Intelligent processing to optimize the benefits of hearing aids

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CHAPTER 3.

THE BENEFITS OF BILATERAL HEARING AIDS I:
A systematic review

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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.
A systematic review on the benefits of bilateral hearing aids

- 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
A systematic review on the benefits of bilateral hearing aids

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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.
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**

*Speech intelligibility*

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, 1982a).

Köbler et al. (2002) used a fixed S/N ratio of +4 dB, 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
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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°. 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° and −45° 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) 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, Vaughan-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 images 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).
- Improvement of the localization ability (Markides, 1982\textsuperscript{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

**Deprivation effect**

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.

**Hearing aid circuit**

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.
A systematic review on the benefits of bilateral hearing aids