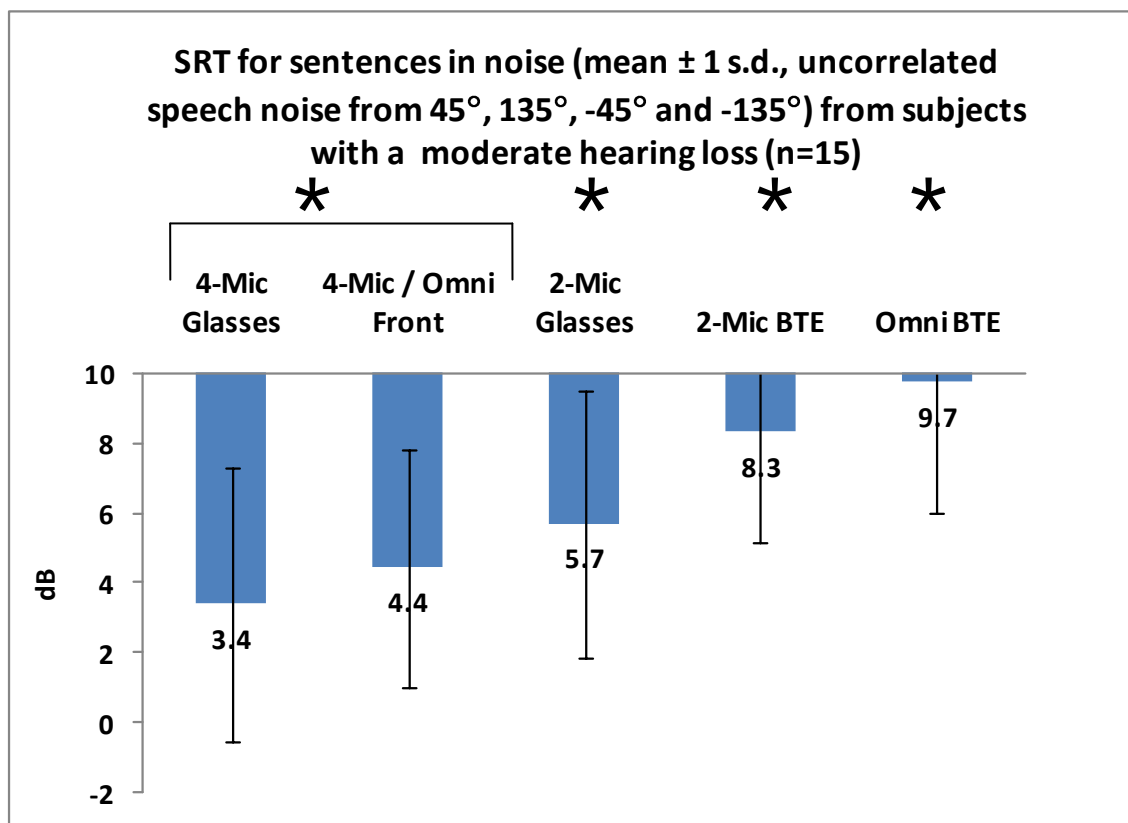


Figure 4. Speech reception thresholds in noise (SRT_n). Uncorrelated noise was played from 45, 135, 225 and 315° at an overall level of 60 dB SPL in a sound treated room. Stimuli were short everyday sentences (VU-lists). Asterisks show that the SRT_n 's are all significantly different from each other, except the SRT_n for the 4-Mic Glasses and the asymmetric 4-Mic Glasses / Omni Front mode. 2-Mic Glasses: low directivity mode with two microphones placed in the legs of the aid. 2-Mic BTE: same two microphones placed slightly above the ear similar to a behind-the-ear hearing aid. Omni BTE: one omnidirectional microphone placed anterior in each leg.

Results from 5 normal hearing subjects showed a highly similar pattern (Figure 5). All SRT_n 's are negative, except for the 2-Mic BTE and Omni BTE conditions. In figure 5, the results from the normal hearing subjects is compared to that of the KEMAR measurements [Boone, 2006]. Only two conditions were directly comparable: 4-Mic Glasses and 2-Mic Glasses. The difference between these two is 2.3 dB (present study) and 2.8 dB (KEMAR). Note that the results for the open ear condition ("None") was collected in a separate group of 11 normal hearing subjects.

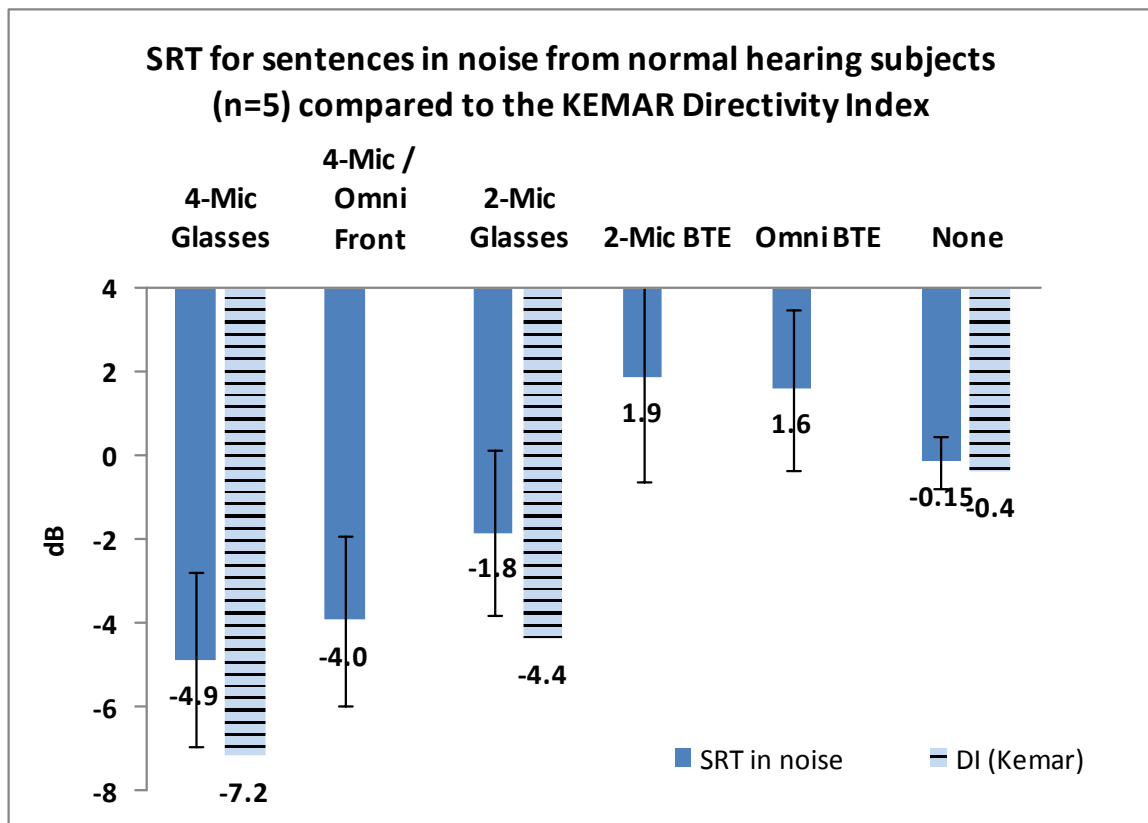
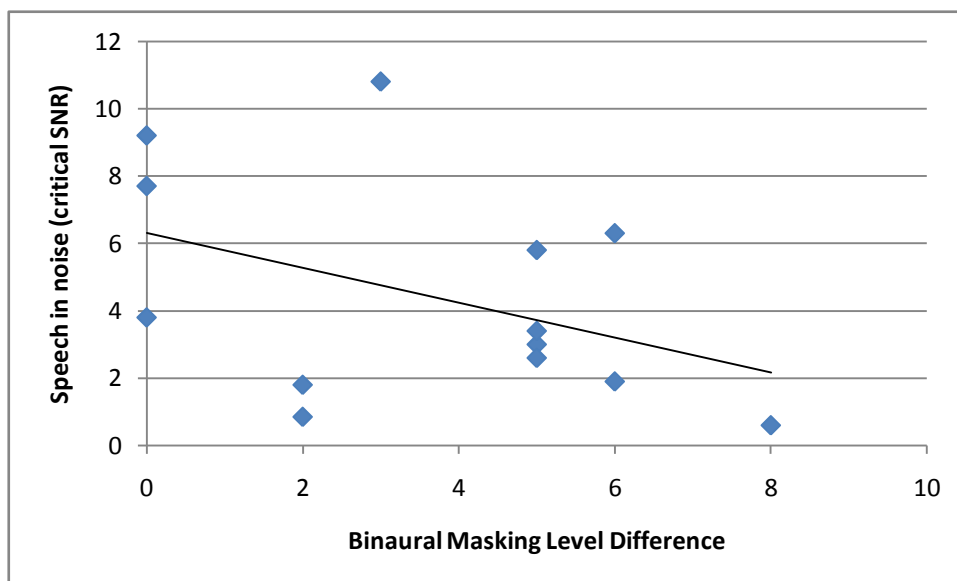


Figure 5. Same results as in Figure 4, but now for 5 normal hearing subjects. The aid was coupled to the ear with a foam insert tip. The SRT in noise with open ears (“None”) was established in separate group of 11 normal hearing subjects. The patterned bars are Directivity Index data from [Boone, 2006].

Binaural Masking Level Difference

The correlation between the individual BMLD score and the speech understanding in noise threshold was calculated for the asymmetric fit condition “4-Mic Glasses / Omni Front”. Although larger BMLD’s tended to correlate with a better SRT_n (see Figure 5), the result was not significant ($r=-.42$, $p=0.15$). Similarly, the BMLD score did not correlate significantly with the SRT_n in other conditions, nor with the directional benefit (4-Mic Glasses vs Omni Front and 2-Mic Glasses vs Omni Front).



Conclusion and Discussion

Compared to using Omni BTE, the highly directional 4-microphone mode improved the speech reception threshold in noise (SRT_n) by 6.3 dB in the hearing impaired subjects. In normal hearing subjects, a highly similar advantage of 6.5 dB was found. The performance-intensity function of the sentence material used is about 15% per dB [Versfeld et al., 2000], so an SRT_n advantage of 6.3 to 6.5 dB translates in a percent correct difference of up to 97% in adverse listening conditions. Several arrays with more than 2 microphones have been evaluated in earlier studies. A predecessor of the Varibel array was tested on patients by Soede et al. [Soede et al., 1993]. In a sound treated room ($T=0.2$ s) and a diffuse noise field, the directional benefit was 6.8 dB. Luts et al. [Luts et al., 2004] used a 4-speaker noise field (semi-reverberant, $T=0.6$ s) and established a 9.2 dB directional advantage for the Etymotic Research ArrayMic-3 (compared to a 3.8.0 dB advantage for a single bidirectional microphone) in normal hearing subjects using the same speech in noise test as in the present study. Surprisingly, Dittberner and Bentler [Dittberner and Bentler, 2007] used an almost identical 4-speaker set-up as presently used (referred to as “anisotropic”), but in semi-reverberant room ($T=0.9$ s) and found a directional benefit for sentence understanding in noise for normal hearing subjects of only 0.9 dB for a cardioid system and 1.4 dB for the Etymotic Research ArrayMic-3. The calculated Directivity Index for that situation was 9.2 dB, identical to the finding of Luts et al. [Luts et al., 2004]. In sum, several experimental and commercial multi-microphone arrays with a fixed polar characteristic have been shown to produce a directional benefit of about 6 to 9 dB; the present result fall within that range.

The 4-microphone mode not only produced a significantly better SRT_n compared to the omnidirectional mode, but also compared to both directional 2-microphone modes. The advantage was 2.3 dB compared to the “2-Mic Glasses” mode (two microphones positioned approximately at the temple) and 4.9 dB compared to the “2-Mic BTE” mode (two microphones above the pinna). This was a within-device comparison directly showing the effect of microphone mode while keeping all other variables (AGC, frequency response as verified using real ear measurements, etc) constant.

The understanding in noise for the 2-Mic Glasses mode was significantly better than for the 2-Mic BTE mode; the difference was 2.6 dB in hearing impaired subjects and 3.7 in normal hearing subjects. It has to be noted that different devices were used for these two conditions, with glasses “A” (2-Mic Glasses) having a slightly better Directivity Index (2.2 dB) than glasses “B” (2-Mic BTE, 1.9 dB). The DI difference of 0.3 dB therefore is not a sufficient explanation of the superior understanding in noise. A possible explanation for this difference is that at the temple, the head attenuates signals coming from the opposite side *and behind* the listener. The same microphone above the pinna finds the head blocking sounds from the opposite side and *in front* of the listener. As a result, noise from the back can be expected to be better suppressed by directional microphones located at the temple than above the pinna.

Obviously, it cannot be directly concluded that the same 4.9 dB advantage would be found when comparing the presently tested device, featuring a fixed polar response, to any other 2-microphone BTE system. A comparison with other directional devices, for instance using adaptive and frequency-dependent directivity, was beyond the scope of this study. Results reported for (commercial) directional devices are difficult to compare due to the confounding effects of test room acoustics, noise source configuration and patient population. General consensus is that available 2-microphone devices provide a directional benefit of about 3-5 dB in everyday listening situations (for a review, see [Chung, 2004]), and perhaps 1 dB more in case of adaptive systems [Dittberner and Bentler, 2007; Ricketts, 2002], which approaches the 6.3 to 6.5 dB presently found. However, a few studies are available in which a noise field was used similar to the one presently used. In a 5-speaker noise field comparable to presently used the 4-speaker arrangement, but placed in a semi-reverberant room, Hornsby and Ricketts [Hornsby and Ricketts, 2007] found a directional benefit (directional vs omnidirectional) of about 3.3 dB using a commercially available 3-microphone system with adaptive directionality in subjects with hearing losses much like our subjects. Larsen [Larsen, 1998] reported a directional advantage of 3.6 dB in 4-speaker noise (monosyllables in noise) for a fixed response 2-microphone system. Luts et al. [Luts et al., 2004] used an active bidirectional microphone in a 4-speaker noise field (although 45° rotated compared to our configuration) and found a directional advantage of 4.2 dB, which was considerable as the test room was reverberant. In conclusion, the directional benefit of the 4-Mic Glasses mode seems to surpass that reported for most (adaptive) 2-microphone systems by 2 to 3 dB, but further study is needed to directly compare the directional benefit of the alternative techniques under identical circumstances.

The asymmetric fit condition with the 4-Mic Glasses mode in the better ear and the omnidirectional mode in the poorer ear resulted in a speech understanding in noise comparable to using 4-Mic Glasses on both ears. The SRT_n difference between the two conditions (1 dB) was not significant. A significant but only

slightly larger decrement of 1.4 dB was reported by Hornsby and Ricketts [Hornsby and Ricketts, 2007] for the asymmetric fit condition. The implication is that an asymmetric fit may be a valuable option for users who want to avoid having to switch from the high to a low- or omnidirectional mode when the situation requires non-focused awareness of the environment, without sacrificing the ability to hear out the speaker in front.

Measurements were made in a sound-treated test room with a reverberation time (T) of about 0.25 s. Less directional benefit is to be expected for reverberant conditions, such as a normal living room. Using a similar 4-speaker noise configuration, Dittberner and Bentler [Dittberner and Bentler, 2007] found a 4.8 dB decrement of the SRT_n for normal hearing subjects tested in a semi-reverberant room (T=0.9 s) compared to an anechoic room. In the present study, the directional benefit in our normal hearing subjects did not differ much from the Directivity Index directional benefit found in an anechoic room on KEMAR, that is, the DI of the 4-microphone mode compared to that of the low directional mode “2-Mic Glasses” (see Figure 5) [Boone, 2006; Luts et al., 2004]. This is another indication that the reverberation level in our test room functionally approached that of an anechoic room. The 4-speaker arrangement was chosen in an attempt to mimic realistic noise conditions as opposed to, for instance, a single noise source at 180°. Nevertheless, the low reverberation of the test room is representative only for rooms that are highly damped. In everyday situations room acoustics may be much poorer and the directional benefit will then be considerably less than shown in the present data.

Subjects were included who could be expected to have a considerable disability when tested in noise due to a speech in quiet score of less than 100%, as these were considered in particular to be potential users of highly directional devices. Within this group, no correlation was found between speech in noise measures or directional benefit scores calculated from these scores on the one hand, and hearing loss and speech discrimination in quiet on the other hand. In other words, the amount of directional benefit in the 4-Mic Glasses, 2-Mic Glasses and 2-Mic BTE condition was the same irrespective of hearing thresholds. However, subjects were included who were expected to be able to complete sentence in noise testing and as a result the range of hearing losses was limited from 35 to 61 dB (PTA 0.5 to 2 kHz). Further study is needed to be able to generalize this finding to larger hearing losses.

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