Intelligent processing to optimize the benefits of hearing aids

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Voor mijn ouders

Intelligent processing
to optimize the benefits of hearing aids

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CONTENTS

CHAPTER 1.

INTRODUCTION

1. Introduction

This thesis describes a number of clinical studies that investigate the benefits of different methods of compensation for hearing-impairment by hearing aids. One of the most important methods is the restoration of binaural hearing by the application of bilateral hearing aids. Therefore, the first part of this thesis is devoted to the benefits of bilateral amplification.

In addition, the introduction of digital hearing aids facilitated advanced signal processing schemes like noise reduction and dual-microphone directionality. The second part of this thesis describes three studies that assess the added value of these complex and sometimes expensive algorithms.

1.1. Benefits of bilateral hearing aids

The most intelligent processing that will help the hearing-impaired listener to compensate for his/her auditory deficit is the processing of his/her own brain. One of the important mechanisms in this respect is binaural processing, that can be optimized by a bilateral fitting with hearing aids.

1.1.1. Rationale of bilateral fitting

It is generally accepted that the use of two ears has a number advantages. With two ears it is easier to localize sounds and with two ears the spatial experience of the room acoustics is more natural than with one ear. Another advantage is better speech intelligibility in background noise. By the use of two ears we are able to separate speech and noise better than with one ear, especially when there is a spatial separation between the sound sources. Finally, binaural hearing decreases the negative effect of reverberation on speech intelligibility. This effect is called binaural dereverberation.

Above-mentioned advantages are relevant for difficult acoustical situations that hearing-impaired people have to cope with. The most heard problem of the hearing-impaired person is that speech intelligibility is difficult in background noise and in reverberation. Unfortunately, this is a situation in which also the hearing aid usually provides only little benefit. Consequently, it is of the utmost importance to maintain or restore the function of binaural hearing in hearing-impaired listeners by a bilaterally hearing aid fitting (Markides, 1977). A systematic review of recent literature with respect to the benefits of bilateral hearing aids will be presented in Chapter 3.

1.1.2. Current criteria for reimbursement of a bilateral fitting with hearing aids

In clinical practice it is rather difficult to assess the improvement of bilateral hearing aid fittings in objective evaluation measurements, because in a one-to-one condition the binaural benefit is hardly present. In the Netherlands the official indication to get hearing aids (partly) reimbursed by the health insurance companies is based on parameters of speech intelligibility and localization.
Speech discrimination should be improved by at least 10 percent due to bilateral fitting. Localization should be restored to within 45 degrees using two hearing aids.
There is no guarantee that especially these parameters correlate well with 'real-life' improvements. In addition, the reliability of the speech intelligibility scores is only limited. Especially when words are presented 'live' (this is not unusual in clinical practice) the improvement to be obtained is of the same order of magnitude as measurement inaccuracy.

Also, there is no clear specification of the way the benefits in speech discrimination should be measured. The use of words or sentences (which is more related to real-life

conditions) has not been defined. It is unclear whether the speech material should be presented in quiet or in background noise (more realistic). Speech intelligibility will strongly depend on the possibility of lip reading and on the spatial positions of speaker and noise sources relative to the listener.
At the moment the improvement in horizontal localization is most frequently used as a motivation for the reimbursement of bilateral hearing aids. A problem with the current fence for reimbursement is that a number of candidates reach already localization ability within 45 degrees with only one hearing aid.

1.1.3. Rationale for the study on the benefits of bilateral hearing aids

As mentioned above, criteria for the (partial) reimbursement of hearing aids by the health insurance companies are poorly specified and lack a strong relationship with real-life situations. Besides this, the decision to choose for one or two hearing aids is not only dependent on speech intelligibility and localization. Therefore, we investigated retrospectively a large number of clinical files. We inventoried different aspects of current fitting practices in the Netherlands to retrieve more information about the anamnestic, audiometric, and the rehabilitation data. In addition, the hearing-impaired people included in this retrospective study were asked to fill in an extensive questionnaire to get additional information about the subjective results.

After this retrospective study still some questions needed a more detailed answer, especially on an individual basis. Therefore, we conducted a prospective study with focus on the following questions:

- Can we predict a positive effect of a bilateral hearing aid fitting?
  To investigate the possibility for predicting the effect of a bilaterally fitting using other information than parameters of the tone audiogram and the speech audiogram, we conducted a prospective study with "new" diagnostic tests. The diagnostic tests were especially based on the capacity of binaural interaction.

- o Does bilateral fitting with hearing aids work?
  In this prospective study evaluation tests were included also, to get information about unilateral and bilateral results objectively.
- o Does bilateral fitting with hearing aids help?
  Because it remains important to get information about the subjective results, questionnaires were used to retrieve subjective information about different situations with one and with two hearing aids.

1.2. Benefits of advanced signal processing in hearing aids

In this section some new features of modern hearing aids are outlined. Some of these features have been implemented already in analogue hearing aids (like multiple-channel processing). Others are specific for the use of digital hearing aids (like the feature of feedback reduction). For all features it can be stated that digital technology allowed more flexibility and/or an improved effectiveness. In addition digital technology stimulated the use of several features in the same hearing aid.

The most intriguing developments are in the field of noise reduction. The term "noise reduction" is used for different methods that aim to improve the balance between the wanted signal (called "speech") and the unwanted signal (called "noise").
Noise reduction uses the differences between speech and noise.

- o Noise reduction by multi-channel compression is based on spectral differences.
- o Modulation-based noise reduction uses a combination of temporal and spectral differences.
- o Noise reduction by directional microphones applies spatial differences between speech and noise sources.

1.2.1. The use of multiple programs

Since long it has been recognized that one fixed setting of a hearing aid is not optimal for the many different auditory tasks in many different acoustical situations. In fact, the hearing aid fitter is trying to find a compromise between optimal speech perception in quiet, optimal speech perception in noise, listening comfort, music perception, etc. The introduction of non-linear hearing aids facilitated the automatic adaptation of the hearing aids to different input levels (compression), but still there is a need for multiple programs by some hearing-aid users. In quiet situations most hearing-impaired subjects prefer their reference gain. When there is more background noise they like to have less gain in the lower frequencies. However, in high frequency background noise and possibly for listening to music, they prefer a flatter response than their reference response (Keidser et al., 1996).

Not every hearing-impaired person wants to have a multiple-program hearing aid. This depends on the number of different acoustical situations and the degree of differences between those acoustical situations. It is also important that the possible range of variation between the programs is large enough, given the requirements for gain and output of the individual subject. For example, a subject with a ski-slope audiogram and near-normal thresholds for the low frequencies is usually fitted with an ear mould with large vent. In this case, the range for adjusting the lower frequencies is very small, and the hearing-impaired listener will not hear much difference between different programs.

In addition, not every one can operate the different programs when the programs have to be switched manually. A solution for this problem could be hearing aids that switch between programs automatically, depending on the amount of background noise. On the other hand, the automatic switching between programs is not always pleasant because sometimes listeners choose to optimize listening comfort instead of intelligibility. In that case, subjects usually prefer to switch between programs manually.

In digital hearing aids the possibilities for automatic adaptation of the hearing aid characteristics improved markedly. This could reduce the need for multiple-program hearing aids. On the other hand, some of the features in digital hearing aids will only be relevant in specific situations (e.g. directivity). This increased the need for multiple-program hearing aids (Dillon, 2001).

1.2.2. Signal processing in multiple channels

For most hearing aids a frequency-dependent gain characteristic is required. For relatively regular hearing losses (flat losses or losses with a uniform sloping character) single-channel hearing aids can do the job, in combination with the filtering characteristics of the ear mould, determined by an appropriate choice of vent and tubing.

For the fitting of subjects with more irregular audiograms, it is easier and more precise to compensate the hearing loss with a multiple-channel hearing aid. In a multiple-channel hearing aid the input signal will be split in different frequency channels and then it is possible to adjust the gain for each specific frequency channel independently (multiple-channel equalizer). In some subjects, also the dynamic range of hearing (the range between threshold and uncomfortable loudness level) is frequency-dependent. In that case multiple-channel hearing aids can be applied in which each channel contains its own compressor. So the compression can be adjusted for each frequency band independently. If the different channels in a multiple-channel hearing aid are equipped with compression limiting, we can also apply multiple-channel compression aids for frequency-dependent output limitation.

Another advantage for multiple-channel hearing aids is the possibility to exploit the differences in energy in different frequency regions between noise signals and speech. With a single-channel compression hearing aid the gain in all frequencies will be reduced even if the energy in only one frequency becomes too high, causing loss of information. With a multiple-channel compression hearing aid the gain in the lower frequencies can be decreased when there is a lot of low-frequency background noise, while the gain in the higher frequencies is maintained. This is called noise reduction based on spectral differences. Noise reduction should increase comfort (Kuk et al., 1990) and theoretically also the amount of upward spread of masking can be reduced (Cook et al., 1997; Van Tasell, 1992).

1.2.3. The use of modulation-based noise reduction

Speech can be distinguished from noise by spectral and temporal characteristics. The range of speech frequencies is roughly between 100 to 4000 Hz, but the most important frequencies for speech intelligibility are between 1000 and 2000 Hz. Speech is not a continuous signal. For a single speaker there are temporal fluctuations caused by pauses between words and sentences and by differences in energy belonging to different phonemes. Therefore, the envelope of the speech shows a characteristic temporal behaviour and shows characteristic temporal modulations. The average speaking rate is about 2.5 words per second. This corresponds to about 5 syllables per second and 12 phonemes per second. Consequently, the most dominant modulation frequencies in speech are between 2 and 8 Hz (Plomp, 1984).

The modulation spectrum for noise differs from speech. Noise often shows higher modulation frequencies than speech and has smaller modulation depths. These differences can be used to discriminate between speech and noise. In order to exploit these differences for modulation-based noise reduction in digital hearing aids the envelopes of the signals will be analysed in different frequency channels. If the signal in a specific channel is classified as "speech", the gain and compression characteristics in that specific frequency channel band will be adjusted according the requirements of the hearing loss. If the modulation spectrum of the signal is classified as "noise", the gain in that specific frequency channel will be reduced. A recent review of the results obtained is presented by Alcántara et al., 2003.

1.2.4. The use of directional microphones

The signal pick-up of the microphone largely determines the signal-to-noise ratio. The best way to reduce background noise is to move the microphone to the speaker, but this is not always practical. Noise reduction by directional microphones is based on differences in the direction of incidence of the speech and the background noise signal. The traditional directional microphone has a front and a rear port. The front port in the microphone should be directed towards the speaker (0^0 azimuth) and the rear port is directed to the back (180^0 azimuth). For a noise source at the back, the sound is detected first in the rear port and the signal will be delayed in the hearing aid ('internal delay') for the same duration it takes to travel from the rear port to the front port ('external delay'). As a result the sounds from both ports will reach the microphone membrane simultaneously, but from different sides and the signals will cancel each other. In contrast, the signals from the frontal direction will pass in a normal way and will not be cancelled.

In digital hearing aids often two omni-directional microphones are used instead of a directional microphone with two ports. With this so-called dual microphone technique one microphone is directed towards the speaker (front microphone) and one directed backwards (rear microphone). The principle is the same as in the directional microphone but now the internal delay between the microphones can be varied electronically. The variation of the ratio between the (electronic) internal delay and the external delay determines the directivity pattern of the dual-microphone combination (see Ricketts et al., 1999[a],1999[b]; 2000[a], 2000[b]; Csermak, 2000).
Another feature is that the delay can be varied adaptively depending on the direction of the (most dominant) noise source. The adaptive dual microphone technique switches

automatically between different directivity patterns in order to reduce the most dominant noise source. So, the adaptive directional microphone varies its directivity pattern that way that a so-called notch is directed towards the most dominant noise source.

Recently, a hearing aid with three-microphone directionality has been introduced. A hearing aid with three omni-directional microphones in a horizontal line, three delay units and three subtraction units. With three microphones it is possible to implement a second-order directivity, which gives an even better directivity pattern than with a first order directivity. However the frequency response of a three-microphone system has an increased low frequency cut and this results in a reduction of sensitivity in the frequency range below 1000 Hz. As expected the sound quality of the extreme low frequency cut in a three-microphone system is not always acceptable. This can be compensated by a higher gain in the lower frequencies, but then the microphone noise will be increased too. For that reason two microphones are used for the lower frequencies and the three microphone processing is used for the higher frequencies only (> 1400 Hz).

1.2.5. The use of feedback reduction

A major problem in hearing aids is feedback oscillation. The output signal of the hearing aid partly leaks to the input of the microphone again. This means that the amplified output signal makes a complete loop again, and will be amplified more and more if the loop gain is larger than unity gain. Feedback is inevitable, but if the damping for the leakage at a specific frequency is less than the gain in the forward direction, feedback oscillation occurs and the hearing aid starts to "whistle".

A traditional method to avoid feedback problems is to make the fitting of the ear mould very tight. But even then feedback problems may be present. The simplest way to reduce the feedback is to turn down the volume wheel in order to reduce the gain, but

then the hearing-aids user misses a lot of information. Another solution is to give only less high frequency gain, but those frequencies are important for speech intelligibility. So both options are not desirable.
A better option is to reduce the gain at those frequencies where feedback occurs. The more frequency bands the more precisely the gain reduction can be reduced locally. Often feedback occurs in specific situations for example when the volume control is higher than the usual setting, or if wide dynamic range compression causes relatively high gain values for low input levels. It is desirable to reduce the maximum gain to a safe value for each frequency region. This can be done by the clinician him/her self or by an in-situ feedback test (in which the fitting system raises the gain automatically until feedback occurs). The problem is that the frequency of the feedback oscillation can vary. When the gain has to be reduced at all those frequencies, a lot of information will be lost again.

With a digital feedback reduction system the hearing aid generates by purpose the same signal as the feedback signal, but now out of phase. The two signals will sum up to zero and cancel the feedback. Another method is feedback reduction with an adaptive filter. The filter will be active when there is a continuous signal at a special frequency for a certain amount of time. A disadvantage of this adaptive feedback is that other signals than feedback signals (of a special frequency for a certain amount of time) will be cancelled too.

Thanks to the increased possibilities of digital feedback systems hearing aids can also be prescribed for hearing-impaired listeners who need a very open ear mould, because of medical reasons or because of occlusion problems.

1.2.6. Rationale for the evaluation of advanced signal processing in hearing aids

As mentioned before hearing-impaired listeners do have a lot of problems in noisy environments. Since the introduction of digital hearing aids several improvements have been claimed. But at the same time a lot of questions came forward:

- What is the experimental evidence that should be the basis for objective information for the hearing-aid users?
- Do the benefits in daily life correspond to the claims of the manufacturer?
- More specific: which developments lead to improved speech intelligibility in noise and which developments lead to subjective benefits?
- Are the benefits valid for every hearing-aid user in every situation?

To answer these questions, this thesis reports about some field tests and laboratory studies to investigate the advantages of the noise reduction and dual microphone technique on speech perception in different acoustical situations.

For the laboratory studies, we conducted different tests to obtain knowledge about the effects of the hearing aid algorithms under study in clinical practice. We used speech perception tests in different background noises to measure the performance with the different hearing aid settings objectively. For the hearing aids with the directional microphones (fixed or adaptive) we also used a Just Follow Conversation (JFC) test with noises coming from different sides. To get more information about the effect of the different microphones on localization, a localization test was performed. Paired comparisons were used to evaluate the subjective preference for different hearing aid settings in different background noises. For the subjective evaluation we used questionnaires. With the results of those studies we could verify the claims of the manufacturer.

CHAPTER 2.

ASSESSMENT OF HEARING AID CANDIDACY AND HEARING AID BENEFIT

2. Assessment of hearing aid candidacy and hearing aid benefit

In both parts of this thesis we apply audiometric test methods that provide extra information complementary to the pure-tone audiogram in order to facilitate auditory rehabilitation with hearing aids. Therefore, this chapter provides an overview of test methods using speech and non-speech stimuli.

2.1. Psychophysical tests with non-speech stimuli

While the pure-tone audiogram measures the absolute threshold as a function of frequency, other audiometric tests are available that focus on the perception of supra-threshold signals. Part of these tests are relevant for the evaluation of hearing aids and/or for the evaluation of binaural hearing, relevant for the fitting of bilateral hearing aids.

2.1.1. Loudness scaling

Sensory hearing loss affects loudness perception and this can only be measured subjectively. Loudness perception can be measured by means of categorical loudness scaling. It is possible to use different types of noises and different ranges of output levels.

One method is the Würzburger Hörfeld Skalierung (Hellbrück et al., 1985). The scaling of loudness is based on a 50-point scale, ranging from "not heard" to "too loud". The instruction is to judge loudness at the end of each fragment. Another method has been proposed by Pascoe (1986). In this method a 10-point scale is used. The results of both methods can be plotted as loudness growth curves; the plot of categorical loudness units (vertical axis) versus presentation level in dB (horizontal axis). The raw data can be fitted by a curve and this curve determines the most comfortable level ("MCL" at 50% of the scale). Also the slope of the loudness growth function can be calculated. MCL is related to the amount of hearing loss and the slope to the amount of recruitment.

Some digital hearing aids provide a form of loudness scaling in their fitting software. Usually, the amount of compression ratio will be adjusted according the results.
For normal-hearing people loudness is greater when this is measured binaurally. Loudness summation is rising from 3 dB near the threshold (Dermody, 1975) to about 6-10 dB for higher intensities (Christen, 1980; Haggard, 1982).

2.1.2. Horizontal localization

To assess horizontal localization ability we usually apply a localization experiment with 13 matched loudspeakers, positioned in half a circle in front of the subject (from -90^0 to $+90^0$). The stimuli are usually broadband noise bursts, 300 ms in duration and gated according to a half cosine function to avoid clicks. The hearing-impaired person responses by indicating the number of the box where he/she thought the noise came from.

For the quality of horizontal localization two parameters can be calculated:

- The root mean square value of the stimulus response differences (in degrees). This parameter is used to get information about the absolute values of the faults, weighting large discrepancies between stimulus and response more severe than smaller ones.

- The correlation coefficient for the stimulus response patterns. This parameter is used to find out whether response patterns correspond to the spatial ordering of the stimuli, irrespective of the absolute values of the deviations.

Because noise bursts are not realistic, a new localization test has been developed with a random selection of several daily sounds, like dog barking, music etc., presented simultaneously at a fixed intensity level The different noises were overlapping that way that at every moment at least three noises were present. When the hearing-impaired listener hears a telephone bell, he/she has to indicate from which speaker box the sound came. Now only five boxes are used and the intensity of the telephone bell had a roving level in order to avoid that differences in the output of the loudspeakers would give unwanted cues to the listener about the location of the telephone bell. For this localization test the order of presentations was also randomized, but now resulting in six presentations for each of the five loudspeakers for each measurement (see Chapter 5).

2.1.3. Binaural Masking Level Differences (BMLD)

The auditory system of the human brain can combine signals from the two ears in order to make a better separation between the signals. For a unilaterally presented signal, this results in a better critical signal to noise ratio (S/N), when the noise is presented bilaterally instead of unilaterally. There is also a better critical S/N ratio for a bilateral tone in noise presented bilaterally, when the tone is out of phase instead of in phase.

The amount of noise suppression is called the binaural masking level difference (BMLD), or binaural release from masking, or binaural unmasking or binaural squelch. The BMLD for low frequency sounds is the strongest, about 15 dB. The effect of BMLD for speech is smaller than for low frequency sounds. The BMLD for speech for normal-hearing subjects is 6 - 8 dB (Johansson et al., 2002).

2.1.4. Interaural Time Differences (IATD)

In free field conditions a signal will arrive first at the ear closest to the sound source, and after some time the signal will also arrive at the other ear. The difference between both arrival times is called interaural time difference (IATD). Interaural time differences depend on the direction of the stimuli and the size of the head. There is no interaural time difference when the sound source is located at 0^0 azimuth, and the IATD is about 0.7 ms for sounds coming from 90^0 (Kuhn, 1982). Interaural time differences are resulting in interaural phase differences. The chance that the interaural phase difference is zero is higher for high frequencies than for low frequencies. Interaural time differences and the interaural phase differences are used to localize sounds.

IATD can be measured with headphones. The stimulus consists of two noise bursts presented binaural, starting with a short interaural time difference for the first noise burst (Δt), while the interaural time difference is reversed in the second noise burst. For example, the first part of the binaural noise burst is presented first at the right ear and Δt later at the left ear. This causes that one noise burst will be heard at the right side of the head. The leading noise burst dominates according to "the precedence effect" (Gardner, 1968; Moore, 1982; Goverts et al., 2000). The next binaural noise burst will be presented first at the left ear and then at the right ear. Consequently, this noise burst will be heard at the left side of the head. So the two binaural noise bursts give the impression of moving from the right-hand side to the left-hand side. When the interaural time difference is zero, the binaural noise bursts will be heard in the middle of the head. During the test Δt will be varied adaptively in order to find the minimum interaural time difference that causes a moving image in the head. The smaller the value the better the IATD.

2.2. Psychophysical tests with speech stimuli

2.2.1. Intelligibility of single words

Traditionally, speech perception ability is measured with short lists with monosyllabic CVC-words (consonant-vowel-consonant words) (Bosman, 1989). The speech material is presented by headphones at different average speech levels, resulting in the so-called speech audiogram. This test is well standardized, relatively fast and it gives a good impression about the speech intelligibility at different speech levels.

Steeneken et al. (1990), developed a speech test, which is based on existing and fictitious CVC words with a balanced frequency of occurrence for each phoneme, in order to allow an analysis of confusions. This test does not only provide information about the percentage of correctly identified words, but also about the type of confusions between phonemes. These confusions can be related to the acoustical features of the phonemes and allows a qualitative analysis of the intelligibility problems. The CVC-words used in this test are presented in carrier sentences of four words. The subject has to identify always the third word in the sentence. There are only five carrier-sentences, and 51 target CVC-words per list. The carrier sentence is shown on a computer screen and the target CVC-word has to be identified and to be typed into the computer. At the end of the test, a list is shown with the target CVC-words and the answers. This test can also be presented in background noise. The disadvantage of the test is that it is very time-consuming especially when a high number of conditions has to be measured.

The output files can be used to generate confusion matrices and these confusion matrices can be used for multidimensional scaling (INDSCAL analysis, Carroll & Chang, 1970) or for Sequential Information transfer Analysis (SINFA, Wang & Bilger, 1973). SINFA analyses the amount of information transfer for each perceptual phoneme category.

2.2.2. Dichotic discrimination tests

In daily practice the listener, listening to speech, can be distracted by another speech signal present at the same time. To imitate this situation we used a test based on the dichotic discrimination test of Feldmann (1965). In a pilot study we investigated the applicability of the Feldmann test material for the assessment of the benefit of bilateral hearing aids (for details see Boymans & Dreschler, 1993; Dreschler & Boymans, 1994).

Twelve hearing-impaired subjects participated in this experiment with moderate (average loss at 1000, 2000, and 4000 Hz between 40 and 70 dB) and symmetrical (average difference between the ears < 15dB) sensorineural hearing losses. They were recently fitted with two (identical) behind-the-ear hearing aids. We compared the results for the following conditions: right ear provided with a hearing aid, left ear open (condition AD), left ear provided with a hearing aid, right ear open (AS), and bilaterally fitted hearing aids (ADS). The order of conditions was counterbalanced to avoid sequence effects.

In the dichotic speech test two concurrent words (3 syllables) or numbers (4 syllables) were presented exactly simultaneously from -45^0 and $+ 45^0$ azimuth. The words were recorded from the same speaker. Both words or numbers had to be replicated, if possible. For words the percentages correct replicated syllables for the different sides were calculated. For numbers the correct replicated units and decades were calculated for every side. The realistic aspect of this experiment was that the subjects had to concentrate at both sides simultaneously. In the evaluation of the results of the conditions with an unilateral fitting a distinction was made between the responses at the so-called contra-lateral side (S-contra; words presented at the unaided side) and at the ipsi-lateral side (S-ipsi; words presented at the aided side). The group results of the dichotic discrimination test are presented in Table 2.1.

	Words		Numbers	
	Av. Scores	St. dev.	Av. Scores	St. dev
Unilateral / S-ipsi	33.7 %	17.1	63.3 %	15.0
Unilateral / S-contra	12.0 %	10.5	32.1 %	14.8
Bilateral	31.5 %	16.8	57.9 %	15.5

Table 2.1. Group results for the test on dichotic discrimination. Average values (and st.dev.) are presented for words and numbers separately for the following parameters:

- *"unilateral / S-ipsi": the average scores in the unilateral conditions for the speech material from the (unilaterally) aided side.*
- *"unilateral / S-contra": the average scores in the unilateral conditions for the speech material from the (unilaterally) unaided side.*
- *"bilateral": the average scores for all speech material presented to the subject wearing two hearing aids.*

In the unilateral case, ipsi-laterally presented speech material is perceived much better than contra-laterally presented speech material. In the bilateral case, there is only a clear improvement relative to unilateral speech discrimination for the contra-laterally presented speech material. The effect is statistically significant (Wilcoxon, $p<0.01$), both for words (from 12% to 31.5%) and for numbers (from 32.1% to 57.9%). The results for words and numbers are closely related (correlation coefficient is 0.73).
On average, the perception of ipsi-laterally presented speech information seems to be slightly hampered rather than improved by adding a second hearing aid (and consequently conflicting information). This effect is not in agreement with the results that are usually found in other speech tests, but the effect is only weak (n.s.). The negative trend can be induced by a conflict of attention due to the task to understand both messages.

In this pilot study we found a significant bilateral benefit in dichotic discrimination relative to unilateral conditions with speech at the unaided side. But the effect relative to unilateral conditions with speech at the aided side was slightly negative. Our results show that dichotic discrimination is much more difficult for words than for numbers. The results suggest that words are too difficult and numbers should be preferred for the dichotic discrimination task.

2.2.3. Intelligibility of sentences

In daily practice speech perception usually concerns the perception of running speech instead of isolated words. Therefore, sentence tests have been developed which can be used to assess objectively the benefits of hearing aids in realistic conditions. The speech reception test (SRT) in noise according to Plomp and Mimpen (1978) is the most well known sentence test used in the Netherlands.

In the SRT-test sentences (spoken with a male or female voice) and noise are presented simultaneously. The noise has a frequency spectrum corresponding to the long-term average spectrum of the speaker and is presented at a constant level (for example 65 dB). The speech level will be varied according to an adaptive up-down procedure following the responses of the subject. The subject repeats the sentences he or she hears. When the sentence cannot be repeated or is not repeated correctly, the next sentence will be presented at a 2 dB higher level each time, until the sentence is repeated completely correctly. Then the next sentence will be presented at a 2 dB lower level, etc., following an adaptive up-down procedure. In total 13 sentences are presented for a single threshold measurement. The average of the last 10 sentences is considered as the SRT-threshold. For normal-hearing subjects, with speech and noise at 0^0 azimuth, the speech can be presented at about 6 dB below the level of the continuous noise for a 50% correct intelligibility score. Consequently, for normal-hearing subjects the critical S/N ratio is –6 dB (for listening with two ears in the free field). The most important

advantage of this procedure is the high test-retest reliability: standard deviations are in the order of about 1 dB.
In some studies an SRT-test with speech-modulated speech noise is used (Festen & Plomp, 1990) as recorded at the FENAC-CD (Federation of Dutch Audiological Centres). The noise used is speech-noise of a male or a female speaker, modulated according to the modulation spectrum of a single speaker. For normal-hearing subjects the critical S/N ratio is usually 6-10 dB lower in modulated noise than in continuous noise (Duquesnoy, 1983). The reason is that normal-hearing listeners take advantage of the pauses in the background noise. This capacity is affected in hearing-impaired subjects (Festen & Plomp, 1990; Bronkhorst & Plomp, 1992). This results in larger differences between normal-hearing and hearing-impaired listeners in modulated noise than in continuous noise.

For a reliable application of the SRT-test, it is not allowed to use the same sentence lists more than once in the same subjects, because the listener can easily recognize the sentences, even after a long period, and then the test is not reliable any more. Therefore, more speech material with sentences of a male and female voice has been recorded on the VU 98 CD (Versfeld et al., 2000). Again, this CD contains matched background noise signals. Traditionally, the SRT-test is applied with speech and noise from 0^0 azimuth. But to make the situation more realistic or to incorporate more of the spatial effects that are important in the case of bilateral fitting, the speech and noise sources can be spatially separated. A spatial separation between sound sources usually improves the critical S/N ratio for normal-hearing listeners.

Another speech test is the Oldenburger Satztest (Wagener et al., 1999[a], 1999[b], 1999[c]). The speech material consists of a closed set of sentences of five words each. The structure of the sentences is always similar: name-verb-numeral-adjective-object. For each of these five components, 10 words are available. The words can be selected at random and great care is taken to make the transitions between the words as smooth and natural as possible. The main advantage of this test is that an almost infinite number of different sentences can be constructed and thus this test can be repeated very often. In addition, the test can easily be automated. Of course, the test can also be presented in quiet or in background noise, and if wanted with spatially separated sound sources. At the moment a Dutch/Flemish version of the test is under construction by the Erasmus Medical Centre in Rotterdam, the University of Leuven, and at the AMC in Amsterdam.

2.2.4. Use of the method of adjustment in speech audiometry

As mentioned before, 13 sentences are needed to measure a single critical S/N in the SRT-test. This takes a considerable time, especially when more situations have to be measured. A faster method is the Just Follow Conversation (JFC) test. In contrast to other speech intelligibility tests, this is a subjective speech test. The listener hears sentences in noise and is asked to adjust the speech level by him/her self till he/she could just follow what is being said. The intelligibility of sentences depends on the acoustic features and the redundancy of the sentence. Therefore, it is possible to choose for a closed set of sentences, which will be repeated every time. The listener knows the speech material and can compare the different settings more easily than when the speech material differs every time.

As mentioned above the JFC-test takes less time than the SRT-test. Therefore, more situations with noise from different directions (or different noises), and more hearing aid settings can be tested. When people know the speech material, there is no learning effect, the speech material can be used frequently and the reliability is high. In our test set-up we typically obtain test-retest standard deviations of 1.4 dB. On the other hand, the subjective results are depending on individual criteria and can show large inter-individual differences. The individual criteria are based on speech intelligibility, but could also be based on comfort. The criterion effect can be a problem if individual

measurements have to be compared in absolute terms. For relative measurements (difference measures), this disadvantage is almost absent.
Another implementation of the JFC-test is to use running speech (Neumann et al., 2000). This is less boring, but more difficult to compare different settings in the hearing aid because speech intelligibility is depending on the kind of speech material. The reproducibility of the tests with running speech is usually higher than in our test set-up.

2.2.5. Use of paired comparisons with speech stimuli

In digital hearing aids many settings are possible. But it is not always clear which setting is preferred for each individual. Therefore, subjective judgements are useful additive to more objective information from speech tests. For this purpose, paired comparisons can be used with speech stimuli (Franck et al., 2003). In a paired comparison the subject can make direct comparisons between speech fragments reproduced by a hearing aid in different settings. The subject hears the same sentences for two different hearing aid settings that are to be compared. The sentences can be presented in quiet or in background noise. The subject has to judge which hearing aid setting is preferred, taken into consideration that the hearing aid setting should be used for the whole day. A set of combinations of hearing aid settings can be presented in a tournament-like procedure in order to find the setting that is judged most frequently as the best (i.e. the winner).

2.2.6. Applications of speech stimuli for the evaluation of hearing aid benefit

A lot of evaluation speech tests are possible, but which test do we have to choose? This depends on different factors:

- The kind of information needed.

- The relationship with daily communication.
- The accuracy of the measurement versus the time requirements.
- The degree of difficulty for the subject.

For every study we want an accurate, detailed, easy and fast test, but not everything is possible in the same test. Therefore we have to prioritise.

The first question is: What do we want to measure? Do we need intelligibility scores, speech reception thresholds, phoneme confusion patterns or subjective preferences? For speech reception thresholds, SRT-tests remain the "golden" standard, but if a large number of conditions have to be compared JFC-tests can be used as a first-order approximation. For comparative measurements between different settings or between different hearing aids, we can start with the measurement of the amount of speech intelligibility before analysing the kind of errors or substitutions made. From an analysis of confusions (as obtained with the test developed by Steeneken) we can gather more qualitative information about the reasons for poor speech perception and/or the effects of signal processing parameters (e.g. attack and release times) on characteristic properties of phoneme identification. For specific aspects of binaural processing, for example the effect of a second hearing aid, the dichotic discrimination test can de used. For subjective measurements, a paired-comparison test can be useful when a direct comparison is needed between different hearing aid settings.

The second question is: How realistic should the test be? In daily practice we speak in sentences, so a sentence test is more realistic than a test with words. However a word-test is easier to analyse phoneme confusions. And with sentences we have to take into account the redundancy that is present in sentences.

Most of the time we have the possibility of lip reading. But for a speech test this gives a lot of bias: we have to separate what is being heard from what is being seen. Therefore, tests without lip reading are generally preferred. In daily practice, often different background noises are present and they are coming from different directions. This is problematic for all hearing-impaired listeners. To make a test realistic, it is useful to imitate those difficult situations. Background noise could be added in all tests, in principle. In daily practise background noise is often speech, and speech can distract, because there is conflicting information in it. To imitate such a situation, a dichotic discrimination test with words or numbers can be chosen.

The third question is related to the interrelated items of accuracy and time consumption. The more detailed information the more time is needed. For detailed information about the specific difficulties in identifying different speech sounds the CVC-identification test, developed by Steeneken, can be used. The test is time-consuming. So the hearing-impaired listener has to concentrate for quite a long time, especially when more conditions have to be measured. Therefore, we should try to avoid that we measure the concentration of the subject instead of his/her speech perception abilities, especially for older people. As discussed above, the SRT-test is an objective speech test and measures the 50 % point of speech intelligibility. The JFC-test is a more subjective measurement converging to an unknown (individually chosen) criterion, but this test is much faster than the SRT-test. For comparative measurements with a lot of different situations the JFC-test can be considered. A paired comparison test is also a subjective test but the result is only a rank order, and with the JFC-test, more specific judgements are measured.

The last question concerns the degree of difficulty for the subject to conduct the test. This depends on the individual subject, but in general the dichotic discrimination test is the most difficult test. For this test we should take into account the concentration of the subject. Apparently, this test is more difficult when words are used instead of numbers. The SRT-test is not experienced as difficult, but of course the subject needs to concentrate and the tests may not last too long. A paired-comparison test is probably more difficult than a JFC-test. Because with the JFC-test the subject can make his/her own reference better by adjusting the gain of the presented sentences, but a disadvantage is that there is no direct comparison in the JFC-test. When the hearing loss is too large for speech intelligibility, lip reading can be added to make the test less difficult. However, not all test material discussed in this section is available with accompanying video material. There is need for further development of test material that can be applied audio-visually.

2.3. Subjective evaluation techniques

Differences in hearing aids are not always measurable with objective tests. Besides, the subjective experiences are important factors. Hearing-impaired people do have different impairments, experience different amounts of disabilities and feel different degrees of handicap, wear their hearing aids in different acoustical situations, and experience different benefits of their hearing aid(s). To map out all those subjective information a lot of questionnaires have been developed.

2.3.1. Traditional hearing aid questionnaires in the Netherlands

There are a lot of questionnaires in circulation, but only a few of them are validated. The "Hearing Handicap and Disability Inventory " (van den Brink, 1995) is validated and focuses on disability and handicap. There is a complete list of 40 questions, and for brief measurements an abbreviated list with 20 questions has been developed (10 questions about disability and 10 questions about handicap). The hearing-impaired listeners are asked to answer the questions for common situations with a hearing aid (or without a hearing aid when this is more usual). For the answers a 4-points scale is used. Questions are asked for different situations like: a quiet situation, a noisy situation, the use of telephone, attending a lecture, listening to television, and visiting a shop.

Another validated questionnaire is the Amsterdam Inventory of Auditory Disability and Handicap, which consists of 30 questions (Kramer et al., 1995; Kramer, 1998). The questions are distributed in five basic disability factors: detection of sounds (5 questions), distinction of sounds (8), intelligibility in quiet (5), intelligibility in noise (5), and auditory localization (5). Each question consists of three parts, the first part is about disability at that specific moment, the second part is about the situation in the past, and the last part is about the handicap. Four answer categories were possible. The 'handicap-question' is about the extent to which the hearing-impaired subjects are annoyed by the experience of difficulty in hearing in that specific situation and the extent to which they are limited in doing activities. When there is no difficulty in hearing in a specific situation, the hearing-impaired is instructed to skip the handicap part. The questionnaire could be filled in for situations without and/or with a hearing aid.

In Rotterdam a questionnaire was developed (Franck et al., 1999), with questions about the hearing aid in general (sounds, function, frequency of wearing the hearing aid etc.) and about speech intelligibility with the hearing aid in different situations. Situations at home, outside, at work, and at school. The subjects are also asked to fill in how often a situation occurred and how important that situation was for the subject. They are asked to visualise their answer on a visual-analogue-scale. This is a horizontal unmarked line, with end markers such as "good" and "bad" (two extremes). When the subjective rating corresponds to a very good intelligibility he/she has to make a vertical line at the horizontal line near the word "good". When the subjective judgement is about 50% the vertical line has to be placed in the middle of the line. This questionnaire is not validated, but gives a good impression about the subjective experiences with different programs in hearing aids or with different hearing aids.

2.3.2. Traditional international hearing aid questionnaires

The Abbreviated Profile of Hearing Aid Benefit (APHAB) is a questionnaire that can be used as part of the fitting procedure (Cox et al., 1995). Firstly, questions are asked about the experience with hearing aids, hearing aid use and about the working situation. Then 24 questions (this is a subset of the original PHAB-questions, Cox, 1990) are asked, which refer to four subscales: ease of communication under relatively favourable conditions, communication in reverberant rooms, communication in settings with high background noise levels, and unpleasantness / aversiveness of environmental sounds. Each item is a statement. The hearing-impaired listener is asked to rate the truth of that specific statement on a 7-point scale, for the situation without a hearing aid and with a hearing aid. So differences between both situations can be measured. It is also possible to answer those questions for example with two different hearing aids, or two different settings of the hearing aid in order to determine whether one is significantly superior.
The International Outcome Inventory for Hearing aids (IOI-HA) is developed as a product of an international workshop on Self-Report Outcome measures in Audiological Rehabilitation (Cox et al., 2000). This questionnaire is translated in different languages to facilitate co-operation among researchers in different hearing healthcare settings across national boundaries. The questionnaire consists of only seven questions, with answer possibilities at a five-point scale.
One question is about the frequency of hearing aid use, three questions about the residual handicap (factor 2), and three questions about the benefit or satisfaction of the hearing aid (factor 1).

The Glasgow Hearing Aid Benefit Profile (GHABP; Gatehouse 1999) is a questionnaire with eight listening situations. Four situations are pre-specified and four situations are user-specified. Questions are asked about initial disability, handicap, hearing aid use, hearing aid benefit, residual disability and satisfaction for each of these eight conditions. The subjects are asked to answer the questions on a 5-points scale.

2.3.3. Composition of AVETA to evaluate bilateral benefit

For the evaluation of the benefit of bilateral hearing aids there was a co-operative effort of the Free University Amsterdam and our lab to compose a specialised questionnaire from existing questionnaires.

For a retrospective study some general questions were included from other questionnaires and more specific questions were added about the reasons for choosing one or two hearing aids.

A large part of the questionnaire exists of questions about the situations without a hearing aid, with one hearing aid and with two hearing aids. For that purpose parts of the adjusted version of the Amsterdam Inventory Disability and Handicap (AIADH) and the Abbreviated Profile of Hearing Aid Benefit (APHAB) were used. In total 7 categories were composed: detection of sounds (5 questions), speech intelligibility in quiet (5 questions), speech intelligibility in noise (5 questions), directional hearing or localization (5 questions), discrimination or recognition of sounds (1 question), speech intelligibility in reverberation (1 question from the APHAB), and comfort of loud sounds (6 questions from the APHAB). Ten questions from the HHDI were used to get information about handicap.

All seven questions of the new IOI-HA were used to get information about hearing aid use, residual handicap and benefit or satisfaction of the hearing aid. Details about this questionnaire were described by Kramer et al. (2002).

Because the questionnaire of the retrospective study was rather long, we applied – after validation based on the results of the retrospective study - a shortened version in the prospective study.

We still used general questions about the daily situation of the subject and about the reasons for choosing one or two hearing aids. But the selection of questions from the

AIADH and APHAB was decreased from 29 to 18. The question about speech in reverberation was skipped. So, only six categories were left (detection of sounds, speech intelligibility in quiet, speech intelligibility in noise, directional hearing or localization, discrimination or recognition of sounds, and comfort of loud sounds) and for each category three questions were included, selected on the basis of the analyses of the retrospective results.

Ten questions from the HHDI were omitted because there was too much overlap with the handicap part of the IOI-HA. The IOI-HA was included as an integral part. The resulting validated questionnaire is called AVETA (Dutch acronym for Amsterdam Questionnaire for Unilateral or Bilateral Hearing Aid Fittings).

CHAPTER 3.

THE BENEFITS OF BILATERAL HEARING AIDS I:

A systematic review

This chapter is submitted to Int.J.Aud. (Rozeboom et al., 2003)

3. A systematic review on the benefits of bilateral hearing aids

Summary

This paper is part of a large nation-wide study on the benefits of bilateral hearing aid fittings in the Netherlands. The study is designed to assess the added value of fitting a second hearing aid and to develop tools to evaluate this objectively. The first stage of the project consisted of a systematic review of the literature until 2002 about the advantages and disadvantages that hearing-impaired people experience with two hearing aids instead of one.

The most important advantages of wearing two hearing aids are improvement of speech intelligibility in noise, improved localization, the absence of a deprivation effect, and an improved sound quality. It is striking that almost no data were found about the benefit of bilateral hearing aids in asymmetric hearing losses.

3.1. Introduction

Due to the ageing population in Western Europe, a strong increase of the number of the hearing aid users is foreseen and as a result a growing pressure on the budgets available for hearing aid fitting. Therefore, local governments and health insurance companies consider different options for reducing the financial reimbursements for hearing aids. One of the options is to cut the financial compensation for the second hearing aid.

In the Netherlands a reimbursement for the second hearing aid is given if the average hearing loss in the better ear (averaged across 1, 2, and 4 kHz) is worse than 35 dB. For the second hearing aid a financial compensation will be given only if speech discrimination improves by 10% or more for the bilateral fitting (relative to a unilateral fitting) or when the localization capacity is restored to within 45 degrees due to the use of two hearing aids. The general problem with these requirements is that they are very global. The measurement conditions are poorly specified and there is no guarantee that especially these parameters correlate well with 'real-life' improvements. In addition, the criteria have not been based on recent scientific evidence.

Given the complications in the criteria mentioned above there is need to design new criteria for the reimbursement of a bilateral fitting with hearing aids. As a starting point it was decided to study the literature on auditory rehabilitation systematically with respect to the proven advantages of the bilateral fitting of hearing aids. We found ten review papers in the existing literature (Bentzen, 1980; Byrne, 1981; Libby, 1981; Markides, 1989; Cashman et al., 1984; Van Wijk, 1993; Kimberley et al., 1994; Agnew, 1997; Klein, 1999; Dillon, 2001). However, these reviews did not apply to the methods of a systematic review that will be used in this study.

3.2. Method

The objective of this systematic review is to get a better view on the advantages of a bilateral hearing aid adjustment over an unilateral adjustment and where possible to point out the different indication criteria. To describe these advantages, literature has been searched systematically by previously selected keywords.

3.2.1. Criteria for selecting studies for this review

The studies that have been selected for this review had to meet a couple of criteria.

- First of all, studies written before 1980 were omitted. The articles written before 1980 contain studies that describe mostly linear hearing aids, while the recent literature comprehend mainly non-linear hearing aids. Therefore, *the time-span 1980 until 2002* has been chosen.

- Second, only studies that have been written in the *English and German* language will be taken into account.
- All subjects described should be *adults with bilateral hearing loss.*

3.2.2. Search strategy for identification of studies

There are a number of important issues with regard to bilateral hearing aid fittings. These issues are localization of sounds, spatial orientation, spatial speech perception, and common auditory functioning. The following keywords have been used: deafness, hearing loss, hearing aid/hearing instrument, stereophonic/binaural/bilateral, auditory amplification, benefit, speech perception, localization, spatial perception, and deprivation. The search has been carried out on three medical databases, that is Medline, EMBase, and Science Citation Index (SCI).

3.2.3. Methodological quality

To describe the methodological quality of the studies, the robustness of the clinical and experimental evidence should be determined. To evaluate the various levels of evidence, the methodology used should be clear. The following aspects, presented in the order of a decreasing robustness of experimental evidence, can be distinguished:

- Randomization can relate to test conditions or test populations: the assignment of the treatment to subjects, the choice of the unilateral (reference) ear, and the order of testing. The most valid experimental design is the randomized clinical trial (RCT). In this design, the researcher randomly assigns a treatment or placebo to his patients. These patients are followed in time to determine the effects of treatment.
- Control groups; more groups can be observed. One group receives the treatment and

one does not receive the treatment under study. These groups are followed in time to measure the developments of the different outcomes (cohort study).

- In some studies patients, identified with a certain treatment, are checked retrospectively to evaluate the treatment effects (case-control study).

Besides these three categories of studies, there are also cross-sectional studies and case series. These two designs usually provide only circumstantial evidence.

3.2.4. Classification of studies

We searched the three databases by the given keywords. This search strategy resulted in a number of 238 articles. 87 Studies were removed because they were duplicates. From the remaining 151 articles, two articles were not in English or German language (149 left). Studies that described cochlear implants or operative measures were beyond the scope of this review. Of the remaining 124 articles, abstracts were read to trace the particular phrasing of the question. Eventually, 72 articles were considered suitable for scoring in the context of this study.

Four articles were not available in any library in the Netherlands and after reading all of the remaining pieces, 12 were not useful, five articles involved children, and 10 articles were already reviews. Finally, we added one article published in 2002. So in total we have 42 original articles and these articles were scored by two independent persons (the first and second author).

As a first step in finding the most important articles, Table 3.1 summarises the main methodological aspects. The following codes are used:

- Randomization: + if the unilateral/bilateral aspect was randomized or counterbalanced, +/- if either the test order or the population selection was randomized. Studies with headphones were also included. Sometimes the authors

Author	Random	Obj/subj	Control	Number	Selection	Score
Allen, 2000	+	o	+	48	+	26,5
Anderson, 1996	-	s	+	53	-	27
Balfour, 1992	+	s	+	15	-	28
Bodden, 1997	-	o	-	5	-	19
Bronkhorst, 1990	-	o	+	28	-	26
Brooks, 1981	-	s	+	204	-	20
Brooks, 1984	-	s	+	571	-	21
Byrne, 1992	+/-	o	+	87	-	27
Carter, 2001	+/-	o	-	4	-	19
Chung, 1986	+/-	s	+	150	-	28,5
Davis, 1982	+/-	o	+	572	-	29
Day, 1988	+/-	o	-	51	-	32
Dreschler, 1994	+/-	o	-	12	+	25
Erdman, 1981	-	s	-	30	-	27,5
Festen, 1986	+	o	+	24	-	30,5
Gelfand, 1987	+/-	o	+	86	+	36,5
Gelfand, 1995	-	o	-	6	-	24,5
Haggard, 1982	-	o	+	29	-	25,5
Hawkins, 1984	+	o	+	23	-	29
Helfer, 1992	+	o	+	18	-	31,5
Hurley, 1993	-	o	-	9	-	22
Hurley, 1998	-	o	+	40	+	25
Hurley, 1999	-	o	+	142	+	24,5
Jauhiainen, 2001	-	o	+	500	-	19
Köbler, 2002	-	o	+	19	+	28
Leeuw, 1991	+/-	o	-	12	-	25
Markides, 1982a	-	o	+	96	-	20,5
Markides, 1982b	-	s	+	31	-	22
McKenzie, 1990	-	o	-	13	-	23,5
Moore, 1992	+/-	o/s	-	20	+	39,5
Mueller, 1981	-	o	-	24	+/-	24
Nabelek, 1980	-	o	+	34	-	32,5
Nabelek, 1981	+/-	o	-	21	-	32
Naidoo, 1997	+	o	-	15	-	32,5
Novick, 2001	+	o	-	10	+	22
Punch, 1991	+/-	o/s	-	17	+/-	27,5
Robillard, 1996	-	o/s	-	224	-	22
Silman, 1984	-	o	+	67	+	27,5
Silman, 1993	+/-	o	+	66	+	33,5
Stephens, 1991	+	s	+	29	+/-	31
Vaughan-Jones, 1993	+/-	o	-	56	-	29,5
Yueh, 2001	+/-	s	+	60	+	36

wrote that the subjects were randomly selected, but this randomization did not always relate to the aspect of a unilateral or a bilateral fitting.

- Results are based on objective or subjective tests.
- Control groups; positive if more than one group have been investigated. The control group should be unilaterally fitted listeners, but this is not always the case. In addition, in some studies the reference groups differed in age, amount of hearing loss, type of hearing aid, etc.
- Total number of subjects included in the study.
- Selection criteria; positive if clear criteria are given with respect to the inclusion and exclusion of subjects in the study.
- The average total score, given by two independent persons.

The last column presents the overall scores according to the criteria of Chalmers et al. (1981). Their method has been developed to assess the quality of a randomized clinical trial (RCT). With the help of this scoring system, it is possible to get an impression of the supplementary value of certain articles. It must be stated that the method used is not a 'golden standard'. In research there are a couple of items that can be used as indicators for the scientific quality. These items are i.e. randomization, blinding, and population selection. Besides blinding also randomization is almost impossible in audiological research with respect to the use of one or two hearing aids. Consequently, the studies described in this review never meet the exact criteria of a RCT.

Table 3.1. Summary of the main methodological aspects that determine the score according to the criteria of Chalmers. The following codes are used:

- *Randomization: + if mentioned +/- if or test or population selection is randomized.*
- *Objective or subjective test.*
- *Control group: positive if more than one group have been researched.*
- *Total number of subjects invited in the study.*
- *Selection criteria: positive if clear criteria are given.*
- *Average score.*

Author	N	Speech in noise	Locali-sation	Sound quality	Other benefits	Depri-vation	Age effects
Moore, 1992	20	X					
Yueh, 2001	60	X		X	X		
Gelfand, 1987	86					X	
Silman, 1993	66					X	
Helfer, 1992	18	X					X
Nabelek, 1980	34		X				
Naidoo, 1997	15	X		X			
Day, 1988	51	X					X
Nabelek, 1981	15	X					
Stephens, 1991	29	X	X	X	X		
Festen, 1986	24	X					
Vaughan-Jones, 1993	56	X	X				X
Davis, 1982	572	X					X
Chung, 1986	150	X	X	X	X		
Balfour, 1992	15	X		X	X		
Köbler, 2002	19	X	X				
Hawkins, 1984	23	X		X			
Punch, 1991	17	X	X	X	X		
Erdman, 1981	30	X	X	X	X		
Silman, 1984	67					X	
Anderson, 1996	53	X		X	X		
Byrne, 1992	87		X				
Allen, 2000	48	X					X
Bronkhorst, 1990	28	X					
Haggard, 1982	29				X		
Dreschler, 1994	12	X	X		X		
Hurley, 1998	40					X	X
Leeuw, 1991	12	X					

Table 3.2. A summary of the aspects that have been investigated in core studies from this review on the benefits of bilateral hearing aids.

If the guidelines for writing a systematic review were enforced strictly, none of the articles would be appropriate. Therefore, the design of this systematic review is different from other reviews. To include the most important articles, we considered the studies with a score of 25 and higher as the "core" of this review. This concerns 28 studies. This does not mean that the other articles are not useful. It was just not possible to determine their methodological quality. The research performed can be of good quality but the resulting article may be of poor quality in terms of the criteria of Chalmers judged from the methodological point of view. Therefore, and for the reasons that some conditions in audiology are difficult to control, the other articles have been described in terms of "additional literature".

3.3. Results

Although most research approaches differ from each other, most experimental results are in reasonable agreement. A couple of important factors are common in most studies. In each section the "core" papers forming the core of this review will be described first. Important other factors that are underexposed in these papers but emerge as important from the additional literature will be added in each section. The factors can be divided into objectively measured performance data, more subjective outcome measures, and other relevant factors. Table 3.2 summarises the aspects of bilateral fitting that have been investigated in the 28 studies.

3.3.1. Performance measures

<u>*Speech intelligibility*</u>

Speech intelligibility is one of the most important aspects for the hearing-impaired (if not the most important). Most studies concentrate on the speech perception in noise and in reverberation, because these are the most critical listening situations. The fitting of bilateral hearing aids introduces two sources of improvement: the binaural squelch effect and the removal of head-shadow effects. The squelch effect is the true binaural component and can be described as the difference (in dB) in the critical signal-to-noise ratio (S/N ratio) between monaural and binaural listening. However, the benefits of bilateral fittings for speech intelligibility appear to be related primarily to the compensation of head-shadow effects. When listening with two hearing aids, the difference (in dB) of the critical S/N ratio between near-ear and far-ear listening is about 6-7 dB smaller than for listening with one aid (Markides, 1982[a]).

Köbler et al. (2002) used a fixed S/N ratio of + 4dB, and they found a statistically significant advantage of 5% in speech intelligibility when the subjects were fitted bilaterally.

Festen and Plomp (1986) investigated the speech-reception threshold (SRT) in noise with one and with two hearing aids in a group of 24 hearing-aid users. All subjects had a nearly symmetrical hearing loss, and they were used to wear two behind-the-ear hearing aids for at least three months. The critical S/N ratio measured (the S/N ratio at 50 % speech perception) proved to be hardly better with two hearing aids than with one hearing aid for subjects with moderate hearing losses when speech and noise came from the frontal direction. However, a significant benefit for bilaterally fitted hearing aids is present in subjects with a pure tone average $PTA_{(.5,1,2\,kHz)}$ larger than 60 dB, and if the speech and noise sources are spatially separated. Day et al. (1988) also concluded that subjects with severe hearing losses experience more benefit from two hearing aids than from one. They used a free field audiovisual sentence-in-noise test (FASIN) in a reflection-free room.

Bronkhorst and Plomp (1989) showed that the binaural advantage due to head shadow effects decreases when the hearing loss at high frequencies is more severe. So, the binaural advantage depends on the audiometric configuration of the hearing loss.

Also, Bronkhorst and Plomp (1990) found that the binaural advantage due to a spatial separation of speech and noise is smaller for small hearing losses than for large hearing losses. In contrast to this study, Moore et al. (1992) showed a binaural advantage for almost all hearing losses when speech and noise were separated. However, in Moore's test design one ear was blocked for the unilateral situation. This suggests that contribution of the unaided ear is mainly responsible for the fact that the benefit from bilateral fitting depends on the degree of hearing loss. Moore et al. did not find differences in binaural advantage for linear and compression hearing aids.

Hawkins and Yacullo (1984) determined the S/N ratio necessary for a constant performance level of word recognition for normal hearing and for hearing-impaired listeners with bilaterally symmetrical mild-to-moderate sloping sensorineural hearing losses. The subjects were tested under three levels of reverberation time (0.3s, 0.6s, and 1.2s), for unilateral and bilateral fittings, using omni-directional or directional microphones. The results for bilateral conditions (averaged across two microphone conditions in the three reverberant situations) were 2-3 dB more favourable than the results for unilateral conditions. This bilateral advantage appears to be independent of microphone type and reverberation time. In addition, there was a directionality advantage for the conditions with directional microphones compared to the same conditions with omni-directional microphones. These two advantages appear to be additive (at least at the two shorter reverberation times) because no interaction between the two was found. The results indicate that the optimum performance in noise is achieved when hearing-impaired subjects wear bilateral hearing aids with directional microphones in rooms with short reverberation times.
Nabelek et al. (1981) measured the effects of unilateral and bilateral fittings for 15 subjects with bilateral sensorineural hearing losses in noise and in reverberation. Word recognition scores were significantly higher in bilateral listening modes. The advantage of bilateral listening did not depend strongly on reverberation time or the use of hearing

aids. The scores improved by 7 % for a reverberation time of 0.1 s and 3.4 % for a reverberation time of 0.5 s.

Leeuw and Dreschler (1991) found better critical S/N ratios for speech intelligibility in noise (SRT-test) tested by normal-hearing listeners using two BTE hearing aids compared to one BTE hearing aid (mean difference 2.5 dB). This implies a significant advantage of bilateral over unilateral amplification, which proved to be dependent on the type of microphone (omni-directional or directional) and the azimuth of the noise source, except for 0^0. Contrary to the results of Hawkins and Yacullo (1984), the bilateral advantage in speech intelligibility is highest with directional microphones.

Dreschler and Boymans (1994) measured SRTs in noise with a spatial separation between speech and noise in 12 hearing-impaired subjects. The results showed better SRTs for the subjects using bilateral hearing aids. Bilaterally fitted subjects make better use of the spatial separation between speech and noise sources, resulting in 5dB better SRT thresholds. In addition, they applied a dichotic discrimination task, where 3-syllable words and 4-syllable numbers were presented simultaneously from $+45^0$ and -45^0 azimuths. Results only show a clear bilateral improvement in speech discrimination for the speech material that was presented from the (unilaterally) unaided side. For the words and for the numbers, this effect was statistically significant.

Not all studies support the findings of improved speech intelligibility. Allen et al. (2000) found a significant evidence of binaural interference for 2 out of 48 elderly subjects ($p<0.05$). Although the small number can easily be explained by normal variability in differences between speech scores, this finding may indicate that for some individuals speech intelligibility scores with two ears can be poorer than with the better ear alone. Bodden (1997) argued that the binaural function of the ears should be restored by hearing aids. When hearing loss deteriorates the binaural function, signal processing should be used as compensation.

In the "additional" literature Mueller et al. (1981) suggest that, if speech recognition scores are the most important measures for the unilateral fitting of hearing aids, bilateral fitting will result in essentially equal performance to unilateral fitting. In their research they found only small differences. To give a judgement about the advantages of bilateral fitting, factors as loudness summation, localization, and spatial balance should be taken into account as well.

Markides (1982[a]) found a difference of 2-3 dB as the bilateral advantage of two hearing aids. His experiments confirm that the effects of the head-shadow compensation are more important than the effects of binaural squelch.

In a study with only four subjects, Carter et al. (2001) found a better word-recognition score for a unilateral fitting than for a bilateral fitting in an one, two and three pair dichotic digit task. The scores were higher for the situation with a hearing aid in the right ear, than for the situation with a hearing aid in the left ear.

Localization

Improved localization is an advantage often mentioned in literature. It means that subjects with two hearing aids are better capable of determining from what direction a sound arrives. Punch et al. (1991) presented objective data of this advantage. Although their research is focused on bilateral fitting strategies, they found that localization with bilateral hearing aids was significantly superior to localization with unilateral hearing aids. Besides this objective advantage, Stephens et al. (1991) found that an improvement of localization is one of the reasons for people to choose for two hearing aids. Dreschler and Boymans (1994) tested localization ability with one and two hearing aids in the same subjects. Outcomes are that the localization ability is significantly better with two aids than with one. The average rms deviation (root mean square value) reduced from 33 degrees with one hearing aid to 17 degrees with two hearing aids. The results of Byrne et al. (1992) show that the bilateral advantage is also applicable for subjects with moderate to severe hearing losses.

In the experiments of Köbler et al. (2002) the subjects had to repeat sentences and indicate the side where the sentence came from. The results for localization were almost the same for the situation without hearing aids and with two hearing aids. A worse result was found for the situation with only one hearing aid.

In contrast with other studies, Vaughum-Jones et al. (1993) found that the localization ability with two hearing aids is worse than with one hearing aid. Speech discrimination in noise was also found to be worse with two hearing aids. Their conclusion is that subjects initially should be aided unilaterally and, if necessary, two aids can be considered.

Nabelek et al. (1980) investigated the effect of asymmetry in sound pressure levels produced by signals coming from two loudspeakers. By changing the sound pressure level (when the sound level at one side was increased by a certain amount of dB's (ΔL), the sound level at the other side was decreased by the same amount) the position of the sound image in a lateralisation experiment varies. In normal-hearing subjects, for sound imagines on the midline, ΔL was zero. In unfitted hearing-impaired subjects with bilateral hearing losses, ΔL was within the normal range. However, in aided balanced (equal gains) and/or unbalanced conditions (10 dB disparity in gains) ΔL for midline images was outside the normal range for some bilaterally fitted subjects. Based on these results, the authors concluded that bilateral hearing aids could give a bias in the symmetry of the presentation levels between both ears.

3.3.2. Subjective outcome measures

An improved sound quality can be seen as one of the subjective advantages of wearing two hearing aids. The paper of Balfour and Hawkins (1992) focuses on this subjective advantage. A group of 15 hearing-aid users showed for eight sound quality dimensions a preference for a bilateral fitting. The dimensions with the strongest preference were: overall impression, fullness, and spaciousness. Other dimensions were clarity, loudness, smoothness, nearness, and brightness. The type of listening environment (audiometric test booth, living room, and music/lecture hall) did not affect the preference for bilateral hearing. For listening to music there was an overall preference for bilateral listening.

Erdman et al. (1981) analysed the subjective preferences of 30 first-fitted hearing-impaired listeners. Eight subjects had asymmetrical hearing losses and 22 subjects had symmetrical hearing losses. The subjects wore unilaterally as well as bilaterally fitted hearing aids, for controlled periods of time. Bilateral fittings were preferred by 90% of the hearing-impaired listeners. The most frequently cited advantage of bilateral amplification was improved speech clarity, followed by: stereo effect, balanced hearing, better overall hearing, relaxed listening, and better speech clarity in noise. The most frequently cited disadvantage was problems to balance volume controls, followed by increased ambient noise.

In a study of Anderson et al. (1996) no clear subjective differences were found between a group with unilateral and a group with bilateral fittings. 76 Consecutive patients (47 fitted unilaterally 29 fitted bilaterally) were asked to participate by answering questionnaires about their hearing aids. The scorings were made on a visual analogue scale with a daily registration for the period of one week, but only part of the results were related to the benefit of bilateral hearing aids. 53 Responses were useful and showed significantly less disturbance of sounds for the bilaterally fitted group.

Stephens et al. (1991) investigated the acceptance of two hearing aids. By randomly assigning one or two hearing aids to 29 subjects and by reversing this procedure in a crossover design, they determined the reasons why people chose for two hearing aids. These reasons were primarily acoustical. Clarity of sound, better localization, and improved loudness were the most frequently mentioned reasons to choose for two hearing aids. The reasons for people to choose for one hearing aid were less obvious. Among them are user convenience and some psychological reasons.

Yueh et al. (2001) found that bilaterally fitted programmable hearing aids with directional microphones were subjectively more effective than bilaterally fitted conventional hearing aids with omnidirectional microphones in terms of ease of communication, speech perception in noise and reverberation, hearing aid use, quality of life, and willingness to pay. However, in this study no direct comparison is made between unilateral and bilateral fittings.

Chung and Stephens (1986) describe a subjective method with 200 subjects. Results of the questionnaire are the following:

- Women appear to reject bilateral fittings more often than men.
- Subjects with asymmetrical hearing losses use their two hearing aids twice as much as subjects with symmetric hearing losses. This suggests that the hypothesis that bilateral adjustments only work for people with symmetrical hearing loss is incorrect.
- Hearing-aid users, who receive more additional help, use their aids more often than those without. The use is also higher for subjects with moderate to severe hearing loss. Besides, the frequent users show a better localization of sounds.

Subjective experiences can be analysed by means of questionnaires but also with paired comparisons. In a study of Naidoo et al. (1997), subjects listened to connected discourse in quiet and in noise and made judgements in a paired-comparison paradigm. In another experiment they rated different situations on a scale from 0 to 10. An improved sound quality and speech intelligibility due to the second hearing aid was shown in conditions with high noise levels, for subjects with symmetrical sensorineural hearing losses.

Because the subjective outcomes can be very diverse, the results emerging from the "additional literature" have been summarised below. Advantages mentioned are:

- Improvement of hearing, especially in situations with one single sound source (Brooks et al., 1981, 1984).
- Improvement in the pleasure of life and improvements of the subjects' social life (Brooks et al., 1981).
- Better speech discrimination, especially in noise (Markides, 1982[b], McKenzie, 1990).
- Improvement of the localization ability (Markides, 1982[b]).

Disadvantages mentioned by subjects are:

- More background noise, especially from wind noise (Brooks et al., 1981).
- In situations with poor S/N ratio hearing aid users with two hearing aids indicate no advantage over the use of one hearing aid (Brooks, 1984).

One of the few studies not showing a bilateral benefit is that of Robillard and Gillain (1996). The conclusion of their satisfaction survey is that bilateral fittings are not superior to unilateral fittings for different listening situations. Therefore, the authors recommend a better utilisation of bilateral aids with professional follow-up as well as an increased use of in-the-ear hearing aids.

3.3.3. Other factors

<u>*Deprivation effect*</u>

One aspect frequently described in the selected articles is the occurrence of a deprivation effect. When the hearing organ is stimulated insufficiently, speech discrimination ability can deteriorate gradually. People that have been fitted unilaterally and who have bilateral hearing losses develop a deprivation effect in the unaided ear.

Gelfand et al. (1987) described the long-term effects of unilateral, bilateral or no amplification in subjects with bilateral sensorineural hearing losses. They compared audiometric thresholds and speech scores for phonetically balanced (PB) words with results obtained 4-17 years later. Speech recognition scores were not significantly different in both ears for the bilaterally fitted subjects and for the subjects not wearing hearing aids. However, in adults with a unilateral hearing aid fitting, speech recognition performance for the unaided ear was decreased significantly. This might be attributed to the deprivation effect. Silman et al. (1984) also used the deprivation effect as starting point for his research. They investigated whether deprivation occurs and if it can be found after a long-term follow-up. 44 Adults with bilateral sensorineural hearing losses were fitted unilaterally with hearing aids and 23 with bilateral aids. For all of these subjects data about auditory functioning were obtained prior to the hearing aid evaluation, at the time of the hearing aid evaluation, and 4-5 years after the evaluation. The most important result is that there were significant differences between initial and follow-up speech-recognition scores only for the unaided ears of the unilaterally fitted group. The authors indicate that this is an auditory deprivation effect that was not found in the bilaterally fitted group. Age and hearing sensitivity factors were partial led out. So, these factors could not have influenced the conclusions. A third study is the work of Silman et al. (1993), who investigated both auditory deprivation and acclimatisation. To investigate both aspects, 19 adult subjects were fitted unilaterally, 28 bilaterally and there were 19 matched control subjects. All of them had a bilaterally symmetrical sensorineural hearing impairment. Their speech recognition ability was tested by three different tests (W-22 CID, nonsense syllable test (NST), speech-reception-in-noise (SRT)). They were initially tested six to twelve weeks following the hearing aid fitting. After one year, the follow-up test was performed. The results of the latter test showed a slight improvement in speech perception in the aided ear, in comparison with the initial test, and a larger decrement in the unaided ear. This was visible in the W-22 test as well as in the NST test. The improvements in the aided ear can be regarded as acclimatisation to amplification at the aided ear; the decrements can be ascribed to auditory deprivation at the unaided ear. The difference in magnitude suggests that more time is needed for a significant acclimatisation effect in the aided ears of both the unilaterally and bilaterally aided groups than for an auditory deprivation effect in the unaided ears of the unilaterally aided group.

In the "additional literature" it is stressed that the occurrence of deprivation is a reason to choose for two hearing aids. Hurley (1999) found that word recognition scores deteriorated in the unaided ear after 5 years of hearing aid use for 25% of the unilaterally fitted subjects. Although there can be some recovery from deprivation, there are also cases known where the auditory deprivation effect is not reversible (Gelfand, 1995). In contrast to other investigators, Jauhiainen (2001) found no indications for the onset of auditory deprivation in unaided ears.

Age

Only adults have been included in the studies included in this review, but in most experimental groups large age differences exist that may have played a role in the assessment of the benefits of two hearing aids. To find out if age is of any importance, Hurley (1998) investigated the decrease (if any) in word recognition score over time in the unaided ear in unilaterally fitted adults with bilateral symmetric sensorineural hearing losses. If such a reduction in recognitions scores exists, is the decrease in the same order of magnitude for older and younger adults? The forty subjects included in this study were divided into two age groups (60-65 years old and 39-45 years old). In every group, ten subjects were fitted bilaterally and ten were fitted unilaterally (right ear). The results show that there is a perceptible decrease in speech scores for the unaided ear over a period of five years. The magnitude of the unaided ear effect (or deprivation effect) does not appear to be related to age. There was no significant difference between the older and younger adults.

The results of Helfer (1992) are only indirectly related to the focus of this review. She described the influence of ageing on the binaural advantage in reverberation and noise. Eighteen subjects (9 young normally hearing adults and 9 older adults with little or no hearing loss) listened to eight versions of the CUNY Nonsense Syllable Test (NST) in a randomized order. There were four different conditions: in quiet, in noise, in reverberation, and in a combination of reverberation and noise. These four conditions were presented monaurally as well as binaurally via insert earphones. Results applicable for this review are that binaural listening leads to better scores in all four conditions, although only significantly better in the noise situation. The fact that the differences in the other situations are not significant could be due to the high-frequency accent of the NST stimuli. Another result was that older and younger subjects did not differ in the amount of benefit of the bilateral condition.

On the other hand, there is some circumstantial evidence that age may play a role. Older people experience more benefit from two hearing aids than younger people do, according to Day et al. (1988). But Davis and Haggard (1982) found that the differences between speech intelligibility scores with one and two hearing aids decrease with age.

<u>*Hearing aid circuit*</u>

A completely different approach to determine the bilateral advantage is the research done by Naidoo (1997). He investigated whether the type of hearing aid circuit influences the preference for unilateral or bilateral fittings. For this purpose, he compared five different hearing aid circuits. In his first experiment (paired comparison test), 73 percent of the subjects indicated a preference for bilateral fittings with regard to sound quality. These preferences were dependent on the hearing aid circuit. In most cases there was a bilateral preference (highest for hearing aids with K-amp), but for asymmetric peak clipping unilateral fittings were preferred. In his second experiment the subjects rated the sound quality of the K-amp significantly higher with two hearing aids than with one. With regard to speech intelligibility in quiet and in background noise all hearing aids scored better when fitted bilaterally than unilaterally, except for hearing aids with a Manhattan II circuit.

Moore et al. (1992) showed that independent compression by two hearing aids does not necessarily degrade the use of binaural cues for speech perception with a spatial separation between the speech and the noise. This is in agreement with the results of Novick et al. (2001), who found no significant effects of the release time of bilaterally fitted compression aids in different acoustical environments.

Fitting strategies

For the fitting of bilateral hearing aids, Punch et al. (1991) evaluated the effects of bilateral hearing aids according to three different fitting strategies to fit the second hearing aid to the subject. The reasons for fitting subjects bilaterally are restoration of symmetry, improvement of speech perception and sound localization, and to achieve more natural hearing. In their study, 17 subjects with symmetrical hearing losses participated. They performed intelligibility estimation and horizontal localization in the laboratory and filled out a questionnaire about the benefits in real world situations. The differences in fitting strategies did not reveal significant differences in preference.

Haggard (1982) points out the importance of binaural loudness summation. For equal loudness the gain in bilaterally fitted hearing aids can be reduced by 6 – 10 dB relative to a unilateral hearing aid fitting. In addition, it is important to realize that the binaural uncomfortable loudness level is on average 5 dB less than the unilateral uncomfortable loudness level.

3.4. Discussion

This review underlines the fact that there are important methodological limitations in the field of Audiology that affect the methodological quality of the papers needed for a systematic review. Probably the most important problem is the lack of (double) blinding. For the fitting of hearing aids it is (almost) impossible to blind the subject as well as the hearing aid fitter. Randomization is also a difficult issue because a clinician has to take into account that every subject has its own audiological characteristics. Tests can easily be randomized, but the fitting must be adjusted to the individual needs. Bad fitting by a clinician can lead to unwanted biases. These factors often complicate the strict application of blinding and randomization in clinical audiology. Consequently, it is almost impossible to obtain high scores on the quality scale Chalmers that we applied or to follow the rules of a Randomized Clinical Trial. On the other hand, also in the audiological field it is important to strive to the best methodological quality that can be obtained. The use of crossover designs and/or well-matched control groups should be stimulated in our field of research.

Randomization of the tests and stimuli is rather important and can be implemented in a sound experimental procedure. Special attention should be given to the presentation of the stimuli. This is an important issue with regard to psychophysical research but there are other factors that should be taken into account.

- It is not clear to what degree the type of hearing aid (BTE or ITE) influences the results.
- There are no strong indications that the benefits of bilateral hearing aids differ from modern hearing aids and from conventional hearing aids. But for fast adapting signal processing schemes binaural cues may get lost.
- Also the time to get used to the hearing aid is important. The acclimatisation period can influence the results.

- Finally, the duration of an experiment is of major importance. If an experiment takes too long, the concentration of the listener will reduce and this can have an effect on the outcome.

To set up a valid trial, all the above-mentioned aspects should be carefully taken into consideration and should be described well in the resulting paper.

Although there are some discrepancies between studies, there is material evidence that bilateral hearing aids provide clear benefits for most bilaterally hearing-impaired subjects. These benefits are found in the field of objective performance measures (speech perception in quiet, in noise, and with separated sound sources and in horizontal localization) as well as in the field of subjective outcome measures (sound quality, clarity of sound, subjective speech perception, overall preference, etc). Usually, subjective research is based on larger populations than objective research and sometimes the effects appear to be larger than in terms of performance measures. On the other hand the subjective measures can be biased by the fact that blinding could not be applied. Fortunately, most objective and subjective results are in close agreement, e.g. the subjective results of Yueh (2001) with the objective results obtained by Hawkins and Yacullo (1984) obtained with performance tests.

Most studies in this review regard hearing-impaired listeners with symmetric hearing losses. Theoretically, subjects with symmetrical bilateral hearing losses can benefit most from wearing two hearing aids and for these subjects their advantage can be predicted to a certain extent (Haggard et al., 1982). These predictions are based on several types of binaural interaction: frequency and intensity DLs (difference limens) and binaural summation of loudness. Davis and Haggard (1982) suggest the following approach for the selection of candidates for a bilateral fitting. First of all, the asymmetry for four frequencies (0.5, 1, 2, 4 kHz) should be assessed. If the difference between the two ears is less than 15 dB, a bilateral fitting is preferred. For differences between 15 and 30 dB, further investigation is needed and above 30 dB bilateral adjustment is not recommended. Dillon described a rule of thumb for unilateral fittings: "Fit the ear that has the four-frequency average threshold (PTA at .5, 1, 2, and 4 kHz) closer to 60 dB (HL)".

It is striking that the advantages of a bilateral fitting with hearing aids have been described almost exclusively for these subjects. How about the people with unilateral or asymmetric losses? Do they profit from bilateral fittings? This aspect has been hardly discussed in studies, except for the study by Nabelek et al. (1980). Bronkhorst and Plomp (1989) found some indications that high-frequency gain in the poorer ear may be important to restore the use of Interaural Level Differences. More attention should be given to the important issue of asymmetrical hearing losses, because it is important for the criteria that should be used to fit hearing aids bilaterally.

However, not only the benefit from a bilateral hearing aid should be considered. Hearing aids have shown to be useful to avoid a deprivation effect. Therefore, bilateral amplification should be the first choice in cases of bilateral hearing loss. The opinion of Hurley (1993) is that each unilaterally fitted hearing-impaired subject should be tested periodically on the deprivation effect at the unfitted ear. If a deprivation effect is found and if this effect is reversible, it should be possible to obtain recovery within six months.

3.5. Conclusions

Although there are several methodological problems in this area of research, there is ample experimental evidence that people with bilateral sensorineural hearing losses profit more from bilateral hearing aids than from unilateral hearing aids.

The most important advantages are:

- There is an objective advantage of wearing two aids with regard to the head-shadow effect. This effect is inherent to the anatomy of the head.
- There is evidence for improvement in speech intelligibility in noise. The results of subjective surveys confirm the benefits measured in performance tests. Not only do hearing-impaired listeners indicate that their speech understanding is improved, they also point out that the clarity of sounds is better with two hearing aids.
- The generally accepted benefit to localize sounds better with two hearing aids than with one is an important factor. Especially subjects with moderate to severe hearing losses seem to have a considerable amount of benefit. The bilateral benefit for subjects with a slight hearing loss is limited. Subjectively as well as objectively, improvements in localization have been observed.
- The deprivation effect is adequately proven. For unilaterally fitted subjects, there is a risk that the residual capacities at the unaided ear will decrease. This is not really an advantage of bilateral but rather a disadvantage of unilateral fittings.

All these advantages are significantly proven in the literature presented in this review. But most of the data refer to subjects with symmetrical hearing losses. Therefore, an interesting field of research would be the other groups of hearing-impaired subjects.

CHAPTER 4.

THE BENEFITS OF BILATERAL HEARING AIDS II:

A retrospective study

This chapter is submitted to Int.J.Aud. (Boymans et al., 2003[a])

4. Retrospective analysis of the benefits of bilateral hearing aids

<u>Summary</u>

This study describes the outcomes of a retrospective analysis of the results for hearing aid prescription in eight Dutch Audiological Centres. In total 1000 clinical files of consecutive hearing aid approvals in 1998 have been investigated. Three categories of data have been collected from clinical files: anamnestic data, audiometric data, and rehabilitation data.

With respect to the fitting practices most bilateral fittings were found for rather symmetrical hearing losses, but also for asymmetries, up to 30-40 dB, bilateral fittings were applied. The percentage of bilateral fittings was 60% and this percentage proved to be almost independent of age and independent of hearing loss, except for small hearing losses in which the better ear was too good for fitting a hearing aid. More bilateral fittings were also found for the group of repeated fittings. However, there is a lot of scatter in the audiological data. So criteria for a successful provision of bilateral hearing aids cannot be derived from standard audiometric data only.

To investigate the benefits of one or two hearing aids after at least one year of practice all patients, involved in the investigation of the clinical files, were asked to fill in an extensive questionnaire. For this purpose a questionnaire was composed of parts of existing questionnaires, covering issues of detection, discrimination, speech intelligibility in quiet and in more difficult situations, localization, comfort of loud sounds, hearing aid use, auditory functioning, satisfaction, benefit, and handicap. 505 Questionnaires were returned and they have been used to evaluate the long-term effects. The subjective data of the questionnaires showed a clear benefit of the second hearing aid in the bilaterally fitted group for detection, localization, and for speech intelligibility in quiet. Even in more difficult situations with noise and/or reverberation significant benefits were found. The aversivess of loud sounds was not significantly worse than for the situation with one hearing aid.

Finally, the relations between objective parameters from audiometric and anamnestic data, and the subjective outcome measures, were analysed. One of the most important conclusions is that the bilaterally fitted group was more satisfied with the hearing aids than the unilaterally fitted group and with regard to the degree of residual handicap the distributions of outcome measures were about the same for both groups. Another conclusion is that hearing aid fitting in subjects with a relatively good ear is not less effective than hearing aid fitting in subjects with higher hearing losses. Furthermore, the group with more severe losses showed about the same satisfaction as the group with mild hearing losses. The repeated fitting group has a higher hearing loss, shows more satisfaction but has a higher residual handicap score than the first fitting group. In 1998 only a few digital hearing aid models were available, but the scores for auditory functioning with digital hearing aids are relatively good.

4.1. Introduction

In the literature many advantages of a second hearing aid have been described (for more details see Chapter 3). Hawkins and Yacullo (1984) found a significant bilateral advantage independent of microphone type and reverberation time. The stimuli were played through earphones. Festen and Plomp (1986) found a better S/N ratio in subjects with two hearing aids than with one hearing aid for higher hearing losses ($PTA_{(.5,1,2\ kHz)}$ >60dB(HL)). A significant improvement in midplane localization performance for a second hearing aid, was found by Punch et al. (1991). This was measured in laboratory conditions, and the outcome measures of the questionnaires in a real life situation were in agreement with the above-mentioned result.

More subjective comparisons, of unilateral and bilateral fittings, were studied by Erdman et al. (1981). They asked the subjects to report the differences between the two modes of amplification after a trial period of 9 days in total. In case of a bilateral fitting more advantages than disadvantages were reported. The mostly mentioned subjective advantages were improved speech clarity, stereophonic effect, and balance in hearing.

Mostly mentioned disadvantages for a bilateral fitting were: difficulties to balance volume controls, increased ambient noise, and cosmetic concerns. Stephens et al. (1991) concluded that persons with worse hearing levels showed a higher improvement for localization with bilateral fittings than persons with better hearing levels. The former group preferred bilateral fittings and made their choice predominantly for acoustical reasons (clarity, localization, loudness). The persons with milder hearing losses showed less benefit from a bilateral fitting and the reasons for their choice were more varied. Balfour et al. (1992) showed a bilateral preference for mild and/or moderate hearing losses in a paired comparison study with recorded material. Judgements were made on eight separate quality dimensions. The bilateral preferences were strongest for speech in quiet and for the dimension fullness and spaciousness. Clarity was ranked as the most important feature.

Furthermore, Silman et al. (1984) found an auditory deprivation effect for speech recognition, for the unfitted ears of subjects with unilateral fittings after 4-5 years of hearing aid use. Gelfand et al. (1987) found also a significant decrease in speech intelligibility scores after 4-17 years for the unaided ears of unilaterally fitted subjects, while there was no decrease in PB scores for their aided ears. Also no decrease in speech intelligibility was found for the bilaterally fitted group, or for the unaided group. Gelfand (1995) described in a case study the recovery of the auditory deprivation effect. For some subjects, in which the deprivation effect developed within two years, the effect recovered completely, for some subjects the effect did recover significantly but not completely, and for some subjects the deprivation effect took several years to develop and did not recover after several years of bilateral fitting.

Many statements about bilateral fittings are based on work of 10 or more years ago. In the mean time hearing aid technology improved. Therefore, the present study investigates retrospectively the current application of bilateral fittings in eight Dutch Audiological centres, using modern hearing aids. The focus of this study is threefold:

- An inventory was made of 1000 clinical files, with respect to current fitting practices of hearing aids in the Netherlands, because the reasons and/or criteria for fitting one or two hearing aids are not always obvious. Many considerations seem to play a role both for the hearing-impaired person and for the hearing-aid prescriber. For example, a large asymmetry in hearing loss can be a contra indication for a bilateral fitting, but it is not clear to which limits. The key question in this part of the study is: What are current fitting practices in a large (multi-centre) clinical population and which are the audiometric characteristics of subjects fitted with one or two hearing aids?

- In addition, we investigated the subjective benefit of one and two hearing aids. For this purpose we applied an extensive questionnaire that was designed to focus on a variety of aspects related to disability and handicap due to hearing-impairment, and related to use, benefit, and residual handicap after fitting with one or two hearing aids. This study describes the subjective results obtained from a total of 505 returned questionnaires out of the same population of 1000 subjects described above. The key question is: what are the subjective outcome measures for the unilateral and bilateral fittings?
- Finally, we combined the subjective results of the populations with unilateral and bilateral hearing aids with the anamnestic and audiometric data from the clinical files. In this analysis we will focus on the differences for specific subgroups in order to answer the key question: How are the relations between subjective judgements on the one hand and anamnestic and audiological data on the other?

4.2. Method

4.2.1. Population

Eight Audiological Centres participated in this retrospective study regarding the fitting results of the hearing aid population in the Netherlands. They are representative for Audiological Centres in the Netherlands and all centres are members of the foundation PACT, the Platform for Audiological and Clinical Testing. PACT was established as a platform for independent clinical research related to the use of hearing aids. As a representative sample of the hearing aid fittings, each audiological centre selected clinical files of 125 consecutive hearing aid approvals in 1998.

4.2.2. Investigation of the clinical files

To characterize the populations with unilateral and bilateral fittings, three categories of data have been extracted from the clinical files.

- Anamnestic data like gender, age, and hearing aid experience.
- Audiometric data like pure tone audiogram and speech audiogram. The speech discrimination as a function of level was measured with CVC-words according a standardized procedure used in the Netherlands. (Bosman, 1989).
- Rehabilitation data like type of hearing aid, unilateral/bilateral, and the duration of the trial period.

4.2.3. Questionnaires

To investigate the benefit of one or two hearing aids after at least one year of practice, all patients, involved in the investigation of the clinical files, were asked to fill in an extensive questionnaire. The questionnaire consisted of different components. First some general questions were asked, for example about the intensity of hearing aid use and about the communication intensity. Parts of existing questionnaires were included like the Hearing Handicap and Disability Inventory (HHDI, van den Brink, 1995), the Amsterdam Inventory of Auditory Disability and Handicap (AIADH, Kramer et al., 1995), questions about aversiveness of loud sounds and about situations with reverberation from the Abbreviated Profile of Hearing Aid Benefit (APHAB, Cox et al., 1995), and the seven questions of the newly developed International Outcome Inventory for Hearing Aids (IOI-HA, Cox et al., 2000). In addition we asked about the reasons why the patients used one or two hearing aids. The AIADH and APHAB questions were asked for the situation without a hearing aid, with one hearing aid, and with two hearing aids (if applicable). Unpaired T-tests were used to measure the significance between the differences of the unilaterally fitted group and the bilaterally fitted group. The significance of the differences between the subjective results with one and with two hearing aids in the same subjects was tested by paired T-tests.

4.2.4. Relations between data from clinical files and the subjective results

A nonparametric correlation technique (Spearman's r) was used to calculate the correlations between the most important parameters from anamnestic and audiologic data, and from outcome measures of the questionnaires. To investigate the different relations between the results from the questionnaires and the data from the clinical files, we used a multiple linear regression technique to predict different outcome measures as dependent variables by a selected set of audiometric and anamnestic parameters as independent variables. In addition, subgroups have been defined in which the average values of input and output variables have been compared. The subgroup profiles indicate the deviations of each subgroup relative to other subgroups and to the total group regarding to age, the degree of hearing loss, and the percentage of bilateral fittings. The results profiles present the mean results per subgroup (as far as the data are available): an index for the use of the hearing aids, the total score of auditory functioning (AIADH and APHAB), the benefit of the second hearing aid (if applicable), the average satisfaction (based on IOI-factor 1), and the experienced handicap (based on HHDI). The significance of the differences between subgroups has been tested with unpaired T-tests.

4.3. Results

Clinical files of in total 1000 patients are investigated (508 men and 492 women). The patients were fitted with either one or two behind-the-ear (BTE) or in-the-ear (ITE) hearing aids. The average age was 64 years old. As expected, the age groups between 65 and 85 years are over-represented.

4.3.1. Fitting results, information from the clinical files.

587 Subjects were fitted with two hearing aids (bilaterally). 413 Subjects were fitted with one hearing aid, but in 7 of these subjects a CROS or biCROS fitting was applied. The latter fittings were regarded as unilateral fittings, because the sound presentation was to one ear only (in all of these subjects the hearing loss at the better ear was worse than 30 dB (HL)).

Anamnestic and rehabilitation data.

Age appeared not a factor of importance with respect to the distribution of bilateral and unilateral fittings: about 60% of every age decade was fitted bilaterally. In 36.5 % of the cases the fitting concerned a first fitting and in this subgroup about half of the patients were fitted unilaterally. For the group of experienced users, 36% of the unilaterally fitted users decided to change to two hearing aids. Most of the patients that were used to wear two hearing aids continued to do so. Only 12% of them changed from two to one hearing aid.

In our population BTE fittings were much more frequent than ITE-fittings (85% and 15%, respectively). To classify the different hearing aids three categories have been chosen: conventional analogue, advanced analogue (like multi-program hearing aids and multi channel compression aids), and digital hearing aids. In 1998 only a few types of digital aids were on the market. In the test population only 14% digital hearing aids were prescribed, and 86% analogue hearing aids (69% conventional and 17% advanced).

The duration of the trial periods was typically between 2 to 4 months. Sometimes the duration was considerably longer. There were no clear differences between the duration of the trial periods for unilateral or bilateral fittings; on average 15.2 and 15.0 weeks, respectively.

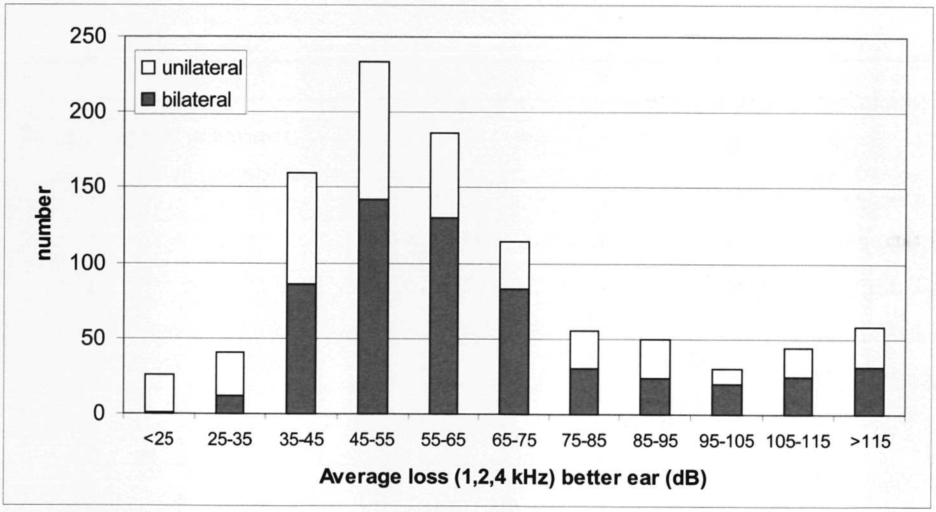


Fig. 4.1. Cumulative histogram for the numbers of unilateral and bilateral fittings for the total group for different hearing losses at the better ear (average 1,2,4 kHz).

<u>*Audiometric data*</u>

Figure 4.1 shows the absolute numbers of unilateral and bilateral fittings as a function of the average hearing loss at the better ear. For mild hearing losses relatively more unilateral fittings than bilateral fittings are found. For larger hearing losses more bilateral fittings were found, ranging from 40% to 69%.

Figure 4.2 represents the absolute difference between both ears for the groups with unilateral and bilateral fittings. Most bilaterally fitted patients have a rather symmetric hearing loss, but bilateral fittings were also found for asymmetrical losses with interaural differences up to 30-40 dB. The average asymmetry between both ears for unilateral fittings is 22.2 dB (±23.0) and for the bilateral fittings 8.0 dB (±8.7).
In the unilateral fitted group 44 % of the hearing losses was symmetrical (± 10dB), and in 65% of the remaining cases the hearing aid was fitted on the better ear.

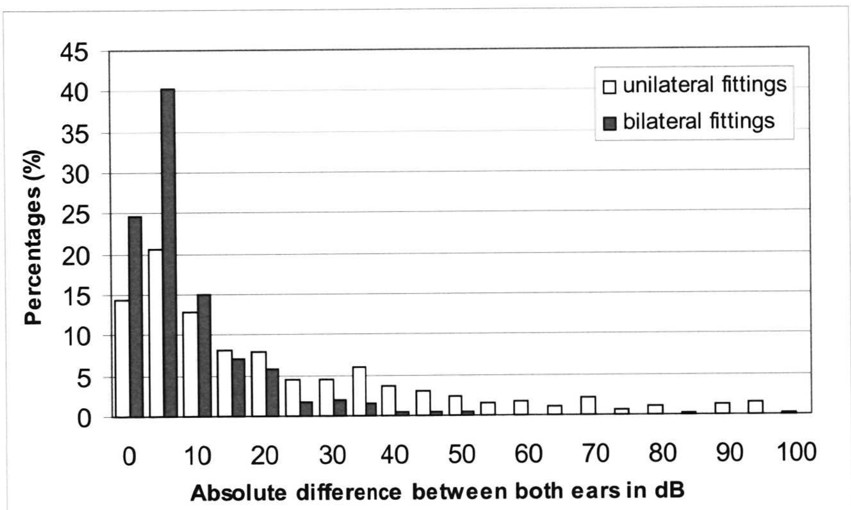


Fig. 4.2. The absolute difference between the PTA's $_{(1,2,4\ kHz)}$ of both ears for the groups with unilateral and bilateral fittings.

For the unilaterally fitted subjects the average hearing loss (.5, 1, 2, 4 kHz) of the right ear (x-axis) is plotted against the average hearing loss of the left ear (y-axis) in Figure 4.3a and 4.3b (for right-ear-fittings and left-ear-fittings, respectively). In both figures a clear asymmetry is shown.

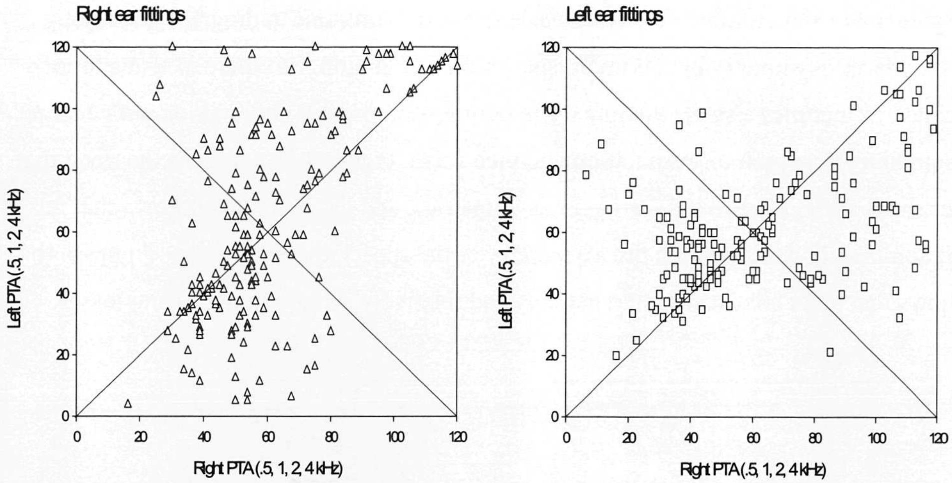


Fig. 4.3. Scatter plots of the average hearing losses (.5, 1, 2, 4 kHz) on the right ear (x-axis) and the left ear (y-axis) for subjects with right-ear-fittings (Panel a) and left-ear-fittings (Panel b).

The figures show a preference for unilateral fittings at the better ear for large hearing losses (panel a: upper triangle, panel b: right-hand triangle), but for small and moderate hearing losses also unilateral fittings have been realized at the poorer ear (panel a: lower triangle, panel b: left-hand triangle). However there is a lot of scatter in the individual data. The diagonal lines will be discussed in the Discussion Section.

In Figure 4.4 the asymmetry in tone audiogram (in dB) is compared with the asymmetry in maximum speech discrimination loss (in %). On the horizontal axis the tone-audiometric differences of the right and the left ear are plotted (average hearing losses at 1, 2, and 4 kHz). On the vertical axis the differences of the right and the left ear are plotted for loss in maximum speech discrimination. In Figure 4.4a the results are shown for the unilaterally fitted group (circles for the right fitted ear, crosses for the left fitted ear) and in Figure 4.4b for the bilaterally fitted group (triangles).

Figure 4.4a shows a trend that a large asymmetry in pure-tone audiogram goes along with a large asymmetry in maximum speech discrimination. But there is also a lot of scatter. Sometimes a small asymmetry in pure-tone audiogram goes along with a large asymmetry in speech discrimination and vice versa. Figure 4.4a confirms the trend that better-ear fittings are found for larger asymmetries, and the figure also shows that this is predominantly dependent on the asymmetry of the speech discrimination. Figure 4.4b shows that most bilaterally fitted patients had relatively symmetrical hearing losses.

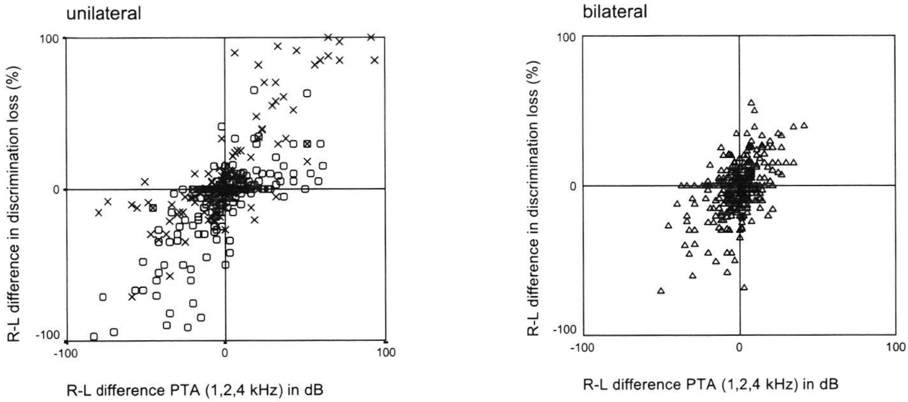


Fig. 4.4. Scatter plots of the differences of the right and the left ear for the average pure-tone hearing loss (1, 2, and 4 kHz) in dB (x-axis), versus the differences of the right and the left ear for the loss in maximum speech discrimination in % (y-axis). Panel A: for the unilaterally fitted group (circles for the right fitted ear, crosses for the left fitted ear) and panel b: for the bilaterally fitted group (triangles).

In our population most hearing losses have a sensorineural origin (75 %). In 25 % of the cases a conductive component is present, usually resulting in mixed hearing losses. The choice between a unilateral or bilateral fitting was clearly influenced by the kind of hearing loss. For purely sensorineural hearing losses the percentage bilateral fittings is 63%. When there is conductive component at least at one ear, this percentage decreased to 48%.

4.3.2. Subjective results / questionnaires

An extended questionnaire has been sent to the group of 1000 patients described before. 505 Returned questionnaires were applicable for processing (50.5% response).

Figure 4.5a shows the distributions of age over different age decades for the total group (n=1000) and for the response group (n=505). There are relatively fewer responses in the group 20-30 years and the group 90 – 100 years than in the middle group. But the distribution of age over the different age decades is not significantly different between the total group and the response group.

Figure 4.5b shows the same trend for both groups with respect to the distribution of the average hearing loss at the better ear. Only the patients with a severe hearing loss are relatively less well represented in the response group than in the total group. This leads to a small but significant ($p<0.001$) difference for the average hearing losses in both groups (59 dB for the response group and 62 dB for the total group). However, both figures suggest that the response group is a representative sample of the total group with respect to age and hearing loss. Also the distributions of unilaterally and bilaterally fitted patients are in agreement. In the total group 59% of the patients were fitted bilaterally and 41% unilaterally versus 58% bilateral and 42% unilateral fittings in the response group.

Part of the questionnaires is devoted to reasons why the patient himself/herself chose for one or two hearing aids. This was partly an open question. In the group of 210 unilaterally fitted patients 410 times a reason was mentioned to choose for a unilateral fitting. The choice of one hearing aid is frequently based on the residual capacity of the other ear that is still relatively good (70x) or just worse (73x). Also using the telephone with the other ear can be a reason to choose for one hearing aid (43x), or problems with the own voice when fitted bilaterally (39x).

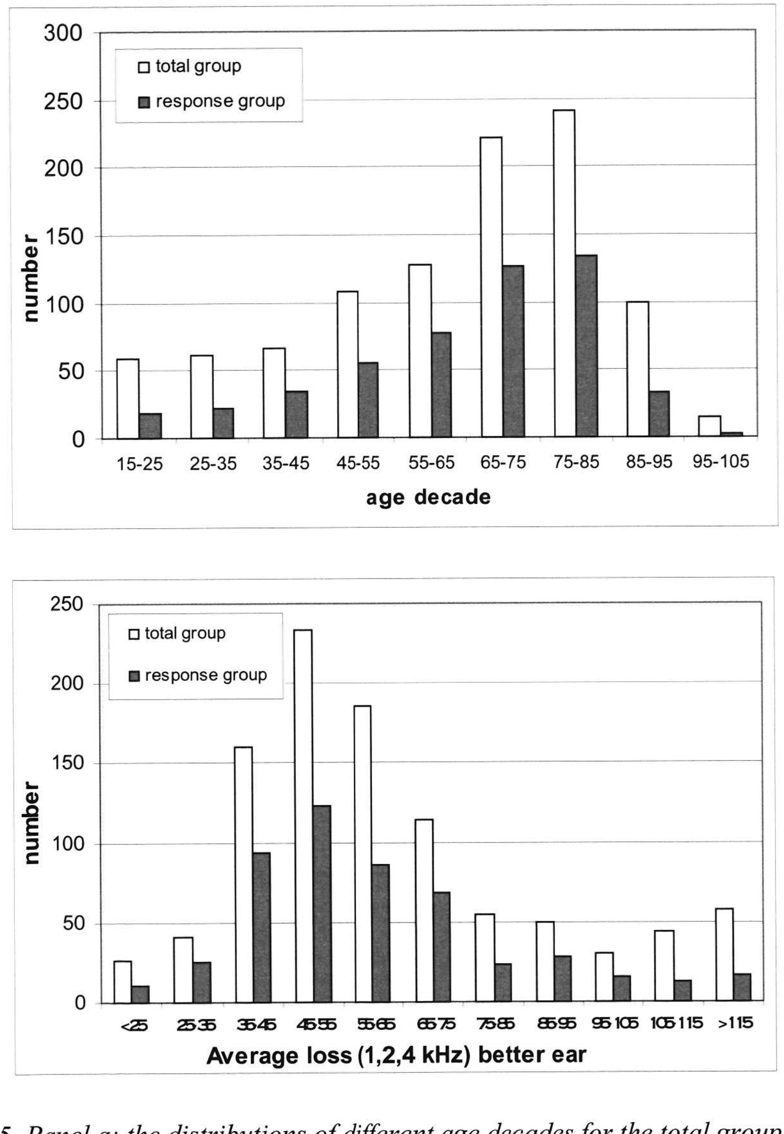


Fig. 4.5. Panel a: the distributions of different age decades for the total group and the response group. Panel b: the distributions of the average hearing loss at the better ear for the total group and the response group.

In the group of 295 bilaterally fitted patients 690 times a reason was mentioned to choose for a bilateral fitting. Obviously, the quality of sound is mentioned as the most important reason (150x). Other reasons like the balance between ears, better localization, and listening to both sides occur in about the same numbers (90x-110x). In only one case it is mentioned that two hearing aids are chosen to stop further deprivation.

Frequency of use of the hearing aid(s)

The patients were asked questions about the frequency of use for the right and the left hearing aids separately. 488 of the 505 patients answered these questions. Therefore, it was possible to assess the frequency of use in three groups: patients fitted unilaterally (n=199), patients fitted bilaterally wearing both hearing aids equally frequent (n=242), and patients fitted bilaterally but wearing one hearing aid more frequently than the other (n=47).

The use of hearing aids for bilaterally fitted patients is slightly higher than for unilaterally fitted patients. 74% Of the bilaterally fitted patients, wearing both hearing aids equally frequent, are wearing the hearing aids for 8 hours or more versus 62% of the unilaterally fitted patients.

In the group of 47 bilaterally fitted patients wearing one hearing aid more frequently than the other, 74% wear only one hearing aid for 8 hours or more, but the use of the second hearing aid is obviously lower.

Twelve hearing-impaired patients (9 unilaterally and 3 bilaterally fitted patients) indicated not to wear the hearing aids at all. Besides, 16 bilaterally fitted patients did not wear the second hearing aid complementary to the first hearing aid. So 31 hearing aids were not used; this is 4% of the total of 777 prescribed hearing aids in the response group. We could not find a systematic relationship between the degree of the hearing loss and the non-use of the hearing aid. Likewise, it can be calculated that 27 hearing aids were used for less than 1 hour a day. This, however, should not be interpreted as inefficient use because selective use can be of great value in specific situations.

Handicap and satisfaction

Ten questions about the degree of handicap according the HHDI (van den Brink, 1995) were part of the questionnaire. The parameter derived from these questions reflects the degree of handicap experienced with hearing aids, ranging from 0 to 3 (lower scores are more favourable). The differences between unilaterally fitted and bilaterally fitted patients were not significant.

	Unilaterally fitted subjects	**Bilaterally fitted subjects**
HHDI-score for Handicap *(on a scale from 0 - 3)*	1.14 ± 0.69	1.10 ± 0.68
IOI-factor 2 *(reverse score for Residual Handicap; scale from 1 - 5)*	3.62 ± 1.00	3.74 ± 0.87
IOI-factor 1 *(Satisfaction; scale from 1 - 5)*	3.23 ± 1.14	3.44 ± 1.07*

* p<0.05 ** p<0.01 ***p<0.001

Table 4.1. Average scores (± st.dev) for handicap and satisfaction indices in two subgroups: patients with a unilateral fitting (n=194) and patients with a bilateral fitting (n=289). The indices presented are the HHDI scores for handicap and the IOI-subscores: IOI-factor 2 (the reverse of the residual handicap) and IOI-factor 1 (for satisfaction). For HHDI a lower value indicates a better result, while for IOI factors lower scores indicate a worse result. The significance of the differences between the groups is indicated by asterisks (unpaired T-tests).

To measure the residual handicap of the hearing aid user, also three questions of the IOI-questionnaire (Cox et al., 2000) have been used. The results of the IOI-factor 2 correspond closely to the results of the HHDI described above, but for the IOI-factor 2 the scale ranges from 1 to 5 and higher scores are associated with less residual handicap (more favourable). Three other questions are related to the benefit or satisfaction of the hearing aid and are combined in the IOI-factor 1 (on a scale from 1 to 5; see also Kramer et al., 2002). The bilaterally fitted group is significantly more satisfied with the hearing aids than the unilaterally fitted group ($p<0.05$). In Table 4.1 the results have been summarized.

Auditory disabilities

To investigate the subjective judgements of functioning without a hearing aid, with one hearing aid, and with two hearing aids, subscales of AIADH (Kramer, 1995) and APHAB (Cox et al., 1995) have been applied. On the basis of 28 questions, 7 categories were composed in which auditory functioning was measured in the next situations: detection of sounds (5 questions), discrimination or recognition of sounds (1 question), speech intelligibility in quiet (5 questions), speech intelligibility in noise (5 questions), speech intelligibility in reverberation (1 question), directional hearing or localization (5 questions), and comfort of loud sounds (6 questions). For each patient and each category the mean scores were calculated only when more than 50% of the questions in that particular category had been answered. All scales range from 1 to 4. The results of the subjective judgements are presented in Figure 4.6 for all seven categories. The average results of unilaterally fitted patients (n=210) and bilaterally fitted patients (n=295) are plotted separately. Higher values always correspond with a better result.

In the group of 210 unilaterally fitted patients (Figure 4.6a) the benefit of a hearing aid can be derived from the difference between the bars without hearing aid and with one hearing aid. Higher grey bars indicate a positive effect of the hearing aid. This is for all categories clearly present, except for the comfort of loud sounds (last two bars). It is remarkable that clear benefits are also found for difficult listening situations (noise and reverberation). The benefit of one hearing aid for localization is only marginal and wearing a hearing aid causes clearly more aversiveness for loud sounds.

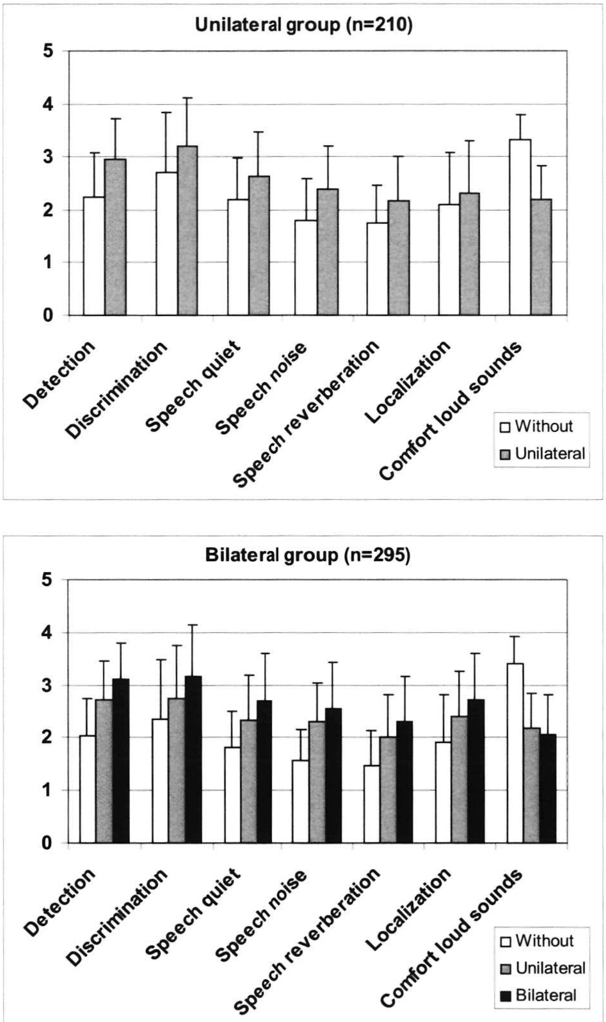


Fig. 4.6. Panel a: the average results of the subjective judgements (according AIADH and APHAB), without and with one hearing aid, for all 7 categories for the unilaterally fitted patients (n=210). Panel b: the average results of the subjective judgements (according AIADH and APHAB), without, with one, and with two hearing aids, for all 7 categories for the bilaterally fitted patients (n=295). All scales range from 1 to 4. The higher the bars, the more positive the result.

For the group of 295 bilaterally fitted patients the results are presented similarly in Figure 4.6b. Again, the benefits of a hearing aid can be derived from the differences between the bars without (open) and with one hearing aid (grey). Although different populations are involved the average effects for the unilaterally and bilaterally fitted patients are in close agreement. In this study, the effect of a second hearing aid is especially important. For this purpose the differences between the scores with one (grey bars) and two hearing aids (black bars) in the group of 295 bilaterally fitted patients can be compared. Despite the fact that some individual scores for specific situations were worse for two than for one hearing aid, the mean results for the whole group (including the patients with bad experiences) show a predominantly positive effect. Improvements of the mean scores were found for all categories except for comfort of loud sounds. The disadvantage of wearing a second hearing aid is that the comfort of loud sounds is somewhat worse for two hearing aids than for one hearing aid. This effect is obviously smaller than the effect of the first hearing aid compared to the situation without a hearing aid.

Only a minority of the patients answered all questions for the situations without, with one, and with two hearing aids. This means that the group results are based on varying numbers of subjects. Consequently, the trends may not be representative for the average effects in the individual hearing-impaired subject. That is the reason why a separate analysis was done on a subset of respondents who did answer all questions. This concerns 75 unilaterally fitted patients and 49 bilaterally fitted patients. In each of these groups paired t-tests were used to investigate the significance of the differences. For both groups the scores with one hearing aid were significantly higher than without a hearing aid ($p<0.001$) for all categories except for comfort of loud sounds for which significantly lower scores were found ($p<0.001$). This implies that a hearing aids leads to significant improvements in six out of seven categories.

In addition, we found significant improvements with two hearing aids relative to one hearing aid in the bilaterally fitted group with respect to detection ($p<0.001$), speech in quiet ($p<0.01$), speech in noise ($p<0.001$), speech in reverberation ($p<0.001$) and localization ($p<0.01$). Again the comfort of loud sounds was significantly lower ($p<0.001$).

Finally, the results of the unilaterally fitted group and the bilaterally fitted group are compared to one another using unpaired t-tests. For the comparable condition with one hearing aid the bilaterally fitted group rated significant lower scores than the unilaterally fitted group with respect to detection ($p<0.05$), discrimination of sounds ($p<0.001$), and speech intelligibility in quiet ($p<0.01$). However, a comparison of the final fitting results shows that the group of bilaterally fitted subjects scored significantly better with two hearing aids than the group of unilaterally fitted subjects with one hearing aid with respect to detection ($p<0.05$), localization ($P<0.001$), and speech in noise ($p<0.05$). This was accompanied by slightly lower scores for the comfort of loud sounds ($p<0.05$) for the bilaterally fitted group. Together these data explain partly why the satisfaction, as measured with IOI-factor 1, was significantly higher in the bilaterally fitted group than in the unilaterally fitted group ($p<0.05$, see Table 4.1).

4.3.3. Relation between subjective results and anamnestic and audiological data

In this section we will describe different relations between the clinical files and the questionnaires. Because the results are partly based on the questionnaires, this analysis includes only the group of 505 hearing-impaired in the response group.

First we investigated the correlations between the most important parameters from anamnestic and audiologic data and from outcome measures. In the total response group the following significant correlations were found:

- The frequency of hearing aid use is lower at higher age ($p<0.01$) and higher for larger hearing losses ($p<0.01$).

- A higher hearing aid use goes along with more satisfaction (IOI-factor 1, $p<0.01$) and more benefit of the second hearing aid ($p<0.01$).
- The benefit of the second hearing aid is positively correlated with the satisfaction ($p<0.01$).
- Average scores for auditory functioning are lower for higher hearing losses ($p<0.01$).
- Better auditory functioning goes along with less handicap ($p<0.01$) and more benefit of the second hearing aid ($p<0.01$).
- Higher handicap scores are found at higher ages ($p<0.05$) and higher hearing losses ($p<0.01$).

As indicated in the Methods section, we applied a multiple linear regression technique to predict different outcome measures as dependent variables by a selected set of audiometric and anamnestic parameters as independent variables. The following outcome measures were predicted: degree of hearing aid use, average auditory functioning, IOI factor 1 (related to benefit and satisfaction), and average handicap (HHDI). As independent variables we only included parameters that were not too closely interrelated with the other parameters in the set ($r<0.50$, i.e. less than 25% shared variance). The set consisted of the 10 parameters listed in the columns of Table 4.2. The results of a stepwise multiple linear regression are presented as rows in Table 4.2. For each of the outcome measures the rows show the (multiple) correlation coefficients and the independent variables included for the prediction. The +/- signs indicate the direction of the relationship and the *-symbols the significance.

Hearing aid use can be predicted to a very limited degree ($r=0.286$) by the independent variables and is mainly related to the factor first/repeated fitting and the degree of hearing loss at the better ear. The average score for auditory functioning is mainly determined by the degree of hearing loss at the better ear ($r=0.457$), but the prediction can be refined up to $r=0.552$ by adding five other variables. The IOI-factor 1 (related to benefit and satisfaction) does not show high correlations with the set of independent variables and consequently, it is hard to predict the benefit/satisfaction from anamnestic and audiological data. Finally, the handicap index HHDI is related to the intensity of communication, the degree of hearing loss at the better ear, age, and the asymmetry of the hearing loss (multiple r=0.448).

Outcome measures	R	Age	1 = first / 2 = repeated fitting	1 = BTE / 2 = ITE	1 = analogue / 2 = comp.an. / 3 = dig.	1 = with / 2 = without noisy environment	1 = high / 2 = low communication	PTA-better ear	Asymmetry tone audiogram	1 = cond. comp. / 2 = sensorineural	1 = unilateral / 2 = bilateral
Use	0.272		+***								
	0.286		+***					+*			
Avg aud functioning	0.457							-***			
	0.500							-***	-***		
	0.518						-**	-***	-***		
	0.532		-**				-**	-***	-***		
	0.541		-**		+*		-**	-***	-***		
	0.552		-**		+*		-**	-***	-***	-*	
IOI-factor 1	0.164									-***	
	0.205		+**							-***	
	0.225		+*							-***	+*
Avg handicap	0.322						+***				
	0.415						+***	+***			
	0.431	+**					+***	+***			
	0.448	+**					+***	+***	+**		

* p<0.05 ** p<0.01 *** p<0.001

Table 4.2. The results of a stepwise multiple linear regression for the response group to predict different outcome measures (dependent variables, first column) and the independent variables (predictors on the horizontal axis). For each of the outcome measures the rows show the (multiple) correlation coefficients (second column) and the independent variables included for the prediction. The +/- signs indicate the direction of the relationship and the asterisks the significance.

In addition, we analysed the effects for specific subgroups. For this purpose we defined so-called profiles, consisting of characteristic data about the hearing-impaired subjects in a specific subgroup (subgroup-profile) and the results obtained (results profile).

The subgroup profiles indicate the deviations of each subgroup relative to other subgroups and relative to the total group. The results profiles present the mean outcome parameters per subgroup (as far as the data are available).

Sub-group profile	Total	unilateral	(bi)CROS	bilateral
N of subjects	505	204	6	295
Avg. Age	64	64	66	65
PTA better	59	57	42	61*
% Bilateral	58%	0%	-	100%
Results profile				
Index for ha use	3.34	3.24	3.7	3.4
Avg. Aud. Functioning	2.96	2.9	2.73	3
Benefit 2nd ha	0.27	-	-	0.28
IOI-factor 1 (avg. satisfaction)	3.35	3.23	3.22	3.44*
Avg. Handicap score (HHDI)	1.12	1.13	1.33	1.1
* $p<0.05$ ** $p<0.01$ *** $p<0.001$				

Table 4.3. Average values of the general parameters for the total group (n=505) and for the subgroups with a unilateral, a (bi)CROS, or a bilateral fitting. The unilateral group is compared with the bilateral group. The significance of the differences between the groups, is indicated by asterisks (unpaired T-tests).

The average values of the total group are presented in the second column of Table 4.3. In the next three columns of Table 4.3 similar profiles have been presented for the subgroups of subjects with a unilateral, a (bi)CROS, and a bilateral fitting, respectively. Given the small number of subjects, we tested only the inter-group differences for bilaterally fitted subjects relative to unilaterally fitted subjects. In the bilaterally fitted group the average hearing loss is slightly higher ($p<0.05$) and the satisfaction scores are higher ($p<0.05$). The trend towards a higher use in the bilateral group (see Section 4.3.2) is only significant at $p<0.10$.

	Communication Intensity		Hearing loss			Max.speech discr.score	
Sub-group profile	high	low	mild	moderate	severe	>90%	≤90%
N of subjects	364	141	37	385	83	237	172
Avg. Age	62	71***	62	67	53***	66	67
PTA better	58	62	26***	54	100***	48	69***
% Bilateral	59%	58%	22%***	62%	58%	51%	63%**
Results profile							
Index for ha use	3.38	3.24	3.04	3.3	3.66**	3.17	3.47**
Avg. Aud. Functioning	3.02	2.78**	3.13	3.08	2.34***	3.2	2.81***
Benefit 2nd ha	0.29	0.23	-	0.29	0.18	0.39	0.2
IOI-factor 1 (avg. satisfaction)	3.4	3.24	3.11	3.39	3.32	3.3	3.35
Avg. Handicap score (HHDI)	0.98	1.49***	0.98	1.07	1.41***	0.97	1.28***
* p<0.05 ** p<0.01 *** p<0.001							

Table 4.4. Average values of the general parameters for the different subgroups based on anamnestic and audiometric parameters (Communication intensity, Hearing loss 'mild': PTA < 35 dB, 'moderate': 35 ≤ PTA ≤ 80, 'severe': > 80 dB, Speech audiogram). The group with a moderate hearing loss is compared with the group with a mild hearing loss, and with the group with a severe hearing loss. The significance of the differences between the groups is indicated by asterisks (unpaired T-tests).

<u>Anamnestic data</u>

We investigated differences in the result profiles for hearing-impaired patients with full-time or part-time *employments* (n=134) and hearing-impaired patients without a job or retired (n=354) (not shown in a table). There were hardly any differences between both groups. Patients without a job have slightly higher handicap scores (p<0.01) and – as expected - a clearly higher age (p<0.001).

The 2nd and 3rd columns of Table 4.4 show the profiles for the subgroups according to the *intensity of verbal communication* in daily life. The first group (high communication intensity) consists of patients with much verbal communication and/or patients who indicated to be active members of a club or a union. Patients in the second group (low communication intensity) are less involved in verbal communication situations. The subgroup profile shows that the group with less intensive communication has a higher age ($p<0.001$). The results profile indicates that subjects with less intense communication have more problems in auditory functioning ($p<0.01$), and they show higher handicap scores ($p<0.001$).

<u>*Audiological data*</u>

In the 4th, 5^{th,} and 6th column of Table 4.4 the effects of the *degree of hearing loss* are shown. The categories are based on the average loss at 1, 2 and 4 kHz for the better ear: mild (losses up to 35 dB, n=37), moderate (losses between 35 and 80 dB, n=385), and severe (losses higher than 80 dB, n=83), respectively.

The effect of a hearing aid for the hearing-impaired with a mild hearing loss is demonstrated by comparing the first group and the second group. In the group of mild losses the percentage of bilateral fittings is significantly lower ($p<0.001$). As a consequence the number of bilateral fittings was too small to assess the effect of the second hearing aid.

The effects of a hearing aid for patients with a severe hearing loss (higher than 80 dB) are demonstrated by comparing the second group and the third group. For the group with severe losses the average age is significantly lower, probably due to the participation of the Institute of the deaf as one of the Audiological centres. Although the hearing losses are (per definition) quite different, the percentage of bilateral fittings is about the same (see also Fig. 4.1). Subjects with severe hearing losses use their hearing aids significantly more frequently ($p<0.01$), their auditory functioning is significantly lower ($p<0.001$) and their handicap scores are significantly higher ($p<0.001$).

Subgroups have also been composed according *maximum speech discrimination scores* (7th and 8th columns in Table 4.4). The results of the analysis based on the speech audiogram are in agreement with the results based on the pure-tone audiogram. The average hearing loss for the group with poor speech discrimination (≤ 90%) is significantly higher than for the group with better discrimination scores (> 90%) and they are fitted more frequently bilaterally ($p<0.01$). The group with poor speech discrimination shows a significantly higher use of the hearing aids ($p<0.01$), a worse auditory functioning ($p<0.001$), and a higher handicap score ($p<0.001$).

	Fitting		Hearing aid		Technology		
Sub-group profile	First	Repeated	BTE	ITE	Conv. analogue	Adv. analogue	Digital
N of subjects	176	329	411	86	323	103	79
Avg. Age	67	63**	65	62	64	66	63
PTA better	47	66***	62	48***	61	57	56
% Bilateral	49%	64%***	59%	62%	55%	63%	66%
Results profile							
Index for ha use	2.96	3.55***	3.37	3.21	3.35	3.34	3.33
Avg. Aud. Functioning	3.24	2.80***	2.9	3.20***	2.89	2.96	3.21***
Benefit 2nd ha	0.22	0.28	0.26	0.33	0.2	0.54*	0.24
IOI-factor 1 (avg. satisfaction)	3.18	3.45*	3.39	3.26	3.39	3.29	3.27
Avg. Handicap score (HHDI)	0.95	1.20***	1.15	0.95*	1.14	1.17	0.96*
* p<0.05 ** p<0.01 *** p<0.001							

Table 4.5. Average values of the results profile for different subgroups based on fitting parameters (first/repeated fitting, hearing aid type, and hearing aid technology: 'Conventional analogue', 'Advanced analogue', 'Digital'). The conventional analogue group is compared with the advanced analogue group, and with the digital group. The significance of the differences between the groups is indicated by asterisks (unpaired T-tests).

Fitting results

In Table 4.5, three types of categorizations in subgroups based on fitting results have been applied. In the 2nd and 3rd columns the differences between patients with a *first* (first group) and a *repeated fitting* (second group) are shown. The average age for the repeated fitting group is lower than for the first-fitting group ($p<0.01$). Hearing aid users with a repeated fitting have a higher hearing loss ($p<0.001$), use their hearing aids more frequently ($p<0.001$), show lower scores for auditory functioning ($p<0.001$) and have higher handicap scores ($p<0.001$), but they obtain a higher satisfaction ($p<0.05$) and are fitted more frequently with two hearing aids ($p<0.001$) than firstly fitted subjects.
The next two columns divide the subgroups according to the *kind of hearing aid.* ITE-users have less hearing loss ($p<0.001$), show higher scores for auditory functioning ($p<0.001$), and have lower handicap scores ($p<0.05$) than BTE-users.

Finally, the group has been categorized according the *technology level of the hearing aids* (6th, 7th, and 8th columns for conventional analogue, advanced analogue, and digital, respectively). The differences of the subgroups with advanced analogue aids and with digital aids have been tested relative to the relatively large group using conventional analogue hearing aids.

There are no significant differences between the different "subgroup profiles". Nevertheless for the digitals (8th column) a significantly better auditory functioning is found ($p<0.001$) and a slightly lower handicap score ($p<0.05$) than for the standard analogue hearing aids (6th column). In the subgroup of advanced analogue hearing aids the benefit from the second hearing aid proved to be significantly higher ($p<0.05$).

4.4. Discussion

This retrospective study provides a thorough analysis of the fitting practice in eight Dutch Audiological Centres using state-of-the-art hearing aids. Special attention is given to the use of bilaterally fitted hearing aids. An inventory was made of 1000 clinical files, with respect to current fitting practices of hearing aids in the Netherlands. About 60% of every age decade was fitted bilaterally and 63.5% of the total group was a repeated fitting.

Current fitting practices show that the degree of hearing loss at the better ear appears to be relatively unimportant for the choice of unilateral or bilateral fittings (see Fig. 4.1), except for mild hearing losses (see Table 4.4). The most plausible reason is that in the mildly hearing-impaired subjects the better ear is too good for fitting a hearing aid. This is in agreement with the results of Stephens et al. (1991) who found that people with hearing levels higher than 45 dB prefer bilateral fittings.

For purely sensorineural hearing losses more bilateral fittings were prescribed. This reflects the fact that some conductive hearing losses can give medical contra-indications for wearing a hearing aid and it seems also to be connected to a larger chance of asymmetry in case of conductive components. Furthermore, the data show that bilateral fittings are usually not applied in case of more than 40 dB asymmetry between both ears.

For unilaterally fittings Dillon (2001) advocates to use the following rule-of-thumb: "Fit the ear that has the four-frequency average (4FA) threshold closer to 60 dB (HL)". The audiometric data of our unilaterally fitted population have been analysed according to this rule-of-thumb. The diagonal lines in Figure 4.3 indicate positions with equal 'distance' to the average hearing loss of 60 dB (HL). Right ear fittings are expected in the upper and lower triangles while left ear fittings are expected in the left-hand and right-hand triangles. Figure 4.3 shows that the rule-of-thumb, described above, is valid in the majority of cases.

Because of the fact that one of the participating audiological centres is an institute for the deaf with relatively young patients and relatively severe losses, the average age for the total group with severe hearing losses is significantly lower. However, the percentage of bilateral fittings is hardly dependent on age.

In addition, we investigated the subjective benefit of one and two hearing aids. The drop out rate of the questionnaires is about 50 %. This seems to be a high percentage but the persons received the questionnaires two years after the last visit at the audiological centre, which is of course unfavourable for the response rate. The mean age of the subjects is high, so it is possible that they were ill, or not able to answer all those questions. In the response group the patients with a severe hearing loss are less well represented than in the total group. The reason could be that part of the questions was judged to be irrelevant for people with such a worse hearing.

The hearing aid use for the bilaterally fitted group is higher than for the unilaterally fitted group (12%). In addition, the bilaterally fitted group is more satisfied with the hearing aids and there is no significant difference in degree of residual handicap between both groups. For the bilaterally fitted subjects that filled in the questions both for 1 and 2 hearing aids, the subjective improvements of bilateral fittings were clearly present (a significant improvement for detection, speech in quiet, speech in noise, speech in reverberation, and localization), but also the comfort of loud sounds decreased significantly. So it is important to pay extra attention to the comfort of loud sounds, as well for the unilateral fittings as for the bilateral fittings. The results of the partly open question: 'why people prefer two hearing aids' are in agreement with the results of Erdman et al. (1981). The most important advantage for a bilaterally fitting was: a better quality of sound and a better balance between ears. The reason to choose one hearing aid was mostly based on the residual capacity of the other ear in our study. In the clinical practice the subjects' preference is a very important component of the decision. That may be the reason that only a few hearing aids are lying in the drawer.

We also combined the subjective results of the questionnaire with the anamnestic and audiometric data from the clinical files. In the multiple linear regression analysis we found that on basis of anamnestic and audiologic data, the average auditory functioning can be predicted the best, followed by the average handicap. It is hard to predict the hearing aid use and the satisfaction. As expected, the audiogram gives a lot of information: the higher the hearing loss the lower the auditory functioning, and the higher the average handicap. The asymmetry can give information about the average auditory functioning: the higher the asymmetry the lower the auditory functioning. So it is important to compensate for the asymmetry. The average handicap is also related to the intensity of communication. People with a high intensity of communication show less average handicap, or the other way around: people who show a high average handicap do not communicate much. This can be due to an isolated life style in which the hearing loss can play a role.

Finally we analysed the relationships between subjective judgements at one hand and anamnestic and audiological data at the other for specific subgroups. In the first instance there seems to be no striking differences between the *unilateral and bilateral* fitted groups because there were only two significant differences between both groups. The most important subjective factor is that the bilaterally fitted group was more satisfied with the hearing aids than the unilateral fitted group. An audiological factor is that they had a slightly higher hearing loss (4 dB). This is related to other factors. It happens that out of the other subgroups, people with a severe *hearing loss* have a higher hearing aid use, a lower auditory functioning and a higher handicap score. This is related to the maximum speech discrimination. The *repeated* fittings and the *BTE*-fittings have also a significant higher hearing loss. The small but significant age effect for the repeated fittings is unexpected and could not be explained. The kind of hearing aid appears not to have a large influence on the results. The fact that ITE hearing aids (and first fittings) gave better results for auditory functioning and lower handicap scores, is undoubtedly influenced by the smaller hearing losses of the ITE users (and the first fittings). Although in 1998 only a few digital hearing aid models were available, it is remarkable that the scores for auditory functioning with digital hearing aids are relatively good.

It would be effective if one can predict whether a hearing-impaired listener is more satisfied by one or by two hearing aids. This study shows that the anamnestic data and audiological data used in this investigation are not able to predict the degree of hearing aid benefit accurately. Therefore, we decided to develop a test battery with other psycho acoustical tests. This will be investigated in a separate study. In that study also the fittings will be evaluated in an objective manner to provide firm evidence for the ultimate choice after a trial period with one or two hearing aids.

4.5. Conclusions

In our population bilateral fittings were found in relatively symmetric hearing losses (interaural differences up to 30-40 dB) and those fittings were slightly more frequently on sensorineural hearing losses than on conductive hearing losses. In the unilateral fitted group 44 % of the hearing losses was symmetrical (± 10dB), and in 65 % of the remaining cases the hearing aid was fitted on the better ear. The percentage bilateral fittings was hardly influenced by the average hearing loss (except for small losses) and proved to be independent of age. Hearing aid fitting on subjects with a relatively good ear is not less effective than hearing aid fitting on subjects with higher hearing losses at the better ear. Subjects with two hearing aids (who answered the questions for one and two hearing aids) showed significant subjective benefit for the second hearing aid in the categories: detection, speech in quiet, speech in noise, speech in reverberation, and localization, except for the comfort of loud sounds.

The analysis of relations between objective parameters from audiometric and anamnestic data and the subjective outcome measures of different subgroups showed the following trends:

- Large asymmetry in tone audiogram is associated with a low average auditory functioning.
- The bilaterally fitted group is more satisfied with a hearing aid than the unilaterally fitted group.
- More severe losses show a higher use, lower auditory functioning, and about the same satisfaction, and a higher handicap score.
- For the digital hearing aids a significantly better auditory functioning is found and a bit lower handicap score than for the standard analogue hearing aids.
- It is difficult to predict the hearing aid use and the satisfaction from anamnestic and audiological data.

CHAPTER 5.

THE BENEFITS OF BILATERAL HEARING AIDS III:
A prospective study

This chapter is submitted to Int.J.Aud. (Boymans et al., 2003[b])

5. Prospective analysis of the benefits of bilateral hearing aids

Summary

In a prospective study we evaluated the benefit of a second hearing aid objectively (evaluation tests) and subjectively (questionnaires). In addition we applied a battery of diagnostic tests (by headphone) in order to investigate whether the benefit and satisfaction can be predicted from a-priori knowledge. The diagnostic tests focused on the binaural functions and the evaluation tests focused on differences in speech intelligibility and horizontal localization in the same subjects fitted unilaterally and bilaterally. The subjects were recruited among the regular populations for hearing aid fitting in eight Audiological Centres. Eventually 214 subjects participated in this study. They were fitted with two new hearing aids and started a trial period. Before the trial period the diagnostic tests were conducted, during the trial period the subjects completed a questionnaire, and after the trial period evaluation tests were conducted with one and two hearing aids.

The most salient outcome is that 200 subjects (93%) decided to keep both hearing aids. The overall trend in the test results is that bilaterally fitted hearing aids offer more benefit than unilaterally fitted hearing aids, both subjectively (questionnaire) and objectively (speech perception in noise and localization), but this is not always the case for the individual subject.

The results of the diagnostic tests (BMLD, IATD, SRT per ear) show that it is hardly possible to base clinical guidelines for the decision unilateral or bilateral on the a-priori information collected in this study. All unilaterally fitted subjects were older than 50 years and had a hearing loss less than 50 dB at the better ear. After correction for age and hearing loss the bilaterally fitted subjects showed a higher hearing aid use and an increased hearing aid benefit.

5.1. Introduction

Indications for fitting one or two hearing aids are not always clear. Various considerations seem to play a role. In a systematic review of the literature (Chapter 3) the advantages and disadvantages of a bilateral fitting were described. There is an advantage of wearing two hearing aids with regard to head shadow effects and there is evidence for improvement in speech intelligibility in noise (also subjectively). The bilateral benefit for subjects with a slight hearing loss is limited, but subjects with moderate to severe hearing loss appear to be able to localize sounds with two hearing aids considerably better than with one hearing aid (subjectively as well as objectively). The studies predominantly refer to subjects with symmetrical hearing losses. A disadvantage of an unilateral fitting is the deprivation effect. When wearing one hearing aid, there is a risk that speech discrimination will degrade in the unaided ear.

In the retrospective part of this study (Chapter 4) the results of 1000 hearing aid prescriptions (for one and two hearing aids) were evaluated based on patient records and questionnaires. The study focused on anamnestic, audiometric, rehabilitation, and subjective data. The main conclusions were that the bilaterally fitted group showed a clear subjective benefit of the second hearing aid for detection, localization, and for speech intelligibility in quiet. Even in more difficult situations with noise and/or reverberation significant benefits were reported. The aversiveness of loud sounds was not significantly worse than for the condition with one hearing aid. Another finding was that the subjects from the bilaterally fitted group were more satisfied with the hearing aids than the unilaterally fitted group. With regard to the degree of residual handicap the distributions of outcome measures were about the same for both groups. However, no clear decision criteria for unilateral or bilateral fittings could be derived from standard audiometric or anamnestic data. After this retrospective study some additional questions raised that had to be answered.

The first question is: "Can we measure the benefit of a second hearing aid objectively with evaluation tests with one and two hearing aids after a trial period?". In this study, evaluation tests were developed which focused on speech intelligibility in background noise (with spatial separations of speech and background noise), and on horizontal localization.

The second question is: "How is the relation between objectively measured benefit and subjective benefit, when the subjects can make a direct comparison between one and two hearing aids in a trial period?". Several studies showed subjective preferences for a bilateral fitting. Loudness summation could be an explanation for this result (Haggard et al., 1982).

The third question is: "Is it possible to predict the benefit of a second hearing aid from a-priori information?". It is difficult to predict the benefit with bilateral hearing aids from binaural tests with headphones. The interaction between both ears may be different for a flat frequency response of the speech signal presented by headphones compared to the shaped frequency response of the hearing aids fitted to an ear mould (Dillon, 2001). Besides audiometric data, more information is needed about the residual auditory capacity of both ears. We composed a set of diagnostic tests that may be expected to be relevant for predicting the benefit of binaural hearing in daily life. The diagnostic tests included speech intelligibility in background noise for each ear separately (Speech Reception Thresholds), and tests on the binaural function of both ears. People can localize sounds based on the interaural differences in intensity and in arrival time. The differences in arrival time are most effective for low frequencies up to about 1500 Hz, while the difference in intensity is greatest for frequencies above 1500 Hz. (Dillon, 2001). Head diffraction produces attenuation at the contralateral side of the sound (head shadow) and a boost at the lateral side of the sound. The ability to localize sounds is important, especially in a conversation with more people. We included a test on the perception of interaural time differences (IATD).

Binaural squelch is the capacity of the auditory system to combine different mixtures of speech and noise presented to both ears, with the result that some noise is removed effectively. This is an important aspect of the cocktail party effect and the same cues may be present when people wear hearing aids, but the signal characteristics are altered. To investigate the effect of binaural squelch, we included a test on the Binaural Masking Level Difference (BMLD).

In summary, the aim of this prospective multi-centre study was to assess:

- The benefit of a second hearing aid. For this purpose direct comparisons between the unilateral and bilateral conditions were made within the same subjects.
- The relation between the subjectively experienced benefits (in different acoustic conditions without, with one, and with two hearing aids) and the objectively measured performance data (evaluation tests).
- The clinical relevance of new diagnostic tests and the predictive power of these tests for the benefit of bilateral hearing aid fittings. For this purpose, preferences for unilateral and bilateral fittings have been studied and the relations between diagnostic tests, evaluation tests, and subjective outcome measures have been investigated.

5.2. Methods

5.2.1. Subjects

To simulate the normal practice as closely as possible, patients from the regular populations of eight Audiological Centres in the Netherlands who started a trial with new hearing aids, were invited to participate in this study. They visited the Audiological Centre for a first fit or for a repeated fitting.

The inclusion criteria involved that they were willing to *start* a trial-period with two hearing aids, in order to be able to compare different practical conditions with one and with two hearing aids. Depending on the preference of the subject, it was allowed to use one hearing aid most of the time. As usual, a decision about the eventual fitting of one or two hearing aids, was taken after one or more trial periods. In the evaluation tests the objective performance of the subjects with one and two hearing aids was compared. Given the focus of this study there was a preference for inclusion of subjects who did not yet know if they would choose for one or two hearing aids, like first-time users or unilaterally fitted patients who wanted to try a second hearing aid.
The average hearing loss (500, 1000, and 2000 Hz) was less than 70 dB for both ears. The subjects had to speak Dutch, were physically able to do some extra tests and of course had to agree with participation.

5.2.2. Measurements

Diagnostic tests.

In an attempt to predict the benefit of a second hearing aid three diagnostic tests were used: Binaural Masking Level Difference test (BMLD), Interaural Time Difference test (IATD), and a monaural test on the Speech Reception Threshold (SRT) in fluctuating noise (independently for each ear). All diagnostic tests were conducted before the trial period.

The *IATD test* measures the sensitivity of the binaural system to perceive interaural time differences. The interpretation of the IATD-result is: the smaller the value the better the sensitivity to interaural time differences. In the IATD test every time two brief noise bursts (narrow-band noise of 500 Hz, 125 ms in duration) were presented binaurally. The duration of the temporal gap between the noise bursts was 250 ms. The binaural noise bursts were presented with a short interaural time difference. Because the time difference between both noises in a binaural noise burst (Δt) was very small, it was perceived as one single percept (fusion of the sounds), but the location of the perceived sound image in the head was largely determined by the ear where the noise arrived first (this is called the precedence effect; Gardner, 1968; Moore; 1982; Goverts et al., 2000). In the second binaural noise burst, the order of both noises was reversed. For example, in the first noise burst the noise was presented first at the right ear and Δt later at the left ear. In the second noise burst the noise was presented first at the left ear and then at the right ear. Consequently, the perceptual image of these two noise bursts in this example was as a noise pair moving from the right-hand side of the head to the left-hand side. For Δt is zero the noise bursts would be heard in the middle of the head. Δt was varied adaptively, starting with a temporal shift of 0.3 ms. The subjects were asked to indicate to which side the noises were moving in their heads. A 3-up 1-down procedure was used to determine the IATD.

For the *BMLD test*, an octave-band noise with a centre frequency of 500 Hz, was presented to both ears. A tone of 500 Hz was also presented binaurally, one measurement with the tone in phase and one measurement with the tone out of phase. The masked thresholds of the tones were determined according to a 3-up 1-down procedure. The Masking Level Difference is calculated by subtracting the in-phase threshold from the out-of-phase threshold. In subjects with normal hearing the threshold of the signal out of phase is considerably lower than for the signal in phase. This means: the more negative the BMLD-value, the better the binaural function (Moore, 1982).

For both adaptive procedures (IATD and BMLD) the thresholds were determined by averaging of eight turning points. The subjects could exercise first until they understood the instruction. Before the IATD and the BMLD test, a matching test at a calculated stimulus level was used, to establish the same loudness of the stimuli in both ears. The stimulus level at the better ear was fixed at 60 dB SPL for average hearing losses up to 40 dB HL (averaged at 500, 1000, 2000, and 4000 Hz). For higher losses the stimulus level was set at the average hearing loss + 20 dB. The stimulus level at the other ear (the poorer ear) was determined by the result of the matching test (the average of three measurements provided that the differences between the test results were smaller than 10 dB. If not, the matching test had to be repeated).

The *SRT-test* (Plomp & Mimpen, 1978) was applied with headphones to measure the critical signal-to-noise ratio in fluctuating noise for each ear separately. This test was chosen to predict the expected benefit in speech intelligibility with spatially separated sources. The fluctuating noise was presented 20 dB above the $PTA_{(.5,1,2\ kHz)}$ and at least at 60 dB (A).

Evaluation tests.

To evaluate the differences between one and two hearing aids for speech intelligibility and for localization, we used a *Speech Reception Test* (SRT-test) with separated sources and a localization test. The speech material was taken from the sentences VU 98 CD (Versfeld et al., 2000). We decided to measure the SRT-test with a spatial separation between the speech and the noise. Two loudspeaker boxes were used, positioned at -45^o and $+45^o$. All subjects were measured with one hearing aid and with two hearing aids. For the tests with one hearing aid, the subjects could choose their ear of preference. If a subject could not choose, we took the ear that was not used for the telephone. Usually this was the poorer ear (Silman et al., 1998). For conditions with speech from the right-hand side, the "noise" came from left and vice versa. The "noise" used was time-inverted speech of the other gender. The noise was presented at 65 dB(A). Measurements concerned: male voice on the left hand side, female voice on the right hand side, and the other way around.

For the *localization test*, a set-up with five loudspeaker boxes was used (-90^o, -45^o, 0^o, $+45^o$, $+90^o$). The distance from loudspeaker to listener was 75 cm. Several mixed sounds were randomly presented from different sides, for instance: children laughing, dogs barking, music, and siren. All sounds were presented at 65 dB(A). The duration of the signals varied between 2.2 and 3.5 seconds. Every 0.7 seconds a new sound was generated randomly from the sounds that were not active at that time. So, after the initial seconds, three to five signals were presented simultaneously at each moment. There was one target sound: the telephone bell. When the subject heard the telephone bell he or she had to indicate the loudspeaker box in question. The duration between the answer and the next stimuli varied between 4 and 10 seconds. The intensity of the target signal was roved over +/- 5 dB. This test was performed with one and with two hearing aids. The order of presentations was randomized, resulting in six presentations for each of the five loudspeakers for each measurement.

Paired T-tests were used to measure the significance between the differences of the results with the unilateral and the bilateral fitting.

Questionnaires.

To retrieve information about the subjective benefit of the second hearing aid, we applied a shortened version of the questionnaire used in the retrospective study. The questionnaire was partly based on existing questionnaires. There were general questions asked about the daily situation of the subject and about the reasons for choosing one or two hearing aid(s). A selection of questions was used from the Amsterdam Inventory of Auditory Disability and Handicap (AIADH, Kramer et al., 1995), and from the Abbreviated Profile of Hearing Aid Benefit (APHAB, Cox et al., 1995). In total 18 questions were asked about detection, discrimination, speech in quiet, speech in noise, localization, and aversiveness of loud sounds. The AIADH and APHAB questions were asked for the conditions without a hearing aid, with one hearing aid and with two hearing aids. The seven questions of the newly developed International Outcome Inventory for Hearing Aids (IOI-HA, Cox et al., 2000) were used to get information about use, benefit, and satisfaction. The questionnaires had to be completed at the end of the trial period.

5.2.3. Relation between the diagnostic measurements and the evaluation tests

A nonparametric correlation technique (Spearman's r) was used to calculate the correlations between the audiometric data, diagnostic data, outcome measures of the questionnaires, and the evaluation data. A multiple linear regression technique was used to predict the different outcome measures of the questionnaires and the evaluation tests as dependent variables, by a selected set of audiometric and diagnostic parameters as independent variables.

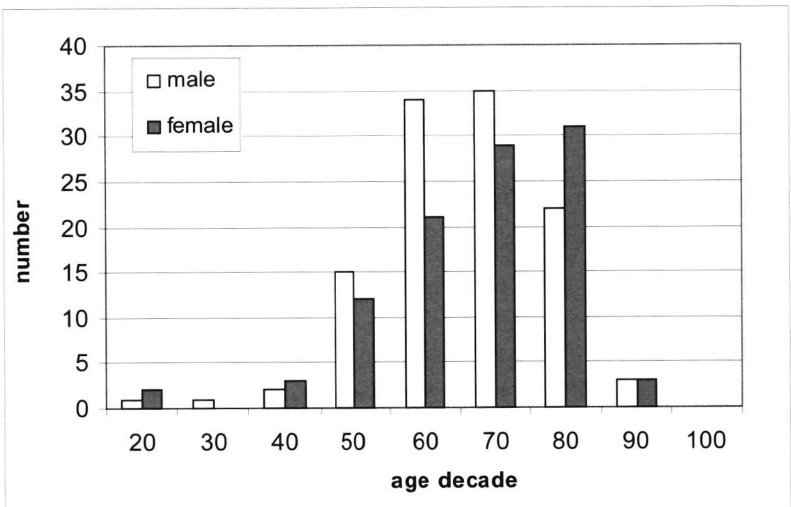


Fig. 5.1. The age distribution in decades for men and women fitted with a hearing aid.

5.3. Results

For this multi centre study 214 subjects were included, 113 men and 101 women with an average age of 66 years (range: 18-88). For 133 subjects the fitting concerned a first fitting (62%). Most hearing losses were sensorineural hearing losses (79%). The average hearing loss (500 - 4000 Hz) was 47 dB for the right ears as well as for the left

ears. After the trial period 200 subjects opted for a bilateral fitting (93%) and 14 subjects (7%) for an unilateral fitting. The small unilateral group is not distinguishable from the bilateral group on base of the asymmetry between both ears.
174 Subjects (81%) were fitted with behind-the-ear hearing aids and 19 % were fitted with in-the-ear hearing aids. 25 Percent of the hearing aids was analogue, 21% was analogue complex (for example with two programs), and 54% was digital. The distribution of male and female subjects as a function of age is shown in Figure 5.1. The peak of the age distribution for males is about ten years earlier than for females.

5.3.1. Diagnostic tests

For the results of the hearing-impaired subjects we distinguished two groups of subjects: a group who preferred one hearing aid (n=14), and a group who preferred two hearing aids (n=200). The median scores and the 25 and 75 percentile scores for the BMLD-test and the IATD-test are presented in Table 5.1. A lower score means a better result. As a reference also subjects with normal hearing were tested. They showed a better result than the hearing-impaired subjects for the BMLD-test, but there is a considerable overlap between the normal-hearing and the hearing-impaired groups.

	BMLD (dB)		**IATD (μsec)**	
	Median	*P25 / P75*	*Median*	*P25 / P75*
Unilateral fitting (n=14)	-15.5	-18.3 / -11.0	123.6	71.3 / 392.3
Bilateral fitting (n=200)	-14.4	-18.4 / -8.6	158.6	81.4 / 793.5
Normal hearing (n=10)	-19.5	-21.5 /-12.0	40.7	33.2 / 48.5

Table 5.1. Results of the unilaterally fitted group, the bilaterally fitted, and the normal-hearing group for the binaural diagnostic tests (BMLD and IATD).

With the IATD-test the differences between the groups are larger, but the trends are similar. There is a clear difference between the hearing-impaired groups and the normal-hearing group. Again, the differences between both hearing-impaired groups are small and there is an overlap between both groups. A few subjects found the test very difficult. The choice for one hearing aid proved to be not related to poor results of the binaural tests.

	S/N ratio for the better ear (dB)		**Interaural difference between S/R ratio (dB)**	
	Median	*P25 / P75*	*Median*	*P25 / P75*
Unilateral fitting (n=14)	-0.8	-3.2 / 2.1	2.2	1.2 / 7.0
Bilateral fitting (n=200)	-0.6	-2.6 / 2.6	2.8	1.6 / 4.8

Table 5.2. Results of the unilaterally fitted group and the bilaterally fitted for the SRT-test measured with headphones.

For the unilaterally and the bilaterally fitted groups the critical signal-to-noise ratios of the SRT-test at the better ear are shown in Table 5.2. For subjects with normal hearing the critical signal-to-noise ratio in fluctuating noise is about 6-10 dB better than for hearing-impaired subjects (Festen et al., 1990). The interaural differences between the critical signal-to-noise ratios are shown in the last two columns. No clear differences were found between the group who preferred one hearing aid and the group who preferred two hearing aids.

5.3.2. Evaluation tests

Speech intelligibility with spatially separated sources.

To measure the difference between one and two hearing aids for speech intelligibility, we conducted Speech Reception Tests (SRT-test) with spatially separated sources.

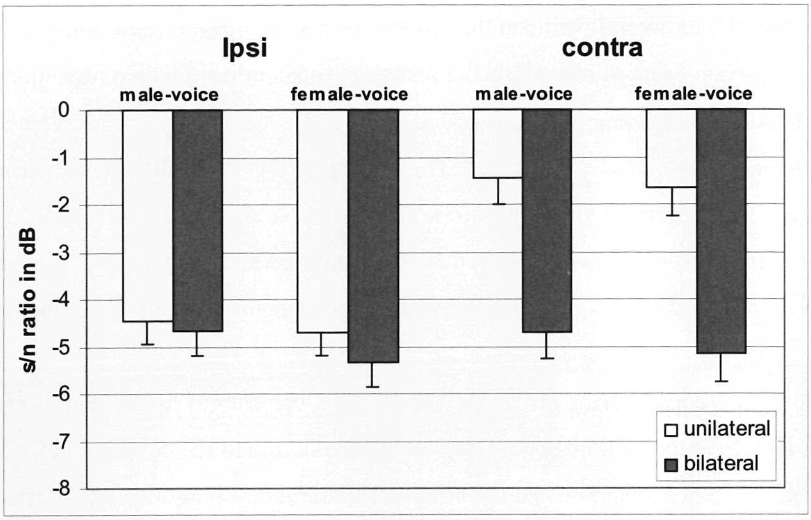


Fig. 5.2. The 1st and 2nd sets of bars show the critical signal-to-noise ratios for the condition with the unilateral hearing aid at speech side (ipsi-lateral side; white bars), and the bilateral condition (grey bars), for sentences spoken with a male-voice and a female voice, respectively. The 3rd and 4th set of bars show the critical S/N ratios of the unilateral condition with the hearing aid at the noise side (contra-lateral side; white bars) and the bilateral condition (grey bars) for sentences spoken with a male-voice and a female voice, respectively.

In Figure 5.2 the first two sets of bars represent the critical signal-to-noise ratios for the situation with the unilateral hearing aid at the speech side (ipsi-lateral side, most favourable side; white bars), and the bilateral situation (grey bars) for sentences spoken with a male-voice and a female voice, respectively. Lower bars (more negative S/N ratios) correspond to more favourable SRT's.

The third and fourth set of bars show the critical S/N ratios for the unilateral situation with the hearing aid at the noise side (contra-lateral side, most unfavourable condition; white bars), and the bilateral situation (grey bars) for sentences spoken with a male-voice and a female voice, respectively. There were no significant differences between

the results of the group who preferred the unilateral fitting at the right ear, and the group who preferred the unilateral fitting at the left ear.
The first and second sets of bars show the results of the condition with a hearing aid on the speech side. When a hearing aid is added at the noise side, a slight improvement in critical signal-to-noise ratio is measured. The average effect is 0.4 dB and the difference is significant for the female voice ($p<0.05$). This is the purely binaural effect.
The contra-lateral condition is the most difficult condition and, as expected, this results in a relatively poor critical signal-to-noise ratio (the lower the bars the better the result).

When adding a second hearing aid on the speech side, the critical signal-to-noise ratio improves significantly ($p<0.001$) (last two sets of bars), due to the combined effect of elimination of the head shadow and the effect of binaural co-operation. These effects together result in a benefit of 3.3 dB.

Localization.

The results of the localization test, measured with one and two hearing aids, are shown in Figure 5.3a and 5.3b. The first and third sets of bars represent the results of the unilateral condition, measured with the hearing aid on the preferred side for a unilateral fitting. The second and fourth sets of bars represent the corresponding results of the bilateral condition, measured in the same subjects. The first two sets represent the group who preferred a hearing aid on the right ear and the second two sets represent the group who preferred a hearing aid on the left ear for the unilateral condition. The total percentage of errors for every condition is shown in the first bar. In Figure 5.3a the percentage of errors within 45 degrees is presented in the second bar, the third bar represents errors between 45 and 90 degrees and the fourth bar represents the percentage of errors of more than 90 degrees.

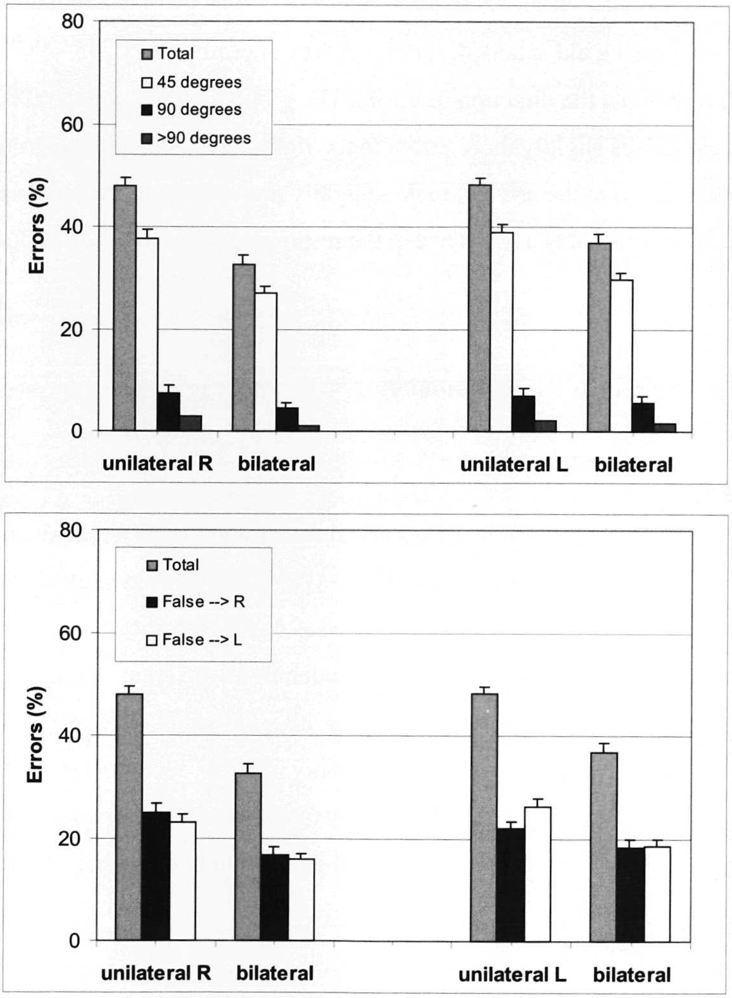


Fig. 5.3. Percentage of errors in horizontal localization for two different groups. The first group with a hearing aid at the right ear (1st set of bars), and with two hearing aids (2nd set); the second group with a hearing aid at the left ear (3rd set of bars), and with two hearing aids (4th set). Panel a represents the total errors (1st bar), errors within 45° (2nd bar), errors between 45°-90° (3rd bar), and errors for >90° (4th bar). Panel b represents the total errors (1st bar), and the errors to the right-hand side (2nd bar), and to the left-hand side (3rd bar).

Most errors were made within 45 degrees. For both groups there is a reduction of errors when a second hearing aid is added, for all degrees of errors ($< 45^0$, 45^0- 90^0, $>90^0$). Figure 5.3b represents the direction of errors. The group with the unilateral hearing aid at the right ear makes slightly more errors to the right-hand side, and the group with the unilateral hearing aid at the left ear, makes slightly more errors to the left-hand side. When fitted bilaterally, this asymmetry in the response pattern almost disappears.

5.3.3. Subjective results / questionnaires

Auditory functioning

To investigate the subjective judgements about functioning in different situations 17 questions of the AIADH and 1 question of the APHAB have been applied. These questions were chosen on the basis of the analyses of the retrospective study (see also Kramer et al., 2002). To measure auditory functioning in different situations, six categories were composed: detection of sounds, discrimination or recognition of sounds, speech intelligibility in quiet, speech intelligibility in noise, localization, and comfort of loud sounds. Each category was represented by three questions. For each patient and each category the mean scores were calculated only when two or three questions in that particular category had been answered. All scales range from 1 to 4.

The results of the subjective judgements are presented in Figure 5.4 for all six categories, for the condition without a hearing aid (first bars), with one hearing aid (second bars) and with two hearing aids (third bars). The average results of the group who preferred a unilateral fitting (n=13) are plotted in panel a, and the average results of the group who preferred a bilateral fitting (n=169) in panel b. Higher bars indicate a more positive result. In the first group there is a significant benefit for one hearing aid compared with the condition without hearing aid, for all categories ($p< 0.01$) except for

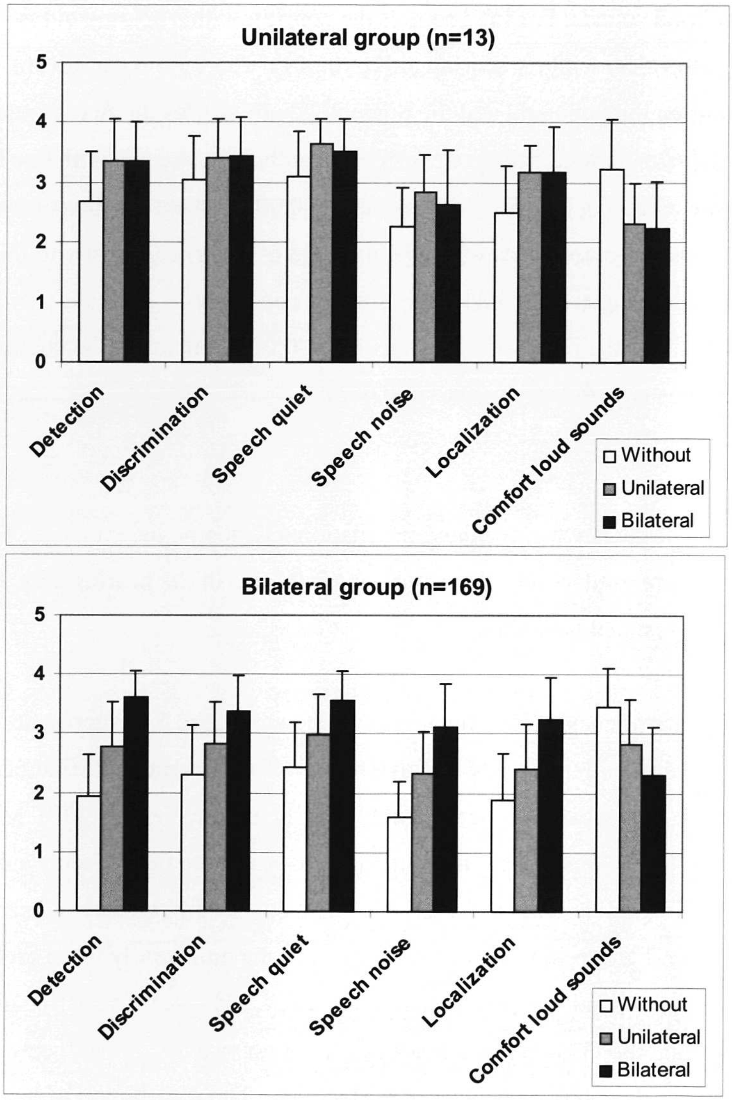


Fig. 5.4. The average results of the subjective judgements (according AIADH and APHAB), without, with one, and with two hearing aids for all 6 categories for the unilaterally fitted subjects (n=13; panel a) and the bilaterally fitted subjects (n=169; panel b). The higher the bars, the more positive the result.

the comfort of loud sounds. For loud sounds the comfort with a hearing aid is significantly lower than without hearing aid ($p<0.001$). There is no significant difference between the unilateral and the bilateral conditions for the first group. The group who prefers a bilateral fitting shows significantly better scores with one hearing aid than without a hearing aid for all categories ($p<0.001$) except for the comfort of loud sounds.Again this score decreases with a hearing aid ($p<0.001$). Contrary to the group who prefers one hearing aid, the bilaterally fitted group shows significantly better scores with two hearing aids than with one hearing aid ($p<0.001$), but again the comfort of loud sounds scores significantly worse ($p<0.001$).

IOI-HA

Seven questions of the newly developed International Outcome Inventory for Hearing Aids (IOI-HA) were used to get information about the use of the hearing aids, the benefits, and the residual handicap.

In Figure 5.5 the frequency of hearing aid use is shown. Figure 5.5a represents the percentage of hearing aid use for the group who wears one hearing aid (first bars, n=12) and for the group who wears two hearing aids equally (second bars, n=170). Most of the subjects of the bilateral group wear their hearing aids for more than 8 hours a day (60%), and 29 % wears the hearing aids 4-8 hours a day. The frequency of hearing aid use of the unilateral group shows more variation. For the unilaterally fitted group only 25% wears the hearing aid for more than 8 hours a day, 33% wears a hearing aid 4-8 hours a day and another 33% wears a hearing aid 1-4 hours a day. 19 Subjects mentioned to wear their second hearing aid selectively. The distribution of hearing aid use for that group is shown in Figure 5.5b. Most subjects wear one hearing aid for 4-8 hours or more than 8 hours (53%, 42% respectively). The second hearing aid is then mostly used for 1-4 hours (53%).

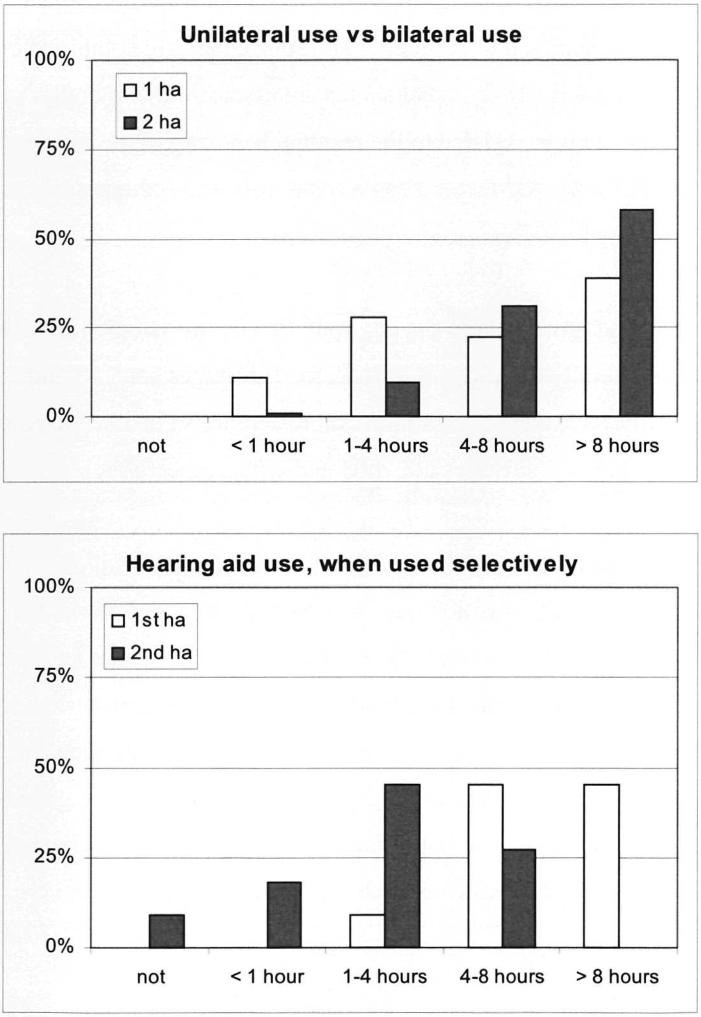


Fig. 5.5. The frequency of hearing aid use. Panel a: for the unilaterally fitted group (n=12) and for the bilaterally fitted subjects who wear their hearing aids equally (n=170). Panel b: for the bilaterally fitted subjects who wear their second hearing aids selectively (n=19).

Three questions are related to the benefit or satisfaction of the hearing aid and, in agreement with the approach of Kramer et al. (2002), they are combined in the IOI-factor 1 (on a scale from 1 to 5; higher scores are associated with higher satisfaction). Another three questions are related to the residual handicap of the hearing aid user, and they are combined in the IOI-factor 2 (on a scale from 1 to 5; higher scores are more favourable/associated with less residual handicap).

The bilaterally fitted group is significantly ($p<0.001$) more satisfied with the hearing aids than the unilaterally fitted group (IOI-factor 1 averages are 3.95 and 2.86, respectively). However, there is no significant difference in residual handicap between both groups (IOI-factor 2 averages are: 4.03 and 4.00, respectively).

Advantages and disadvantages for an unilateral or bilateral fitting

The subjects were asked to mention reasons why they preferred one or two hearing aids. More than one reason was possible. 138 Times a reason was given for the advantage of a unilateral fitting and 649 times for a bilateral fitting. Most mentioned reasons for a unilateral fitting were: own voice was more pleasant with one hearing aid (31%) and the unaided ear was used for the telephone (25%). For the bilateral fittings most mentioned reasons were: intelligibility from both directions (20%), better localization (19%), better sound quality (20%), and a better stereophonic effect/balance (19%).

5.3.4. Relations between the diagnostic measurements and the evaluation tests.

For the total group, first the correlations between the *outcome measures* of the questionnaires and the audiometric data have been analysed. Hearing aid use is lower at higher age ($r = -0.17$; $p<0.05$) and higher for larger hearing losses at the better ear ($r = 0.17$; $p<0.05$). A higher hearing aid use goes along with more benefit of the hearing aid ($r = 0.34$; $p<0.001$), and less residual handicap ($r = -0.16$; $p<0.05$).

Auditory functioning scores lower for larger hearing losses ($r = -0.20$; $p<0.01$) and a better auditory functioning goes along with less residual handicap ($r = -0.38$; $p<0.001$) and a higher benefit of the hearing aid ($r = 0.28$; $p<0.001$).
The benefit of hearing aids is positively correlated with the average hearing loss at the better ear ($r = 0.21$; $p<0.01$) and negatively with the residual handicap ($r = -0.31$; $p<0.001$). These results are generally in agreement with the results found in the retrospective study (Chapter 4).

There were only few significant correlations between the results of the *diagnostic tests* and other parameters used in this study. No significant correlations were found for the BMLD. A poor IATD (corresponding to a high value) is related to poor maximum speech discrimination score at the better ear ($r = -0.21$; $p<0.01$). A poor critical signal-to-noise ratio at the better ear (i.e. a high SRT-value) is found at high ages ($r = 0.20$; $p<0.01$) and for large hearing losses at the better ear ($r = 0.33$; $p< 0.001$), while a poor critical signal-to-noise ratio goes along with a low value for the maximum speech discrimination score at the better ear ($r = -0.31$; $p<0.001$).

Finally, we analysed the relations of the *evaluation tests* with other data. The benefit for speech perception with spatially separated sound sources, caused by elimination of head shadow and binaural hearing, is higher for higher hearing losses ($r = 0.28$; $p<0.001$), for poorer maximum discrimination scores ($r= -0.16$; $p<0.05$), and for poorer critical signal-to-noise ratios (higher SRT's) at the better ear ($r = 0.23$; $p<0.01$).
The benefit in localization is related to the benefit in speech perception with spatially separated sound sources ($r = 0.19$; $p<0.01$), but localization proves to be rather independent of the other data, with the exception of a positive correlation with total auditory functioning ($r = 0.18$; $p< 0.05$).

The average critical signal-to-noise ratio for the monaural measurements by headphones correlates significantly with the average critical signal-to-noise ratio in the free field

with signals coming from the left and the right hand side measured bilaterally (r = 0.47; p<0.001). These correlations did not increase when the best critical signal-to-noise ratio measured with the headphones was taken (r = 0.44; p<0.001).
There was a small but significant correlation between the difference in critical signal-to-noise ratio of the right and the left ear and the difference in critical signal-to-noise ratio of the right and the left hand side in the free field (r = 0.16; p<0.05).

A stepwise multiple linear regression was conducted to predict outcome measures from audiometric and diagnostic data.

- The most important predictor for hearing aid use is PTA at the better ear (r = 0.18, p<0.05). The correlation factor increases to r = 0.24 if both PTA and age are taken into account.
- For the total auditory functioning again PTA is the most important predictor (r = 0.26; p<0.001) and no significant improvement is obtained by adding a second predictor.
- Also, for the benefit of the hearing aid(s) (IOI-factor 1) PTA is the single best predictor, but again the correlation obtained is rather low (r = 0.17; p<0.05).
- For the residual handicap (IOI-factor 2) the critical signal-to-noise ratio at the better ear is the most important predictor (r = 0.17; p<0.01).
- For the benefit in speech perception with spatially separated sources caused by binaural function and head shadow again PTA at the better ear is the single best predictor (r = 0.23; p<0.01).

The type of fitting (unilateral or bilateral) proved to be significantly related with average hearing loss at the better ear and with age (p<0.05). All unilaterally fitted subjects were older than 50 years and had a smaller hearing loss than 50 dB(HL) at the better ear. To get more information about the differences between the unilateral and the bilateral groups we made a correction for age and hearing loss in order to avoid bias

between the groups. We analysed a subgroup of the bilaterally fitted subjects, with a hearing loss at the better ear smaller than 50 dB and an age above 50 years.
For this subgroup there were no significant differences any more between the unilateral group (n=14) and the bilateral group (n=126) for the average hearing loss at the better ear (38 dB HL and 39 dB HL, respectively). A small but significant difference was still found for the average age ($p<0.05$). The unilaterally fitted group was 6 years older than the bilaterally fitted group. After this correction, the bilaterally fitted group had a higher hearing aid use ($p<0.01$) and also a higher hearing aid benefit ($p<0.001$).

5.4. Discussion

The results show an asymmetrical distribution of the unilateral and bilateral fittings. This causes that the results of the unilaterally fitted subjects are based on relatively few subjects. The main reason is that this study included only subjects that were willing to wear two hearing aids, at least during the trial period. A consequence of the inclusion criteria is also that only subjects with relatively symmetrical hearing losses were included. Ideally, the final choice for one or two hearing aids should be based on the experienced benefit of the second hearing aid during the trial period. But we have to consider that the inclusion criteria used may have caused some bias. However, other approaches would have introduced other methodological problems.

If we had included all hearing aid users, independent of the type of fitting, the evaluation tests would not be available with one and two hearing aids in each subject. The expected distribution of the unilateral and bilateral fittings is then about 40% and 60%, respectively. The results of the subjects who are fitted unilaterally due to medical reasons can be analysed separately. Only if the unilaterally fitted subjects are willing to participate in a second trial period with two hearing aids, the evaluation measurements can be completed. It would be nice if all unilaterally fitted subjects would be willing to try a second hearing aid, but then a lot of extra ear moulds have to be produced for experimental purposes only. This will be very expensive. A crossover design with one or two hearing aids in consecutive trial periods in a random order has the ethical disadvantage that some hearing-impaired listeners strongly rely on the use of two hearing aids.

Due to the inclusion criteria we used in this study, only subjects with relatively symmetrical losses were included. This can have influenced the binaural capacities. Perhaps more effect could have been measured when more asymmetrical hearing losses were included. So, our inclusion criteria resulted in a percentage higher than usual, but it is striking that the percentage is that high (93% versus 7%). This result is in agreement with the study of Erdman and Sedge (1981), who found that 90% of the subjects preferred a bilateral fitting over a unilateral fitting. As a consequence, the group with unilateral fittings is relatively small for statistical analyses.

As indicated in the introduction, the first important experimental question concerned the difference within subjects between conditions with one hearing aid and two hearing aids. For the total group the effect of the second hearing aid is obvious for the speech perception in noise with separated sources and for localization. But, unexpectedly, all subjects who preferred an unilateral fitting had either better scores in localization, or in speech perception, or both when fitted bilaterally. On the contrary, some subjects who preferred two hearing aids had poorer scores in speech perception and/or in localization with two hearing aids than with one. In this respect the evaluation test could not distinguish the group who preferred an unilateral or a bilateral fitting. However, for the majority of subjects their positive experiences in the trial period were in agreement with objectively measured benefits in standardized and controlled conditions.

The second question concerned the correspondence between the objective performance data (diagnostic and evaluation tests) and subjective data from the questionnaires. The subjects experienced more benefit when there was an advantage in speech perception with separated sources caused by the elimination of head shadow and binaural co-operation. When there was an advantage in localization, the subjects experienced a better total functioning.

The third question concerned the predictability for a successful bilateral hearing aid fitting from a-priori diagnostic tests. As mentioned in the Introduction it is difficult to predict the binaural effect with speech material presented by headphones because of the difference in frequency responses of headphones and hearing aids. For narrow-band signals as used in the diagnostic tests this problem is solved. But a complication for the diagnostic tests is that some subjects experienced the IATD test as very difficult. Beside the IATD, interaural level differences (IALD) are an important cue for localization. A test on IALD is possibly easier than the IATD, but the IALD effects are predominantly present in the high frequencies, which may be a complication for the use in hearing-impaired listeners with steep high-frequency losses. Despite a large inter-individual spread, the IATD was related to the maximum speech discrimination score (poor IATD give poor speech discrimination scores). The BMLD test proved to be much easier and less inter-individual spread was obtained. But no significant correlations were found with BMLD.

As expected the critical signal-to-noise ratio at the better ear is also correlated with the maximum speech discrimination score at the better ear (and correlated with high ages and large hearing losses). A poor critical signal-to-noise ratio at the better ear is correlated to a higher benefit for speech perception with spatially separated sound sources, caused by elimination of head shadow and binaural hearing. However, for the prediction of a successful bilateral fitting, the traditional audiometric parameters like PTA and maximum speech discrimination appear to be more important than the parameters derived from the diagnostic test battery used in this study (IATD, BMLD and SRT per ear).

The consequence of our findings for the provision of hearing aids is that the benefit of the second hearing aid has to be experienced individually, if the hearing loss is present bilaterally. The nature of the binaural interaction may change after some days, weeks, or even months (Dillon, 2001). So the duration of the trial period should take some time. An expensive disadvantage of this approach is that every subject needs two ear moulds or two in-the-ear shells to assess the individual effect. On the other hand, this study shows that the benefits to be obtained are significant in the majority of cases. These benefits can be assessed "objectively" both by performance data as speech perception with separated sound sources and by localization tests. But also they can be derived from questionnaires like the one applied in this study.

5.5. Conclusions

From this study the following conclusions can be drawn:

- Hearing-impaired subjects who are willing to try two hearing aids can experience the effect of the second hearing aid and in this study 93% of the subjects wanted to keep two hearing aids after the trial period.
- After an appropriate correction for age and hearing loss, the bilaterally fitted group showed a higher hearing aid use and a higher hearing aid benefit.
- The evaluation tests showed clearly better results when subjects were fitted bilaterally than unilaterally. This holds for the speech reception test with separated sound sources as well as for the horizontal localization test. The largest effect comes from the elimination of the head shadow.
- The questionnaires showed convincing evidence for the benefit of the second hearing aid in all categories except for the comfort of loud sounds.
- The most important factor to predict different outcome measures is the PTA at the better ear. The diagnostic tests could not predict the outcome measures, the IATD correlates negatively with the maximum speech discrimination at the better ear.

CHAPTER 6.

CLINICAL EVALUATION OF A FULL-DIGITAL IN-THE-EAR HEARING AID

This chapter has been published in Audiology (Boymans et al., 1999)

6. Clinical evaluation of a full-digital in-the-ear hearing aid

Summary

In this study we measured the efficacy of a digital hearing aid with compression and noise reduction in a well-controlled clinical field trial in two independent centres. The experiments focused on a number of aspects of the application of the digital hearing aids.

The study combines a field test of 2x4 weeks with laboratory experiments. We used objective measurements (speech perception tests in background noise, loudness scaling) and subjective assessments (questionnaires). The measurements were performed before and after the field test. The questionnaires were collected after each field test. The results of the digital hearing aids were compared to the results of similar tests with newly fitted analogue reference aids. The study involved 27 sensorineural hearing-impaired subjects, wearing new hearing aids. They comprised a representative sample of ITE-users. We used a crossover design in which the subjects used successively digital hearing aids and analogue reference aids in a randomized order.

On average, the subjective data are more positive than the objective data. In the end, 20 out of 27 subjects had an overall preference for the digital hearing aid. The financial implications were not taken into consideration. However, objective data do not support this strong subjective preference. A reason could be that the method of analysis (short sentences in a short-duration background noise) is not suited for the digital hearing aid; the testing procedure does not allow the noise-reduction algorithm to adapt to the background noise. There was a striking difference between the results for the two centres. This difference can, at least to a certain extent, be attributed to the timing of speech relative to the background noise in the objective tests. This illustrates that the testing conditions are critical in modern non-linear signal-processing hearing aids with long time constants. New evaluation techniques should be developed for this new generation of active non-linear hearing aids.

6.1. Introduction

Digital hearing aids have some specific features that may provide extra benefit for the hearing-impaired users (Verschuure and Dreschler, 1993). We tested this assumption on a population wearing a full digital in-the-ear hearing aid. The hearing aid was a three-channel device with compression and noise reduction in each of the frequency channels. The results of the digital aid were compared with the results for state-of-art, analogue in-the-ear hearing aids, fitted to the same subjects, using a crossover design. The experimental focus was on the tested performance of users under well-controlled laboratory conditions and subjective performance data obtained from questionnaires after a trial period.

There are only a few well-controlled clinical trials with digital hearing aids thus far. Arlinger et al. (1998) tested a seven-channel digital hearing aid with the subject's own analogue aids as a reference. They found superior performance for the digital aid, but the subjective data, gathered with the Abbreviated Profile of Hearing Aid Benefit (Cox et al., 1995) and the Gotheburg Profile, were more positive than the objectively measured improvements for speech perception in noise.

Hearing-impaired listeners often have problems with speech intelligibility in environments with background noise. For that reason we used different kinds of background noises in the laboratory experiments, continuous speech-shaped noise, speech-modulated speech-shaped noise and a car noise. We measured the critical signal-to-noise ratio of sentences in these noises. The noises represent conditions to which we are often exposed in daily life. The thresholds were measured in the laboratory under fully controlled experimental conditions. Other problems experienced by hearing-impaired listeners have to do with their reduced dynamic range. We performed loudness scaling tests to investigate the effects of the compression in the digital hearing aids on the perceived dynamic range.

Finally, subjective judgements on listening performance in different conditions were obtained in a field test. Specific attention was given to general aspects of wearing comfort, ease of an automatic volume control, the cosmetic aspects, the feedback problems, and the internal noise. Preferences have been assessed comparing the digital aid and the analogue reference aid with respect to the sound quality, acoustic feedback, the automatic volume control, the perception of loud sounds and the overall judgement.

6.2. Method

The study was designed as a two-centre study of the Academic Medical Centre Amsterdam (AMC) and the Erasmus University Rotterdam (EUR) in order to compensate for bias due to local experience and/or preference in Amsterdam or in Rotterdam. Furthermore there is a long-standing tradition of co-operation between both Audiological Centres involved, which guarantees an optimal tuning of the assessment procedure, both for the objective measurement and for the subjective assessment.
The study combines a field test of 2x4 weeks with laboratory experiments before and after the field test in order to get an indication of acclimatization (Gatehouse, 1992). The results of the digital hearing aid were compared with the results of similar tests with a reference analogue hearing aid. Laboratory experiments included measurements of speech perception in continuous speech noise, in speech-modulated speech noise, and in low-frequency car-noise. Loudness scaling with constant noise, speech- and car noise resulted in two parameters: the most comfortable level (MCL) and the slope of the loudness growth function. The subjective performance during field tests was assessed by means of extensive questionnaires.

6.2.1. Subjects

We selected 27 subjects from the clinic population seeking help for audiological problems in the AMC or the EUR, ensuring that the subjects comprised a representative sample of ITE-users. They were asked to participate in the study on a voluntary basis. There were no age restrictions, except that children (<16 years) were not included in the study. Selection criteria were that subjects should:

- be capable of assessing a hearing aid in a rational manner
- not have any language problems which may influence the speech tests
- choose to wear two in-the-ear hearing aids
- have a symmetrical sensorineural hearing loss (interaural differences < 15dB)
- have a PTA (0.5, 1 and 2 kHz) hearing loss between 30 and 75 dB(HL).

Participants in the study who expressed strong disappointment when they had to return the digital hearing aids after the test, were allowed to keep their digital hearing aids at the same cost as the analogue hearing aids. This was not known to them until after they had expressed their preference for either one of the hearing aids.

Table 6.1 shows the population statistics and the average hearing losses in the subgroups participating in AMC and EUR.

	AMC	**EUR**
number of subjects	15	12
first-time users	9/15	12/12
Range of ages (years)	27 - 86	36 – 78
av. loss at 500 Hz (dBHL)	27 ± 13.4	35 ± 14.2
av. loss at 1000 Hz (dBHL)	38 ± 9.6	44 ± 14.0
av. loss at 2000 Hz (dBHL)	58 ± 6.8	49 ± 10.4
av. loss at 4000 Hz (dBHL)	69 ± 14.9	59 ± 11.9

Table 6.1. Subject characteristics and mean hearing losses.

Subject	Age	Av.loss .5 - 4 kHz	analogue reference aid	IG re NAL .5 - 4 kHz
AMC				
1	45	60	Danavox 161 K-Amp	4,5
2	78	49	Dahlberg Invisa +	3,7
3	68	41	Danavox 161 K-Amp	5,8
4	70	45	Oticon 155-Micro	2,1
5	46	48	Oticon 155-Micro	1,8
6	70	44	Widex LX	2,6
7	48	61	Oticon I-22P	0,7
8	86	46	Oticon Logic Communicare	4,1
9	26	38	Philips M60-O(H)	4,3
10	31	53	Siemens Cosmea CM 122	7,1
11	72	55	Oticon I55	3,7
12	52	39	Danavox 161 K-Amp	2,5
13	40	41	Oticon I54	1,3
14	66	44	Philips M60-O(F)	2,1
15	42	55	Oticon I55 mini	1,2
EUR				
21	59	55	Danavox 131	7,3
22	51	38	Danavox 131	0
23	67	53	Philips M60-O	3,7
24	76	41	Beltone Invisa +	5,9
25	75	56	Oticon Prima Focus	6,6
26	79	39	Oticon I54	7
27	59	36	Beltone Invisa +	5,6
28	47	43	Beltone Invisa +	7,6
30	56	58	Danavox 161CD	4,1
31	37	59	Danavox 161CD	2,9
32	68	40	Danavox 151 premier	8,6
33	68	43	Philips M20	6

Table 6.2. Summary of individual data of age and average hearing loss (.5 - 4 kHz). For each subject the analogue reference aid is indicated, as well as the rms-value of differences between the IG-responses and the NAL-targets (.5 - 4 kHz)(after corrections for the setting of the volume wheel).

6.2.2. Hearing aids

Half of the subjects started the experiment by using the digital hearing aids and the other half by using the analogue hearing aids. The type of hearing aid (digital or analogue) was switched over after half the trial period. It was impossible to use a blinded protocol, but the order of the trial period over digital and analogue hearing aids was randomized.

The reference hearing aid was a newly fitted analogue in-the-ear hearing aid. We used many different brands for the reference hearing aids, see Table 6.2. Concha in-the-ear hearing aids and CIC aids (completely-in-the-channel) were not used as reference aids, nor were multi-program in-the-ear hearing aids, with a remote control. All reference aids had volume controls.

6.2.3. The fitting procedure of the conventional hearing aid

The reference hearing aid always was a new analogue in-the-ear hearing aid. The conventional aid was fitted according to the standard clinical selection method and checked by insertion-gain measurement. We tried to achieve a frequency characteristic according or close to the NAL-r prescription rule (Byrne & Dillon, 1986). Table 6.2 also presents the rms-values of the differences between the measured insertion gains and the NAL-predictions. The maximum output power was limited according to the subject's uncomfortable loudness level.

6.2.4. The fitting procedure of the digital hearing aid

The digital hearing aid in this study was a Widex Senso. We used the LP2 Programmer for the fitting of the digital hearing aid using the manufacturer-designed integrated in-situ fitting procedure. A feedback-reduction system is incorporated in the hearing aid and it was programmed according to the standard procedure prescribed by the manufacturer using the LP2 Programmer. The frequency crossover points between low-, mid-, and high-frequency channels were chosen according to the recommendations of the fitting procedure. We selected one out of three filter settings according to the audiogram. In all cases the standard filter setting could be used, except for subject 3.

We first fitted the hearing aid on the data from the normal pure-tone audiogram (in the HTL mode). For the standard filter setting, the HTL-values for the three channels were derived from the audiometric losses at 500, 1000 and 3000 Hz respectively. In the HTL-mode acoustical properties of the hearing aid shell, and the residual volume of the ear canal were not taken into account. Next the standardized audiogram-based in-situ fitting procedure was used. Tones were generated by the hearing aid, and we measured a hearing level for each of the three frequency bands (low, middle and high). This procedure was not affected by the aid in the other ear. After the aid had been fitted according to the two methods the feedback test was conducted. The subject was then asked to chew and the feedback test was repeated. When the value for one of the bands (low, middle or high) was below -10 a new impression of the ear canal was made in order to achieve a tighter fit of the hearing aid in the ear canal. The values of the UCL-mode (uncomfortable level) were recorded. The subject was asked to report on the sound quality and the loudness of both hearing aids. This resulted in readjustments of the fitting in a number of cases.

6.2.5. Objective evaluation with speech

The pre-trial testing was done in weeks 0 and 4, the post-trial testing was done in week 4 and 8. It was expected that testing with isolated words was not appropriate for the given digital aid in view of the relatively long time constant of the noise reduction algorithm. For that reason we used speech-reception thresholds (SRTs) for sentences as described by Plomp and Mimpen (1979) in a number of background noises. This test reflects better daily-life situations.
The SRT threshold was determined for a continuous speech-shaped noise, for a speech-modulated speech-shaped noise and for a low-frequency car-noise. The speech-shaped noises had the same long-term spectrum of the speaker (according to Plomp and Mimpen) and we used the modulated noise as described by Festen and Plomp (1990). For every situation we used a male and a female speaker.

Testing was conducted with ten lists of sentences with an adaptive up-down procedure. This test has been proven to be accurate (test-retest standard deviation between 0.9 to 1.5 dB) and fast. The order of the lists was randomized. The noise level was set at 64 dB(A). The noise started 5 seconds before the speech, which we initially thought to be early enough to activate the automatic processing of the digital hearing aid.

In an evaluation discussion the manufacturer provided additional information about the time constants of the noise reduction scheme. Because of a time-lag between the two centres the EUR-group then decided to produce a CD with each test sentence preceded by another sentence in noise to present noise and speech long enough for the noise-reduction algorithm to be activated. In order to distinguish the target sentence from the leading adaptation sentence, the leading sentence was a sentence played backwards. There was no gap between the leading sentence and the test sentence. The same inverse sentence was used for all test sentences. The CD was used for the testing of all EUR subjects. This implies that the testing procedure differed somewhat between the two institutes in this respect.

6.2.6. Laboratory experiments on loudness scaling

We obtained data on loudness perception by means of loudness scaling.
In Amsterdam the method of the Würzburger Hörfeld Skalierung (Hellbrück and Moser, 1985) was applied based on a 50-point scale. Loudness scaling was measured for each individual and each of the following types of noise: fragments of constant speech noise, single-speaker speech and car noise. The ranges of output levels were 30-80, 30-90, and 30-90 dB(A), respectively. The noises were presented for 5 seconds. This was long enough to reach a steady state response of the automatic loudness processing of the digital hearing aid, although the noise reduction was not yet fully activated. The subjects were asked to judge the loudness of the sounds presented on a 50-point scale ranging from “not heard” to “too loud”. They were instructed to judge loudness at the end of each fragment. In the EUR-group a similar procedure was applied, based on a 10-point scale according to Pascoe (1986). In Rotterdam loudness scaling was measured for narrow-band noises for the centre frequencies 500, 1000, and 2000 Hz.

Loudness scaling was done before and after the trial periods with the different hearing aids. The data points were fitted by straight lines and the parameters of loudness growth were based on the fit in order to reduce measurement error. Two parameters were calculated from the fit: the level at which a loudness level of 50% of the scale was reached (called "MCL") and the slope of the loudness growth function. The former is related to the amount of hearing loss, the latter to the amount of recruitment.

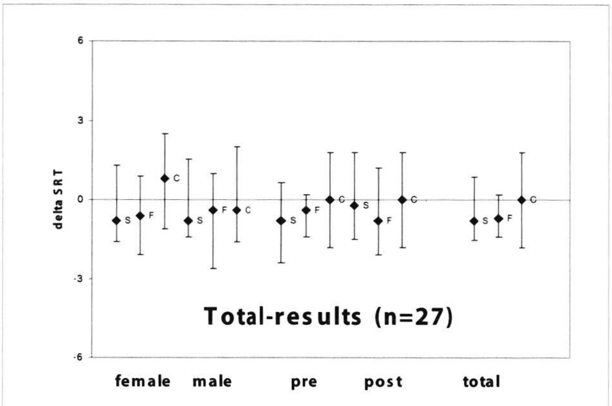
6.2.7. Subjective assessment

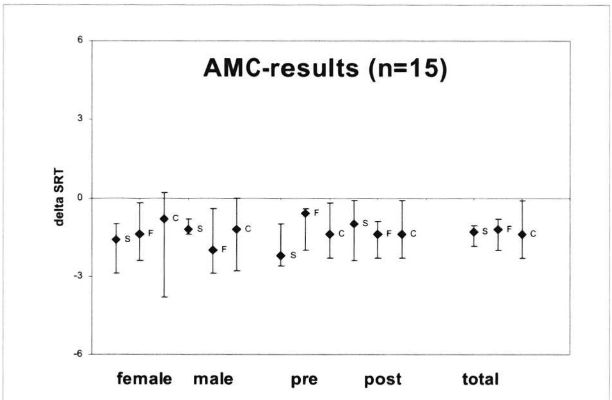
The trial period gave each subject the opportunity to become accustomed to the sound of each pair of the hearing aids, and to make possible a subjective assessment of the subject's performance with the hearing aids. After a trial period each subject came to the Audiological Centre for a debriefing and for the laboratory experiments. The debriefing gave the experimenter at the Audiological Centre the opportunity to confirm and complement the subjective assessment of the hearing aid.

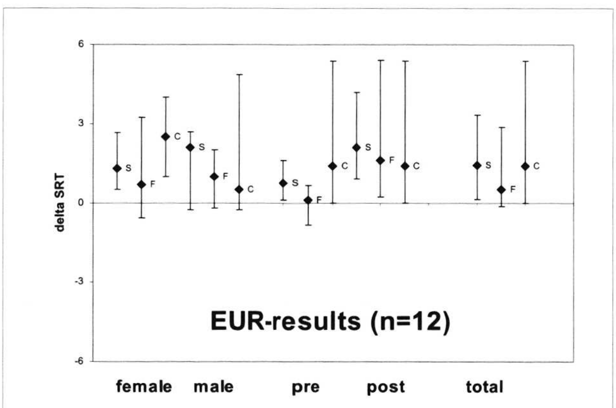
In week 4 and 8 the subjects completed a questionnaire on their experiences with the hearing aids. The subject had no access to their previous responses. The questionnaire used a visual analogue scale. All indications were performed on unmarked lines with end markings such as:

bad__________________________good.

The subjects were asked to make a mark on each scale corresponding to their subjective rating of their performance in that condition. Questions were asked about the hearing aid in general (sound quality, functioning, frequency of use etc.) and rated speech intelligibility with the hearing aid in a number of situations. Situations were divided into a number of categories such as at home, outside and at work. They were also asked to indicate how often the described situation occurred and how important that situation was for the subject (all using visual analogue scales).
At the end of the study each subject completed a final questionnaire in which they were asked to rank the two hearing aids in a number of important situations. The results determined the relative subjective differences between the two kinds of hearing aids.


Total-results (n=27)
delta SRT
6
3
0
-3
-6
female male pre post total
S F C


AMC-results (n=15)
delta SRT
6
3
0
-3
-6
female male pre post total
S F C


EUR-results (n=12)
delta SRT
6
3
0
-3
-6
female male pre post total
S F C

6.3. Results

We present the results in four categories: critical S/N ratios in different background noises, loudness scaling for different noises, subjective data from the questionnaires, and the overall preference after two trial periods.

It can be seen from Table 6.1 that the subjects in the AMC-group had on average greater and more sloping hearing losses than those in the EUR-group. In the AMC-group there was a mix of experienced and first-time users, while the EUR-group consisted entirely of first-time users.We ordered new ear moulds in 17% of the cases. The decision to do so was based on the results of the feedback test. We found this test to be very helpful in detecting malfunctioning ear moulds, although in individual cases there have been some complaints about acoustical feedback in spite of a good result in the feedback test.

6.3.1. Data on speech perception in noise

Figure 6.1a shows the results of the SRT-test for the total group (n=27). The medians and 25 and 75 percentile points are represented for the differences in critical S/N ratios between the digital hearing aid and the conventional hearing aid in a number of conditions. When the value represented by the diamond is positive it indicates that the speech perception threshold with the digital hearing aid was better than with the conventional hearing aid, in that situation. The left diamond represents the difference in

Fig. 6.1. Panel a-c: The medians and the 25 and 75 percentile points for differences in the critical S/N ratios (in dB) between the digital hearing aid and the analogue hearing aid for the total group (6.1a) and for the subgroups AMC and EUR (6.1b-c). Positive diamonds corresponds for better speech perception for the digital hearing aid. S=continuous noise, F=fluctuating noise, C=car noise.

the S/N ratio in continuous noise (S), the diamond in the middle represents the difference in S/N ratio in fluctuating noise (F) and the right diamond represents the difference in S/N ratio in car noise (C). The first set shows the results obtained with the female voice, the second set with the male voice, the third set is measured after the hearing aid fitting (pre-trial) and the fourth set is measured four weeks after the hearing aid fitting (post-trial). The last set shows the combined result for male voice and female voice and pre- and post-trial testing. The differences, between the pre- and post-trial scores were not significant. This implies that we did not find measurable effects of acclimatization in our experimental set-up. In the subgroups of AMC and EUR (Fig. 6.1b and 6.1c, respectively) significant but opposite effects appear to be present. In the AMC-results the digital hearing aid performed clearly worse ($p<0.01$ for the continuous and fluctuating noises and $p<0.05$ for the car noise). In the EUR-results the digital hearing aid performed significantly better in the continuous noise and in the car noise ($p<0.05$). For the interpretation it is important to realize the difference in speech material (EUR: extra time to allow switch-on of noise-reduction algorithm) between the centres and the differences in the patient characteristics.

6.3.2. Data on loudness scaling

Loudness scaling was performed before and after the trial periods. There are no systematic effects of acclimatization on loudness perception, at least not within the 4-weeks duration of the trial period. For that reason the presented results have been averaged over tests before and after the trial period.

For the AMC-group we assumed that the dynamic range to be used for speech ranges from the levels scaled as 'soft' (Categorical Loudness Units, CLU =10) to the levels scaled as 'too loud' (CLU=50). We calculated the dynamic ranges from the loudness slopes. For the EUR-group a similar approach was followed using the Pascoe scores, averaged over 500, 1000 and 2000 Hz.

Compression may be expected to reduce the slope of the loudness curve, which is increased in the majority of sensorineural hearing-impaired subjects. If compression is effective this would show up as a difference in the loudness curve (a lower slope value and a higher dynamic range) for the compression digital hearing aid relative to the linear reference aid. We compared the results on loudness scaling for the 22 subjects who used a linear reference aid. In 23% of the cases (AMC n=3, EUR n=2) the calculated dynamic range in the digital aid was more than 10 dB higher than in the linear analogue aid. In the majority of the cases (16) the difference was less than 10 dB, while in one case the dynamic range was more than 10 dB higher in the analogue aid. We concluded that the effects of compression do not clearly influence the average dynamic range.

The correlation between the slopes of the "aided" loudness curves for the analogue and digital hearing aids is shown in Fig. 6.2 for a number of different sounds. For the AMC-group no clear effect of compression is present.

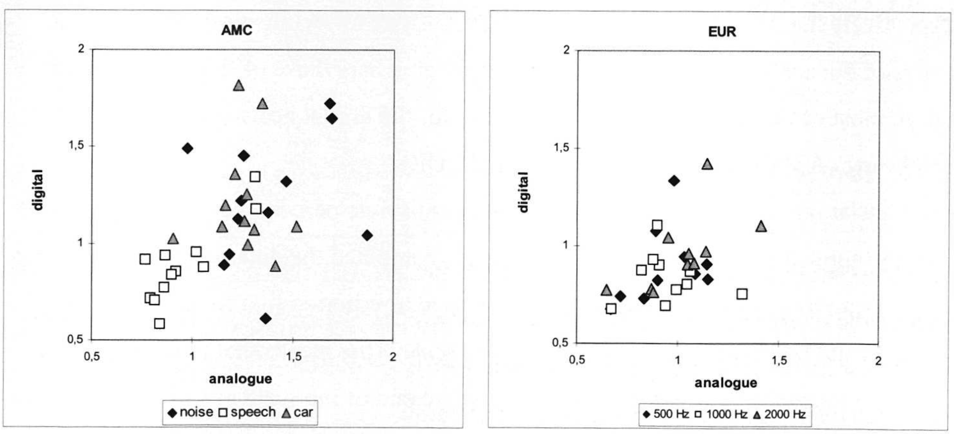


Fig. 6.2. Panel a and b: The relations between "aided" loudness slopes for the linear analogue and compression digital hearing aids for different noises for AMC and EUR, respectively.

For the EUR-group a slight trend can only be found for lower loudness slopes for the digital aid. The range of slopes is larger for the AMC-group than for the EUR-group. It is difficult to interpret these differences due to the different noises used in AMC and EUR. There were lower loudness slope values for single speaker noise and higher slopes for the other noises. No systematic differences were found between different frequencies.

6.3.3. Subjective data from the field test questionnaires

The questionnaires were very comprehensive, and therefore we constructed composite ratings summarising six important groups of acoustical situations: in quiet, in noise, in a car, on a telephone, watching TV or being in a theatre, and listening to music.

Figure 6.3a and b present composite scores on the speech intelligibility ratings for respectively the AMC-group and the EUR-group. The left white bars represent the scores of the analogue hearing aid and the right grey bars those of the digital hearing aid. In most of the cases we see a better rating for the digital hearing aid except for TV/theatre (AMC) and telephone (AMC and EUR).
The translation of individual field test data into absolute percentages can only be done after the application of a criterion value. As we computed the data from questionnaires with 4.2-cm long analogue-visual scales, we used as criterion that for a better score the rating should be in the "best" third part of the scale. This means that the judgement should be more than 2.8 points from the negative end of the scale or less than 1.4 points from the positive end of the scale.

The subjects were also asked about the frequency of occurrence and the individual relevance of each situation. These data have been used to weigh the intelligibility scores according to the perceptual relevance. There is no systematic difference between the

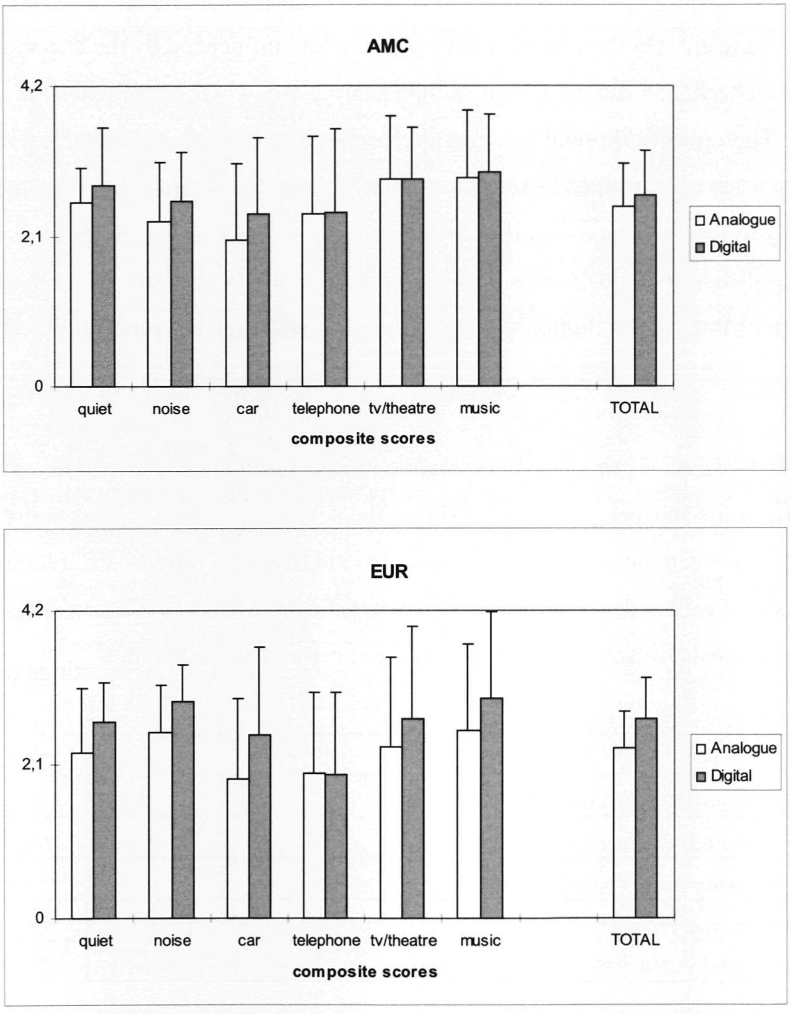


Fig. 6.3. Panel a and b: intelligibility ratings composed from answers to questions on different acoustical situations for the analogue and digital aids, for AMC and EUR.

weighed scores for use and importance and the unweighted scores. For almost all conditions we see a better score for the digital hearing aid.

Absolute scores are important because they are not related to an unknown reference like the old hearing aid. On the other hand, they are clearly influenced by the expectations of what should be "ideal" and there is no single hearing aid, which approaches the ideal situation. Therefore, additional information can be obtained from the relative data, especially when care is taken to select a good reference. In this study we investigated thoroughly in this reference condition by performing a completely new binaural fitting with state-of-the-art analogue aids. It is our opinion that these relative data reflect well the benefit of this type of digital hearing aid over an analogue reference aid used in the study.

For the relative data we used the comparative ratings for the two hearing aids given in the questionnaire in week 8. Table 6.3 shows the subjective results related to the differences between the analogue and the digital aid. Here we did not differentiate between significant and small but possibly insignificant differences. Some differences are only marginal. However, others are large and certainly significant.

	AMC	EUR	Overall %
Subjects with improved sound quality in the digital aid	9/5	10/12	70%
Subjects with less acoustic feedback with the digital aid	6/15	7/12	48%
Subjects with greater ease of handling due to automatic volume control	8/15	12/12	74%
Subjects with improved comfort of loud sounds in the digital aid	9/15	9/12	67%
Subjects with higher overal preference for the digital aid	10/15	10/12	74%

Table 6.3. Subjective results regarding the preferences for analogue or digital aids

Figure 6.4 a-b represents the relative ratings on general aspects of the hearing aid and about intelligibility ratings for AMC (black bars) and EUR (grey bars). For most of the considered conditions the subjects prefer the digital hearing aid, except for power consumption, visibility, intelligibility during a meeting and telephone at work for the AMC-group and wearing comfort and visibility for the EUR-group.

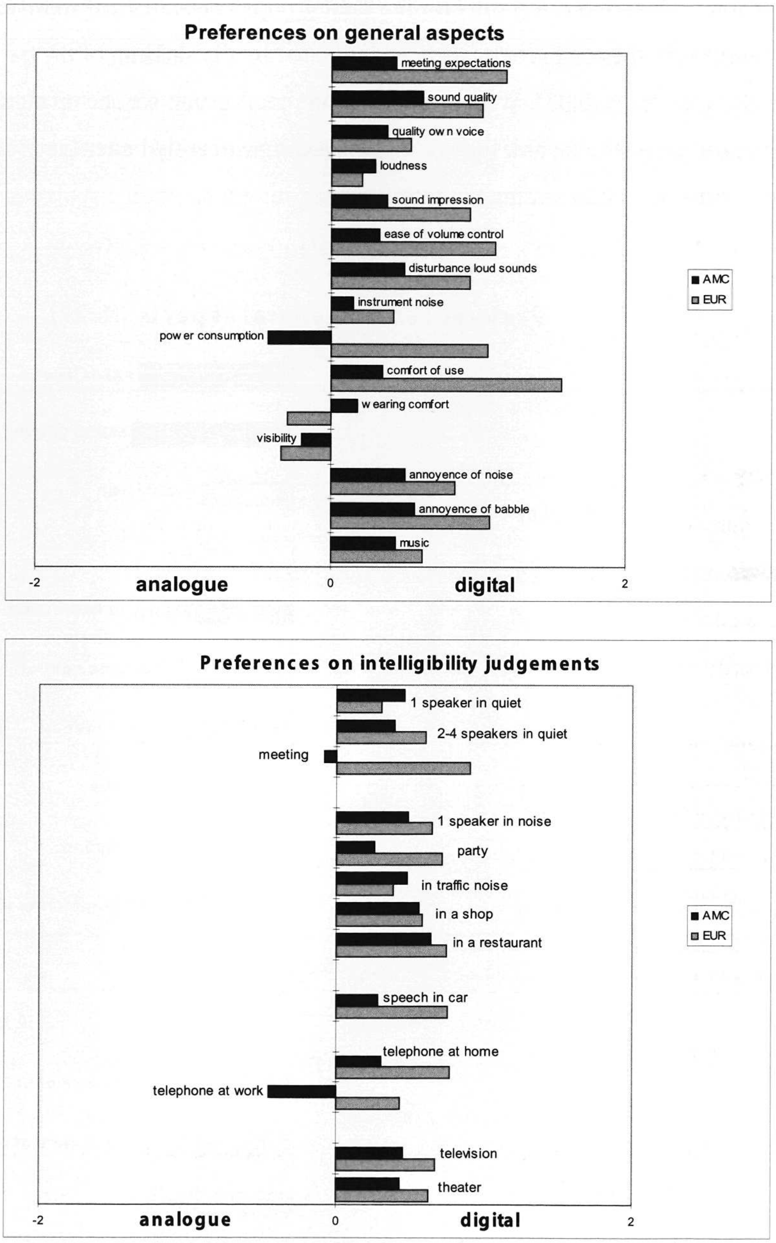
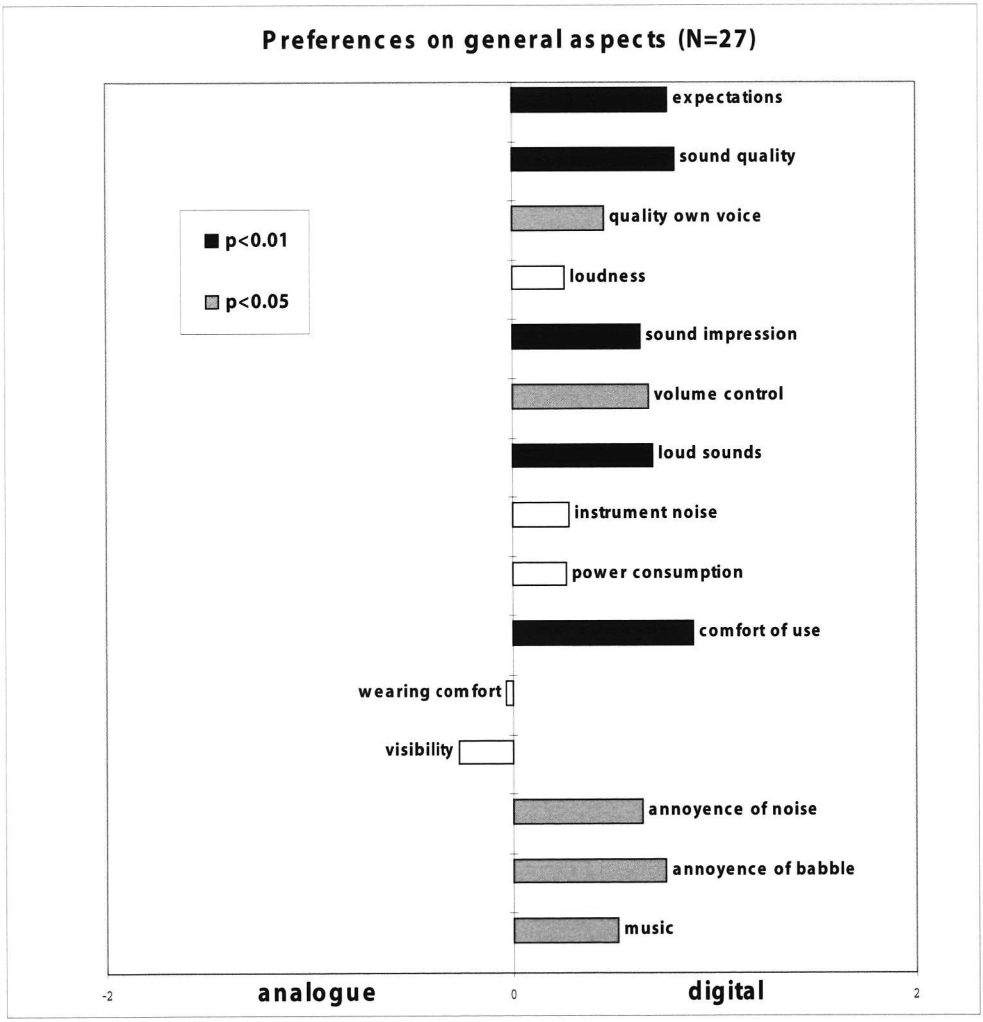


Fig. 6.4. Panel a - b: relative ratings for AMC (black bars) and EUR (grey bars) on general aspects of the hearing aid and on intelligibility aspects.

Figure 6.5 a-b shows the results for the total group. The statistical significance for the preferences in the total group has been indicated by the shading of the bars (black for $p<0.01$, grey for $p<0.05$). When we look at the total-group we see no significantly better scores for the analogue aid. Eleven aspects are significantly better (at 1% level) for the digital hearing aid, including the total score.



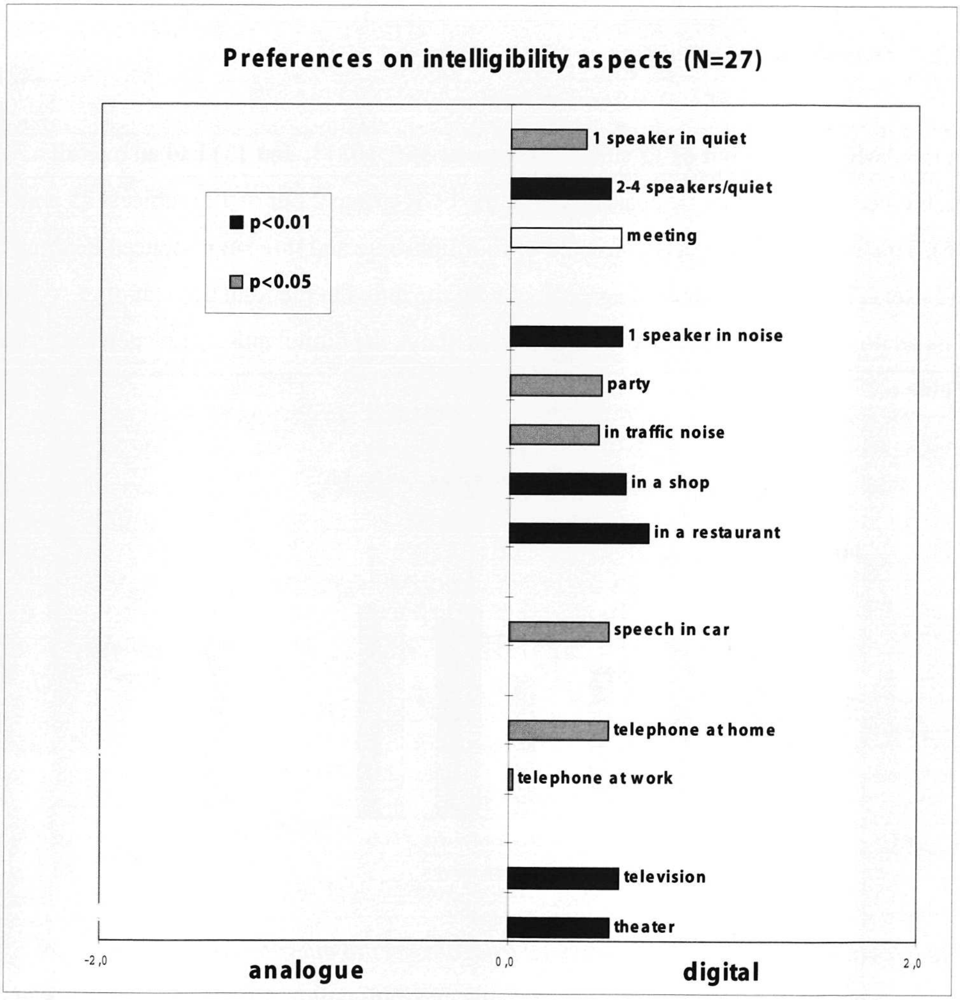


Fig. 6.5. Panel a - b: relative ratings for the total group. The level of significance is indicated by the shading of the bars (black for p<0.01 and grey for p<0.05).

6.3.4. Overall preference after two trial periods

In the AMC-group 5 out of 15 subjects (subjects 3, 5, 10, 11, and 13) had an overall preference for the analogue hearing aid, in the EUR-group 2 out of 12 (subjects 25 and 26). This group of 7 subjects consisted of four first-time and three experienced hearing-aid users. This is reasonably in agreement with the ratios in the total population.
The analogue hearing aids that were preferred above the digital aids can be derived from Table 6.2.

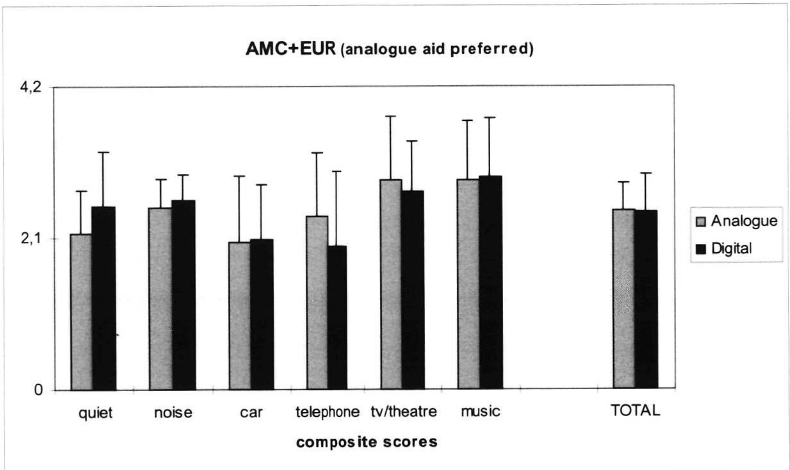


Fig 6.6. Intelligibility ratings composed from answers to questions on different acoustical situations for the analogue and digital aids, for the subjects who had an overall preference for the analogue hearing aid (AMC and EUR).

We could not detect a systematic effect to explain the overall preference. The reasons for choosing the analogue hearing aid differed from individual to individual. The composite scores of the subgroup choosing the analogue aid do not show a clear preference for the analogue aid, but the results are less supportive for the digital aid than the data for the total group (see Fig. 6.6 relative to Fig. 6.3).

6.4. Discussion

A number of aspects of our results favour the digital hearing aid, in other aspects the digital hearing aid is not superior to a well-fitted analogue hearing aid. The results in the EUR-group are more favourable than in the AMC-group, both in the speech intelligibility data and in the subjective ratings. The audiological difference between the two groups is that the EUR-group consists entirely of first-time hearing-aid users and that their losses were relatively mild and less sloping. It has been hypothesised that the results of the analogue reference aids may be relatively good, because they are completely adapted to conventionally amplified sounds. However, we found no experimental evidence in our data that the experienced users in the AMC-group performed better with the analogue hearing aid than the first-time users.

Compression may be expected to reduce the loudness slopes, which are steeper for the majority of sensorineural hearing-impaired subjects. In our data no clear evidence was found to support this assumption, although there is a slight tendency in the EUR-data for a reduced loudness slope with the digital compression aid.

The critical signal-to-noise ratio for the digital hearing aid was found to be better than the critical signal-to-noise ratio for the analogue aid in the EUR-group, but not in the AMC-group. The difference between the results in the subgroups shows that this is a substantial effect, possibly related to the differences in the testing procedures used. A possible explanation can be that in the experimental set-up at the AMC the stimulus condition at the beginning of the test sentence changes from noise only to speech in noise. This may degrade the perception of the test sentence, at least temporarily. In the EUR-approach the stimulus condition is acoustically the same at the beginning of the test sentence. Only the time-scale of the speech signal is reversed. Thus, the acoustical contrast (the difference between the background noise and the test sentence) at the beginning of the test sentence is minimal. However, we were rather surprised about the amount of improvement in the critical signal-to-noise ratios found. The possibility that differences in the fitting procedure of the reference aid influence the differences found, cannot be excluded.

The differences in the results in the speech testing data between the centres underline the problems associated with the validation of the effects of non-linear compression and noise-reduction hearing aids with long time constants. One may argue that the test procedure should be chosen in a way optimized for the signal processor, but one can also argue that sudden changes in the acoustical background are an inevitable part of daily life and should be included in laboratory testing to give it face validity. The time constant of the noise-reduction algorithm can be up to 20 seconds, which is considerably longer than most clinicians realize. Therefore, the question arises how we can perform speech testing relevant for daily-life situations.

The subjective scores are not always in agreement with the objective scores. In Figure 6.7 the differences in the total composite scores (see Fig. 6.3) have been plotted against the differences of the overall SRT-results (averages for total scores for continuous, fluctuating, and car noises in Fig. 6.1) for each individual subject. Positive values point to better results for the digital hearing instrument. The objective and subjective scores appear to be hardly correlated. Fig. 6.7 also shows that the subjective scores are more positive for the digital hearing aid than the objective results.

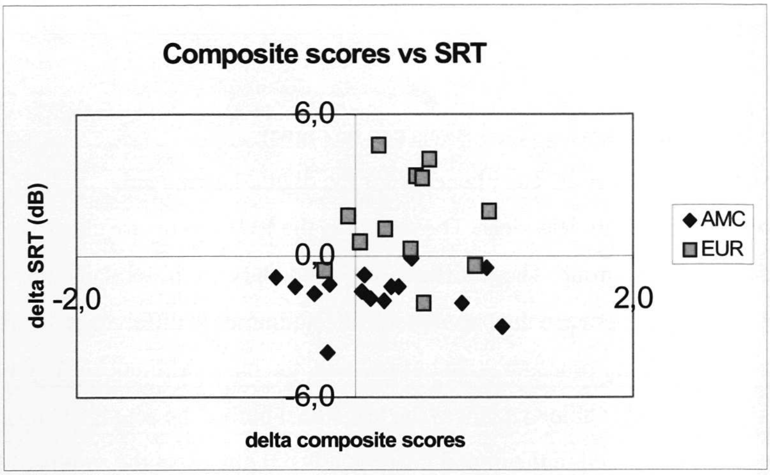


Fig. 6.7. The difference in the total composite scores (subjective scores) against the difference of the overall SRT-values (objective scores, averages for total scores for continuous, fluctuating and car noise.

One reason can be that small changes cannot always be measured objectively due to measurement accuracy. On the other hand, a subjective bias may be present. Although we tried to rule out subjective preferences as far as possible, the study design could not be blinded. The information about digital hearing aids in the media and in advertisements may have played a role resulting in a halo effect for digital. On the other hand, the profile of the subjective outcomes are quite realistic in our opinion, indicating that there are also disadvantages with the digital aid such as the visibility, the power consumption, and its use with the telephone at work. The trend of our data is in agreement with the results of Arlinger et al. (1998), who also found clearer benefits for the subjective data than for the objective results.

6.5. Conclusions

From this study the following conclusions can be drawn:

- The subjective data show clear benefits for the digital hearing aid.
- The objective data are less clear. The results in the EUR-group are clearly better than those in the AMC-group. These differences are too large to be explained by relatively small differences between the populations, the audiometric differences, or the differences in fitting procedures. In our opinion, the main difference is in the way the digital hearing aid is able to adapt to the test signal before the actual testing starts.
- The compression used in the digital hearing aids did not affect the results of the loudness scaling tests.
- In the end, 20 out of 27 subjects had an overall preference for the digital hearing aid. Halo effects cannot be excluded.

CHAPTER 7.

NOISE REDUCTION AND DUAL-MICROPHONE DIRECTIONALITY

This chapter has been published in Audiology (Boymans et al., 2000)

7. Noise reduction and dual-microphone directionality

Summary

In this study we measured the effects of a digital hearing aid on speech perception in noise for two noise reduction concepts; noise reduction by speech-sensitive processing (SSP) and improved directionality by a dual-or so-called twin-microphone system (TMS). This was conducted in a well-controlled clinical field trial in 16 hearing-aid users, using a single-blind crossover design. The hearing aid fitting was controlled by insertion gain measurements and measurements with loudness scaling.

This study combined laboratory experiments with three consecutive field trials of four weeks each. We used performance measurements (speech perception tests in background noise), paired comparisons, and self-report measurements (questionnaires). The speech perception tests were performed before and after each field trial, the paired comparisons were performed in weeks 4 and 12 and the questionnaires were administered after each field trial.

For all subjects, results were obtained for three different settings: no noise reduction, SSP alone, and TMS alone. In the last week, we also performed speech perception tests in background noise with both noise reduction concepts combined. Three types of results have been reported: "objective" results from the critical S/N ratios for speech perception in different background noises for different settings and "subjective" results: paired comparisons and questionnaires. The "subjective" scores show the same trend as the "objective" scores. The effects of TMS were clearly positive, especially for the SRT-tests and for the paired comparisons. The effects of SSP were much smaller but showed significant benefits with respect to aversiveness and speech perception in noise for specific acoustical environments. There was no extra benefit for the combined effect of SSP and TMS relative to TMS alone.

7.1. Introduction

The introduction of the digital hearing aid has stimulated the application of specific features such as noise reduction and dual-microphone techniques. It is important to assess the benefits of these features for hearing-impaired people in carefully controlled field trials. The most common complaints of hearing-impaired listeners are difficulties in understanding speech in noisy environments.

Three different techniques have been developed and are available in commercial hearing instruments, but none covers the whole range of difficult listening situations. As expected, the signal processing schemes at issue need differences between the wanted signal (usually speech) and the interfering signal (usually, but not always non-speech sounds):

- If there are spectral differences between the speech signal and the noise signal, multi-channel compression may be effective for speech perception in noise by means of a relative reduction of the gain in the frequency channels with the highest intensity levels (usually caused by the noise in those channels). If, for example, these high levels are caused by low-frequency noises the noise is amplified to a lesser extent than the speech and the overall signal-to-noise ratio may be improved (although not in the individual channels) with a reduced amount of upward spread of masking. This technique has been applied already in analogue hearing aids and shows only a limited benefit in relatively specific situations (van Dijkhuizen et al. 1991; Humes et al. 1997; Moore et al. 1986; Gordon-Salant et al. 1992).
- A further refinement to benefit from spectral differences between the wanted and the unwanted signal became possible with the introduction of digital techniques for commercially available hearing aids. Where there are differences in the modulation characteristics of the speech signal and the noise signal, algorithms have been introduced to discriminate between speech and noise in each frequency channel and to adapt the gain accordingly. This feature is called modulation-based noise

reduction. Again, the S/N ratio does not change within each channel, but the overall S/N ratio may improve in case of spectral differences between the target speech and the jammer signal. Up to the present time, only limited experimental evidence is available on the benefit of this technique. Boymans et al. (1999) found clear "subjective" preferences, but it appeared to be difficult to assess an "objectively" measured benefit in critical S/N ratio in a three-band hearing aid with noise reduction based on modulation analysis.

- Finally, if there are spatial differences between the speech signal and the noise signal, directional microphones may be effective in selective amplification of the speech (usually from the front) relative to the noise (usually from the other directions). The introduction of dual-microphone systems has renewed the interests in directionality, and various studies point out that an important benefit can be obtained in specific situations within the direct sound field of the target speaker. A number of studies point out that the application of the dual-microphone technique yields a significantly improved S/N ratio for conditions with the speaker in the direct sound field in front of the listener and the noise coming from a diffuse sound field or from other directions (Valente et al., 1995).

In commercial publications it has been suggested that new features, now available in digital hearing instruments, can compensate almost completely for the problems of listening in noise. Earlier experiences in clinical field trials, showed that a number of points need to be addressed carefully in the design of evaluation studies on advanced signal processing in hearing aids and in the interpretation of the results (Dreschler et al., 2000). The positive information in the media may strongly influence the subject's expectations and the subjective outcome measurements can easily be biased unless the test can be carried out blind. Consequently, discrepancies between "objective" and "subjective" data may be found and a careful control of the information presented to the subject is particularly important. Therefore, this study concentrates on differences within the same hearing aid, in which the actual setting is blind for the subject, and the conditions were randomized over trial periods.

In this study we tested a full digital, four-channel, behind-the-ear hearing aid with different noise reduction strategies. We tested the combined value of the second and third noise reduction concepts. The modulation-based noise reduction concept in the trial hearing aid is called speech sensitive processing (SSP), with a possibility of activating it for each of the four frequency channels in a maximum or medium setting. The dual-microphone system in the trial hearing aid is called a Twin Microphone System (TMS). The results without noise reduction concept were compared with the results using the SSP setting and with the results using the TMS setting. For the last two settings, we used a single blind crossover design.

The fitting was evaluated by means of loudness scaling. In some cases we modified the setting of the hearing aid according to the dynamic range, the most comfortable level (MCL), and the loudness slope (Bachmann et al., 1998). For each setting used for the trial period, we measured the critical S/N ratio for sentences in noise before and after the trial period. Paired comparisons were used to find the subjectively preferred noise reduction setting for every subject in different background noises (Valente, 1994). Finally we used the Abbreviated Profile of Hearing Aid Benefit (APHAB, Cox et al., 1995) to evaluate the subjective judgement of the subjects according to the different hearing aid settings in the field trial. This study focuses on the following questions:

- What are the separate benefits of SSP and TMS for speech perception in noise?
- Are these effects additive if SSP and TMS are combined?
- How is user satisfaction and subjective benefit being influenced by SSP and TMS?

7.2. Method

The study combined three field trials of four weeks each with laboratory experiments before and after each field trial in order to get an indication of acclimatization (Gatehouse, 1992). The purpose of the laboratory study was to evaluate, by means of "objective" measurements, the effect of the different noise reduction settings on the critical S/N ratio. The results of the initial setting (both SSP and TMS off) were compared with the results of the two different noise reduction settings alone (SSP active / TMS off and TMS active / SSP off). Laboratory experiments included measurements of speech recognition in a speech babble (cocktail) noise and in low frequency car noise. At the beginning of the experiments, we made comparable measurements with the subjects' own hearing aids, and after the three field trials (after three months) we measured the effect of the combination of the two noise reduction settings (SSP active / TMS active). We also applied paired comparisons to define the subjectively most preferred noise reduction setting for each subject in different background noises.

7.2.1. Subjects

We selected 16 subjects from the regular population of our audiological centre ensuring that the subjects were a representative sample of BTE-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 cooperated on a voluntary basis. They had to wear the hearing aid(s) at least 4 hours a day.

The subjects had a predominantly sensorineural hearing loss (average air-bone gap < 15 dB). All subjects had at least 2 months of experience in wearing one or two BTE hearing aids. They were all carefully fitted according to the standard procedures of our audiological centre. In 50% of the cases, the former hearing aid had advanced features such as programmability or multi-channel compression. In the test group, 12 subjects were fitted bilaterally and 4 subjects were fitted unilaterally. For unilaterally fitted subjects, the hearing aid was fitted to the better ear, and we verified that the unaided ear did not contribute significantly to speech intelligibility at the levels of testing. Table 7.1 shows some key data on the 16 subjects.

Subject	*Age*	*Average Hearing (.5, 1, 2, 4 kHz)*		*Fitted Ear*	*Former Hearing Aid*
		Right	*Left*		
A	*52*	*63*	*66*	*Right, left*	*Widex Q9*
B	*66*	*54*	*50*	*Right, left*	*Siemens S2+*
C	*68*	*59*	*51*	*Right, left*	*Siemens S1+*
D	*40*	*58*	*68*	*Right, left*	*Danavox 143 AGC-I*
E	*66*	*42.5*	-	*Right*	*Widex ES8*
F	*51*	*60*	*68*	*Right, left*	*Widex L12E*
G	*75*	*49*	*55*	*Right, left*	*Danavox 143 AGC-I*
H	*64*	*61*	-	*Right*	*Siemens 564P*
I	*66*	*30*	-	*Right*	*Widex L8E*
J	*66*	*53*	*50*	*Right, left*	*Widex ES8*
K	*66*	*56*	*58*	*Right, left*	*Oticon Digifocus Compact*
L	*61*	*41*	*36*	*Right, left*	*Philips L61O*
M	*49*	*38*	-	*Right*	*Siemens 568W*
N	*65*	*40*	*65*	*Right, left*	*Oticon Digifocus Compact*
O	*71*	*55*	*54*	*Right, left*	*Widex C8*
P	*68*	*48*	*44*	*Right, left*	*Oticon Personic 410*

Table 7.1. Summary of individual data on the participating subjects.

7.2.2. Hearing aids

The test hearing aid was a digital BTE hearing aid (Siemens Prisma). This hearing aid is equipped with two user-controlled programs, which can be switched without a remote control. There is no external volume control at the disposal of the user (for more details, see Holube (1998).

As described, one of the features under test is the modulation-based noise reduction (called SSP). Speech can be described with respect to its temporal structure or its frequency distribution in the spectrum. Typically, the spectrum of speech shows frequency components between 100 Hz and 8 kHz. The envelope of the signal, which is only changing slowly and has therefore much lower frequencies than the spectrum, is often not taken into account. The envelope of the speech is determined by phonemes, syllables, words, and sentences. Voices can normally articulate about 12 phonemes, 5 syllables, and 2.5 words per second. To formulate a sentence, several seconds are necessary. Therefore, the envelope of speech shows a characteristic temporal behaviour that is, in general, independent of the speaker or the spoken language. The envelope is a characteristic feature of signals that now can be used in hearing instruments. The modulation spectrum is different for speech and for most types of background noise. The maximum in the modulation spectrum of speech is in the area of 2 to 8 Hz. The modulation spectrum of noise usually shows fewer and faster modulations and therefore has its maximum at higher frequencies. This difference in the modulation spectra between speech and noise can be used to detect speech and to reduce the noisiness of the signals. A reduced noisiness can result in a more comfortable sound, a reduced hearing effort, and an increased speech intelligibility. For this purpose, the envelope of the signals is analysed in different frequency channels. If the characteristic modulation frequencies of speech are detected, the speech is amplified according to the requirements of the hearing loss. If the characteristic modulation frequencies of speech do not exist in the signal, the gain in that frequency channel is reduced. The gain reduction is higher for higher modulation frequencies and lower modulation depth. The largest gain reduction is achieved for stationary signals like sinusoids or white noises. The value of the largest gain reduction can be selected independently in each frequency channel and can be set to medium (5 dB) and maximum (10 dB). In addition, it is of course possible to deactivate the processing algorithm in each frequency channel.

The second feature is the Twin Microphone System (TMS). By using a combination of two microphones, directionality can be improved considerably. The amount of improvement can be expressed as a front-random index, which is usually higher for the higher frequencies. Merks (2000) measured front-random indices for the Siemens Prisma hearing aid in an artificial diffuse sound field. For the AI-weighted front-random index, he found values of −1.4 dB for the test hearing aid with omni-directional microphone and +3.3 dB for the test hearing aid with TMS. Thus the acoustical gain in front-random index for the TMS-system is 4.7 dB.
All subjects started in an individually selected basic setting (see chapter on fitting) without noise reduction or directionality for both programs (programs P1 and P2 were exactly the same), in order to adjust to the hearing aid. After four weeks, one of the two noise reduction schemes (SSP or TMS) was activated in program P2. Again, after four weeks, we changed the noise reduction concept in program P2, according to a randomized scheme.

The subjects had no information about the differences between the noise reduction concepts in program P2. They were told that they had a second program in the hearing aid and were asked to use it in different situations. They knew that after each field trail they had to fill in a questionnaire about the different programs.

7.2.3. Fitting procedure of the digital hearing aid

All hearing aids were fitted in a quiet surrounding. The frequency response and compression parameters were based on the hearing thresholds and uncomfortable levels according to desired sensation level (DSL) (input/output) (Cornelisse et al. 1995) using the individual real ear unaided response. We checked the target setting objectively by means of insertion gain measurements with speech-shaped noise (according to long-term average speech spectrum, LTASS, Byrne et al. 1994) at input levels of 50, 65, and 80 dB(A). If feedback problems occurred, we modified the ear moulds. When the ear mould was correct and there was still a feedback problem we did some fine-tuning according to the manufacturer-provided recommendations (the so-called Fitting Assistant in the programming software).

In addition, we applied a subjective check of the target setting by means of loudness scaling. Aided loudness scaling was performed for each ear using the Würzburger Hörfeld Skalierung (WHS), which is based on a 50-point scale (Kiesling 1995). We used narrow band noises with a duration of 5 seconds, the ranges of output levels were 30 to 90 dB(SPL). During this measurement, the noise reduction concepts were inactivated. We applied curve fitting to reduce measurement error. The fitting resulted in two parameters: the level at which the loudness level of 50% of the scale was reached (called MCL) and the slope of the loudness growth function. The former is related to the degree of hearing loss, the latter to the amount of recruitment. For the verification of the fitting, the correspondence between the aided loudness contours and the normal loudness contours was considered.

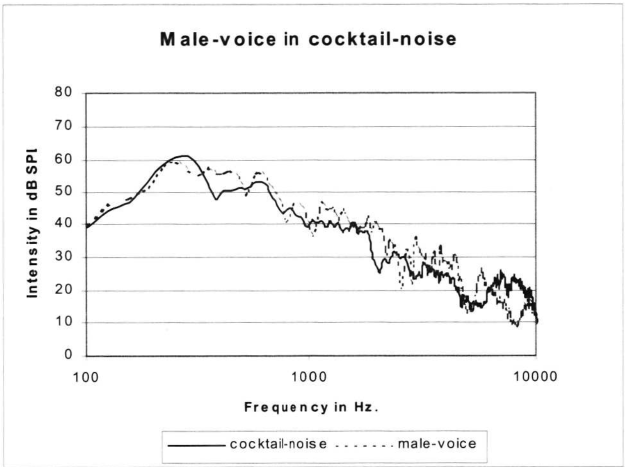
The decision for fine-tuning was always based on a combination of different factors: the sound impression of the subject, the insertion-gain measurements, and the results of the aided loudness scaling. Generally, the complaints were the same: most subjects found the initial settings of the hearing aid too loud. When the loudness curves were too steep we gave more compression for that particular frequency band, and when the loudness curve was shifted we adapted the gain for that particular frequency band. We were reluctant to perform further fine-tuning when the subject still had some complaints, but when the results of the WHS were in agreement with the loudness curves of a normal-hearing person. In that case we tried to persuade him/her to start trying the hearing aid for one week. When the subject could not get used to the hearing aid, we performed some fine-tuning after one week, according to the suggestions of the Fitting Assistant in the fitting software (but as little as possible). We always repeated the insertion gain measurements and the WHS-measurements for the final setting.

Fortunately, there were only slight differences between the initial and final fittings for the majority of the subjects. These differences may be assumed not to influence the differences between the noise reduction schemes under test, because the same ear moulds and the same basic settings were used throughout the remainder of the experiments.

7.2.4. Performance with speech in noise

For each setting used for the trial periods, we measured the speech-reception thresholds (SRTs) for sentences in background noise, according the method of Plomp and Mimpen (1979), before and after the trial period. This test uses an adaptive up-down procedure and has been proven to be relatively fast and accurate (test-retest standard deviation between 0.9 to 1.5 dB). We used two different speakers (male and female, at 0^0 azimuth), and two different background noises (cocktail noise and car noise[1]) coming from three uncorrelated noise sources (at 90^0, 180^0, and 270^0 azimuth). The speech material from the male voice was presented in cocktail noise and the speech material from the female voice was presented in car noise (the spectral differences are shown in Figure 7.1a and 7.1b, respectively).

[1] Tracks 50 and 54 from the cd "Fitting and testing of hearing programs", produced by Colosseum Musikstudios, 1992.



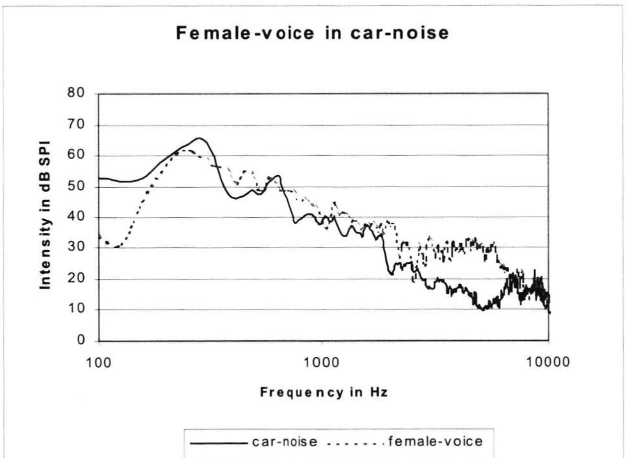


Fig. 7.1. Panel a: frequency spectra of the male voice in cocktail noise. Panel b: frequency spectra of the female voice in car noise.

The spectra show clearly that the spectral differences between the male speaker and the cocktail noise are only marginal, whereas there are marked spectral differences between the car noise (with more low-frequency emphasis) and the female speaker (with more high-frequency emphasis).

We used an adaptive procedure to find the 50% point by changing the S/N ratio. The noise level was fixed at 65 dB(A) at the listener's position. The speech level was calibrated by a continuous noise with an identical spectrum of the speaker, expressed as equivalent long-term rms level in dB(A) (without silent gaps). The results will be reported in terms of the S/N ratio at threshold (the so-called critical S/N ratio). Testing was performed with 20 lists of sentences. The order of the lists was randomized. In previous studies the psycho-acoustical measurements have been severely hampered by the long adaptation times of noise-reduction algorithms (Boymans et al. 1999). In this study, we applied speech testing in noise and the noise was constantly present during testing. The SRT-test was performed with the subject's own hearing aid, before and after the field trials without the noise reduction concept, with TMS (pre- and post-trial) and with SSP (pre- and post-trial); in the end, we also performed the SRT-test with both noise reduction concepts (TMS active and SSP active).

7.2.5. Paired comparisons

The subjective preferences for the hearing aid settings under test were investigated by means of the technique of paired comparisons (Eisenberg et al., 1997; Kuk, 1994) in week 4 (after the first field trial: test) and week 12 (after the last field trial: retest). Four different hearing aid settings were tested. (SSP off / TMS off, SSP active / TMS off, SSP off / TMS active, and SSP active / TMS active). The subjects were asked to listen to standard speech fragments and state which program they preferred when they had to understand speech in "this situation" through the whole day. The choice was always one of two programs. Six combinations were possible. As with the SRT-test, two background noises were used (cocktail noise and car noise). The noises came also from three sides (90^0, 180^0, and 270^0) the speech came from 0^0 azimuth. Thus, in total, the subjects had to make twelve choices (test). During the changing of programs, the noise remained on. For each noise at 65 dB(A), the same two sentences were used at 70 dB(A). When the subjects could not choose, they were allowed to hear the speech samples again.

7.2.6. Self report

In the first trial period, each subject became accustomed to the sound of the new hearing aid. After the first week, the subject was asked to fill in a questionnaire about general aspects (sound quality, speech intelligibility, and own voice) of their new hearing aids using visual analogue scales (not reported in this paper).

To compare the different settings of the test hearing aid we used a Dutch version of the APHAB questionnaire (Cox 1995). APHAB is a subjective assessment scale that measures the benefit from amplification. It consists a set of 24 items (a sub-set of the original PHAB questions) and yields scores in four sub-scales:

1. EC: ease of communication, the strain of communication under relatively favourable conditions.
2. RV: reverberation, communication in reverberant rooms.
3. BN: background noise, communication in settings with high noise levels.
4. AV: aversiveness of sounds, the unpleasantness of environmental sounds.

Each item is a statement. The subject is asked to indicate if that statement is true using a 7-point scale. We asked the subject to fill in the APHAB in different situations: in week 0, without a hearing aid and with their own hearing aid; in week 4 (after the trial period with the new hearing aid without a noise reduction concept); in week 8 (after the trial period with a noise reduction concept in program P2); and in week 12 (after the trial period with the other noise reduction concept in program P2). The aided scores (with the own hearing aid) obtained at week 0, were used as a reference score in week 4. After that, the scores of the new hearing aid (O+O) were used as a reference score (in weeks 8 and 12).

7.3. Results

We will present three types of results: SRT measurements with the subject's own hearing aid and with different settings of the digital hearing aid, paired comparisons with different hearing aid settings, and subjective data obtained by the APHAB.

7.3.1. Performance on speech perception in noise

Figure 7.2 presents the results of the SRT test for the total group (n=16). The left group of bars represents the critical S/N ratio of a male voice in speech-babble (cocktail) noise; the right group represents the critical S/N ratio of a female voice in car noise.

The first bars of both groups represent the critical S/N ratio of the own hearing aid. For the test hearing aids, two measurements are available (before and after each trial period). There were no significant learning effects. Therefore, pre- and post-trial results have been averaged. The second, third, and fourth bars represent these averaged critical S/N ratios for the different hearing aid settings: SSP off / TMS off (O+O), SSP off/ TMS active (O+D), and SSP active / TMS off (N+O), respectively. The subjects did not have a trial period with both noise reduction concepts active (SSP active and TMS active (N+D)), so we made only one measurement (see the fifth bar in Figure 7.2). The statistical significance of the differences between the hearing aids was tested by means of Wilcoxon-tests (matched pairs signed ranks).

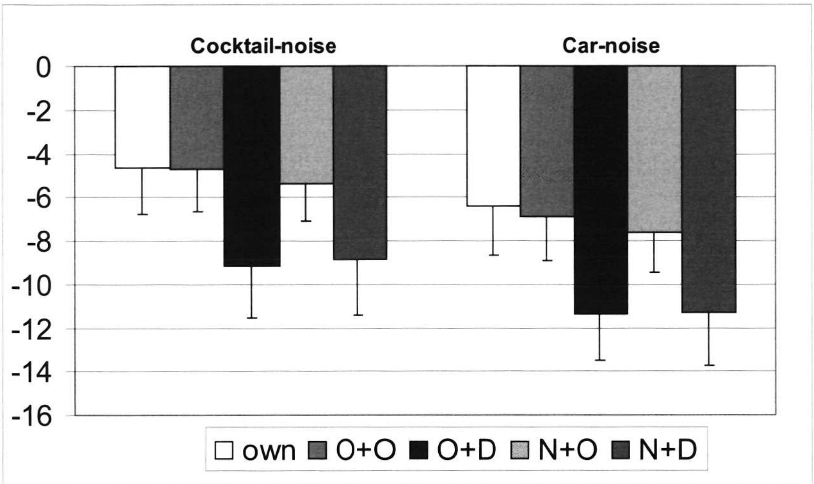


Fig. 7.2. Critical S/N ratios in cocktail noise and in car noise for different hearing aids and/or settings: Own: own aid, O+O: test aid without noise reduction, O+D: test aid with TMS, N+O: test aid with SSP, N+D: test aid with SSP and TMS.

It is clear that, on average, there were no differences between the scores of the own hearing aid and the new hearing aid without noise reduction strategies. The settings with TMS active showed a clear improvement in critical S/N ratio with respect to the setting without noise reduction ($p<0.01$ for cocktail noise, $p<0.05$ for car noise). There also appeared to be some improvement for the setting with SSP active, but this was only modest (n.s.). The combination of both noise reduction concepts (N+D) does not give an added value relative to the setting with the TMS active only (O+D). The trends of the results in cocktail noise and in car noise were similar. As expected, the overall thresholds in car noise are better (lower S/N ratios) than in speech noise.

7.3.2. Subjective data on paired comparison

Figure 7.3 presents the results of the paired comparisons for different hearing aid settings in different noises. The first set of bars shows the percentages of preferences without any noise reduction setting. The second set shows the percentage of preferences with the TMS active, the third set with SSP active, and the last set with both noise reduction algorithms active. The preference for the TMS setting is almost 60% higher than for the setting without noise reduction ($p<0.001$ for a sign test). The subjects prefer the SSP setting less than the TMS setting, but the preference is 10-20% higher than the setting without noise reduction ($p<0.001$ for a sign test). There is not much difference when the SSP is added to the TMS. In general, there is only little difference between the preference in speech noise and in car noise.

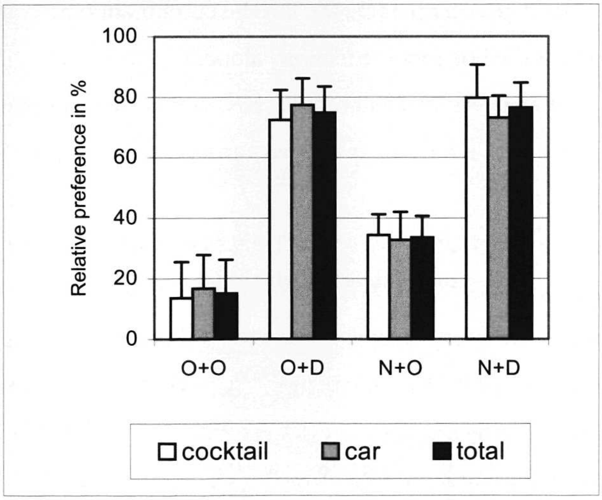


Fig. 7.3. Percentage preferences for the different settings of the test hearing aid, measured by paired comparisons in cocktail noise and in car noise: O+O: without SSP, O+D: with TMS, N+O: with SSP, N+D: with SSP and TMS.

7.3.3. Comparison of the "objective" (SRT) and "subjective" results (PC)

Figure 7.4 presents the "subjective" results of the paired comparisons versus the "objective" results of the SRT-tests in different noises. Three effects can be distinguished from this figure:

- The points for the car noise are shifted to more negative S/N ratios because of the "objective" thresholds in car noise are better than in cocktail noise.
- For each of the noises the "subjective" and "objective" results are well in agreement. When better SRT-thresholds are found (lower critical S/N ratios for a hearing aid setting), the subjective scores of the paired comparisons become also better (a higher preference for that particular setting). The scores with SSP alone (N+O) are slightly better than without noise reduction (O+O). A much better result is obtained when the TMS-setting is active (O+D), but the combination SSP and TMS (N+D) does not give added value relative to TMS alone.
- The pattern is comparable for both noise types, which suggests that the effects described are insensitive for the type of background noise and the S/N ratio of the signal presentations.

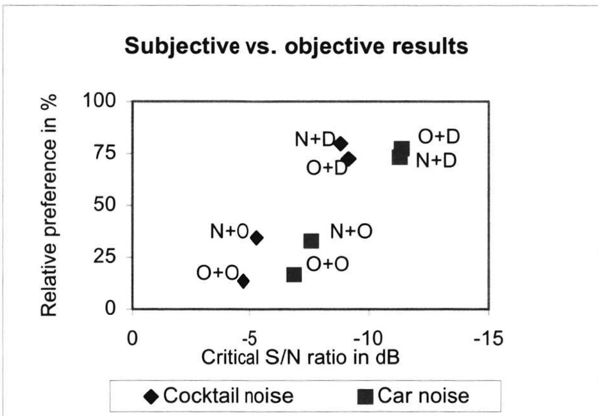


Fig. 7.4. Correspondence between "subjective" and "objective" results for the four hearing aid settings in cocktail noise and in car noise.

7.3.4. Subjective data from the field trial questionnaires

Figure 7.5 shows the results of the APHAB questionnaires, which were summarised in four sub-scales: ease of communication (EC), reverberation (RV), background noise (BN) and aversiveness of sounds (AV). All sub-scales are expressed as percentages of problems. Consequently, lower values indicate better results.
The response pattern shows that the use of a hearing aid (relative to unaided) reduces the percentage of problems drastically, partly at the cost of a higher aversiveness. Despite the fact that some subjects indicated that the test hearing aid was relatively loud in the beginning, the aversiveness for the test hearing was slightly lower than for the own hearing aid. This can be an indication that, in those subjects, an adequate limiting of high output levels compensates for the higher gain values. However, these data are subjective and can also be biased by a preference for the new digital hearing aid per se.

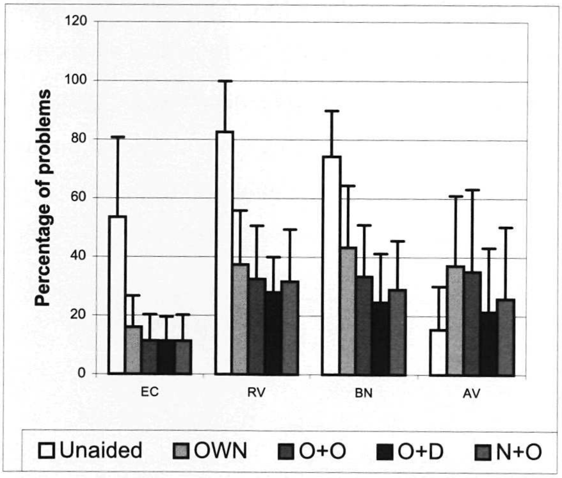


Fig. 7.5.APHAB scores for the different hearing aids and/or hearing aid settings. Own: own hearing aid, O+O: test aid without noise reduction, O+D: test aid with TMS, N+O: test aid with SSP. EC: ease of communication, RV: reverberation, BN: background noise, AV: aversiveness of sounds

In this respect, the comparisons between the different settings of the test hearing aid are more informative.

For this study, the effects of SSP and TMS are of particular interest. When we consider the differences between the settings in the test hearing aid, few effects were statistically significant. Only the effect of TMS on aversiveness (the difference between O+D and O+O) is significant at $p<0.05$ (Wilcoxon matched-pairs signed-ranks test). The absence of other significant effects may be due to the fact that the APHAB sub-scales are composed of six answers to questions for different conditions, while possible benefits may be present for only some of them. Therefore, we analysed the answers to the individual questions for SSP (N+O versus O+O) and for TMS (O+D versus O+O) by means of a sign test. These data were obtained by direct comparison during the second and third field trials.

Positive effects of SSP were statistically significant for speech perception in car noise ($p<0.05$) and for the aversiveness for sudden loud sounds like alarm bells ($p<0.01$) and traffic noises ($p<0.01$). Positive effects of TMS are found for all six questions on aversiveness (4 effects with $p<0.01$) and for three questions on speech perception in noise: in car noise ($p<0.05$), in a conversation with one person at dinner with several people ($p<0.01$), and for a conversation in a crowd ($p<0.01$).

7.4. Discussion

In spite of the careful fitting procedures applied, the results obtained with the test hearing aid without special processing (O+O) are no better than the results of the subjects' own hearing aid. This suggests that digital technology per se does not help the main problem of hearing-impaired listeners, which is speech perception in noise. However, digital technology facilitates the use of modulation-based noise reduction and the application of dual-microphone techniques. This may bring additional benefits:

- o Noise reduction is a system that can distinguish speech from noise on the principle that there is a difference of the modulation spectrum between speech and noise. So, if the modulation frequencies of speech do not exist in the signal, the gain in that frequency channel is reduced. For that reason increased speech intelligibility in background noise (especially when the noise deviates from speech, for example, constant low frequency noise) and a more comfortable sound can be expected.
- o The dual-microphone technique improves directionality. Thus, the spatial separation of speech and noise favours the sounds from the front. Here also, increased speech intelligibility in background noise and a more comfortable sound can be expected, although the effectiveness is not dependent on the spectral difference between speech and noise.

It is important to test the benefit of these developments in the field. However, there are many aspects to be taken into account. It is difficult to do a blind study because different hearing aids are often needed. However, in our experimental design, bias was minimised by comparing different settings in the same hearing aid. However, each comparison with the subject's own hearing aid may be biased because he/she knew which was their own and which was the new hearing aid. Another aspect we have to take into account is the adaptation effect. This is avoided by a common adaptation period for all subjects. In our set-up, all subjects had the same reference. After the adaptation period, two conditions (SSP and TMS) were tested successively, with the order randomized.

Laboratory tests do not always resemble the real-life situation. In our study we used a nice combination of field trials with questionnaires and "objective" SRT-tests in two different background noises coming from three sides. Direct comparisons could be made in the paired comparison test also in two different background noises coming from three sides.

The fitting of the test hearing aid was very comprehensive (and thus time consuming). Individual differences of the ear canal and the ear moulds were taken into account. For the target fitting, the real ear unaided response was used and the fitting was checked by insertion gain measurements. A number of subjects judged the gain prescribed by the DSL(i/o) as relatively loud. This is in agreement with other studies (Stelmachowicz et al. 1998). Fine-tuning was done when the loudness scaling deviated too much from the reference curves.

The positive effects of SSP are relatively small. In the SRT results, the improvements due to SSP (N+O re. O+O) are not significant and in car noise they are hardly better than in cocktail noise. Our hypothesis that SSP would be more effective for a constant noise with a spectrum that deviates from speech (like car noise) than for a fluctuating noise with a speech-like spectrum (like cocktail-party noise) cannot be confirmed in the performance data. However, SSP adds to the subjective benefit as shown in the preference data of the paired comparisons. Although the effects of SSP were not significant for any of the APHAB sub-scales, some of the specific questions showed significantly better scores (e.g. regarding speech perception in car noise and some questions on aversiveness).

The positive effects of the TMS are obviously present in the results of the SRT-test, the paired comparison, and the questionnaires. For the SRT-test there is a clear difference between the results with the TMS active and the initial setting (no SSP no TMS). The first results are in agreement with the results of Wouters et al. (1999) and Ricketts et al. (1999). The degree of improvement in the SRT data of this study (4.5 dB, both for the cocktail noise and for the car noise) is close to the gain that can be expected on the basis of acoustical measurements (4.7 dB according to Merks, 2000). However, it is slightly smaller than the 5.7 dB gain that was observed in a recent study by Pumford (2000). Ricketts and Dhar 1999[a] described results of the combination of SSP and TMS in a living room environment (the noise came from five different directions). Although not significant, they found a better score for a nonsense syllable test with both SSP and TMS active compared with TMS alone. In our results, the combination of SSP and TMS was not significantly better than TMS alone, for either the SRT results or for the paired comparisons. So, in this experiment, there is no added value of both TMS and SSP (N+D) relative to TMS (O+D). It is possible that the lower gain for the background noise due to TMS made further noise reduction by SSP less necessary or at least more difficult to perceive.

For the sub-scores of the APHAB questionnaire, there is only a significant difference for the sub-scale aversiveness (O+O vs. O+D). The reason could be that a lot of answers were already positive for the setting O+O so there was not much space for further improvement. Also, the analysis of the effects of SSP and TMS on the separate questions revealed that significant effects might easily disappear when conditions are combined in which possible positive effects are only found for a sub-set of the conditions. The positive effect of TMS on aversiveness is unexpected. One reason may be that the overall loudness impression of the test hearing aid in the directional mode is softer (the subjects have no volume control). However, the gain reduction in the low frequencies for the directional mode is likely to be the most important reason.

The paired comparison is a subjective test, but in contrast of the APHAB it is always in the same acoustical situation. It is important always to give the same instruction. Many subjects will choose O+O when the instruction is "which program is the best". In principle, they want to hear everything. But when is added: "when you have to sit in this situation for a long time", they will choose a more quiet setting. The paired comparisons are in agreement with the SRT-test. The lowest scores are obtained without noise reduction, better scores were found with SSP active and the best scores with TMS active. Here also the two noise reduction settings are no better than TMS alone. However, the results of SSP alone tend to be more favourable than in the SRT-tests. The SRT-test is a threshold measurement (S/N ratio is variable) and the paired comparisons were measured at fixed S/N ratio (S/N = 5 dB). For most subjects this was well above their speech reception thresholds in noise, for car noise more than for cocktail noise. The critical S/N ratios of the SRT results without noise reduction are between –4 and –7 dB. At such a poor S/N ratio it can be that the noise reduction does not work well, which could be the reason why the SSP does not improve scores significantly. Therefore, positive effects are only found in the paired comparisons where, usually, a better S/N ratio (+5 dB) has been used.

The "subjective" scores from the questionnaires are in reasonable agreement with the "objective" scores. For the subjective questionnaires, more attention is paid to different situations. The scores of the questionnaires show no difference in ease of communication (EC) for the different hearing aid settings in relatively favourable conditions. We did not use this relatively favourable condition (speech intelligibility in quiet) in the "objective" tests. In spite of the fact that some subjects indicated that the test hearing aid was relatively loud in the beginning, the aversiveness scores for the test hearing aids were better than for the own hearing aids. This can be an acclimatization effect because in the end of the four weeks, most subjects did not find the hearing aids too loud.

We also analysed the effects in different subgroups. The differences were not significant, but some of the trends will be described below. The eight subjects with the most sloping audiogram scored better in cocktail noise and worse in car noise relatively to the average of the whole group. This can be due to upward spread of masking and the reduced capacity to use high-frequency information for the group with sloping losses. The eight subjects with the worst SRT-scores in the O+O setting do score below the average of the whole group for all other SRT-tests. The trends of SSP and TMS are similar in both subgroups. The type of hearing aid used before (conventional or advanced) did not influence the results either.

In the end all subjects wanted to purchase the test hearing aid. Most of the subjects were allowed to obtain a new hearing aid. A few subjects determined to replace their own hearing aid. Nine of 16 subjects chose the combination P1: O+O and P2: O+D; 3 subjects chose P1: O+O, P2: N+O; 3 subjects chose P1: N+O, P2: O+D and one subject chose P1: O+D P2: N+D.

7.5. Conclusions

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

- Positive effects of SSP are only modest. No significant differences for SRT were found but APHAB-scores were significantly better for some specific questions.
- Positive effects of TMS (O+D vs. O+O) are significant both for SRT-thresholds and paired comparisons. APHAB results show significant effects for aversiveness and for some conditions in background noise.
- There was no extra benefit for the combined effect of SSP and TMS relative to TMS alone (N+D vs. O+D).

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., 1999[a]; 1999[b]; 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 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, 1999[a]). 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 haring 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.

	Average HL in dB	st.dev.
500 Hz	34.1	16.9
1000 Hz	41.9	15.9
2000 Hz	55.7	16.7
4000 Hz	67.7	18.4

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 211dAZ 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.

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.

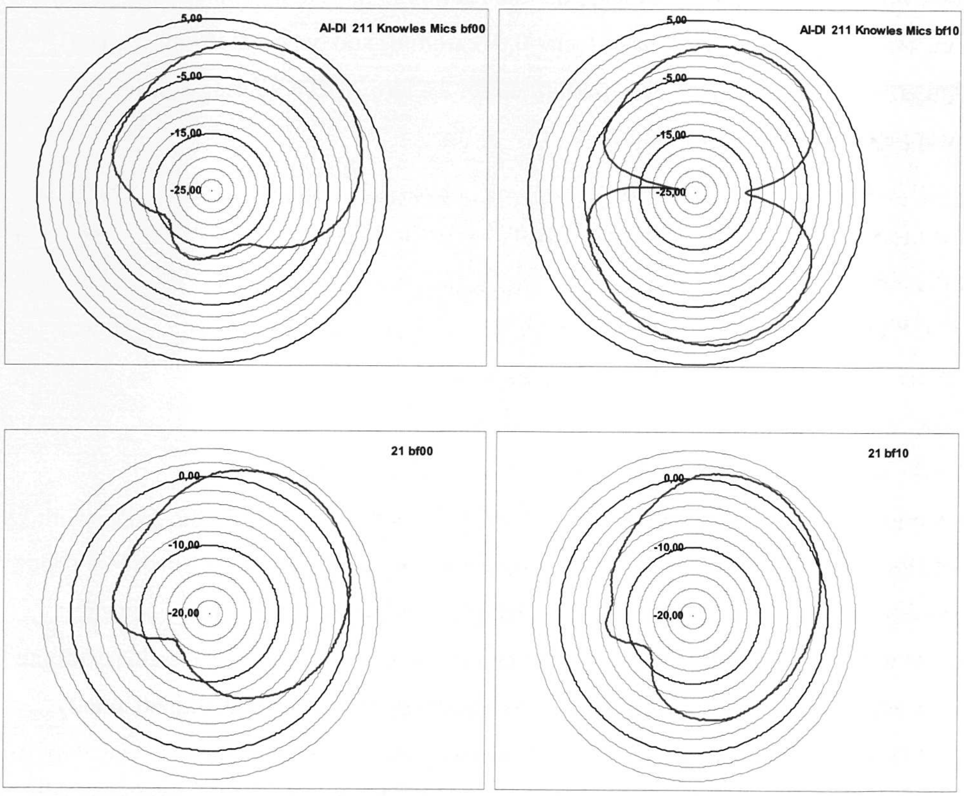


Fig. 8.1. AI-weighted polar patterns measured for the test hearing aids in KEMAR. The upper panels represent the patterns for the test BTE: left the cardioid response (beta=0.0, panel a) and right the bi-directional response (beta=1.0, panel b). The second row (panel c and d) shows the results of similar measurements in the test ITE. The measurements have been conducted by Phonak in an anechoic room.

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 ($p>0.05$).

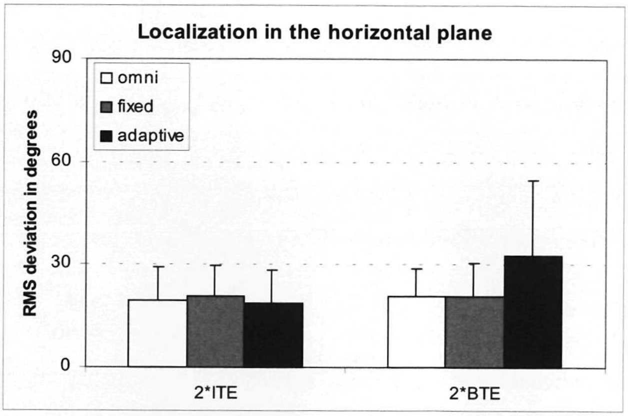


Fig. 8.2. Average RMS errors in horizontal localizations for bilateral ITE-users and BTE-users. The bars show the average errors for hearing aids with omni-, fixed-, and adaptive directional microphones, respectively.

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.

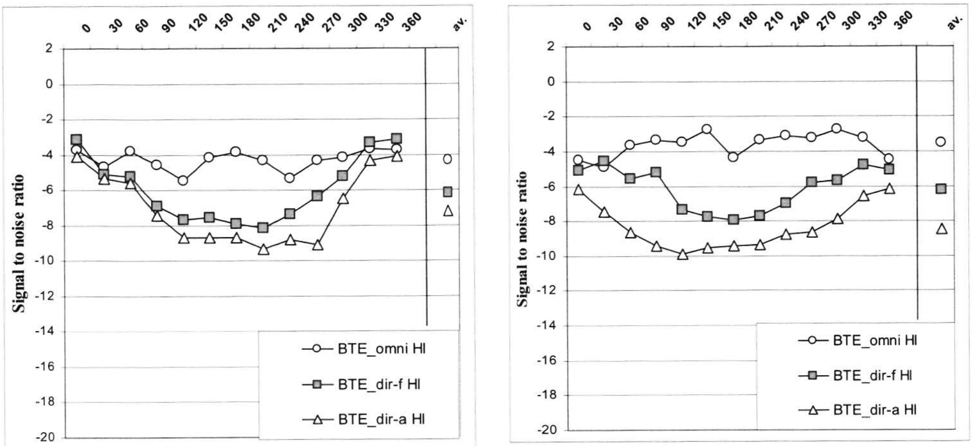


Fig. 8.3. Average JFC-thresholds for the group of 9 bilateral BTE-users in a single-noise background (panel a) and in two-noise background (panel b). The curves show the average S/N ratios for the BTE's with omnidirectional, fixed directional, and adaptive directional microphones, respectively. Lower points correspond with more favourable results.

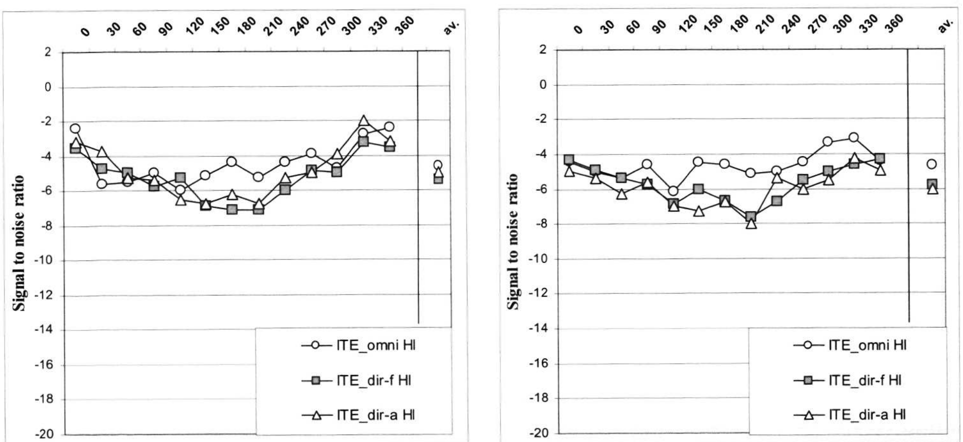


Fig. 8.4. Average JFC-thresholds, plotted similarly as Fig. 8.3, but now for the ITE's with omnidirectional, fixed directional, and adaptive directional microphones, respectively.

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 270^0 for the primary noise at the right-hand side (from $0^0 - 180^0$) and at 90^0 for the primary noise at the left-hand side of the subject (from $180^0 - 360^0$).

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 90^0 or 270^0. 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 0^0, 180^0 or 360^0 the results are equal for both types of directional microphones.

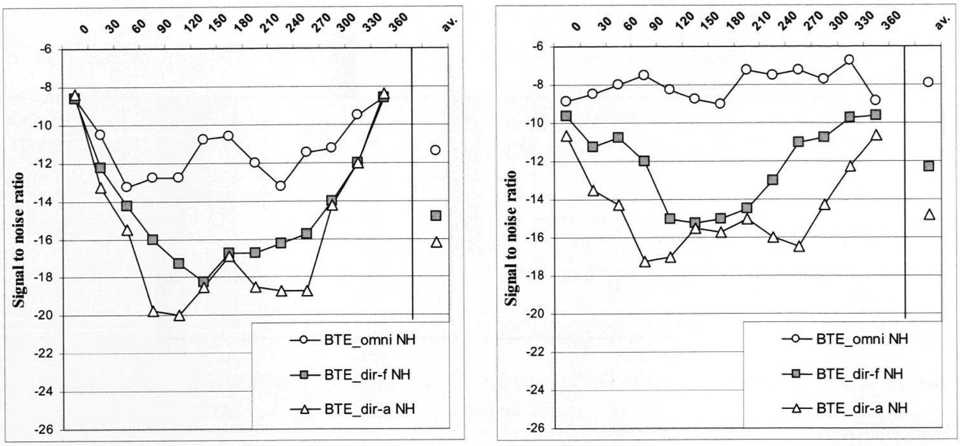


Fig.8.5. Average JFC-thresholds for the reference group of 4 normal-hearing subjects, wearing bilateral BTE's, for the situation with one background noise (panel a) and for the situation with two background noises (panel b). The curves show the average critical S/N ratios for the BTE's with omnidirectional, 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.

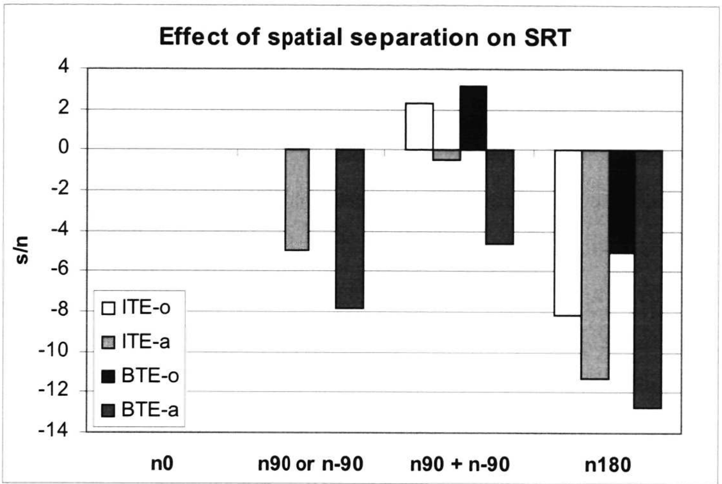


Fig. 8.6. Critical S/N ratio of the SRT-test for the situation with speech always from 0^0 and the noise from 90^0 or -90^0 (first set of bars), the noise from 90^0 and -90^0 (second set of bars), and the noise from 180^0, relatively to the situation with speech and noise at 0^0, (n0) for ITE-omni (white bars), ITE adaptive (light grey bars), BTE omni (black bars), and BTE adaptive (dark grey bars).

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 0^0 azimuth.

In the first measurements, the noise was also presented at 0^0 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 dB and –7.8 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 dB for the BTE-group and 3.2 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 dB.
The last four bars show the critical S/N ratio of the condition with the noise presented at 180^0. 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 dB and –3.2 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".

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.

CHAPTER 9

FINAL DISCUSSION

9. Final discussion

In this chapter we will address some methodological issues that are related to the evaluation of hearing aid benefit or to the comparison between different hearing aids and/or different hearing aid settings. Then, we like to review the most important results from the studies described in this thesis. We will end with some recommendations for future research.

9.1. Methods for the assessment of benefit

It appears that small differences between hearing aids and or hearing aid settings are not always measurable with the mostly used "objective" clinical tests. For example, it is difficult to assess the benefit of modulation-based noise reduction in an objective way. However, the subjective difference between different types of processing or between different settings can be very important for the hearing-impaired. For some subjects the scores of questionnaires are more positive than the scores extracted from the clinical tests. On the other hand, larger differences like head shadow effect or the effect of a directional microphone could be captured more easily in objective outcome parameters.

Despite of the theoretically expected relation between headphone tests like IATD and BMLD and the benefit of bilateral fittings in speech intelligibility, no clear correlations were found in the clinical practice (except for correlations with the pure-tone audiogram). One reason can be that the IATD and the BMLD-test are too specific. For those tests we used only one frequency, while a relatively broad range of frequencies determines speech intelligibility. However, also the SRT-test per ear did not give predictive information either. An option might be to measure BMLD directly with speech material in future experiments on bilateral hearing aids.

Speech perception plays an important role in our communication. To evaluate hearing aids, different speech tests can be used. One of the most natural speech tests is an SRT-test with sentences in continuous background noise, as often used in the Netherlands. This is a standardized test with a high precision and an acceptable duration (it takes about 3 minutes per list). However, if many conditions have to be tested, it is too time-consuming. In addition, the speech stimuli cannot be used more than once, because there is a chance that the subject can remember the sentence or parts of the sentence.

For repeated measurements, there is need for a test that can be repeated endlessly, like the Oldenburger Satztest that is currently under development for the Netherlands (see Chapter 2.2). When many conditions have to be compared in a study, the JFC-test can be used. In this test also subjective factors play a role like listening comfort. Consequently, this test does not converge exactly to 50% speech intelligibility, and differences in the individually used criteria are likely. However, for comparative measurements the JFC-test has proven to be able to distinguish between different hearing aid settings, and takes considerably less time than the SRT-test. However, this test is less pronounced than the SRT-test and the SRT-test should be regarded as the "golden standard".

Another subjective test with sentences that can be applied to compare different hearing aid settings is a paired-comparison test. This test is used in Chapter 7. The results of the paired-comparison test provide a more qualitative judgement about specific aspects of the different settings (e.g. listening comfort or subjective intelligibility), and the test results show an ordinal order of preferred settings. As for the JFC-test, it is hard to obtain data of speech intelligibility only. Aspects of sound quality and listening effort may play a role.

For some studies we need a more sensitive test, to measure differences between settings. Why is one setting of the hearing aid more preferred than another? A questionnaire is an important tool to get subjective information, but the results of a questionnaire can give a bias if the conditions are not blinded. Sound quality is related to speech intelligibility and to the listening effort it takes to understand speech. To measure subjective aspects in an objective way, we can also think about measurements that are related with effort. One possibility to is to add a measurement of reaction time. When it is more easy to understand speech with a specific hearing aid or with a specific hearing-aid setting, the subject will react faster than when the mental effort is higher to understand speech. Another test to collect data about listening effort is the measurement of pupil dilatation. There is a relation found between the pupil dilatation and the difficulty of speech perception in noise (Kramer et al., 1997). Pupil dilatation will increase for more difficult listening conditions (lower S/N ratios).

Because people communicate in different acoustical environments, we should invest in the use of more different background noises in speech tests. However, with all tests it is important to take into account the characteristics (for example the attack and release time) of the hearing aid. The test material can influence the results. The duration of the background noise should be long enough to activate different processing in the hearing aid.

In summary, the battery of tests that are available for comparative measurements should be extended in the future in order to be able to use objective evaluation tests also for the more subtle differences between hearing aids and hearing aid settings.

9.2. Comparisons between hearing aids

In Chapter 6 we compared modulation-based noise reduction hearing aids with the own analogue hearing aids of each subject. This was the only way to make direct comparisons because the hearing aid under test had only one program, and it was not possible to switch off the noise reduction. There is some risk to use the own hearing aid as a reference, because now the test cannot be blinded. The subjects can think that the new hearing aid is better, because it is more expensive, it is digital, or they heard it from the commercials, etc. (e.g. Bentler et al., 2003). This can give a bias, especially for the questionnaires. In Chapter 7 we investigated a hearing aid, which had more than one hearing aid program, and we could switch off the noise reduction and/or the dual microphone. The subjects were not told which program was activated. This is a more objective way, because of blinding. Now the own hearing aid was also tested, just as a case of control. An even better approach is double blinding, but this requires different test leader to program the hearing aids and to conduct the evaluation methods.

Besides blinding, another reason for using one hearing aid is the fact that it is essential to have identical hearing aid characteristics. For a correct comparison of settings it is important to change only one parameter of the hearing aid. For that reason it is obvious that there has to be detailed knowledge about the hearing aid specifications. Sometimes certain characteristics are linked to other characteristics. This cannot always be seen from the specifications of the hearing aid or from the fitting software of the manufacturer.

To control the hearing aid settings in an objective way, an insertion gain measured with speech noise is recommended. In our opinion, it is the only way to see what is happening at the eardrum, taken into account the ear canal and the acoustical properties of the ear mould. The noise reduction should be switched off. When this is not possible ICRA noise can be used (Dreschler et al., 2001) at least for modulation-based noise reduction algorithms. There is an option to select a single-speaker (male or female) speech noise. With that noise the noise reduction will not be activated, and it is possible to see what the output is as a function of different frequencies.

One of the negative components of hearing aids is the aversiveness of loud sounds, as we encountered most clearly in Chapters 4 and 5. With two hearing aids this becomes even worse. To optimize speech intelligibility it is important to use the complete (residual) dynamic range of the impaired ear. However, the maximum output of the hearing aid should be selected with great care in order to avoid negative effects in terms of sound quality and overexposure.

9.3. The benefits of bilateral hearing aids

As mentioned in this thesis, hearing-impaired people do often complain about speech intelligibility in background noise. This plays an important role in the studies on the benefit of a unilateral or bilateral fitting and/or the effect of different signal processing in hearing aids.

The advantages of two ears above one ear, are better localization and better speech intelligibility in background noise. For hearing-impaired people, a logical consequence or a "natural way" to rehabilitate, is to choose for a bilateral fitting instead of an unilateral fitting. When sounds are arriving at both ears the intelligent processing of the brain can be exploited. However, not every subject derives benefit from two hearing aids, and not every subject wants to have two hearing aids. Different reasons could play a role, like medical aspects, the amount of hearing loss, the symmetry of hearing loss, and the cosmetic aspects.

In the retrospective study (Chapter 4) 60% was fitted bilaterally. And in the unilaterally fitted group, even 44 % of the subjects had a symmetrical hearing loss (± 10dB). The bilaterally fitted group was more satisfied with a hearing aid than the unilaterally fitted group.

In the prospective study (Chapter 5), the subjects were asked to start a trial period with two hearing aids. After the trial period 93 % opted for a bilateral fitting. Although this skewed distribution resulted in a relatively small group of subjects with a unilateral fitting (and thus in some problems with regard to the interpretation of the results), the high percentage per se clearly indicated that subjects who once experienced the benefits of bilateral hearing aids do not want to give up these benefits. In this respect it is important to note that most subjects pay part of the hearing aid costs themselves. So, they were also willing to invest in a bilateral fitting.

In the prospective group, all subjects have been measured unilaterally and bilaterally and evaluation tests showed clearly better results when subjects were fitted bilaterally. This advantage is measured for the speech reception test with separated sound sources as well as for the horizontal localization test. The largest effects originate in the elimination of the head shadow. Also the questionnaires show convincing evidence of the subjective benefit of a bilateral fitting above a unilateral fitting. Except for the comfort of loud sounds. After an appropriate correction for age and hearing loss, the bilaterally fitted group showed a higher hearing aid use and a higher hearing aid benefit.

It would have been nice if we could predict the effect of a unilateral or bilateral fitting for each individual on the basis of a-priori testing. Then an individual advice could be given more exactly. One of the outcomes of Chapters 4 and 5 is that a bilateral fitting is better, but not for all, and this is difficult to predict. The most important factor to predict is the PTA at the better ear. When hearing-impaired listeners can experience the effect of two hearing aids, they become motivated to choose for a bilateral fitting, especially for subjects with symmetrical hearing losses. This will cost at least one ear mould, but then each individual subject can experience the benefits of a bilateral fitting himself or herself. Hearing-impaired people who start with one hearing aid will not experience the advantages of the second hearing aid at that moment.

In addition, Chapter 3 summarises experimental evidence that the deprivation effect of the unfitted ear exists and this is a hidden danger of an unilateral fitting. Given the evidence about deprivation, the hearing aid fitter should seriously consider if a trial period with bilateral hearing aids should not be promoted. If there are some hesitations, based on lack of acceptance or for cosmetical reasons, the hearing-impaired subject should be persuaded at least to try two hearing aids in a trial period. Some additional counselling should be considered.

9.4. The benefits of digital signal processing

The studies in this thesis show that – within currently available technologies – the most effective signal processing within hearing aids is directivity. With a fixed directional (or an adaptive directional microphone), significant advantages relative to an omnidirectional microphone have been found, especially for speech intelligibility in background noise with separated sources of speech and noise (see Chapters 7 and 8). The subjective experiences with directivity are in agreement with the "objective" SRT-results (see Chapter 7).

For modulation-based noise reduction, no clear effects are measured for speech intelligibility in background noise (see Chapters 6 and 7). However, subjective experiences are also important. By means of questionnaires or paired comparisons, subjective experiences have been investigated. In Chapters 6 and 7 subjective advantages have been found for modulation-based noise reduction relative to the own hearing aid, and to the same hearing aid without noise reduction, respectively.

From the studies described in this thesis, it is clear that modern technology made important steps forward to reduce the problem of speech perception in noise. However, the benefits are only found in selected areas (e.g. with the direct sound field and/or in listening comfort) and even high-end digital hearing aids do not yet provide an overall solution for the "speech-in-noise problem".

9.5. Some remarks about future research

To compare different hearing aid settings in an objective way, we need more sensitive test material. As mentioned before, this could be a test with special attention for the listening effort, like tests on reaction times or tests with the measurement of pupil dilatation. The test material has to be realistic, fast and reproducible. Also, there should be a possibility to measure many conditions. The test set up should be standardized to make different studies more directly comparable.

To compare settings or even different hearing aids, a standardized and precise fitting method should be developed. The use of generic fitting rules instead of manufacturer-specific fitting rules is important. The actual amplification of the hearing aids should be checked by means of insertion-gain measurements with appropriate test signals.
When hearing aids are fitted and tested, there should be detailed knowledge about the hearing aid characteristics, not only what is seen on the screen of the fitting software.

We experienced that a close co-operation between the researcher and the manufacturer is an essential condition for this kind of research. We have to verify if the test conditions are appropriate (for example we need to know what the attack and release times are). Sometimes different programs proved to be coupled: when one parameter is changed in the first program, the algorithm is also changing in other programs. If this is not desirable for the purpose of the research, special precautions should be taken or special versions of the hearing aids should be produced. When the hearing aid is fine-tuned by means of the insertion gain, it is effective to make a copy of that specific hearing aid setting, and then change only the algorithm under test. When this is not possible in a custom hearing aid it would facilitate to use non-standard hearing aids especially for research.

One of the goals of field-testing is to verify the benefits of new hearing aids and/or new algorithms in real-world conditions and to find indications for further improvements. Independent feedback to the manufacturer about problems with the hearing aid, software bugs or critical remarks, in an early stage of development has also proven to be very useful.

Another goal is that we need independent data on the benefits of specific hearing aids and hearing-aid options to provide hearing-impaired consumers with objective and independent information about modern hearing aids. This information should be based on independent research. Given the high number of innovations in digital hearing aids that are ahead of us, the high costs that are required for these innovations (and consequently the high prices that hearing-impaired consumers have to pay) and the high expectations that are raised by commercial brochures and advertisements, we need objective data and objective tests. Therefore, it is important to continue independent research in this area.

Unfortunately, the results of this thesis show that the "speech-in-noise problem" has not been solved yet, even if we use high-end digital hearing aids and we use them bilaterally. There is ample room for further improvements before most hearing-impaired listeners can participate without limitations in acoustically difficult situations.

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SUMMARY

Summary

In this thesis a few clinical studies have been described and the advantages of different methods to compensate hearing loss with hearing aids were investigated. One of the most important methods is to recover binaural hearing by fitting two hearing aids. The first part is devoted to the advantages of bilateral hearing aid fittings.
Due to the introduction of digital hearing aids advanced signal processing became feasible, such as modulation-based noise reduction and directionality by dual microphone techniques. In the second part of this thesis three studies have been described which point out the added value of those algorithms.

Part 1:

The added value of bilateral hearing aid fitting (Chapters 3 - 5)

The purpose of the study

Possible changes in the system of the financial reimbursements for hearing aids require a solid underpinning of current clinical fitting practice for bilateral hearing aids. PACT (Platform for Audiological Clinical Testing) initiated a broad retrospective study in different audiological centres to evaluate the current fitting practices and the subjective advantages of a second hearing aid.
Additionally, a prospective study was performed with the purpose to have better criteria for bilateral hearing aids. Therefore we investigated the objective and subjective parameters that correlated to a better stereophonic effect and to an advantage of a bilateral fitting compared to an unilateral fitting.

Methods of the study

The study consists of three parts: a literature review, a retrospective study, and a prospective study.

In the retrospective study 1000 clinical files of consecutive hearing aid approvals of one or two hearing aids were investigated. All patients involved in the investigation of the clinical files were asked to complete an extensive questionnaire, about two years after the hearing aid approval. Eventually, 505 questionnaires were returned. These questionnaires were used for the evaluation of the long-term effect. Different relations between anamnestic, audiological, and subjective aspects were investigated.

In the prospective study the subjects were selected from the regular clinical populations of eight audiological centres who started a trial with two hearing aids. Before the trial period diagnostic tests were conducted, to get more information about the binaural function and the critical S/N ratio per ear, because it is difficult to compose new criteria for reimbursement of a second hearing aid based on the standard audiometric data only. The diagnostic tests consist of BMLD-tests (Binaural Masking Level Difference), IATD-tests (Interaural Time Difference), and SRT-tests (Speech Reception Test) per ear. After the trial period, evaluation tests were conducted with one and with two hearing aids. The evaluation tests consisted of SRT-tests with spatially separated sound sources and localization tests with daily sounds. Also a questionnaire was used, in which the subjects were asked to answer questions about different situations without, with one, and with two hearing aids. Eventually, the results of 214 subjects were analysed.

Results

The systematic review of literature showed obviously an added value of the second hearing aid. The effect of auditory deprivation is a real risk for unilateral fittings.

The results of the retrospective study gave detailed insights into current fitting practices. It showed that the bilaterally fitted group was more satisfied with the hearing aids than

the unilaterally fitted group. People with large hearing losses used the hearing aid more often, experienced a lower auditory functioning, experienced the same satisfaction and had a higher handicap score than people with smaller hearing losses.
For digital hearing aids a significantly better auditory functioning and a slightly lower handicap score was found than for standard analogue hearing aids. It was difficult to predict hearing aid use and satisfaction on base of anamnestic and audiological data.

The prospective study showed that it was also difficult to predict the advantage of a second hearing aid by the results of the diagnostic tests used in this study. An obvious difference between both studies was that in the prospective study 93% of the subjects were fitted bilaterally in contrast to about 60% in the retrospective study.
The evaluation tests showed an objective view of the advantage of the second hearing aid, both for speech intelligibility with spatially separated sound sources and for directional hearing. For the speech test in background noise with spatially separated sources positive effects were measured for the second hearing aid, for the larger part due to cancellation of the head shadow effect and for a smaller part due to a purely binaural effect. There was an obvious subjective bilateral advantage for detection, discrimination, speech intelligibility in quiet, in noise and for localization. However, the aversiveness of loud sounds is higher with two hearing aids than with one.

Part 2:

The added value of advanced signal processing (Chapters 6 - 8)

The purpose of the study

Since the introduction of digital hearing aids there were a lot of changes, both for the hearing aid user and for the hearing aid prescriber. The question was what the real effect is of different algorithms in hearing aids. Therefore different studies were conducted to measure the added value of:

- digital hearing aids with noise reduction compared to analogue hearing aids without noise reduction (Chapter 6),
- digital hearing aids with noise reduction and/or a dual microphones compared to the same hearing aids without noise reduction and omnidirectional microphones (Chapter 7),
- digital hearing aids with adaptive dual microphones compared to fixed dual microphones and omnidirectional microphones (Chapter 8).

Methods of the study

Field tests of 2 x 4 weeks, with laboratory tests at two audiological centres, were used to determine the added value of the noise reduction in a first-generation digital hearing aids. 27 Hearing-impaired subjects with sensorineural hearing losses were conducted in field tests with digital in-the-ear hearing aids (with noise reduction) and with a newly fitted analogue in-the-ear hearing aid (without noise reduction). The order of field tests was randomized. At the start and at the end of each field test, objective measurements were conducted (loudness scaling and speech intelligibility in continuous speech-shaped noise, speech-modulated speech-shaped noise, and car noise, with speech and noise at 0^0 azimuth). At the end of each field test the subjects completed a questionnaire. The results of both hearing aids were compared.

Different algorithms within one hearing aid were used to determine the added value of a dual microphone. 16 Hearing aid users participated in three field tests, each of four weeks. For four weeks the hearing aids were fitted without noise reduction, for four weeks the hearing aids were fitted with noise reduction (based on spectral and temporal differences) and for four weeks the hearing aids were fitted with a dual microphone. The order of fittings was randomized. Both 'objective' measurements (SRT-test with a male voice and a female voice at 0^0 azimuth, in cocktail noise or car noise coming from -90^0, $+90^0$ and 180^0), and 'subjective' measurements (paired comparisons and questionnaires) were conducted. SRT-tests were conducted both before and after each field test. In weeks 4 and 12 paired comparisons were conducted with 4 different hearing aid settings (also the setting with both noise reduction and dual microphone activated). The questionnaires were completed after each field test. In the last week SRT-tests were also conducted for the setting with both noise reduction and dual microphone activated.

The effect of the adaptive dual microphone is compared to the omnidirectional microphone and the fixed dual microphone (within the same hearing aid). Localization tests with 13 loudspeaker boxes in a horizontal plane from -90^0 to $+ 90^0$ were performed first. JFC-tests (Just Follow Conversation) with different sound sources were performed to measure the effects on speech intelligibility. The speech was always presented in front of the subject (0^0) and the continuous noise was presented from different (fixed) spatial locations: 0^0, 30^0, 60^0, 90^0, 120^0, 150^0, 180^0, 210^0, 240^0, 270^0, 300^0, 330^0, 360^0. The measurements were repeated with an extra noise from -90^0 or 90^0, respectively. The noise was presented at a constant level, the subject was asked to adjust the level of the speech until he/she could just follow the sentences. SRT tests were performed with the noise from the front, from the left- and the right-hand side, and from the back. Nine subjects with two in-the-ear hearing aids and nine subjects with two behind-the-ear hearing aids were measured.

Results

In general, there were subjective preferences for digital hearing aids above newly fitted analogue hearing aids. However, this was not confirmed by the results of the SRT-test in the free field, and the results of loudness scaling. There was also a difference between the results of both centres. For the SRT-test the choice of background noise proved to be a determinant for results of evaluation. In one centre the noise was activated 5 - 6 seconds before the speech, while in the other centre the noise was activated about 10 seconds before the speech. Therefore more time was left to activate the noise reduction in the hearing aid. In the subjective evaluation large differences were shown and we have to realize that 'bias' of personal preferences of the hearing-impaired subjects could be an important factor (halo effect).

The advantage of testing different algorithms within the same hearing aid is the possibility of blinding the experiment, such that there is no bias by personal preferences of the subjects. The effects of the dual microphone are clearly positive, especially for the SRT-test and the paired comparisons. The objective and subjective results were in agreement. The effect of noise reduction was obviously smaller than the effect of the dual microphone. However, noise reduction reduced the aversiveness of loud sounds significantly. There is no difference between the benefits of the dual microphone per se and the effects of the combination of dual microphone and noise reduction.

Compared to other settings, the adaptive directional microphone had no negative effect on localization of noises (especially for in-the-ear hearing aids). The dual microphone, both fixed and adaptive, showed a better result in speech intelligibility with spatially separated noise sources than the omnidirectional microphone. The behind-the-ear hearing aid with adaptive directional microphones had a clearly added value for noise conditions with two spatially separated noises.

SAMENVATTING

Samenvatting

In dit proefschrift wordt een aantal klinische studies beschreven waarbij de meerwaarde van verschillende methoden voor compensatie van gehoorverlies met hoortoestellen wordt onderzocht. Eén van de belangrijkste methoden is het herstellen van binauraal horen door het aanpassen van twee hoortoestellen, zodat de intelligentie van het binaurale systeem optimaal kan worden benut. Het eerste gedeelte wordt dan ook gewijd aan het voordeel van een tweezijdige hoortoestel aanpassing.
Door de komst van digitale hoortoestellen zijn er ook geavanceerde signaal bewerkingen geïntroduceerd zoals ruisonderdrukking op basis van modulaties in het signaal en richting gevoeligheid door dubbele microfoons. In het tweede gedeelte van dit proefschrift worden drie studies beschreven die de toegevoegde waarde van deze signaalbewerkingen in kaart brengen.

Deel 1:
De meerwaarde van tweezijdige hoortoestel aanpassingen (hoofdstuk 3 t/m 5)

Doel van het onderzoek

De huidige praktijk van het voorschrijven van een tweezijdige aanpassing met hoortoestellen zal nader onderbouwd moeten worden in verband met veranderingen in de regelgeving. Door de Stichting PACT (Platform for Audiological Clinical Testing) is een brede retrospectieve studie in verschillende Audiologische Centra opgezet om het huidige voorschrijfbeleid en de subjectieve meerwaarde van het tweede hoortoestel te evalueren.
Vervolgens is er een prospectieve studie uitgevoerd met als doel een betere indicatiestelling van een tweezijdige aanpassing. Daarbij is inzicht vereist in: de parameters die gecorreleerd zijn met een gunstig stereofonisch effect en de meerwaarde

van het tweede hoortoestel t.o.v. een eenzijdige aanpassing zowel objectief als subjectief.

Methoden van onderzoek

Het onderzoek bestaat uit drie gedeelten: een literatuuronderzoek, een retrospectief onderzoek, en een prospectief onderzoek.
Bij de retrospectieve studie zijn 1000 statussen onderzocht van opeenvolgende goedkeuringen voor één of twee hoortoestellen. Twee jaar na goedkeuring is er een uitgebreide enquête naar alle patiënten gestuurd en uiteindelijk zijn er 505 bruikbare enquêtes geretourneerd en deze zijn gebruikt voor de evaluatie van het lange termijn effect. Er is gekeken naar de relaties tussen de anamnestische, audiologische, en subjectieve gegevens.

Bij de prospectieve studie zijn proefpersonen geselecteerd uit de reguliere praktijk die twee hoortoestellen wilden proberen. Voor de proefperiode zijn er diagnostische testen uitgevoerd, die informatie geven over de binaurale functie en de kritische signaal ruisverhouding per oor, omdat het moeilijk blijkt om een nieuw criterium voor vergoeding van twee hoortoestellen te baseren op de standaard aanwezige audiometrische data. De diagnostische testen bestaan uit: een BMLD-test (Binaural Masking Level Difference), een IATD-test (Interaural Time Difference), en een SRT-test (Speech Reception Test) per oor. Na de proefperiode zijn evaluatie testen uitgevoerd met één en twee hoortoestel(len). De evaluatie testen bestaan uit een SRT-test met ruimtelijk gescheiden signaal bronnen en een lokalisatie test met dagelijkse geluiden. Verder is er gebruik gemaakt van een enquête waarbij de proefpersoon vragen moest beantwoorden over verschillende situaties zonder, met één, en met twee hoortoestellen. Uiteindelijk zijn de resultaten van 214 proefpersonen geanalyseerd.

Resultaten

Uit literatuuronderzoek blijkt dat het tweede hoortoestel een duidelijke meerwaarde heeft en dat auditieve deprivatie een aangetoond gevaar is bij een eenzijdige aanpassing.

De resultaten van de retrospectieve studie geven een gedetailleerd inzicht in de huidige praktijk van voorschrijven. Het blijkt dat de bilaterale groep meer tevreden is met het hoortoestel dan de unilaterale groep. Mensen met een groot verlies gebruiken het hoortoestel vaker, vinden dat zij slechter auditief functioneren, hebben dezelfde satisfactie en hebben een hogere handicap score dan de mensen met een kleiner verlies. Bij de digitale hoortoestellen is er een significant beter auditief functioneren gevonden en een iets minder lage handicap score dan bij de standaard analoge hoortoestellen. Verder blijkt het moeilijk te zijn om de mate van het hoortoestel gebruik en de satisfactie te voorspellen uit de anamnestische en de audiologische gegevens.

Uit de prospectieve studie blijkt dat de baat van een tweede toestel ook moeilijk te voorspellen is uit resultaten van de gebruikte diagnostische testbatterij. Een opvallend verschil tussen beide studies is dat 93% van de mensen uit de prospectieve studie bilateraal zijn aangepast tegenover ongeveer 60% uit de retrospectieve studie.
De evaluatie testen geven een objectief beeld van de winst van het tweede toestel, zowel voor ruimtelijk spraakverstaan als voor richtinghoren. Bij de spraaktesten in achtergrond ruis met ruimtelijk gescheiden bronnen is er een duidelijk positief effect van het tweede hoortoestel gemeten, dat grotendeels is te verklaren door het opheffen van de hoofdschaduw en voor een kleiner gedeelte door het zuiver binaurale effect. Verder is er een duidelijk subjectieve meerwaarde van het tweede hoortoestel voor wat betreft detectie, discriminatie, het spraakverstaan in stilte, in achtergrondlawaai, en het lokaliseren. Hoortoesteldragers hebben met twee hoortoestellen wel meer last van harde geluiden dan met één hoortoestel.

Deel 2:

De meerwaarde van geavanceerde signaalbewerkingen (hoofdstuk 6 t/m 8)

Doel van het onderzoek

Sinds de komst van digitale hoortoestellen is er veel veranderd voor de hoortoesteldragers en de voorschrijvers. De vraag is nu, wat het werkelijke effect is van de verschillende algoritmen in de toestellen. Daarom zijn er verschillende onderzoeken gedaan naar de meerwaarde van:

- een digitaal hoortoestel met ruisonderdrukking in vergelijking met analoge hoortoestellen zonder ruisonderdrukking (Hoofdstuk 6),
- een digitaal toestel met ruisonderdrukking en/of een dubbele microfoon in vergelijking met hetzelfde toestel zonder ruisonderdrukking met een omnigevoelige microfoon (Hoofdstuk 7),
- een digitaal hoortoestel met een adaptieve richtinggevoelige microfoon in vergelijking met een gefixeerde dubbele microfoon en een omnigevoelige microfoon (Hoofdstuk 8).

Methoden van onderzoek

Voor het bepalen van de meerwaarde van ruisonderdrukking in de eerste generatie digitale hoortoestellen is gebruik gemaakt van een veldtest van 2 x 4 weken met laboratorium testen, op twee Audiologische centra. 27 Mensen met een perceptief verlies hebben een veldtest gedaan met een digitaal in-het-oor toestel (met ruisonderdrukking) en met een nieuw aangemeten analoog in-het-oor toestel (zonder ruisonderdrukking), de volgorde was gerandomiseerd. Aan het begin en aan het einde van iedere veldtest zijn er objectieve metingen gedaan (loudness scaling en spraakperceptie in continue spraakruis, in gemoduleerde spraakruis en in laag frequente auto ruis, met spraak en ruis van voren). Aan het einde van iedere veld test heeft de proefpersoon ook een vragenlijst ingevuld. De resultaten van beide typen toestellen werden vergeleken.

Voor het bepalen van de meerwaarde van een dubbele microfoon is gebruik gemaakt van verschillende algoritmen binnen één hoortoestel. 16 Hoortoesteldragers hebben 3 veldtesten gedaan, ieder van 4 weken. De hoortoestellen werden 4 weken zonder ruisonderdrukking gedragen, 4 weken met ruisonderdrukking (gebaseerd op spectrale en temporele verschillen) en 4 weken met de dubbele microfoon. De volgorde van de instellingen was gerandomiseerd. Er zijn "objectieve" metingen uitgevoerd (SRT-test met een mannenstem en een vrouwenstem komende van voren, in cocktail ruis en auto ruis komende van links, rechts en achteren) en "subjectieve" metingen (paired comparison en enquêtes). De SRT-test is zowel voor als na iedere veldtest uitgevoerd. In week 4 en 12 is er een paired comparison gedaan met 4 verschillende hoortoestel instellingen (ook de instelling waarbij zowel de ruisonderdrukking als de dubbele microfoon geactiveerd waren). De vragenlijst werd na iedere veldtest ingevuld. In de laatste week zijn ook SRT testen gedaan waarbij zowel de ruisonderdrukking als de dubbele microfoon waren geactiveerd.

Het effect van de adaptieve richtinggevoelige microfoon is vergeleken met een omnigevoelige microfoon en een gefixeerde dubbele microfoon (binnen hetzelfde hoortoestel). Eerst is er een lokalisatie test gedaan met 13 geluidsboxjes in het horizontale vlak van -90^0 tot $+ 90^0$. Voor het effect op het spraakverstaan is gebruik gemaakt van een JFC test (Just Follow Conversation) met meerdere signaalbronnen. De spraak kwam altijd van voren (0^0) en de continue ruis varieerde van 0^0, 30^0, 60^0, 90^0, 120^0, 150^0, 180^0, 210^0, 240^0, 270^0, 300^0, 330^0, 360^0, en hetzelfde is gemeten met een extra ruis op respectievelijk -90^0 of 90^0. De ruis werd op een constant niveau aangeboden en de proefpersoon moest de spraak zo instellen dat hij/zij de zinnen nog net kon verstaan. Verder is er een SRT-test gedaan met de ruis van voren, van links en van rechts, en de ruis van achteren voor de situatie met een omni en een adaptieve richtinggevoelige microfoon. Uiteindelijk zijn er 9 mensen gemeten met twee in-het-oor toestellen en 9 mensen met twee achter-het-oor toestellen.

Resultaten

Over het algemeen is er een subjectieve voorkeur voor het digitale hoortoestel boven een nieuw aangemeten analoog hoortoestel, maar dit wordt niet bevestigd door de resultaten van de SRT-test in het vrije veld en de resultaten van de loudness scaling. Tevens is er een verschil in de resultaten tussen beide centra. Bij de SRT-test blijkt de keuze van de achtergrondruis bepalend voor de uitkomst van de evaluatie. Op het ene centrum wordt de ruis ongeveer 5-6 seconden eerder aangeboden dan de spraak, terwijl op het andere centrum de achtergrond ruis al 10 seconden wordt gehoord voordat de spraak wordt aangeboden. Daardoor is er meer tijd beschikbaar om de ruisonderdrukking te activeren in het hoortoestel. Bij de subjectieve evaluatie zijn er grote verschillen en dient men zich te realiseren dat "bias" door persoonlijke voorkeuren van de slechthorenden een belangrijke rol kan spelen.

Het voordeel van het testen van verschillende algoritmen binnen hetzelfde hoortoestel is dat het onderzoek geblindeerd kan worden uitgevoerd en er dus geen bias kan zijn door persoonlijke voorkeuren van slechthorenden. Het effect van de dubbele microfoon is duidelijk positief vooral bij de SRT-test en de paired comparison. De objectieve en subjectieve resultaten komen goed met elkaar overeen. Het effect van de ruisonderdrukking is duidelijk kleiner dan het effect van de dubbele microfoon, maar ruisonderdrukking doet "de last" van harde geluiden significant afnemen. Er is geen verschil tussen het effect van de dubbele microfoon alleen en de combinatie van de dubbele microfoon met de ruisonderdrukking.

De adaptieve richtinggevoelige microfoon heeft in vergelijking met de andere instellingen, geen negatief effect op het lokaliseren van ruizen (dit geldt vooral voor in-het-oor toestellen). De dubbele microfoon, zowel gefixeerd als adaptief, geeft een beter resultaat in spraakverstaan voor de conditie met ruimtelijk gescheiden bronnen dan de omnigevoelige microfoon. De adaptieve richtinggevoelige microfoon heeft bij een achter-het-oor toestel, een duidelijke meerwaarde voor de conditie met twee ruimtelijk gescheiden ruisbronnen.

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Dankwoord

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CURRICULUM VITAE

Curriculum vitae

Monique Boymans werd op 27 september 1965 geboren in Port Harcourt (Nigeria). Zij behaalde het HAVO-diploma in 1983 in Assen, waarna zij werd uitgeloot voor de opleiding voor logopedie. Een jaar later werd zij echter alsnog ingeloot voor de opleiding in Groningen en in 1988 heeft zij het diploma voor logopedie behaald.
In 1991 heeft zij het doctoraal examen behaald in de vrije studierichting Spraak- en Taalpathologie in Nijmegen. In die zelfde periode kreeg zij een baan als logopedist op het Audiologisch Centrum in het Academisch Medisch Centrum in Amsterdam. Zij heeft kinderdiagnostiek en -revalidatie gedaan, en heeft een periode vervangen op de afdeling logopedie. Toen haar aanstelling werd uitgebreid ging zij de volwassenen revalidatie doen. Daarnaast kreeg zij een steeds groter wordende rol bij de opzet en uitvoering van klinisch audiologische research projecten, waar dit boekje getuige van is.

Intelligent processing
to optimize the benefits of hearing aids

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor

aan de Universiteit van Amsterdam

op gezag van de Rector Magnificus

prof.mr. P.F. van der Heijden

ten overstaan van een door het college voor promoties ingestelde

commissie, in het openbaar te verdedigen in de Aula der Universiteit

op woensdag 24 september 2003, te 10.00 uur

door Monique Boymans

geboren te Port Harcourt (Nigeria)

promotor: *Prof.dr.ir. W.A. Dreschler*

Stellingen

1) Bij de indicatie voor een hoortoestel bij eenzijdige slechthorenden dient men uit te gaan van het gehoorverlies per oor en niet van het beste oor (*dit proefschrift*).

2) Sinds de komst van digitale hoortoestellen is er alleen met een meer-microfoon techniek een objectief meetbare verbetering in het spraakverstaan in geroezemoes aangetoond (*dit proefschrift*).

3) Bij de huidige gestandaardiseerde testen om de spraakverstaanvaardigheid te meten kan helaas geen onderscheid worden gemaakt tussen "met gemak" 100% spraakverstaan en "met moeite" 100% spraakverstaan (*dit proefschrift*).

4) Voor symmetrische gehoorverliezen geldt: beter twee goedkope hoortoestellen dan één duur hoortoestel (*dit proefschrift*).

5) De techniek van de hoortoestellen ontwikkelt zich sneller dan de techniek om de effecten van de technische innovatie te meten (*dit proefschrift*).

6) Openheid over de technische specificaties van hoortoestellen door fabrikanten bevordert het onderzoek en komt daardoor de slechthorende ten goede.

7) Ondanks dat een proefpersoon bij experimenteel onderzoek niet met een beter hoortoestel de deur uit gaat, is het werken met slechthorende proefpersonen dankbaar werk.

8) Als alle communicatieproblemen binnen een ziekenhuis plotseling zouden kunnen worden opgelost met een hoortoestel, zouden er lange wachtlijsten komen voor de levering van hoortoestellen.

9) Het is minder ingrijpend wanneer een auto met één hand wordt bestuurd dan wanneer de besturing concurentie krijgt van processen "tussen de oren". Daarom zal het aantal verkeersongelukken niet afnemen door hands-free te telefoneren (*dr. C. Spence, 2003*).

10) De overeenkomst tussen skiën en roeien is dat men een andere richting opgaat dan dat meestal wenselijk is in de arbeidssituatie. Het is een kwestie van interpretatie of men het om die reden "ontspanning" mag noemen.