Intelligent processing to optimize the benefits of hearing aids
Boymans, M.

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CHAPTER 5.

THE BENEFITS OF BILATERAL HEARING AIDS III:
A prospective study

This chapter is submitted to Int.J.Aud. (Boymans et al., 2003b)
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 ($\Delta t$) 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 $\Delta t$ 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 $\Delta t$ is zero the noise bursts would be heard in the middle of the head. $\Delta t$ 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\(_{(0.5,1,2\ kHz)}\) 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\(^{\circ}\) and +45\(^{\circ}\). 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\(^{\circ}\), -45\(^{\circ}\), 0\(^{\circ}\), +45\(^{\circ}\), +90\(^{\circ}\)). 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.

<table>
<thead>
<tr>
<th></th>
<th>BMLD (dB)</th>
<th>IATD (μsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>P25 / P75</td>
</tr>
<tr>
<td>Unilateral fitting (n=14)</td>
<td>-15.5</td>
<td>-18.3 / -11.0</td>
</tr>
<tr>
<td>Bilateral fitting (n=200)</td>
<td>-14.4</td>
<td>-18.4 / -8.6</td>
</tr>
<tr>
<td>Normal hearing (n=10)</td>
<td>-19.5</td>
<td>-21.5 / -12.0</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th></th>
<th>S/N ratio for the better ear (dB)</th>
<th>Interaural difference between S/R ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>P25 / P75</td>
</tr>
<tr>
<td>Unilateral fitting (n=14)</td>
<td>-0.8</td>
<td>-3.2 / 2.1</td>
</tr>
<tr>
<td>Bilateral fitting (n=200)</td>
<td>-0.6</td>
<td>-2.6 / 2.6</td>
</tr>
</tbody>
</table>

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).

\textit{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 cooperation. 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.