Intelligent processing to optimize the benefits of hearing aids

Boymans, M.

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CHAPTER 8.

THE EFFECTIVENESS OF ADAPTIVE DIRECTIONALITY BY DUAL-MICROPHONES
8. The effectiveness of adaptive directionality by dual microphones

Summary
Recently, microphones with adaptive directivity have been introduced in digital hearing aids. This study provides experimental data on the effects of adaptive directivity in a clinical population of 18 subjects, half of them were fitted with two in-the-ear hearing aids and half of them with two behind-the-ear hearing aids. We applied both SRT-measurements using an up-down method, and Just Follow Conversation (JFC) measurements using a method of adjustment.

The results show that speech perception in a single-noise background from different angles in the near field of a moderately reverberant room, can improve. The overall improvement due to dual-microphones, with a fixed directivity and with an adaptive directivity (re. omni-directional microphones) amount to 1.9 and 2.9 dB, respectively in S/N ratio for BTE hearing aids. Similar measurements using ITE’s show that the effect of fixed directivity was smaller (0.8 dB benefit), and the effect of adaptive directivity in ITE’s was slightly less (0.4 dB benefit re. omni-directional microphones).

When a second noise was added from a different position (both noises at different sides of the head), an additional benefit of adaptive directivity was observed: both adaptive microphones adapt independently towards different polar patterns to cancel out the most dominant noise for each ear. Consequently, adaptive directivity introduces an extra advantage for bilaterally fitted hearing aids. Adaptive directivity in BTE’s was 4.9 dB better compared with omnidirectional microphones in the same conditions. For ITE’s this effect was only 1.3 dB.

Fortunately, there was no significant difference between the localization with an omnidirectional microphone and with an adaptive directional microphone.
8.1. Introduction

The main target in the development of new hearing aids is the improvement of the signal-to-noise ratio, either by noise reduction or by signal enhancement. Noise reduction techniques are designed to profit from characteristic differences between the wanted signal (usually speech) and the unwanted signals (usually background noises). The systems currently available in hearing aids use spectral differences (multi-band compression systems), temporal differences (modulation-based noise reduction) or spatial differences (directional microphones). While signal-processing schemes, based on spectral and temporal differences, only have positive effects in terms of listening comfort, directional microphones have proven to be really effective in terms of an improvement of the signal-to-noise ratio (e.g. Boymans and Dreschler, 2000).

The introduction of dual-microphone systems has renewed the interests in directivity and various studies show that a significant benefit can be obtained in specific situations (Preves et al., 1999; Wouters et al., 1999; Ricketts et al., 1999a; 1999b; Yueh et al., 2001). This study provides further experimental data on the effects of adaptive directivity in a clinical population. There are two essential requirements before any profit from the use of directional microphones can be obtained: there needs to be a profitable spatial separation between the speech signal and the noise signal and the microphone needs to be within the so-called near field of the target speech source. Recent developments in digital hearing aids allow adaptive directivity: the delay between the microphones can be varied in order to find a polar pattern that optimally filters out the most dominant noise source. Until now, there are only few studies that evaluate the effects of adaptive directivity in a clinical population (Ricketts et al., 2002).

The directional effect can be documented by directivity patterns (polar patterns) that usually are measured in a reflection-free environment ('anechoic room'). The polar patterns show the attenuation of signals from different angles of incidence relative to
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frontally incident signals as a function of azimuth. The polar patterns are usually strongly frequency dependent. This frequency dependence increases when the diffraction effects of the head are taken into account. Polar patterns measured at KEMAR usually show asymmetric polar patterns that are more or less predictive for the actual effects of a hearing aid in situ.

The total effect of directivity is often expressed in a kind of front-random ratio: the directivity index DI as a function of frequency. For hearing aids with a non-adaptive directional microphone DI can be calculated from the polar pattern. To predict the effects for speech perception, the directivity indices for different frequencies can be weighted according to their importance for speech perception cf. the articulation index (AI; see Greenberg et al., 1993), the articulation weighted DI or AI-DI.

For a diffuse sound field the noise may be expected to come equally from all angles. In the diffuse sound field the technique of adaptive microphone directivity may be assumed to have no added value, because there is not a single dominating noise source that can be eliminated. For a non-diffuse sound field the test set-up will greatly influence the result. For hearing aids with a fixed directivity pattern the actual effects can be predicted to a certain degree from the polar patterns of the microphones in relation with the spatial configuration of the noise sources. Thus the choice of the spatial configuration can be optimized to find a better result for a pair of microphones with a specific polar pattern. This complicates the comparison across studies (Ricketts, 1999a). For a hearing aid with adaptive directivity it will be much more complex to predict the actual effects, at least for non-diffuse noise sources and if more than one noise source is present.

Another aspect of adaptive directivity concerns the accuracy for horizontal localization. Dynamical changes in the polar patterns may induce unwanted cues of the interaural level differences and this may be negative for an accurate localization.
This study provides further experimental data on the effects of adaptive directivity in a clinical population and the selection of tests especially focuses on the following questions:

- Is there a negative effect of adaptive directivity on the accuracy of horizontal localization?
- What is the added value of adaptive directivity relative to fixed directivity measured in the same hearing aids, for the same subjects for single noise sources as a function of azimuth?
- What is the added value of adaptive directivity in conditions with two spatially separated noise sources?
- What are the effects of hearing aid type (BTE versus ITE)?

8.2. Method

8.2.1. Subjects

18 Hearing-impaired subjects participated in this study. They were selected for a broad study on the general benefits of the test hearing aid (Phonak Claro) at the Lucas/Andreas Hospital. This study reports only measurements that were conducted in the Academic Medical Centre (AMC) to assess the added value of adaptive directivity, one of the features of the test hearing aid.

The subjects are a representative sample of hearing aid users for the fitting range of the test hearing aid. There were no restrictions, except that children (<16 years) were not included in the study and that the subjects had to be able to complete the extensive test protocol. The subjects co-operated on a voluntary basis. The subjects had to wear both hearing aids at least 4 hours a day.
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Table 8.1. Average audiometric thresholds and standard deviations for the group of 18 hearing-impaired listeners

The average age of the subjects was 62 years (range from 38 to 85) and the average audiometric thresholds (with standard deviations) are presented in Table 8.1. The subjects had a predominantly sensorineural hearing loss (average air bone-gap < 15 dB). For reasons of comparison, a small reference group of 4 normal-hearing subjects was added. The average age of the reference group was 34 years (range from 26 to 48) and all audiometric thresholds were better than 15 dB HL (for the standard octave frequencies between 250 and 8000 Hz).

8.2.2. Hearing-aid fitting

All subjects were fitted bilaterally (nine with Claro 21dAZ BTE’s, and nine with Claro 21dAZ ITE’s). The manufacturer, using the manufacturer-prescribed procedures including loudness scaling, fitted the hearing aids carefully. Fine-tuning was performed on the basis of subjective reports. All subjects had 3 months or more experience with the test hearing aids when they came to the AMC for additional testing. Before the measurements, the individual hearing-aid fittings were checked at the AMC using real-ear measurements with modulated ICRA noise (Dreschler et al, 2001). Only in case of large discrepancies between the actual gain curves and the target insertion gains, further fine-tuning occurred.
The reference group consisted of four normal-hearing subjects. They were measured with two Claro 111dAZ BTE hearing aids in an identical setting (target setting for a mild flat audiogram). The Claro 111dAZ is similar to the Claro 211dAZ, but more appropriate for mild hearing losses. The hearing aids were connected to the ears of the normal-hearing listeners via Libby horns housed in unvented expending foam earplugs.

Noise reduction was always switched off. Measurements were conducted with three different settings of the hearing aids (omnidirectional, fixed directional, and adaptive directional). It is important to note that in the hearing aids under test the fixed directional microphone had a cardioid pattern (see Fig. 8.1a and 8.1c). The setting of the hearing aid was blinded for the subjects. The order of the tests with different hearing aid settings was counterbalanced.

8.2.3. Test on horizontal localization

For the test on horizontal localization, a set-up with 13 loudspeaker boxes was used (-90° to 90° in 15° steps). The stimulus was a broadband noise, 200 msec in duration with appropriate gating to avoid clicks. The order of presentation was randomized. After each presentation, the subject had to indicate the loudspeaker box that was assumed to have produced the noise stimulus.

8.2.4. Speech in noise measurements

Speech perception in noise was measured by two different techniques: the classical SRT measurements using different sentence lists with a stepwise up-down procedure (Plomp and Mimpen, 1979) and JFC-measurements (Just-Follow-Conversation) using a method of adjustments.
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In all JFC measurements the speech came from the front (0° degrees azimuth). The used speech was one sentence list of the SRT-test (13 sentences which were repeated periodically). The subject had to listen to all sentences first, to avoid learning effects. In the single-noise conditions a masking noise of 65 dB(A) was presented from different (fixed) spatial locations: 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°, and 360° degrees. In the double-noise conditions the first noise changed similarly from 0° to 360° in 30° steps and a second uncorrelated noise (with identical spectrum) was added at the contralateral side. The extra noise came from 270° degrees for conditions that the first noise was between 0° and 180° and the extra noise came from 90° for conditions that the first noise was between 180° and 360°. The results have been corrected for the higher overall noise level of the double-noise conditions at the position of the listener. The subject was asked to adjust the level of the speech until he/she could just follow the sentences. Then the masking noise moved to the next spatial location, and the subject had to adjust the speech level again.

The SRT measurements followed the procedure by Plomp and Mimpen (1979) converging to the level of 50% intelligibility (called the critical S/N ratio). SRT measurements were carried out for a subset of the conditions mentioned above. For the omnidirectional situation the measurements were conducted with speech always from the front in three conditions: noise also from the front, from the left- and right-hand side at the same time, and from the back. The same conditions were measured for the adaptive directional situation, and extra measurements were conducted with only one noise at the right-hand side, and only one noise at the left-hand side. These conditions have been included as an extra check for the most important conditions, because they are much more time-consuming than JFC-measurements.
8.2.5. **KEMAR measurements**

For the hearing aids under test, KEMAR measurements have been carried out in an anechoic room. For each condition a complete set of measurements consisted of polar patterns for pure tones of 500, 1000, 1600, 2000, 2500, 3150, 4000, 5000, and 6000 Hz.

![Polar patterns](image)

**Fig. 8.1.** AI-weighted polar patterns measured for the test hearing aids in KEMAR. The upper panels represent the patterns for the test BTE: left the cardioid response (beta=0.0, panel a) and right the bi-directional response (beta=1.0, panel b). The second row (panel c and d) shows the results of similar measurements in the test ITE. The measurements have been conducted by Phonak in an anechoic room.
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The polar patterns for the different frequencies were combined into an AI-weighted polar pattern. These data have been measured for a Claro 211 BTE in omni-directional mode, fixed directional mode (cardioid; beta = 0.0), and six settings of the range of options available for the adaptive directional mode (beta = 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0, with beta = 1 - (internal delay / external delay)).

In the upper panels a and b of Figure 8.1 the resulting AI-weighted polar patterns have been plotted for the extreme cases: beta=0.0 (cardioid) and beta=1.0 (bi-directional). Similar measurements have been performed for a Claro 21 ITE hearing aid, see the lower panels c and d of Figure 8.1.

8.3. Results

8.3.1. Localization

In Figure 8.2 the results of the horizontal localization test are shown for the groups with two ITE’s and two BTE’s, respectively. The bars show the average RMS errors (consequently larger errors have a relatively high weighting). The first bars show the results with the omnidirectional mode, the second and third bars show the results with the fixed and adaptive directional microphone, respectively. For the group with bilaterally fitted ITE’s there is no difference for the three different microphone types. For the bilaterally fitted BTE users, no difference is shown between the omnidirectional mode and the fixed directional mode, but more faults in localization are shown with the adaptive directional microphone. However, these differences are not statistically significant (p>0.05).
Fig. 8.2. Average RMS errors in horizontal localizations for bilateral ITE-users and BTE-users. The bars show the average errors for hearing aids with omni-, fixed-, and adaptive directional microphones, respectively.

8.3.2. JFC results with a single noise source

The results from the single-noise experiment are shown in Figure 8.3a and Figure 8.4a for the BTE and for the ITE-users, respectively. All data have been plotted in terms of the average adjusted S/N ratio as a function of azimuth. The three lines connect the results for the three modes of directivity: omnidirectional, fixed (=cardioid) directivity, and adaptive directivity. Lower data points correspond with better results. The average S/N for the different microphone modes are shown at the right-hand side of each plot.

Fig. 8.3a shows the average results of 9 subjects with bilaterally fitted BTE’s. Averaged across all angles, the fixed directional microphone performs 1.9 dB better than the omnidirectional microphone (see the difference between the position of the square and the circle at the right-hand side of the plot). The average added value of the adaptive mode compared with the fixed mode is 1.0 dB.
Fig. 8.3. Average JFC-thresholds for the group of 9 bilateral BTE-users in a single-noise background (panel a) and in two-noise background (panel b). The curves show the average S/N ratios for the BTE's with omnidirectional, fixed directional, and adaptive directional microphones, respectively. Lower points correspond with more favourable results.

Fig. 8.4. Average JFC-thresholds, plotted similarly as Fig. 8.3, but now for the ITE's with omnidirectional, fixed directional, and adaptive directional microphones, respectively.
Similarly, Fig. 8.4a shows the average results for the 9 subjects with bilateral ITE’s. Averaged across all angles the fixed directional microphone performs only 0.8 dB better than the omnidirectional microphone, and there is no further improvement from adaptive directivity (the results of the adaptive directional mode are only 0.4 dB better than in omnidirectional mode). The average results with the omnidirectional microphone are slightly better for the ITE-group than for the BTE-group (0.3 dB), but a direct comparison is not possible, because the differences also reflect differences between the groups (e.g. with respect to the average hearing loss). However, for the BTE-group better results are measured with both types of directional microphones compared to the ITE-group, especially with the adaptive directional microphone.

8.3.3. JFC results with two spatially separated noise sources

In Figure 8.3b and Figure 8.4b the average JFC results, measured with two noises, are shown for the bilaterally fitted groups with BTE’s and ITE’s, respectively. The presentation of the data is, similar to the single-noise conditions, in terms of the average adjusted S/N ratio for the results of the three modes of directivity: omnidirectional, fixed (=cardioid) directivity, and adaptive directivity. However, in this experiment an extra noise is added at 270° for the primary noise at the right-hand side (from 0° – 180°) and at 90° for the primary noise at the left-hand side of the subject (from 180° – 360°).

For the BTE-group, the average difference over all angles between the omnidirectional mode and the fixed directional mode is 2.6 dB and the added value of adaptive directivity is 2.3 dB. Again the results with the BTE’s are more obvious than the results with the ITE’s (compare Fig. 8.3b and Fig. 8.4b). The difference between the omnidirectional mode and the fixed directional mode for the ITE-group is 1.1 dB, and the adaptive mode does not give extra benefit.
Again, the ITE-results for the omnidirectional mode are slightly better than the BTE-results. But, for the BTE-users the effect of adaptive directivity is larger than in the single-noise condition, resulting in better performance for the BTE-users with adaptive directivity, in spite of their more severe hearing losses.

8.3.4. JFC results with one and two noise sources in normal hearing using BTE’s

Figure 8.5 shows the JFC-results for a small reference group of normal-hearing listeners, bilaterally fitted with BTE hearing aids. As in previous figures, all data have been plotted in terms of the average adjusted S/N ratio as a function of azimuth, for the results of the three modes of directivity. Panel a shows the results of the situation with one background noise, and panel b shows the results with two background noises. For the situation with one background noise, the average S/N over all angles is \(-11.4\) dB for the omnidirectional microphone and \(-14.8\) dB for the fixed directional microphone. The added value of the adaptive directional microphone compared to the fixed directional microphone is \(1.4\) dB.

The curve of the adaptive directional microphone shows clear differences with the curve of the fixed directional microphone, especially for the situation with the noise coming from \(90^\circ\) or \(270^\circ\). Clearly better results are shown for the adaptive directional microphone compared with the fixed directional microphone when the noise is presented at the left-hand or the right-hand side. This is in agreement with the fact that the adaptive microphone will have the maximum difference relative to the fixed (cardioid, beta = 0) microphone, when a bi-directional polar pattern (beta = 1) is activated, i.e. when the noise is coming from the right- or left-hand side. When the noise is coming from \(0^\circ\), \(180^\circ\) or \(360^\circ\) the results are equal for both types of directional microphones.
Fig. 8.5. Average JFC-thresholds for the reference group of 4 normal-hearing subjects, wearing bilateral BTE’s, for the situation with one background noise (panel a) and for the situation with two background noises (panel b). The curves show the average critical S/N ratios for the BTE’s with omnidirectional, fixed directional, and adaptive directional microphones, respectively. Lower points correspond to more favourable results.

When a second noise is added at the other side of the head, the average results are poorer (higher S/N ratios) for all azimuths and for all microphone modes (Fig 8.5b). The differences between the fixed and adaptive modes at $90^0$ and $270^0$ are larger for the situation with two background noises than with one background noise. The trends of the results that we found in normal-hearing listeners correspond to the trends of the JFC-results for the hearing-impaired group fitted with BTE’s. However, on average the reference group shows larger effects than the hearing-impaired group.
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8.3.5. SRT results

In Figure 8.6 the results of the SRT-tests are presented. The critical S/N ratios are shown as a function of different measurement conditions (the lower the bars, the better the results). The SRT-tests are conducted with bilaterally fitted ITE’s and bilaterally fitted BTE’s, programmed in omnidirectional mode (white and black bars, respectively) and adaptive directivity mode (light grey and dark grey bars, respectively). The speech was always from 0° azimuth.

In the first measurements, the noise was also presented at 0° and this measurement is taken as the reference condition. Consequently, the result of this measurement is 0.0, both for the omnidirectional microphone and for the adaptive directional microphone, with both hearing aids (ITE and BTE).
The first two bars show the critical S/N ratio for the condition with noise presented at the right-hand side or at the left-hand side, measured for the adaptive directional mode for the ITE-group (light grey bars) and for the BTE-group (dark grey bars). A directional benefit of $-4.9\, \text{dB}$ and $-7.8\, \text{dB}$ relative to the reference condition is shown for the ITE-group and the BTE-group, respectively.

The next four bars show the results for the condition with the noise from the right- and left-hand side at the same time. For the omnidirectional microphone the critical S/N ratios become poorer ($2.3\, \text{dB}$ for the BTE-group and $3.2\, \text{dB}$ for the ITE-group) relative to the reference condition. This is caused by the fact that we now apply two independent noises at each side of the head instead of one noise from the frontal direction. However, the S/N ratio with the adaptive directional mode is better than for the reference condition, especially for the BTE-group, being $-4.6\, \text{dB}$.

The last four bars show the critical S/N ratio of the condition with the noise presented at $180^\circ$. The effect of the adaptive directional mode compared to the omnidirectional mode is larger for the BTE-group than for the ITE-group ($-7.6\, \text{dB}$ and $-3.2\, \text{dB}$, respectively).

The trends of the results obtained with the SRT-test and the results obtained with the JFC-test are in agreement. However, there is some difference in the size of the effect due to the fact that the JFC-measurement is influenced by the subject’s subjective criterion about the level of “Just Follow Conversation”.

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8.4. Discussion

This study shows that better results are found with the adaptive directional mode, compared to the omnidirectional mode for the ITE group as well as the BTE-group. Because of the azimuth-dependent attenuation of the directional microphones and the additional dynamic behaviour of adaptive directivity, it was necessary to assess possible negative effects on horizontal localization. Horizontal localization was not clearly affected, although we found a slight (non-significant) reduction for adaptive directivity in the BTE-group.

The differences between the JFC-results with one background noise (Fig 8.3a and Fig 8.4a) and with two background noises (Fig 8.3b and Fig 8.4b) are clear for the BTE-group, especially for the adaptive directional microphone. For the omnidirectional mode, the JFC-results averaged over all angles are slightly worse with two background noises compared to the situation with one background noise. However, there is a clear benefit for the adaptive directional microphone in the two-noise condition compared to the situation with one background noise.

With both speech tests, the BTE-group shows a larger benefit of adaptive directivity relative to an omnidirectional microphone than the ITE-group. The difference between both tests is that the effect size for the JFC-test is smaller than for the SRT-test. The SRT-test can be regarded more or less as an objective test; 50% speech intelligibility will be found. The JFC-test is a more subjective test. The subject has to adjust the level of the speech, until he or she can just follow the speech. This subjective factor can influence the results. Also, other signal properties like loudness and listening comfort may play a role in the JFC-results.

The advantage of the SRT-test is that the test is well standardized and measures speech intelligibility without a possible bias due to subjective factors. The advantage of the
JFC-test is that this test is quick and the speech material can be used frequently. So more conditions can be measured in a shorter measuring time than with the SRT-test. Despite the fact that subjective factors are included, there is a good reproducibility. The test-retest standard deviation is 1.4 dB (individual results range from 0.65 to 2.27 dB). The subjects do have their own reference, which can change over time. So, measurements at the same day are preferred, and the JFC-test can be used only for comparative measurements within the same subjects.

The curves of the JFC-results for the normal-hearing subjects are more symmetrical than the curves of the hearing-impaired subjects. This can be caused by the fact that for the normal-hearing subjects the symmetry between the ears was higher. This was not always the case for the hearing-impaired subjects. In addition, the hearing aids for the normal-hearing listeners had identical settings, while the setting could be different for the hearing-impaired listeners. In spite of a careful individual fitting for each individual ear, controlled by insertion gain measurements, higher differences than in the normal-hearing group between right and left are likely.

The differences between the results with the omnidirectional mode and the other two directional modes (fixed and adaptive) are larger for the BTE-fitted group than for the ITE-fitted group. This discrepancy can be explained by the difference of the microphone position and the accompanied effect on the polar patterns for BTE and ITE hearing aids (see Fig. 8.1). For the omnidirectional mode the critical S/N ratio is slightly better (lower values) in the ITE-fitted group than in the BTE fitted group, especially for the conditions with two noises (see Fig. 8.3b and Fig. 8.4b). For the omnidirectional mode the ear shell is advantageous for the ITE-fitted subjects, because it adds to directivity in spite of the omnidirectional character of the microphone. On the other hand, Figure 8.1 also shows that the variation between the polar patterns (from beta = 0.0 to beta = 1.0) is considerably smaller for ITE’s than for BTE’s. As a consequence, the added value of adaptive directivity is only marginal in ITE’s.
The added value of adaptive directivity is more pronounced for the conditions with an extra noise at the other side of the head. Obviously, one of the additional advantages of adaptive directivity in case of bilateral fitting is that each of the two hearing aids can minimise the effect of that noise that is dominant at that particular side. In fact, this additional advantage adds to the benefits of a bilateral fitting, as described in Chapters 3 to 5.

8.5. Conclusions

In our group of hearing aid users the following conclusions can be drawn:

- There is no negative effect of adaptive directivity on the accuracy of horizontal localization, for the BTE-group as well as for the ITE-group.
- The results of the SRT-test and the JFC-test show the same trends. However, the results of the SRT-test are more pronounced.
- The added value of the adaptive directivity relative to the fixed directivity is on average 1.0 dB measured with the JFC-test for the hearing-impaired subjects who were bilaterally fitted with BTE hearing aids.
- The added value of adaptive directivity in conditions with two background noises is 1.3 dB comparing to the adaptive condition with only one background noise (also measured with a JFC test, and BTE’s).
- The JFC-results show no extra benefit for the subjects who were bilaterally fitted with ITE hearing aids, for the condition with the adaptive directivity relative to the fixed directivity and for the condition with adaptive directivity with two background noises relative to the adaptive directivity with one background noise.