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**BILATERAL HEARING AIDS FOR  
BILATERALLY HEARING-IMPAIRED  
PERSONS – ALWAYS THE BEST  
CHOICE?**

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*To Stephan*



## **ABSTRACT**

The most logical solution if a person has a hearing impairment on both ears, seems to be bilateral hearing aid amplification in both ears. Numerous studies have shown the advantages of this fitting strategy. However, there were always some individuals not benefiting from bilateral hearing aids; until recently a neglected group of persons.

The first part of the present work examines patterns of usage of bilateral hearing aids and situations where the users benefit most from bilateral hearing aids. Measurements of speech recognition in noise and localization with two, one and no hearing aids were performed. The second part of this work concentrates on persons rejecting bilateral hearing aids because of unspecified reasons, not related to practical or technical issues.

Paper I describes an enquiry-based, retrospective study with questions on experienced advantages and disadvantages of bilateral hearing aids as well as the pattern in which the hearing aids were used. A majority of the 144 persons participating in the survey used bilateral hearing aids. Two hearing aids were mainly appreciated in complex listening situations with high demands on speech recognition. Improved sound quality was one of the reasons to use two rather than one hearing aid. The users of two hearing aids described better localization abilities than users of one hearing aid.

In the second study, paper II, 19 bilaterally hearing-impaired persons, provided with two hearing aids, participated in psychoacoustical measurements of speech recognition in noise and localization. Both measurements showed an advantage for bilateral hearing aids. Localization could not be improved beyond the score, that the participants reached without hearing aids, but the level of localization could at least be retained with two hearing aids whereas it deteriorated with a unilateral hearing aid.

In the study described in paper III, methods to measure individual auditory performance with focus on binaural aspects of the auditory system were put together. An evaluation with normal-hearing subjects showed significantly different results for measurements of speech recognition in noise and signal analysis abilities under monaural and binaural listening conditions. A measurement of central auditory and cognitive function also was included in this evaluation.

The final step of this work, paper IV, was the application of the methods developed in paper III on two groups of hearing-impaired persons, one group appreciating bilateral hearing aids, one group rejecting them and using unilateral amplification instead. The study had a diagnostic approach with all measurements performed unaided. Significant differences between the two groups were found in central auditory performance and cognition with an advantage for the group benefiting from bilateral hearing aids. To a less degree, also peripheral hearing might be degraded in the group preferring one hearing aid and they also might have been provided with too much amplification in their hearing aids. The binaural performance was about the same in both groups.

This work has shown, in which situations it is advantageous to use bilateral hearing aids. Tests have been identified to provide better understanding and diagnostic possibilities for hearing-impaired persons, who are not able to benefit from bilateral amplification.

Keywords: bilateral hearing aids, binaural hearing, speech-in-noise, dichotic tests, binaural masking level difference

## LIST OF PUBLICATIONS

This thesis is based on the following papers. They will be referred to by their Roman numerals (I-IV)

- I. Köbler S, Rosenhall U, Hansson H (2001) Bilateral hearing aids – effects and consequences from a user perspective. *Scandinavian Audiology* 30(4): 223-35
- II. Köbler S, Rosenhall U. (2002) Horizontal localization and speech intelligibility with bilateral and unilateral hearing aid amplification. *International Journal of Audiology* 41(7):395-400
- III. Köbler S, Hagerman B. (2006) Clinically feasible test to measure binaural performance – test battery and evaluation with normal-hearing subjects. *Submitted to International Journal of Audiology*
- IV. Köbler S, Lindblad AC, Olofsson Å, Hagerman B. (2006) Successful and unsuccessful users of bilateral amplification – differences and similarities in binaural performance. *Submitted to International Journal of Audiology*

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## LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
BMLD	Binaural masking level difference
CV	Consonant-vowel combination
DR	Directed report
FR	Free report
FUM	Fully modulated
G-G	Greenhouse-Geiser epsilon factor
HA	Hearing aid
H-F	Huynh-Feldt epsilon factor
HL	Hearing level
IHC	Inner hair cell
ILD	Interaural level difference
IPD	Interaural phase difference
ITD	Interaural time difference
NAL	National Acoustic Laboratories (Australia)
OHC	Outer hair cell
PMTF	Psychoacoustical Modulation Transfer Function
PTA3F	Pure tone average threshold at the frequencies 500, 1000, 2000 Hz
PTA4F	Pure tone average threshold at the frequencies 500, 1000, 2000, 4000 Hz
REA	Right ear advantage
RMS	Root-mean-square
S/N	Signal-to-noise ratio
SM	Slightly modulated
SPL	Sound pressure level
SSQ	Speech, Spatial and Quality of Hearing Scale



# 1 INTRODUCTION

All mammals, including humans, are equipped with two ears. This feature is important for localization purposes and it facilitates understanding speech in noisy backgrounds. In the case of a hearing impairment in both ears, the most logical solution therefore seems to be to provide both ears with hearing aids.

This thesis will examine advantages and disadvantages with this amplification strategy as well as trying to find explanations for cases not being successful with wearing two hearing aids. The research contains four parts, represented by the four papers appended. The first paper describes the results of an enquiry with the goals to examine patterns of usage of hearing aids for persons provided with bilateral amplification. We also studied consumer satisfaction with the rehabilitation provided, we put a special interest in questions about sound localization and tried to gather information on differences between users of unilateral and bilateral hearing aids (HAs). Bilateral amplification seems to be the better choice for most of the subjects in the study. However, almost one third of the study group rejected bilateral amplification for various reasons.

Within the second paper, we invited a subgroup of the first one to participate in psychoacoustical measurements of speech recognition and localization. The measurements were performed with two, one, and no HA at all. Analysis of the results for the tests showed an advantage in both speech recognition and localization with two compared with one HA for the study group.

The following two papers aimed to a closer examination of those persons who reject bilateral amplification. As we assumed different problems in the auditory pathways for persons preferring one and two HAs, we developed a test battery with the goal to compare binaural and central auditory abilities in two groups of bilaterally hearing-impaired persons provided with bilateral amplification. One group was satisfied with using two hearing aids, the other preferred to use only one because of various, presumably hearing related problems.

In the first of the remaining two studies, test methods for the project were developed and evaluated with normal-hearing subjects. The second part used these methods to evaluate binaural hearing in the two already mentioned groups of bilaterally hearing-impaired persons.

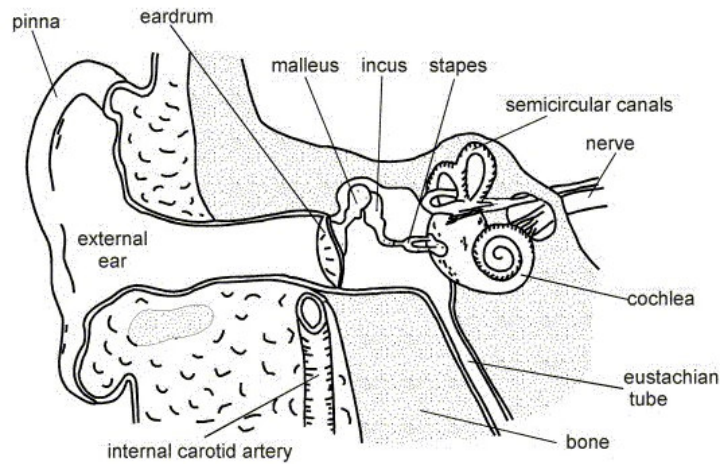
The results described in the last paper indicated worse function in central auditory abilities of the group preferring one hearing aid. This is revealed by worse results in a speech-in-noise task and in a test examining central auditory pathways and cognitive function. Minor problems for this group could also occur in the peripheral auditory function and in slightly too high amplification of the hearing aids.

## 1.1 BINAURAL HEARING IN NORMAL-HEARING PERSONS

### 1.1.1 Structure of peripheral and central auditory function

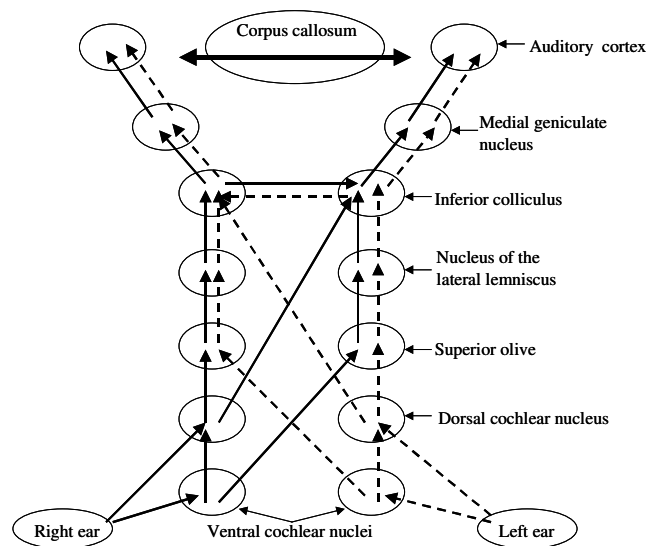
In general, peripheral auditory functions are those parts of the auditory system that conduct the sound pressure wave of a sound to the auditory nerve, which is connected to the inner ear, where the mechanical sound vibrations are converted to electrical signals. Those parts of the auditory system that conduct the electrical signals to the relevant regions of the brain are defined as the central auditory pathways.

The peripheral system consists of the outer ear with the auricle (pinna) and the ear canal, the middle ear with eardrum (tympanic membrane) and ossicles (malleus, incus and stapes) as well as the inner ear, the cochlea. Figure 1 shows an overview of outer, middle and inner ear.



**Figure 1. Structure of the peripheral auditory system. Picture adapted from [www.patient.co.uk](http://www.patient.co.uk)**

Sound entering the ear canal is conducted to the tympanic membrane and there causes vibrations. These vibrations are transmitted via the ossicles to the oval window. The oval window is connected to the fluid-filled, spiral shaped inner ear, the cochlea. The vibrations of the oval window are transformed to a travelling wave in the fluid of the cochlea. The cochlea is divided into three compartments by two membranes, the Reissner's membrane and the basilar membrane. The basilar membrane contains the inner hair cells (IHC) and outer hair cells (OHC), which are connected to the auditory nerve. These two kinds of cells react to movements of the basilar membrane caused by the travelling wave of the fluid in the cochlea after sound stimulation. The mechanical movements of the basilar membrane are converted into electrochemical signals mainly in the IHCs and sent to the brainstem via the auditory nerve. Frequency information of the incoming signal is coded by the position of the hair cells on the basilar membrane and the temporal pattern of nerve pulses activated. Intensity is coded by the total number of nerve pulses excited. The OHCs respond to the vibrations of the sensory organ, amplifying the vibrations in case of very weak signals. Furthermore, the OHC react on signals coming from the brain via the efferent nerve system. Figure 2 shows a schematic drawing of the auditory pathway from the brainstem to the auditory cortex.



**Figure 2. Schematic overview of the stations signals, originating in the right and left ear, pass on the way to the cortex. The figure only shows signals traveling ‘upwards’ to the brain, not the signals traveling ‘downwards’ via the efferent system.**

As the figure shows, signals are conveyed to the auditory cortex through both ipsilateral and contralateral pathways, with the contralateral pathway being the dominant one (Kimura, 1961). The auditory pathways are quite complex and not yet totally understood. There are, however, results pointing towards general features in the different nuclei. The following short description of these general functions of some of the different nuclei is based on Kandel et al (2000).

The ventral cochlear nuclei have, similar to the cochlea, a tonotopical structure. Incoming signals are decoded depending on frequency and time. It is considered to have the function of a switchboard, distributing auditory information to several different areas in the auditory pathway.

In the superior olive, predominantly differences in level (intensity), time, or phase of the signals between the ears are decoded (interaural level differences, ILD, interaural time differences, ITD, and interaural phase differences, IPD). Both features are of great importance for sound localization. Ease of localization has been one of the major arguments when discussing bilateral hearing aids (HAs) for hearing-impaired persons.

Also the inferior colliculus is sensitive to ILDs and ITDs, as well as spectral changes such as amplitude and frequency modulations. This ability is essential for recognizing certain phonemes and intonations, an important feature for understanding speech.

The medial geniculate nucleus is situated in the thalamus and its function in the auditory pathway seems to be mainly a relay station for the signals, also providing comparisons of relative intensities and durations.

The auditory cortex seems to be organized both tonotopically, temporally, and spatially. Functions such as timbre discrimination, spatial localization, or noise filtering are possible in the auditory cortex.

The corpus callosum is the connection and switchboard between the two hemispheres of the brain. Signals reaching the auditory cortex from mainly one ear are transferred through the corpus callosum to the relevant hemisphere in the brain. For example, speech signals are

decoded to language in the left hemisphere (see Gazzaniga, 2000, for a review on the different aspects of the corpus callosum).

### 1.1.2 Advantages of binaural hearing in speech perception

Although only one ear is necessary for perfect speech intelligibility (Cherry, 1953), binaural listening can be advantageous for speech recognition. Several aspects have to be considered:

- 1) Summation of incoming stimuli
- 2) Facilitation of speech in noise
  - a. Binaural Masking Level Difference
  - b. Head shadow effect (better ear effect)
  - c. Squelch effect

It is well established, that binaural thresholds for stimuli are better than monaural ones (Shaw et al, 1947; Markides, 1977). Binaural listening also enhances the loudness of signals (Marks, 1978; Hall & Harvey, 1985; Whilby et al, 2006). For both effects, the difference of binaural and monaural listening offers a gain in the magnitude of about 3 dB (Markides, 1977).

One factor facilitating the recognition of speech in noise is based on ITDs and is commonly known as Binaural Masking level difference (BMLD) or binaural release from masking. The detectability of a bilaterally masked signal improves, when its interaural phase difference is different from the interaural phase difference of the masker. This effect is known for both pure tones and speech since 1948 (Hirsh, 1948; Licklider, 1948) and has been used in several studies on binaural hearing since then. BMLD for pure tones is largest for frequencies lower than 1500 Hz and depends on the interaural configurations of target and masker (Moore, 2003; Akeroyd, 2006). Evaluation of the BMLD also included experiments with more complex signals such as syllables (Carhart et al, 1969), monosyllabic words (Levitt & Rabiner, 1967), spondaic words (Wilson et al, 1994; Johansson & Arlinger, 2002) and sentences (Bocca & Antonelli, 1976). It has, however, to be pointed out that the detectability improvement of speech under BMLD conditions usually is larger than the intelligibility improvement of the speech signals (Levitt & Rabiner, 1967).

Signals occurring on one side of the listener are easier to detect with the near ear (the ear close to the signal) than with the far ear (the ear opposite to the signal). Obviously, the head attenuates the signal in the far ear. This phenomenon is referred to as the head shadow effect or better ear effect. If the listener e.g. is targeting a speech signal originating from the front, masked by a noise from one side, the target will be detected more easily under a binaural listening condition than under a monaural one. This improvement is based on the fact, that there is no difference in ILD for the target signal for the two ears, but there is a difference for the masker because of the head shadow (Markides, 1977; Bronkhorst & Plomp, 1988; Akeroyd, 2006).

Whereas the head shadow effect is a purely physical phenomenon, based on the diffraction of sound waves at the head, the squelch effect is more complex and based on physiological features of the auditory system and the brain. The cochleae and the brain have the ability to work similarly to an adaptive noise reduction system, where total waveforms of signals and maskers are compared and subtracted. The auditory system can make combinations of the different waveforms at the two ears and by that significantly decrease the effects of noise (Koenig, 1950; Arsenault & Punch, 1999; Dillon, 2001).

### 1.1.3 Directional hearing

Several important aspects of directional hearing will be covered by this summary:

1. Interaural level differences
2. Interaural time differences
3. Head movements
4. The pinna effect
5. Echo suppression and precedence effect

The two main factors influencing the ability of a listener to localize signals are the already mentioned interaural differences of time and intensity of the signals reaching the two ears. Due to the physical nature of sounds, the effectiveness of ILDs and ITDs as a tool to localize sounds varies with frequency. ILDs are most effective at high frequencies as the wavelength of high frequency sounds is short in comparison with the dimensions of the head. Therefore, little diffraction at the head occurs, the sound cannot 'bend' around the head and the far ear lies in a kind of 'acoustical shadow' (Moore, 2003; Akeroyd, 2006). The effect of ITDs in localization on the other hand, is most effective for low frequencies. A signal closer to one side will reach the near ear before it reaches the far ear. For pure tone signals, an ITD can be expressed as an IPD. The short period of high frequency tones introduces an ambiguousness of the location in the waveform cycle for the far ear already for very short ITDs (Moore, 2003; Akeroyd, 2006). The described effectiveness of ILDs and ITDs for localization mainly concerns pure tones in quiet. Localization of pure tones in noise reveal, that in those conditions neither effect dominates completely (Lorenzi et al, 1999b; Akeroyd, 2006). Complementary factors also have to be taken in account for the localization of more complex sounds.

It has been shown, that head movements can enhance localization of more complex sounds such as white noise (Hirsh, 1971; Markides, 1977; Moore, 2003). These enhancements are effective for localization in both the lateral and the horizontal plane (Markides, 1977; Moore, 2003) and are suggested to be based on the changes in the spectral pattern of the signal at the two ears during head movements.

Also the external ear, particularly the pinna, plays an important role for sound localization especially in the vertical plane (Batteau, 1967; Markides, 1977; Middlebrooks & Green, 1991; Moore, 2003). It has also been pointed out, that the pinna effect is monaural, as it depends on spectral cues due to filtering and refraction at the pinna with no need for interaural comparisons (Middlebrooks & Green, 1991).

In real life listening situations, reverberation and room acoustics cannot be neglected. Sounds do not occur with clearly defined phases and directions as in experimental settings with presentations of sound through headphones or in anechoic chambers. In those situations, echo suppression and the precedence effect are important. Echo suppression occurs, when two successive sounds are heard as one single sound if the gap between them is sufficiently short (Moore, 2003). The interval between the two sounds to be heard as fused varies from 5 ms for clicks to 40 ms for speech or music (Moore, 2003).

The precedence effect is the phenomenon, that the location of two successive tones of discontinuous or transient character is determined by the location of the first signal if they are perceived as fused (Moore, 2003). It has been shown, that the ability to detect the lagging sound

is reduced for a short time after onset of the leading sound (Zurek, 1980), which has been used as a quantitative measure of the precedence effect. Often, the precedence effect is not present at once but is built up. At the first few presentations of two following sounds, they can be heard separated, but fuse after being repeated at rate (Freyman et al, 1991; Moore, 2003). Changes in the acoustical conditions such as changing the directions of leading and lagging sounds after repeated presentation can cause the precedence effect to be disrupted temporarily, until it is built up again as described before (Clifton, 1987; Moore, 2003). Although physiological correlates of the precedence effect have been described (Litovsky et al, 1999), it partly may reflect high level cognitive processes (Clifton et al, 1994). Echo suppression seems to occur mainly, when the echoes are consistent with the listener's experiences regarding the sound source and the room acoustics. The precedence effect is not only important regarding localization, but also in order to interpret and identify every day sounds.

## **1.2 HEARING-IMPAIRED LISTENERS**

Hearing loss can be categorized in several classes: Conductive hearing loss, sensorineural hearing loss, retrocochlear hearing loss and damage to the central auditory pathways.

Conductive hearing loss is caused by reduced mobility of one or several components of the middle ear. The reason could be fluid in the middle ear after infections such as otitis media preventing the tympanic membrane from normal vibrations or reduced mobility of the stapes because of growth of bone at the oval window (otosclerosis). Conductive hearing losses lead to an attenuation of incoming sounds over the whole frequency spectrum and can often be treated successfully with hearing aids or surgery.

Sensorineural hearing loss is situated in the cochlea and is usually caused by damaged OHCs and/or IHCs. The OHCs are most sensitive to damage for example from noise (Borg et al, 1995), but also IHCs are affected by noise exposure (e.g. Canlon, 1988). Damage to the cochlea caused by aging effects have been attributed mainly to OHC damage with genetic factors as underlying mechanism (Jennings & Jones, 2001). Most often, high frequencies are more effected by sensorineural hearing loss, than low frequencies (Moore, 2003). Sensorineurally hearing-impaired persons not only have elevated hearing thresholds, but also loss of frequency selectivity (Oxenham & Bacon, 2003) and decreased suprathreshold signal analysis abilities (Dreschler & Plomp, 1985; Glasberg & Moore, 1989; Moore, 1996).

Retrocochlear hearing loss usually is caused by tumors on the auditory pathways between cochlea and brain. Usually, only one side is affected and experienced difficulties and exact symptoms differ depending on where in the auditory system the problem is situated. Treatment consists mainly of surgery if possible. Often surgery leads to deafness on the affected side.

### **1.2.1 Binaural advantages in speech perception for hearing-impaired listeners**

The following description of problems hearing-impaired persons encounter in connection with speech recognition and localization is concentrated on sensorineural hearing losses.

Hearing-impaired persons generally have a decreased ability to recognize and thus to understand speech. Two aspects have to be taken in consideration, when discussing this problem.



The first one is the fact, that parts of the speech spectrum of a speaker at given level are below the hearing-impaired listeners' hearing threshold (Zurek & Delhorne, 1987; Humes & Lee, 1994; Moore, 1996). Therefore, hearing-impaired persons are more often confronted with the problem to be forced to decode speech signals close to threshold. As already mentioned in the section on binaural advantages in speech reception for normal-hearing subjects, binaural summation at threshold and binaural loudness summation can enhance speech recognition. For a hearing-impaired person, a few dB better threshold can make the difference between speech exactly at threshold and speech over the hearing threshold.

Another aspect are the decreased suprathreshold signal analysis abilities in hearing-impaired persons (Dreschler & Plomp, 1985; Glasberg & Moore, 1989; Moore, 1996). This problem is the reason that sensorineurally hearing-impaired persons need a higher signal-to-noise ratio than normal-hearing persons to achieve the same performance in a speech recognition task in noise (Hagerman, 1984; Plomp, 1986).

As discussed before, binaural listening can enhance speech recognition in noise. The head shadow effect is equally effective for both normal-hearing and hearing-impaired persons as long as the signal levels are above the threshold of the hearing-impaired person. The other two aspects, BMLD and squelch effect are based on binaural processing in the auditory pathways and might therefore be less effective for a hearing-impaired person. BMLD has been investigated in a large scale with normal-hearing and hearing-impaired persons. The results show the presence of the BMLD effect also in hearing-impaired persons, even if the effect is shown to be less pronounced (Bronkhorst & Plomp, 1989; Arbogast et al, 2005). There are also some reports suggesting that there is no difference in BMLD between normal-hearing and hearing-impaired persons when comparing monaural and binaural listening (Bronkhorst & Plomp, 1989; Bronkhorst & Plomp, 1992).

Similar to the BMLD effect, which is less pronounced in hearing-impaired persons than in normal-hearing persons, the squelch effect is present, but in a less degree (Peissig & Kollmeier, 1997). It has been suggested in a study by George et al (2006), that the deficits in suprathreshold processing of speech in noise for the hearing-impaired mainly is determined by deficits in temporal resolution.

### **1.2.2 Localization ability of hearing-impaired listeners**

Often, hearing-impaired persons are not aware of having localizing problems before they are specifically questioned about orientation. Hearing-impaired persons have deteriorated localization abilities in both quiet and noise (Noble et al, 1994; Lorenzi et al, 1999a). The worse results in hearing-impaired listeners' localization abilities compared with normal-hearing listeners cannot totally be explained by the reduced audibility of the signals but have to be related to deteriorations in central processing, as already mentioned in section 1.2.1. Persons with sensorineural hearing losses but with relatively good hearing in the lower frequencies, have access to rather intact ITDs and therefore most often no problems to localize in the frontal horizontal plane. Vertical plane localization is deteriorated for persons with high frequency hearing losses, which is most common in sensorineural hearing losses. Front-rear accuracy is most affected for hearing losses in the range 4-6 kHz (Noble et al, 1994). It has been suggested that localization problems in persons with sensorineural hearing loss are caused by decreased spectral processing and in persons with tumors on the auditory nerve by impaired signal

transmission. Results for persons with central auditory involvement suggest, that there are separate processors for localization cues in the central auditory system (Häusler et al, 1983).

### **1.3 SPEECH PERCEPTION AND COGNITIVE ASPECTS**

Speech perception is not only dependent on audibility and relevant signal analysis in the auditory pathway, but also on cognitive abilities in the listener. Complex signals such as speech are processed and interpreted in context of previous experiences. Thus, a functioning cognitive system is important to simultaneously store and process small amounts of information during brief periods of time. This function is commonly known as working memory (e.g. Baddeley, 2003) and influences the ability to understand speech, especially for hearing-impaired persons (Lunner, 2003). Both the ability to use semantic context (Wingfield, 1996) and the role of lexical discrimination (Sommers, 1996) are important for speech understanding in natural environments.

Cognitive aspects in connection with hearing loss are commonly discussed for elderly persons, as aging is an important reason of decreased cognitive abilities. Persons with age related hearing loss not only encounter the problem of a decreased amount of signals passing the auditory system. More effort and concentration has to be put on following the signals, which consumes cognitive resources otherwise used to store information in the working memory (Pichora-Fuller et al, 1995; Lunner, 2003). There is evidence, that there is a correlation between hearing loss and loss of cognitive abilities, but it remains unclear, if increasing hearing loss leads to a decline in the cognitive functions, or if both effects are part of a general age-related decline (see Arlinger, 2003, for a review).

The cognitive system in hearing-impaired persons is generally used to a higher degree than in normal-hearing persons, as words missed in a conversation have to be filled in by guessing, in order to be able to follow the conversation. With an already stressed working memory as described above, auditory performance is further affected.

## **2 EFFECTS OF BILATERAL AMPLIFICATION**

Listening with two ears provides several advantages and is beneficial for both normal-hearing and hearing-impaired persons as discussed before. Being able to sense signals in both ears is therefore important for bilaterally hearing-impaired persons. Hearing aids, of course, do not only increase audibility but may also have additional features such as compression, directional microphones, noise suppression algorithms and feedback cancellation systems. I will not discuss the general features of hearing aids (for details see Dillon, 2001). The focus of this work will be put on the questions of advantages and disadvantages of bilateral hearing aids.

Besides the already mentioned advantages of bilateral hearing aids, presumably making it possible for the hearing-impaired person to benefit from binaural hearing in a similar way as normal-hearing persons, there are other advantages. Sound quality often improves (e.g. Dillon, 2001; Noble, 2006), there are reports on decreased tinnitus with two hearing aids (e.g. Brooks & Bulmer, 1981) and the user is not totally without hearing device if one breaks down. Additionally, there are reports on decreased abilities to process speech in the unaided ear for unilaterally fitted persons after a longer period of using HA in just one and the same ear (Silman et al, 1984; Gelfand et al, 1987; Dillon, 2001; Arlinger, 2003). This phenomenon is called the deprivation effect and is controversial. There is a lot of discussion about it. The effect seems to be reversible in some individuals (Neuman, 1996; Arlinger, 2003), but apparently the reversibility only regards suprathreshold speech discrimination, and not tone thresholds or speech recognition thresholds (Silman et al, 1984; Noble, 2006). The deprivation effect has been suggested to be correlated to presentation level as it seems present for input signals at high levels, but not for input levels at low levels (Gatehouse, 1989). Therefore, it has been suggested, that the deprivation effect might rather be a sign of perceptual learning effects than changes in the auditory system (Gatehouse, 1989; Gatehouse, 1993; Neuman, 1996).

Of course, there are also more obvious disadvantages of bilateral hearing aid fittings. These include the higher cost of two hearing aids compared with only one and the larger exposure to wind noise. Elderly persons might have difficulties to handle two HAs and some persons feel more handicapped with two than with one HA. Binaural interference, an effect causing a disturbing fusion of the signals to the two ears, might lead to better performance with a unilateral fitting for some individuals especially in tasks involving speech in noise (Allen et al, 2000; Dillon, 2001; Walden & Walden, 2005).

### **2.1 RESULTS OF QUESTIONNAIRES ON ADVANTAGES AND DISADVANTAGES OF BILATERAL HEARING AIDS**

According to Markides (1977), interest in the question of bilateral versus unilateral fittings aroused already at the beginning of the 20<sup>th</sup> century, when the first stereophonic hearing aid system was patented. Questionnaires are a common tool to assess the benefit of hearing aid satisfaction in the individual users. This tool has been used in rehabilitation follow-ups as well as in several scientific research approaches on the question of the benefits of bilateral fittings compared to unilateral ones. One of the first bigger surveys on consumer satisfaction with two HAs was done by Jordan et al (1967), who found that only 19% of 1147 participants of the study rejected bilateral HAs and preferred to use only one. They found a correlation between

satisfaction with two HAs and hearing loss; the more severe the hearing loss, the more likely it was that the person chose bilateral amplification. More recent research is described below and the interested reader is referred to the review by (Noble, 2006).

The traditional research questionnaires usually contain questions on the pattern of usage of the HAs: speech recognition in quiet and in noise, in familiar and unfamiliar environments, localization of stationary sounds in familiar and unfamiliar environments, and often also open questions where the participants of the studies had the possibility to explain preferences and individual experiences with HA amplification. Recent research points out, that it is important to consider everyday life when designing questionnaires and measurements to assess localization abilities in order to examine the effects of bilateral versus unilateral amplification (Noble & Gatehouse, 2004; Gatehouse & Akeroyd, 2006; Noble, 2006; Noble & Gatehouse, 2006). In real life, localization of stationary sounds rarely occurs. Dynamic sounds such as cars approaching or leaving are more important for a listener. This aspect is neglected in traditional questionnaires and should be included in future research both in terms of enquiries and psychoacoustical measurements assessing the effects of bilateral HAs.

Advantages of bilateral amplification stated in enquiry-based studies were descriptions such as 'better overall hearing', 'experience of stereo-hearing', 'better sound quality', 'more balanced hearing' and 'better speech clarity' (Erdman & Sedge, 1981; McKenzie & Rice, 1990; Stephens et al, 1991; Balfour & Hawkins, 1992; paper I; Noble, 2006). There were also studies pointing out release of tinnitus as being more pronounced for bilateral HAs than for a unilateral HA (e.g. Brooks & Bulmer, 1981). Reduced effort when listening with two HAs (Erdman & Sedge, 1981; Noble & Gatehouse, 2006) is also an important feature especially when considering cognitive aspects connected to listening effort. Subjective rating of speech recognition in quiet and/or noise also showed an advantage of bilateral fittings over unilateral ones in several studies (Erdman & Sedge, 1981; Schreurs & Olsen, 1985; paper I; Noble, 2006; Noble & Gatehouse, 2006). Inconclusive results or even a disadvantage of bilateral HAs regarding speech in noise were found in a few studies (Brooks & Bulmer, 1981; Schreurs & Olsen, 1985; Chung & Stephens, 1986; Vaughan-Jones et al, 1993). Localization abilities with two HAs and with one HA were the subject of many studies. An advantage for bilateral fittings was reported in the majority of the studies (Schreurs & Olsen, 1985; Chung & Stephens, 1986; Stephens et al, 1991; Noble et al, 1995; paper I; Noble & Gatehouse, 2006). The already mentioned report by Vaughan-Jones et al (1993), however, showed a disadvantage for bilateral HAs compared to a unilateral HA regarding localization. This particular report describes a cross-over study with two groups having two successive regimes of a unilateral fitting followed by one of bilateral fitting and one group with an initial regime of bilateral HAs followed by two of an unilateral HA. The preference for a unilateral fitting in this report might be biased by the order of the fitting procedures as suggested in the review by Noble (2006). Disadvantages in localization for bilateral amplification compared to unilateral might indicate problems with the bilateral fitting routines used (Noble, 2006). Correlations between self estimated handicap, hearing thresholds and preference for one or two hearing aid/aids show, that generally, persons preferring two HAs have worse hearing thresholds and/or regard themselves as more severely hearing-impaired than persons preferring one HA (Chung & Stephens, 1986; Stephens et al, 1991; Noble et al, 1995).

## **2.2 PSYCHOACOUSTICAL TESTS ON THE EFFECTS OF BILATERAL HEARING AIDS**

Bilateral amplification has been shown to be advantageous for speech recognition in quiet and noise as well as localization in the enquiry-based studies. Thus, studies involving psychoacoustical measurements of the effects of bilateral amplification often concentrate on these aspects.

Even if measurements of speech recognition with two, one, and no HAs showed results in favor of two hearing aids in some studies (Erdman & Sedge, 1981; paper II), other studies are inconclusive regarding this question (Sebkova & Bamford, 1981; Festen & Plomp, 1986; McKenzie & Rice, 1990; Dillon, 2001; Noble, 2006). Especially in noisy situations, bilateral amplification fails to benefit more than unilateral amplification. Many of these studies are done before newer generations of hearing aids with features such as programmable circuits and multichannel compression were common in clinical practice. It is therefore suggested that many of the obtained results were influenced by the fact, that most of the HAs used in these studies were linear and/or used peak-clipping to limit the maximum output of the HAs (Naidoo & Hawkins, 1997; Dillon, 2001; Holmes, 2003; Bentler et al, 2004). However, also a recent report by Walden & Walden (2005) shows better speech-in-noise-results for unilateral amplification and it is recommended to consider removing one hearing aid in complex, noisy listening situations if necessary. In this report, the main problem for the subjects was suggested to be a binaural interference effect, i.e. the signals from the ear with worse hearing interferes with the signals from the ear with better hearing in a way that disturbs overall speech recognition (Jerger et al, 1993; Chmiel et al, 1997; Carter et al, 2001; Holmes, 2003; Walden & Walden, 2005).

Whereas localization abilities subjectively were estimated as better with bilateral amplification than unilateral in the studies based on questionnaires, results of psychoacoustical measurements are inconclusive. The study described in paper II showed similar results of localization in the unaided and bilaterally aided test situation. With unilateral amplification, localization abilities in the subject group decreased. Other studies did not find any difference between unaided and aided situations (Noble & Byrne, 1990), and a recent study showed that localization abilities were degraded with bilateral hearing aids in hearing-impaired listeners performing equally well as normal-hearing persons in an unaided test situation (Van den Bogaert et al, 2006). It has been suggested that technical features of ear moulds and modern HAs can disturb binaural cues and by that lead to decreased localization abilities for users of bilateral HAs (Byrne et al, 1998; Noble et al, 1998; Van den Bogaert et al, 2006).

## **2.3 UNSUCCESSFUL USERS OF BILATERAL HEARING AIDS**

The most interesting reports on unsuccessful users of bilateral amplification have been published by Chmiel et al (1997), Carter et al (2001), and Walden & Walden (2005). The first study is a case report describing one elderly female subject with extensive tests in the psychoacoustical, electrophysiological and central auditory spheres. The second is a work on four male subjects between 52 and 79 years of age tested with dichotic tests, speech recognition in quiet and speech-in-noise. The third study describes a group of 28 persons (26 male, 2 female) aged 50 to 90 years. This group was tested with dichotic tests and speech recognition in noise.

Common to the studies was, that the speech-in-noise tests showed markedly better results for the condition with unilateral amplification in the right ear. Unilateral amplification in the left ear was not beneficial at all for the subjects and bilateral amplification also gave worse results. In the first two studies, also the dichotic tests showed a larger than normal right ear advantage.

None of the studies compared the obtained results with a group of successful users of bilateral amplification. Such a comparison could be a tool to improve the diagnostic possibilities for persons preferring unilateral amplification. A study using this experimental design is described below in paper IV.

### 3 AIMS OF THIS WORK

The present study consists of four parts, a retrospective enquiry study (paper I), psychoacoustical measurements of speech recognition and localization in noise (paper II), development and evaluation of tests to measure binaural integration (paper III), and measurements of peripheral and central auditory functions in two groups of bilaterally fitted hearing-impaired persons; one group preferring one and one group preferring two hearing aids (paper IV).

In paper I, subjective experiences with bilateral versus unilateral HAs in a large group of hearing-impaired persons were evaluated with help of a questionnaire. The questions covered the following areas of interest:

- Patterns of HA use for persons provided with bilateral HAs and reasons for continued or discontinued use of bilateral amplification
- Consumer satisfaction regarding bilateral HA amplification
- Possible differences between users of bilateral and unilateral HA amplification
- Subjective abilities regarding speech recognition and sound localization in users of bilateral/unilateral HAs

Paper II describes psychoacoustical measurements of speech recognition and localization in a subgroup of the participants of the study described in paper I. This investigation aimed to study the possible benefits of bilateral compared to unilateral HA amplification with regard to the results obtained in paper I:

- Is bilateral amplification advantageous compared to unilateral amplification for speech recognition in noise?
- Is localization easier with bilateral amplification than unilateral?

The final two parts of this work concentrated on hearing-impaired persons rejecting bilateral amplification for diffuse, hearing related reasons.

Consequently, the third step, described in paper III was the development of test methods to measure individual binaural integration. The measurements were aimed to cover the following aspects of auditory performance and evaluate the developed methods in normal-hearing subjects:

- Peripheral auditory function with regard to binaural performance
- Central auditory function with regard to binaural performance
- Cognitive aspects in auditory performance

In the study described in paper IV, the methods developed in paper III were used to compare two groups of hearing-impaired persons: One group experienced great benefit of bilateral amplification and the other rejected bilateral amplification and used unilateral instead. The goal of the study was to answer the following questions:

- Are there differences between successful and unsuccessful users of bilateral amplification regarding auditory performance?
- Do binaural abilities influence the possibility to benefit from bilateral amplification?
- Are there differences between successful and unsuccessful users of bilateral amplification regarding cognitive performance?

## **4 MATERIAL AND METHODS**

### **4.1 QUESTIONNAIRE ON EXPERIENCES WITH BILATERAL AND UNILATERAL AMPLIFICATION (PAPER I)**

#### **4.1.1 Questionnaire**

Specifically for this study we constructed an enquiry, which was designed to put an emphasis on bilateral HAs and binaural hearing. Ten of the 44 items were taken from a questionnaire used in the clinic for quality management and was thus validated in clinical practice. The remaining 34 items were partly adopted from existing instruments, partly developed exclusively for this study.

The first part of the questionnaire contained general questions on age, gender, and demographic data followed by questions about patterns of usage of the HAs and the reasons for this individual decision.

The enquiry also included questions about various aspects of bilateral HA listening: speech recognition, sound localization in general, quality of sound, naturalness of external sounds and the own voice as well as the technical aspect of matching the volumes of the two HAs. The questions were formulated as positive or negative statements and the participants were asked to describe their experiences by means of choosing one of the alternatives 'agree in a very high degree', 'agree in a high degree', 'agree in a certain degree', 'agree in a small degree', and 'agree not at all'. Within this part, there were also questions whether the use of two HAs resulted in a feeling of increased disability and if the cost of batteries could be a reason to use only one HA.

In the following section of the questionnaire, specific listening situations were described for the subjects. For each situation they were asked if they used both aids, one aid on a preferred side or one aid without side preference. For some of these specific listening situations, we also asked if the consumers were satisfied with the function of their HAs. A special emphasis was put on sound localization and auditory orientation.

#### **4.1.2 Subjects**

The questionnaire was mailed to a group of patients selected from the files of the Department of Audiology, Karolinska Hospital, Stockholm. These persons had been provided with bilateral HAs between January 1994 and May 1997. Since they had been using their HAs between eight months and four years at the time of the mailing, we expected them to be experienced enough to give valid answers to the questions.

A smaller subgroup of these subjects did only use unilateral amplification despite the fact that they were provided with two HAs. In order to be able to compare this relatively small subgroup with the subjects using bilateral amplification, we supplemented the subgroup with subjects who were fitted unilaterally within the same period of time at the same clinic. These unilaterally fitted subjects were matched by gender and age with the original group of subjects. The unilaterally fitted subjects answered only those questions of the enquiry suitable even for users of only one HA.



For the group of bilaterally fitted subjects, 190 persons were selected from a list of patients, who had been provided with HAs between January 1994 and May 1997 at the Department of Audiology, Karolinska Hospital, Stockholm. The only inclusion criteria were bilateral fitting of HAs and age over 15 years at the time of the investigation. The response rate was 79%, 144 participants. The population consisted of 52% men and 48% women. The median age of the responders was 68 years with extreme values of 18 and 95 years. Most of the subjects were fitted with behind-the-ear HAs (86%), 13% had in-the-ear types and two persons had hearing spectacles.

The pure tone threshold average (PTA4F) over the frequencies 500, 1000, 2000 and 4000 Hz in dB HL showed approximately the same value for both ears. According to Parving & Newton (1995) and Liu & Xu (1994), 28% of the material could be classified as 'mildly impaired' (PTA4F on the better side between 20 and 40 dB HL), 60% as moderately impaired (PTA4F on the better side between 40 and 70 dB HL) and 11% as severely impaired (PTA4F on the better side between 70 and 95 dB HL). There was one case of profound impairment with a PTA4F worse than 95 dB HL on the better side.

The unilaterally fitted group of subjects, which formed the group of unilateral users together with the subjects from the original population, who only used one HA, consisted of 60 persons. Within this group, the response rate was 74%, 40 persons.

In the social aspects (marital status, being working or on retirement) there was no significant difference between the groups. Also in this group, most of the subjects were fitted with behind-the-ear HAs (90%), 10% had in-the-ear type HAs.

The two groups fitted unilaterally and bilaterally originally were not matched regarding hearing impairment but an analysis of variance (ANOVA) showed no statistically significant differences for the PTA4Fs of the two groups of bilateral and unilateral HA users.

## **4.2 SPEECH PERCEPTION AND LOCALIZATION WITH TWO, ONE AND NO HEARING AIDS (PAPER II)**

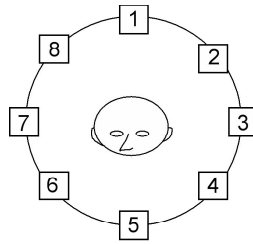
### **4.2.1 Measurement methods and procedure**

In order to provide a somewhat realistic listening situation, the horizontal localization test was included in the speech intelligibility test. The subject was seated in the centre of a circle formed by eight loudspeakers arranged symmetrically in the horizontal plane (45° between them). When a speech signal was presented from one loudspeaker, the other seven simultaneously emitted noise. The subject was instructed not to move his/her head during the measurement. The subject was requested to repeat the speech signal (a five word sentence) and, at the same time, point out which loudspeaker had emitted the signal. Throughout the procedure, the subjects were wearing their own HAs as provided by the clinic. They were instructed to set the volume control to a level providing comfortable listening.

The speech-in-noise-test used was a Swedish sentence test (Hagerman, 1982), available on commercial CD and used in hearing clinics. We used a permanent signal-to-noise ratio of +4 dB. Every subject was tested with two consecutive lists (20 sentences), for each part of the experiment, in order to get a sufficient number of horizontal localization measurements. The number of correct words as well as the number of correct localization decisions was scored.

The experiment was performed in a sound-insulated room treated with absorbents. The spectral distribution of the background noise remained stable even when a single loudspeaker was shut down from the array prior to sending the speech signal from this loudspeaker. The circle of loudspeakers had a radius of 1.7 m and the subjects sat in a height adjustable chair, so that ears and loudspeakers were in the same horizontal plane.

The loudspeakers were numbered from one to eight; starting with one, directly behind the subject, and continuing clockwise. That means that loudspeaker #1 was situated directly behind the subject, #3 - 90° to the left, #5 - directly in front, and #7 - 90° to the right of the subject. Loudspeakers #2, #4, #6 and #8 were positioned at 45° to the other loudspeakers (see Figure 3). The sequence of loudspeakers, assigned to the sequence of sentences for the partial experiments, was randomized in advance.



**Figure 3. Experimental design for the study described in paper II. The subjects were sitting in the center of a circular array of eight loudspeakers, arranged in the horizontal plane. Loudspeakers were numbered one to eight, starting with one directly behind the subject and continuing clockwise.**

Since the subjects had to perform a relatively complicated task, two training lists were performed at the beginning of each measurement. Both training lists were performed with bilateral amplification. During the test situation, the speech signals were presented well above the subjects' hearing thresholds ( $S/N = 73/69$  dB(A)).

The experiment was designed in four parts: measurement without hearing aids (1), measurement with bilateral amplification (2) and measurement with unilateral amplification on each side, separately (3,4). The test started with bilateral HA amplification and continued with HA in the right ear, after that, with HA in the left ear and finally, without HAs.

## 4.2.2 Subjects

Nineteen subjects with mild to moderate sensorineural hearing loss, according to pure tone audiometry, participated in the experiment. The group consisted of 9 men and 10 women in the age between 64 and 73 years (median age 69) and the participants were experienced HA users. Eight of the subjects alternated between bilateral and unilateral use of the hearing aids, the other ten usually used bilateral amplification. Most of the subjects (16) were using behind-the-ear hearing aid models, two used in-the-ear types, and one subject used completely-in-the-canal hearing aids. All subjects except one used the same HA-model in both ears. None of the HAs had a directional microphone.

## 4.3 MEASUREMENTS OF INDIVIDUAL BINAURAL PERFORMANCE, NORMAL-HEARING SUBJECTS (PAPER III)

### 4.3.1 Methods

The tests developed in the study described in paper III were aimed to measure both peripheral and central auditory function with an emphasis on binaural integration, as well as cognitive abilities. As we wanted the test to be included in clinical routines as easily as possible, the testing procedure had to be designed with as little changes in clinically available test procedures as possible. All test methods therefore are modifications of existing tests, or tests that can easily be implemented in standard equipment.

We chose tests measuring speech recognition and signal analysis performance as well as dichotic tests. The different tests are described more thoroughly below.

The chosen speech recognition and signal analysis performance tests are normally used under monaural conditions. However, for this study, these two tests were modified to use the phenomenon of BMLD. The signals for the tasks were always presented monaurally, the maskers ipsilaterally and bilaterally respectively, in order to provide the listener with a spatially well-defined signal. BMLD was calculated as the difference between the thresholds with ipsilateral masker and thresholds with bilateral masker.

#### 4.3.1.1 *Speech recognition in noise, Hagerman's sentences*

In order to measure speech recognition, we used the same Swedish sentence test, as in the study described in paper II (Hagerman, 1982). In this study, we used two different maskers: a slightly, 10%, (SM) and a fully, 100%, (FUM) modulated version. The SM noise is the one routinely (and in paper II) used and sounds more or less continuous, the FUM noise was designed to simulate speech signals. The exact features of speech and noise in this test are described in Hagerman (1982) and Hagerman (2002).

The masker was presented at a constant level of 70 dB RMS SPL re 20  $\mu$ Pa; the speech level was adjusted after every sentence to maintain 40% recognition.

In our study, the test contained 4 modes: ipsilateral and bilateral masker during the SM-masker condition as well as ipsilateral and bilateral masker during the FUM-masker condition. Each mode was measured for both right and left ear.

#### 4.3.1.2 *Psychoacoustical Modulation Transfer Function (PMTF)*

For the signal analysis performance task, we used a measurement developed at our department, which we call the Psychoacoustical Modulation Transfer Function, PMTF. The threshold of a brief tone, 4 ms, is measured in a 100% sinusoidally intensity modulated octave-band noise. We used two different sets of PMTF-measurements: one with a signal at 2000 Hz and one with a signal frequency of 4000 Hz. The masker consisted of octave-band noise with the same centre frequency as the corresponding signal. The modulation frequency of the masker was 2.5 Hz for signals at 2000 Hz and 10 Hz for signals at 4000 Hz. The threshold is expressed as a S/N in dB.

Within this task, we measure noise level dependant separate curves for thresholds of the brief tones placed temporally exactly on the peak of the modulated noise (peak-threshold) and in the valleys of the modulated noise (valley-threshold). We also analyze the difference curve of peak- and valley-thresholds (threshold difference). For a first look at results see figure 9, chapter 5.3.2.1.

Former studies showed characteristic level dependant shapes of the threshold-curves as a function of the noise level with a maximum for the peak-thresholds at a noise level of around 55 dB SPL. The valley-thresholds are decreased in comparison to the peak-thresholds and show the maximum shifted approximately 10 dB towards higher noise levels (Lindblad & Hagerman, 1999).

The PMTF-measurements were first performed with ipsilateral masker on each ear, and then with bilateral masker. Every subject was tested with both sets of the PMTF, signal at 2000 Hz with 2.5 Hz intensity-modulated masker, and signal at 4000 Hz with 10 Hz intensity-modulated masker. We measured at the masker levels 35, 45, 55, 65, 75, and 85 dB SPL re 20  $\mu$ Pa.

#### 4.3.1.3 *Dichotic tests*

Dichotic tests were included into the study in order to measure both central auditory and cognitive abilities in the subjects, as those tests have been shown to be influenced by both auditory and cognitive factors like attention (Jerger et al, 1994; Shinn et al, 2005; Roup et al, 2006). During dichotic listening tasks, different signals are presented simultaneously to both ears. The auditory pathways for these competing signals have a contralateral pattern, which means that signals to the left ear are directly conducted to the right hemisphere of the brain and signals to the right ear to the left hemisphere of the brain (Kimura, 1961). Due to the fact, that decoding of speech signals is connected to the left hemisphere (see Hickok & Poeppel, 2004, for a review), signals from the right ear reach the relevant parts of the brain prior to signals from the left ear, which leads to a right ear advantage (REA). During a dichotic listening task, the subject is instructed to either report both signals in optional order (free recall, FR) or to disregard one of the signals and only report the signals reaching one predefined side (directed recall, DR). During FR conditions, both ears have to be monitored simultaneously and the subject has to remember one of the signals while reporting the other. Therefore, cognitive factors influence FR more than DR conditions, where the cognitive demands are reduced. Substantial better performance during the DR condition compared with the FR condition can therefore indicate cognitive dysfunction (Carter et al, 2001). On the other hand, persons, who show better performance during FR than DR conditions or reduced performance during both FR and DR are rather considered to have an auditory deficit, as they do not benefit from the reduced cognitive demands in the DR condition (Carter et al, 2001).

For the dichotic tests in this study, we used a single digits test and a syllable test with consonant-vowel combinations (CV). The tests consisted of six different signals each: 1, 2, 3, 5, 6, 7 for the digits, and ba, pa, da, ta, ga, ka for the CV, spoken by a female voice. The material used was developed and recorded by Hällgren et al (1998). Both digits and CVs were measured in a FR and a DR condition. During the FR condition, the subjects were instructed to report both signals in optional order. During the DR condition, the subjects reported the signals from one, predefined, side and disregarded signals from the other side. The lists for FR consisted of 20 presentations (i.e. 40 words, 20 to each side), the lists for DR had 40 presentations, 20 to each

side. The DR condition started with a male voice, giving the direction of attention (left or right ear). Direction of attention was changed after five words. Presentation level was 65 dB SPL re 20  $\mu$ Pa.

### **4.3.2 Equipment, subjects, and procedure**

#### *4.3.2.1 Equipment*

Our equipment for the tests consisted of a Tucker Davis Technologies (System III) system with integrated signal processors and 24-bit AD/DA-converters. The system was controlled by a personal computer. Signals were presented via circumaural headphones of type Sennheiser HAD 200.

All measurements were performed in a sound proof audiometric room.

#### *4.3.2.2 Subjects*

Measurements were conducted on 14 normal to almost normal-hearing subjects, 7 women and 7 men. Criteria for inclusion were hearing thresholds not exceeding 20 dB HL in the frequency range up to 2000 Hz and not exceeding 35 dB HL in the frequency range above 2000 Hz. The subjects were 30-65 years old, each 5-year-interval within the age range was covered by one man and one woman. The subjects were paid a small amount of money for their participation.

#### *4.3.2.3 Procedure*

All subjects started the test battery with measurement of hearing thresholds at the frequencies 500, 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz with fixed frequency Békésy technique, followed by Hagerman's sentences, a short 5 minute-break and the dichotic test. This part took about one hour and 45 minutes. After this, we took an approximately 30 minutes break, with coffee/tea. After the break, the PMTF ended the session. The whole procedure took about three and a half hours.

## **4.4 BINAURAL PERFORMANCE OF SUCCESSFUL AND UNSUCCESSFUL USERS OF BILATERAL HEARING AIDS (PAPER IV)**

### **4.4.1 Methods**

The measurement methods in this part of the study were identical to those of the study described previously in paper III, with hearing thresholds, Hagerman's sentences in SM and FUM noise with ipsilateral and bilateral masker, PMTF at 2 and 4 kHz with ipsilateral and bilateral masker as well as dichotic digits and CV tests.

As we now conducted measurements with hearing-impaired persons, we also measured individual hearing aid gains and we needed a subjective rating of different aspects of listening aided and unaided. We therefore complemented the study with a questionnaire. We choose the

Speech, Spatial and Quality of Hearing Scale (SSQ), which was developed and evaluated by Gatehouse and Noble in 2004 (Gatehouse & Noble, 2004; Noble & Gatehouse, 2004).

The SSQ contains questions on the three aspects speech perception, localisation and spatial orientation, and sound quality experiences of hearing aid amplification. A recent study by the two investigators showed that benefits of bilateral amplification for the participants in their study were present mainly in the section of localisation and spatial orientation (Noble & Gatehouse, 2006). Mainly questions dealing with moving sounds seem to be important when evaluating the benefits of bilateral hearing aids. We used a Swedish translation of the questionnaire in the present study. The participants filled in the questionnaire for two conditions: estimation of the described situations without hearing aid/aids (only relevant questions) and with hearing aid/aids. The hypothesis was, that users who prefer unilateral amplification might differ from the bilateral amplification group in the ranking of their abilities already without hearing aids.

## **4.4.2 Subjects and procedure**

### *4.4.2.1 Subjects*

In order to invite subjects to the study, we cooperated with the Hearing Clinic at Karolinska University Hospital in Stockholm. Inclusion criteria were age between 18 and 65, mild to moderate hearing impairment (pure tone hearing threshold at the frequencies 500, 1000 and 2000 Hz, PTA3F, up to 45 dB), bilateral hearing aid prescription and no history of often irritated ear canals. We did a survey of the clinic's questionnaires obtained from patients after a rehabilitation program between September 2002 and March 2005. With help of those questionnaires (based on HAUQ, Dillon et al, 1999) we found 74 persons meeting the inclusion criteria. Forty-eight of them used regularly two hearing aids, 26 used only one. Those persons were invited by letter to participate in the study. We received 11 positive responses from bilateral users, 13 from unilateral users. Two unilateral users had to be excluded from the experiment

The group of unilateral hearing aid users consisted of eight female and three male persons with a median age of 63 years (range 56-65). All subjects were experienced users of HAs, nine of them had used HAs for more than five years, the other two for three years. Seven of the subjects used always the right one, one almost always the right, sometimes the left one, and three subjects always the left hearing aid.

The eleven subjects in the group of bilateral hearing aid users consisted of seven women and four men with a median age of 61 years (range 48-65). Within this group, four of the subjects had used hearing aids for more than five years, the rest for one to two and a half years.

Each subject in both amplification groups had the same hearing aid type and brand on both ears.

The subjects were paid a small amount of money for their participation.

### *4.4.2.2 Procedure*

All subjects started the test battery with measurement of hearing thresholds at 500 to 8000 Hz with fixed frequency Békésy technique, followed by Hagerman's sentences, a short 5 min-break

and the dichotic tests. This part took about 1 hour and 45 minutes. After this, we took a break for coffee/tea (approx. 45 min). During the break, the subjects filled in the questionnaire, if needed with assistance of the experiment leader. After the break, the PMTF ended the session. The whole procedure took about four hours. During this procedure, the hearing aid measurements were performed.

## 5 RESULTS

### 5.1 EFFECTS AND CONSEQUENCES OF BILATERAL HEARING AIDS FROM A USER PERSPECTIVE (PAPER I)

The following results up to section 5.1.2.2 are based on data collected from the original group of 144 bilaterally fitted subjects.

#### 5.1.1 Patterns of bilateral HA use

A majority of the subjects (68%) used both HAs most of the time. The second biggest group used mostly the left HA (15%). To use the right HA was a little less popular (10%) and least persons used their HAs alternatively in both ears (8%).

We did not find any audiometric explanation why about one third of the subjects rejected bilateral amplification. An ANOVA analysis showed neither a statistically significant difference for the hearing thresholds nor a difference in ear asymmetry (measured as difference between left and right PTA4F) between those who used two aids and those who used only one.

The participants reported an extensive HA use, both regarding how often the devices were used per week (Table Ia) and how many hours per day (Table Ib). Statistical analysis showed no age or gender correlations for the participants regarding these aspects.

**Table Ia. Frequency of HA use in the study group: days per week.**

Every day	Almost every day	Only sometimes	Never
76 %	17 %	6 %	0 %

**Table Ib. Frequency of HA use in the study group: hours per day.**

More than 6 hours per day	Between 6 and 4 hours per day	Between 4 and 2 hours per day	Less than 2 hours per day
69 %	13 %	13 %	4 %

It can be assumed, that most of the persons could not decide from the beginning, if bilateral or unilateral amplification would be the best choice. Therefore we asked, how the subjects' pattern of using their HAs had changed with time. Table II shows the result of this question.

**Table II. Change of pattern of using two hearing aids for the study group.**

Use of two HAs increased in a high degree	Use of two HAs increased in a certain degree	Use of two HAs was unchanged	Use of two HAs decreased in a certain degree	Use of two HAs decreased in a high degree
27 %	26 %	36 %	5 %	6 %

Within the group who did not increase or decrease their use of two HAs, 78% preferred two HAs, the rest only one.



The practical aspects of handling the HAs were obviously no problem for most of the participants. Between 82% and 96% answered that the handling of the device including the ear moulds could be done easily. A statistical analysis showed no age or gender correlation regarding this issue.

## **5.1.2 Consumer satisfaction**

### *5.1.2.1 Aspects of bilateral hearing aid listening*

The questions concerning aspects of bilateral hearing aid listening were constructed both to give a judgment of benefit of amplification and, if possible, to give a comparison between using one and two hearing aids. The comparison is justified since a majority (at least 64 %) had experience of both situations according to Table II. Even the rest of the bilateral users were assumed to have this experience when one HA temporarily was out of batteries or under repair.

The majority of the subjects experienced better speech recognition with two HAs and better localization abilities. They also judged the overall sound quality with two HAs as better than with one aid only. The sensation of naturalness of external sounds and the own voice were not affected by using two HAs.

Some subjects (4%) had HAs without volume control. Among the remaining participants, about half of the subjects (51%) did not have any difficulties to match the sensation levels in both ears by regulating the volume controls. 21% of the subjects had some and 12% had small difficulties regarding that issue, 12% had difficulties 'in a high' or a 'very high degree'. The social aspect of feeling more disabled with two HAs than with one could be a factor not to wear bilateral HAs. For 65% of the participants, this factor did not matter at all. Nevertheless, as much as 27% of all subjects experienced problems to accept two HAs because of this feeling. The results on this question were neither correlated to age, gender, nor PTA4F. The question about saving money by buying batteries for only one HA was answered with 'no, not at all' by 91% of the participants.

### *5.1.2.2 Classification of listening situations suited for bilateral amplification*

The participants were asked to explain in which situations they used bilateral amplification, and in which situations they preferred unilateral or no amplification at all. Figure 4 shows a ranking of situations when bilateral amplification was preferred. Most of the owners of bilateral HAs regarded it as very important to use bilateral amplification when attending a lecture. For the similar situation of being at the theatre almost as many used bilateral HAs. In these situations, apparently some of the persons normally using only one HA upgraded to two HAs, since the percentages are higher than 68 % (= amount of subjects using bilateral amplification most of the time). Even when conversating in smaller and in some degree also in bigger groups, some subjects did switch from unilateral amplification to bilateral HAs. In less complex listening situations, however, many participants switched from bilateral to unilateral amplification.

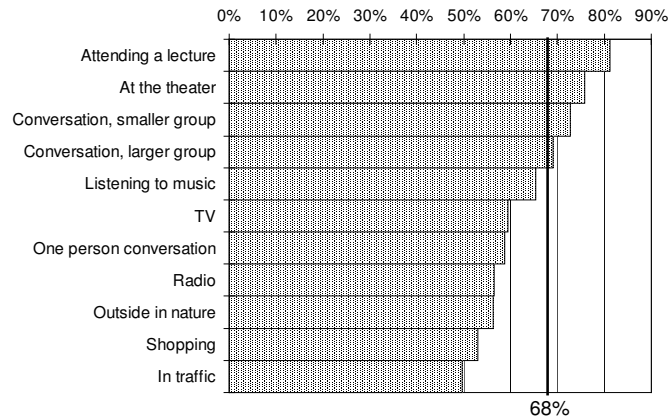


Figure 4. A ranking of different listening situations when two HAs are preferred (n=138).

### 5.1.2.3 HA processed signals in different environments

The following two sections about HA processed signals in different environments, and about localization, contain data for both users of bilateral and unilateral HAs. From now on, the original group of subjects was divided into two subgroups: the bilateral users group with 98 subjects and the unilateral users group with 86 subjects. The unilateral users group consisted of those subjects who had two hearing aids but used only one, and those who were fitted unilaterally from the beginning.

To get an impression about what the participants thought about the quality of HA processed signals in some of the situations mentioned in section 5.1.1.2.2, they were asked to classify the sound quality in terms of ‘very bad’, ‘bad’, ‘relatively bad’, ‘acceptable’, ‘relatively good’, ‘good’ and ‘very good’ for the following situations: listening to somebody when other persons are talking in the background, listening to radio and watching TV, and noticing the telephone signal.

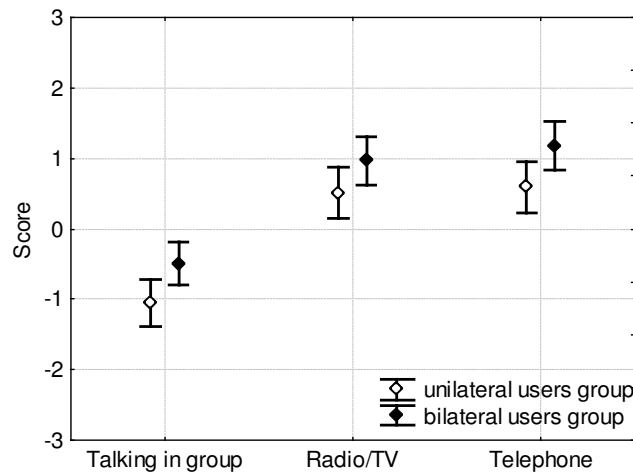
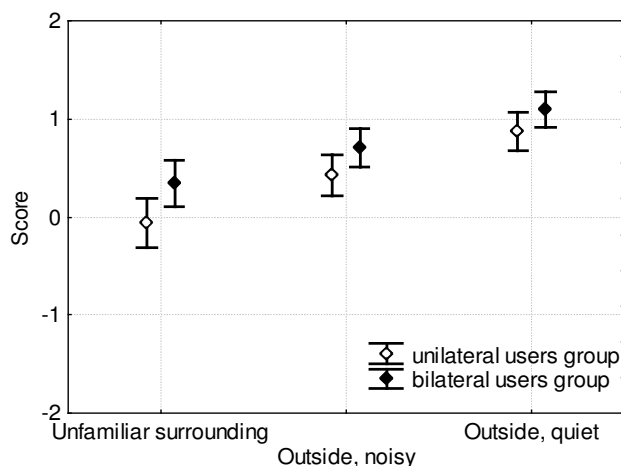


Figure 5. Sound quality of HA processed signals in three different listening situations: listening to somebody when other persons are talking in the background, listening to radio and watching TV, and noticing the telephone signal. “0” means “acceptable”. Open rectangles represent average scores for the unilateral users group, filled rectangles for the bilateral users group. Vertical bars denote 0.95 confidence intervals.

A well-known difficult communication situation is, to listen to somebody while other persons are talking in the background. Within the unilateral users group, 68 % of the subjects judged the sound quality in this situation as very bad to relatively bad. Within the bilateral group, 48% of the subjects shared this opinion. For statistical analysis, the categorical scale of the answers was transferred to a numerical scale with values between  $-3$  and  $+3$ . In paper III, we used t-tests for the statistical analysis of the questions. The more correct procedure would have been an analysis of variance (ANOVA) for repeated measurements. ANOVA for repeated measurements showed a significantly better result for the users of bilateral amplification ( $p < 0.01$ ). Figure 5 shows the average ratings for the both groups.

#### 5.1.2.4 Localization

The final part of the questionnaire gave information about the directional hearing of the subjects. The subjects were asked the following questions: ‘When you are in an unfamiliar surrounding, do you hear from which direction the telephone rings?’ ‘When you are on the street and someone talks to you unexpectedly, do you turn in the correct direction?’ and ‘When you are outside in quiet situations and someone talks to you unexpectedly, do you turn in the correct direction?’ Answering alternatives were ‘never’, ‘seldom’, ‘sometimes’, ‘often’, ‘always’. Also here, the categorical scale was transferred to a numerical scale ( $-2$  to  $+2$ ), and the original t-tests were substituted by a repeated measurements ANOVA. The analysis showed a significant difference in the ratings of the two groups for the mentioned questions ( $p < 0.05$ ). Figure 6 shows the average scores of these questions.



**Figure 6. Score for estimated localization ability in three different situations: localization of a telephone signal in unfamiliar environments, localization of signals while being on the street, and localization of signals while outside in quiet surroundings. Results are shown for bilateral/unilateral users. “0” means “sometimes”. Open rectangles represent average scores for the unilateral users group, filled rectangles for the bilateral users group. Vertical bars denote 0.95 confidence intervals.**

## 5.2 SPEECH PERCEPTION AND LOCALIZATION WITH TWO, ONE AND NO HEARING AIDS (PAPER II)

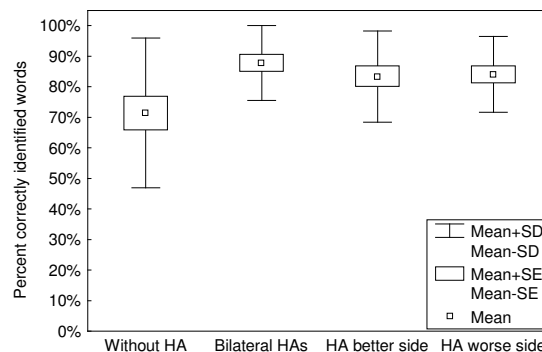
In this study, speech recognition in noise was measured as a percentage of correctly identified words. Each measurement was run with two lists of 10 sentences each - with 5 words in every sentence. Thus in each situation, unaided, bilaterally aided, unilaterally aided (better side), unilaterally aided (worse side), 100 words were used.

Horizontal localization was measured as the number of correctly identified loudspeakers presenting the speech signals. As every test situation consisted of two sentence lists with 10 sentences in each, and a localization decision was made for each sentence, 20 randomized loudspeaker locations were tested for each test situation.

Statistical analysis in paper II was conducted with nonparametric statistical methods, mainly Wilcoxon matched pairs tests. As this type of analysis is not totally applicable for this kind of tests, we present the results of the data analyzed with a repeated measurements ANOVA here.

### 5.2.1 Speech recognition in noise

In this study, the poorest speech recognition in noise was achieved without HAs (about 70%). With unilateral amplification, speech intelligibility improved by about 13 % and, with bilateral amplification by about 18 %. Both improvements were statistically significant according to an ANOVA for repeated measurements ( $p < 0.001$ ). Also, the difference between bilateral and unilateral amplification (calculated as average value for better and worse ear) was statistically significant ( $p < 0.05$ ). The results for speech recognition in noise are shown in figure 7.



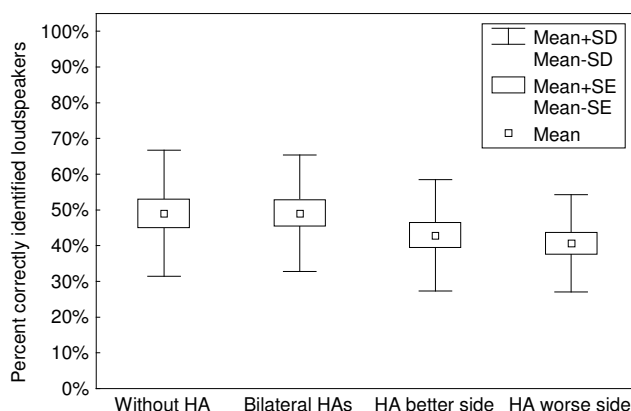
**Figure 7. Speech recognition in noise: percent correctly identified words in the unaided, bilaterally aided and unilaterally aided (better and worse ear) situations. Small rectangles indicate averages, boxes indicate average  $\pm$  standard error, vertical bars indicate averages, boxes indicate average  $\pm$  standard error, vertical bars indicate average  $\pm$  standard deviation.**

### 5.2.2 Horizontal localization

Both without HAs and with bilateral HAs, the subjects were able to correctly identify about 50% of the directions of the signals. With unilateral amplification, the subjects' horizontal localization abilities decreased by about 10%. A repeated measurements ANOVA for all four

listening conditions showed a tendency for a difference between the conditions ( $p=0.1$ ). A comparison between the bilaterally aided and the unilaterally aided (again calculated as average value for better and worse ear) showed a stronger tendency for different results ( $p=0.06$ ). Figure 8 shows the results for percentages of correctly or incorrectly identified sentence directions.

Generally, the poorest identification values were observed for loudspeakers #4, #5 and #6, covering the frontal direction in the test situation. Loudspeaker #4 was most often identified as #2, loudspeaker #5 as #1, and loudspeaker #6 as #8. This means, that the subjects had more difficulties to correctly identify front – back signals than right – left signals.



**Figure 8. Localization test: percent correctly identified loudspeakers in the unaided, bilaterally aided and unilaterally aided (better and worse ear) situations. Small rectangles indicate averages, boxes indicate average  $\pm$  standard error, vertical bars indicate average  $\pm$  standard deviation.**

### 5.3 MEASUREMENTS OF INDIVIDUAL BINAURAL PERFORMANCE, NORMAL-HEARING SUBJECTS (PAPER III)

The different tests used in this part of the study were measurement of hearing thresholds at frequencies 500 to 8000 Hz with fixed frequency Békésy technique, Hagerman's sentences with ipsilateral and bilateral masker (SM and FUM noise) in an adaptive measurement routine, dichotic tests (digits and CVs), and PMTF with ipsilateral and bilateral masker at 2 kHz and 4 kHz.

Hearing thresholds showed normal to almost normal values in the 14 subjects, with no statistical difference between men and women.

#### 5.3.1 Hagerman's sentences with ipsi- and bilateral masking

For both slightly and fully modulated masking noise, the signal-to-noise-ratio for 40 % recognition decreases by about 5 dB for bilateral masking compared with ipsilateral masking. In both cases, this difference is highly statistically significant ( $p<0.001$ ) according to a repeated measurements ANOVA. We did neither find a statistically significant learning effect between the two test lists, nor gender- or age related effects. There was no side difference (right-left) for this measurement.

Table III shows a summary of the results in terms of means, medians, upper and lower quartiles and standard deviation.

**Table III Results for Hagerman’s sentences with ipsilateral and bilateral masking noise in slightly (SM) and fully (FUM) modulated masking noise. The results are shown as S/N in dB for 40% speech recognition. The table contains values for mean, median, upper and lower quartile and standard deviation (SD).**

		Ipsilateral masker (S/N) <sub>ipsi</sub> , dB	Bilateral masker (S/N) <sub>bi</sub> , dB	Release of masking, dB (S/N) <sub>bi</sub> - (S/N) <sub>ipsi</sub>
Right ear, SM	Mean	-7.03	-12.07	-5.04
	Median	-7.08	-12.15	-5.05
	Upper quartile	-8.15	-13.60	-5.80
	Lower Quartile	-6.60	-11.45	-4.05
	SD	1.26	1.61	1.17
Left ear, SM	Mean	-7.12	-12.09	-4.97
	Median	-7.30	-12.30	-5.08
	Upper quartile	-7.85	-13.45	-5.75
	Lower Quartile	-6.80	-11.05	-4.45
	SD	0.98	1.59	1.11
Right ear, FUM	Mean	-16.61	-22.07	-5.46
	Median	-16.35	-21.85	-5.85
	Upper quartile	-18.20	-23.80	-6.30
	Lower Quartile	-15.60	-21.40	-4.60
	SD	1.52	1.75	1.24
Left ear, FUM	Mean	-16.54	-21.66	-5.12
	Median	-17.20	-22.10	-4.90
	Upper quartile	-17.60	-23.20	-6.00
	Lower Quartile	-15.90	-19.60	-4.30
	SD	1.44	1.86	1.04

The release of masking is about –5 dB for both ears and both noise types.

### 5.3.2 Psychoacoustical Modulation Transfer Function (PMTF) with ipsi- and bilateral noise

Generally, as shown in Lindblad & Hagerman (1999), the results for normal-hearing subjects use to show a characteristic level-dependant pattern for measurement with ipsilateral masking noise. Thresholds for the brief tone placed on the peak of the octave band noise show a maximum at midlevels. Placing the brief tone in the valleys of the modulated noise also uses to result in a maximum for the thresholds, most often shifted to some higher noise level compared to the peak-thresholds. Consequently, also the curve for the difference between peak-threshold and valley-threshold shows a maximum value. The same patterns are observed in the present study, see figure 9 below.

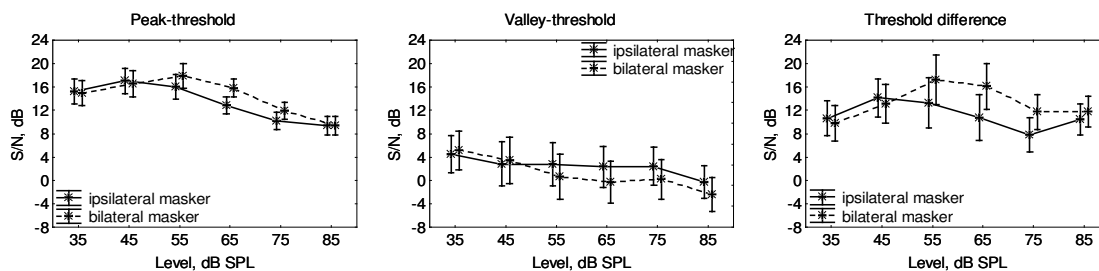
For both PMTF modes in this experiment (2000 Hz signal with 2.5 Hz modulated masker and 4000 Hz signal with 10 Hz modulated masker), there were tendencies for a gender difference with slightly better thresholds in the women for the thresholds with ipsilateral masker, statistically significant for the difference between peak- and valley-thresholds in the right ear at 2000 Hz and for the peak-thresholds in the left ear at 4000 Hz. No gender differences at all were found for thresholds with bilateral masker. In the case of stimulation at 2000 Hz, there was no correlation between thresholds and age. For stimulation at 4000 Hz with ipsilateral masker, some of the thresholds were correlated to age with higher thresholds for older subjects. Statistically significant were valley thresholds at 65 dB SPL and difference thresholds at 75 dB for the right ear, as well as peak thresholds at 85 dB SPL and valley thresholds at 65 and 85 dB SPL in the left ear. No differences between the ears were found.

The following results show how the characteristic patterns of the PMTF change, when the masker is applied bilaterally. As the within subject variances were not homogenous, all calculated p-values were corrected with Greenhouse-Geiser (G-G) and Huynh-Feldt (H-F) epsilon factors.

### 5.3.2.1 PMTF for short tones at 2000 Hz, 2.5 Hz modulated masker

Most of the differences between thresholds with ipsilateral and bilateral masker are noticed at levels above 55 dB SPL as shown in figure 9. The maximum of the curve seems to be shifted to slightly higher levels and peak-thresholds elevated. Valley-thresholds decrease and consequently, threshold differences increase.

#### Left ear



#### Right ear

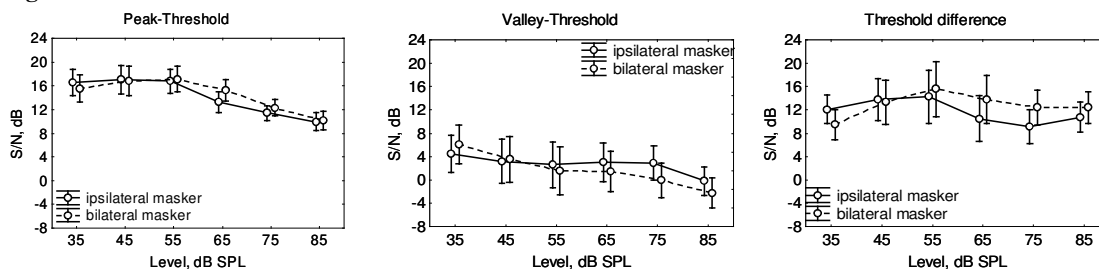


Figure 9. PMTF average results with stimulation at 2000 Hz, masker modulation 2.5 Hz. Results for the left ear (marked by crosses) in the upper part of the picture, for the right ear (marked by open circles) in the lower part. Thresholds with ipsilateral masker are indicated by the solid lines, with bilateral masker by dashed lines. Vertical bars denote 95% confidence intervals.

Statistically significant differences between measurements with ipsilateral and bilateral masker are shown for peak-thresholds ( $p < 0.05$  (G-G and H-F)) and threshold differences ( $p < 0.01$  (G-G, H-F)) in the left ear. In the right ear, only a strong tendency for different results during the different masking conditions can be observed (threshold difference:  $p = 0.09$  (G-G) and  $p = 0.08$  (H-F)).

Analysis of the maximum positions for the different threshold curves showed, that there was a statistically significant shift towards higher levels for the maximum peak-threshold in the right ear and for the maximum peak- and threshold differences in the left ear.

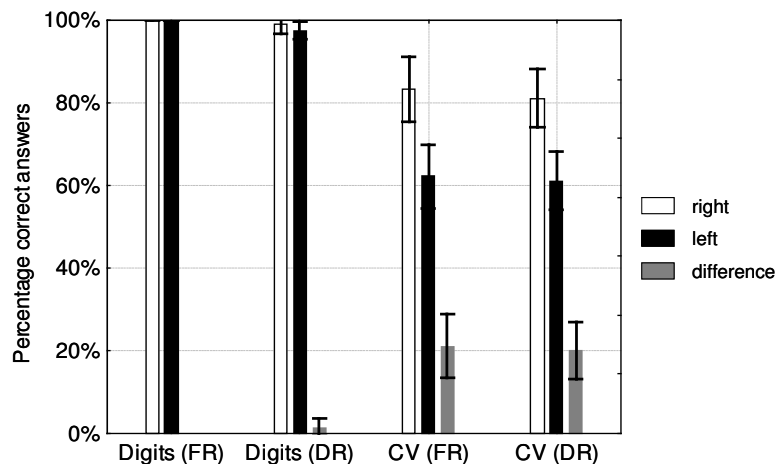
### 5.3.2.2 PMTF for short tones at 4000 Hz, 10 Hz modulated masker

Generally, the same tendencies for short tones at 4000 Hz, 10 Hz modulated masker as for stimulation at 2000 Hz with a 2.5 Hz modulated masker can be observed. Peak-threshold maxima are slightly shifted towards higher levels, valley-thresholds decreased and threshold difference increased with bilateral masker. Only the increased threshold differences in the left ear show statistically different results for ipsilateral and bilateral masking ( $p < 0.05$ , repeated measurements ANOVA).

### 5.3.3 Dichotic tests

As described in 'Methods', the dichotic task consisted of FR and DR of single digits (the Swedish words for 1, 2, 3, 5, 6 and 7) and consonant-vowel combinations, CVs (ba, pa, da, ta, ga and ka).

Figure 10 shows the obtained results in terms of mean and 95% confidence interval for digits and CV, FR and DR.



**Figure 10. Dichotic word-recognition in percent correct. Columns indicate mean values; vertical bars the 95% confidence interval for digits FR and DR and CV FR and DR. White columns denote right ear, black columns left ear, grey columns the difference between right and left ear. Vertical bars denote 95% confidence intervals.**



There was no correlation between the results of the dichotic tests and gender. All subjects had a 100% score for digits in the FR condition. Some of them had some single misses in the DR conditions. For the DR condition to the right within the digits test, the two subjects forming the oldest age group (60-65 years) showed significantly worse results than the rest of the group. The ceiling effect in the dichotic digits test was expected for normal-hearing subjects, but we nevertheless wanted to include the task, as this quite easy test might be important when testing hearing-impaired persons.

For the CV combinations, there was a clear right ear advantage (REA) for both FR and DR condition. The REA was of about the same magnitude for both conditions, which indicates normal cognitive function (Carter et al, 2001).

#### **5.4 BINAURAL PERFORMANCE OF SUCCESSFUL AND UNSUCCESSFUL USERS OF BILATERAL HEARING AIDS – DIFFERENCES AND SIMILARITIES (PAPER IV)**

The measurement methods described in paper IV were identical with those described before (paper III). Participants in this study were two groups of hearing-impaired persons. One group preferred bilateral hearing aids (bilateral amplification group), one preferred unilateral (unilateral amplification group). In this part of the study, we also measured the hearing aid gain of the participants' hearing aids. As a tool to correlate measurement results to the HA preferences, a questionnaire was used (SSQ).

##### **5.4.1 Hearing thresholds and hearing aid gain**

Hearing thresholds were measured at frequencies 500 to 8000 Hz.

The hearing thresholds were not correlated with gender for any of the two groups. The threshold at 6000 Hz at the left ear was significantly correlated to age. A repeated measurements ANOVA showed no statistically significant difference between the two groups for either of the ears and there was no statistically significant difference between the ears for any of the two groups.

Similar to the hearing thresholds, the hearing aid gain curves were not correlated to gender. Gain values at 6000 Hz for both left and right ear, and at 4000 Hz for the right ear were correlated to age with higher gain for older subjects. As all subjects were fitted bilaterally originally, both hearing aids for all subjects, except one, were included in the analysis. One subject in the unilateral amplification group did not bring his second hearing aid.

An analysis of variance showed a significant difference between the ears with slightly higher gain in the left ear ( $p < 0.05$ ). There was also a tendency for a gain difference between the groups ( $p = 0.06$ ). As an average, the gain is about 5 dB higher for the unilateral amplification group than for the bilateral amplification group.

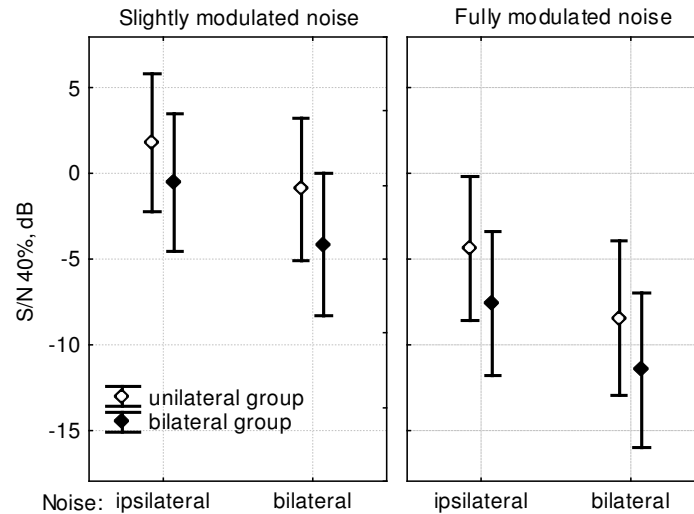
##### **5.4.2 Hagerman's sentences with ipsi- and bilateral masker**

Hagerman's sentences also here were measured for both SM and FUM background noise. The level for the background noise was individually established as slightly above the comfortable

level. The speech level was varied in order to find the signal-to-noise ratio corresponding to 40% speech perception.

The results were not correlated to gender, but to age. The older the subjects, the worse were the results for this speech-in-noise task. Figure 11 shows the results for the unilateral and the bilateral amplification group and ipsilateral and bilateral noise conditions.

Both groups showed significantly different results between the two modes of the test ( $p < 0.001$ ). There was also a tendency for different results between the two groups ( $p = 0.05$ ). For both noise conditions, SM and FUM, there was a tendency for different results between the groups by about 3 dB in SM-noise ( $p = 0.06$ ) and 3.9 dB in FUM-noise ( $p = 0.05$ ).



**Figure 11. Results for Hagerman's sentences as signal-to-noise ratio for 40% speech perception. Lower values represent better results. Results for slightly modulated background noise to the left, fully modulated noise to the right. Open rectangles represent the unilateral amplification group, filled rectangles the bilateral amplification group. Results are shown for both ipsilateral masker and bilateral masker. Vertical bars denote 95% confidence intervals.**

The obtained BMLD effect was about 2.7 dB for the unilateral amplification group and about 3.5 dB for the bilateral amplification group during the test with SM background noise. For the FUM background noise, the unilateral amplification group benefited with about 4.1 dB from bilateral noise and the bilateral amplification group with about 3.7 dB. The BMLD-values were not significantly different between the groups.

We did not find a significant difference between right and left ear, or a learning effect for any of the background noise types. The covariate 'age' was no statistically significant factor in the analysis.

### 5.4.3 Psychoacoustical Modulation Transfer Function, PMTF

The general results of the PMTF were not correlated to age and gender, except for some isolated measurement points. There was nevertheless an age correlation for the thresholds of the brief tone without noise. Analysis of variance with age as covariate showed no difference between the ears of the two subject groups for the threshold of the brief tone in quiet.

The important features of the PMTF are not necessarily the values of each measurement point, but the shapes of the threshold curves, as explained in 'Methods'. In the present study, the individual curves were measured at partly very different noise levels, depending on the individual hearing thresholds. Therefore, the curves were classified as curves with a maximum, that means demonstrating the nonlinearity of the cochlea, and curves without maxima. The most important curves for information on outer hair cell performance are those of the peak- and valley thresholds. For each person, we measured at two frequencies, both ears, each with ipsilateral and bilateral masker. Four subjects could not be measured at 4 kHz because of a very high threshold for the probe tone even without masker. In total, 320 curves for peak- and valley-thresholds were obtained. Only 110 of those showed a maximum, similarly distributed between the two amplification groups.

An alternative parameterization of the PMTF was to calculate the average value over the thresholds at all measured noise levels, as we expected slightly higher or unchanged averages for the peak-thresholds, lower averages for the valley-thresholds and consequently higher averages for the difference thresholds with bilateral masker than with ipsilateral masker (paper III). As the number of measured subjects was decreased by four persons due to their severe hearing impairment at 4 kHz, our analysis is restricted to the measurements with signals at 2 kHz with a 2.5 Hz modulated masker. Also this parameterization showed no statistically significant difference between the unilateral and the bilateral amplification groups, even if peak-threshold shifts are slightly higher and valley-threshold shifts slightly lower for the left ear in the bilateral group.

### 5.4.4 Dichotic tests

Both the dichotic digits and the CV test were conducted in a FR and a DR condition. In the DR condition, the subjects were instructed to just repeat the signals from one side and disregard the signals from the other.

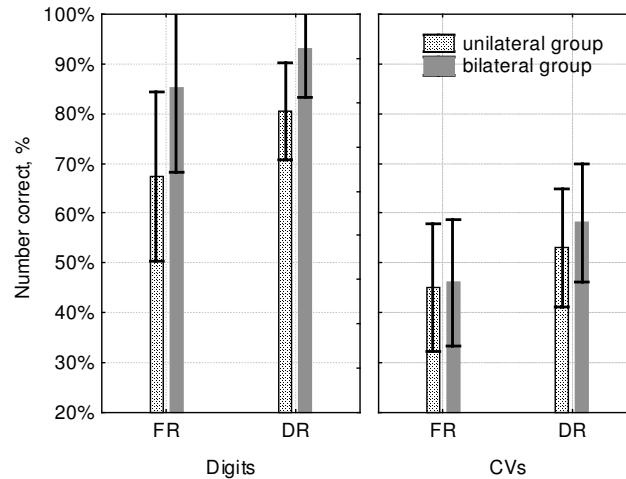
The results were not correlated to gender, but there was a correlation with age for all results involving the left ear with worse results for older subjects. Figure 12 shows the results for digits and CVs in FR and DR conditions.

The general analysis of variance showed only a tendency for different results of the two amplification groups ( $p=0.10$ ), and for an age effect ( $p=0.08$ ). Separate analyses for the digits test and the CVs were performed. To account for the obvious ceiling effects and to normalize the distribution in the digits test, the data was arcsine transformed according to (Studebaker, 1985).

The digits test showed no impact of age. The results of the two amplification groups were significantly different ( $p<0.05$ ) with the better results for the bilateral amplification group. PostHoc tests showed significantly different results between FR and DR only for the left ear of the unilateral amplification group ( $p<0.05$ ) and a tendency for the right ( $p=0.09$ ). For the

bilateral amplification group, there was a tendency for different FR and DR results for the left ear ( $p=0.06$ ). We did not find a significant ear effect, i.e. REA for the dichotic digits test.

For the dichotic CV test, we found a significant effect of age ( $p<0.05$ ). PostHoc tests showed a significant difference between FR and DR for the bilateral amplification group, left ear ( $p<0.05$ ) and a tendency for different results in FR and DR mode for the unilateral amplification group, right ear ( $p=0.08$ ). PostHoc tests also revealed substantial REAs for both groups within the dichotic CV test.



**Figure 12.** Dichotic test results for digits and CV during FR and DR conditions. Dotted columns represent the unilateral amplification group, grey columns the bilateral amplification group. The columns represent average values for both ears. Vertical bars denote 95% confidence intervals.

#### 5.4.5 Speech, Spatial and Quality of Hearing Scale, SSQ

There were no correlations with age or gender for the results of the SSQ. The participants of the study answered the questionnaire for the situations ‘unaided listening’ and ‘aided listening’. Some of the questions for both situations were strongly correlated to the preference for one or two hearing aids. For the unaided listening situation, only questions within the ‘spatial’ section of the questionnaire showed a significant correlation with preference for one or two hearing aids. From the seventeen questions in this section, five were significantly correlated to HA-preference: to locate a speaker round a table, to locate a door slam in an unfamiliar house, to locate above or below on a stairwell, to locate a dog barking and to locate a vehicle from the footpath. Persons preferring bilateral hearing aids judged their localization abilities as better than persons preferring unilateral amplification.

The correlation between preference for one or two hearing aids and the above mentioned questions in the ‘spatial’ section of the questionnaire was consistent also when the subjects rated their abilities in the aided listening situation for the above questions except the question on locating a speaker round a table. Three further questions from this section (about locating a lawnmower, if sounds sound closer than expected, and if sounds occur in the expected location) were correlated with preference for unilateral/bilateral amplification. Besides, even some questions from the ‘speech’ section showed a similar correlation: talking with five people in noise with and without vision, conversating in an echoic environment and ignoring interfering voices of the same pitch.

## 6 DISCUSSION

### 6.1 EFFECTS AND CONSEQUENCES OF BILATERAL HEARING AIDS FROM A USER PERSPECTIVE (PAPER I)

The test group in this study was selected randomly from a patient register of an audiological clinic in Stockholm, and can be regarded as representative for an urban population. It has been shown that if the rejection rate of a questionnaire of HA use is 25-37%, many of the non-responders are likely to be non-users of HAs (Stephens, 1977), and the result of the questionnaire therefore could be biased to give a too favorable impression of HA utility. The present non-response rate of 21% is relatively low, and the study group can therefore be considered as representative for adult bilateral HA users.

However, the non-response rate for the group of persons fitted with a unilateral HA was 26%. Thus, the non-response rate is close to the above-mentioned border for representative study groups. Together with the fact, that the hearing threshold levels for these unilaterally fitted subjects were generally about 10 dB better than those of the bilateral group (see section 'Subjects'), the results of the questionnaire for the unilateral group might indicate a slightly too positive judgment of their hearing abilities in comparison with the original group of subjects. Those persons were pooled together with a sub-group of the original group preferring to use only one HA, forming a 'unilateral user group'. Thus, the 'unilateral user group' might also be biased towards slightly too positive results.

A striking finding of the study was the high frequency of reported use of HA amplification in the bilateral fitted group of subjects: 3/4 of the participants used their HAs daily. It can be speculated if the study group with two HAs represent a "crème de la crème" of HA users, caused by a selection process related to the fact that bilateral HA prescription was relatively rare in Sweden at the time of the study.

As already mentioned in the introduction, there are reports, that bilateral amplification is not the best option for some individuals (Schreurs & Olsen, 1985; Chmiel et al, 1997; Carter et al, 2001). Also in our study, one third of the population rejected bilateral amplification. It has been suggested, that subjects with comparatively poor hearing benefit more from two HAs than subjects with less pronounced hearing loss (Stephens et al, 1991; Byrne et al, 1992). However, we could not find a PTA4F difference between users of bilateral and unilateral amplification within the group of bilaterally fitted subjects. Also asymmetry of hearing thresholds could be a reason not to recommend bilateral amplification (Brooks & Bulmer, 1981; McKenzie & Rice, 1990), but a comparison of ear asymmetry in the present study group for those using two or one HA respectively gave no reason to suspect a higher asymmetry in either of the groups. Thus, we could not find an audiometric explanation for the rejection of bilateral amplification in these subjects.

A majority of bilaterally fitted persons in this study also became bilateral users with time. A time-consuming acclimatization program suggested by Jordan et al (1967) and Vaughan-Jones et al (1993) seems to be unnecessary according to the results presented here. However, a long-term follow-up could identify persons ultimately rejecting bilateral HAs.

Bilateral amplification was most appreciated by the participants in the study in listening situations with high demands. Such situations were attending lectures or theatre performances, in

which 75-80% preferred two HAs. In different communication situations like conversation in groups, bilateral HAs were highly appreciated (approximately 70%). In situations with less demand on communication, still about half of the participants preferred two aids. Accordingly, a majority of the participants preferred two HAs in noisy conditions. This finding supports a result by Erdman & Sedge (1981), but is inconsistent with studies by Dirks & Carhart (1962), Byrne (1981) and Schreurs & Olsen (1985).

A very important aspect of HA amplification is the question of localization ability, since the previous studies in this field are inconsistent. Another reason for the interest we put in this aspect is the fact, that most hearing aid fitting procedures do not take localization into account.

The bilateral users in this study experienced better sound localization abilities than the unilateral users even in a noisy condition such as 'being on the street'. Our conclusion is, that bilateral amplification seems to be superior to unilateral for orientation purposes.

## **6.2 SPEECH PERCEPTION AND LOCALIZATION WITH TWO, ONE AND NO HEARING AIDS (PAPER II)**

The results of the speech recognition test in this study show an improvement in speech recognition when the subjects were using HA amplification. Bilateral amplification resulted in a greater improvement than unilateral amplification. This finding agrees with earlier studies by e.g. Day et al (1988), McKenzie & Rice (1990) and Feuerstein (1992).

Regarding horizontal localization, earlier studies have shown that sound localization is affected by hearing impairment (e.g. Häusler et al, 1983; Noble et al, 1994; Slattery & Middlebrooks, 1994; Rakerd et al, 1998). According to the present study, horizontal localization is further compromised by introducing unilateral HA amplification, since the ability to localize a sound source was poorer with one HA than without any amplification at all. For the subjects in this study, bilateral amplification restored the horizontal localization, but did not (in contrast to a study by Rakerd et al, 1998) improve this function beyond the unaided level. As the signals in our experimental set-up were presented at favorable S/N ratios and at relatively high levels, it is understandable that bilateral amplification cannot, or only to some degree, improve the function of horizontal localization.

Front-back estimations revealed that errors were common in this situation. Sound sources presented in the loudspeakers in front of the participants were often erroneously identified as coming from the corresponding back position. To correctly identify the position of a sound target in the front – back situation, similarly to achieving sound localization in the vertical plane, the pinna effect is very important, as mentioned in Chapter 1. This effect involves high frequency sound cues; in contrast to binaural horizontal directional hearing which is based on the head shadow effect and low frequency spectral cues. Since a majority of our subjects had high frequency hearing loss, it is understandable that the pinna effect was deficient in the unaided condition. Especially when using behind-the-ear HAs, as the majority of the subjects in this study, the placement of the microphone outside the concha affects the pinna effect. Plugging the concha and the external ear canal with HA(s) and earmolds, can lead to a distortion of low-frequency interaural time and phase differences leading to decreased localization abilities in the horizontal plane for hearing-impaired persons (Byrne et al, 1996; Noble et al, 1998). All

the subjects with behind-the-ear hearing aids in this study had closed earmolds, which could partly explain the lack of improvement in horizontal localization with hearing aids.

In this study, we worked with subjects more familiar with bilateral than unilateral amplification. The results for naïve HA-users or a comparison between experienced bilateral HA users and experienced users of unilateral amplification might have differed from our results. Nevertheless, as already mentioned above, the measurements were conducted at a favorable S/N ratio and at a relatively high level, which should give them binaural hearing also in the unilaterally aided condition. Both for speech intelligibility and horizontal localization, bilateral HA amplification seems to be favorable for hearing-impaired persons. Measurements with bilateral HA amplification resulted in better scores in both the speech intelligibility test and the horizontal localization test and therefore this study supports a general bilateral HA fitting strategy.

### **6.3 MEASUREMENTS OF INDIVIDUAL BINAURAL PERFORMANCE, NORMAL-HEARING SUBJECTS (PAPER III)**

Paper III describes the development of methods to measure individual binaural abilities for both peripheral and central auditory functions. We gathered several tasks measuring the mentioned functions, and evaluated the test battery with normal-hearing subjects. All the methods per se have been used in research and/or clinical routine and the binaural complements we included should not change the reliability of the tests.

Of course, the result of the evaluation might have been clearer, if more subjects had been involved, especially in the case of the PMTF, a measure often showing strong individual variability (Lindblad & Hagerman, 1999). Nevertheless, we found good evidence for both speech-in-noise and PMTF to give an effect of bilateral masking conditions compared to ipsilateral ones. The dichotic tests showed results as expected with normal-hearing subjects (Hällgren et al, 1998).

For both speech-in-noise and PMTF, we chose to present the speech signal monaurally only. The reason for this decision was to ensure a spatially well-defined signal, as it has become apparent that localization issues are crucial when examining benefits of bilateral hearing aids, as planned as the next part of this study (paper IV). This has been shown before (e.g. Noble & Gatehouse, 2006; Van den Bogaert et al, 2006). For this condition, there is hardly any literature to compare our results with, as all studies use bilateral presentation of the signals when evaluating binaural release of masking. For monaural stimuli with tonal target signals, the BMLD is expected to be somewhat lower than with a binaural stimulus (Moore, 2003), and we expected the results of the more complex stimuli used in the present study to follow this trend. Compared to former studies with sentences or spondaic words (Bocca & Antonelli, 1976; Johansson & Arlinger, 2002), the BMLD results in our study are about 1 to 2.5 dB lower. The BMLDs for both SM and FUM noise in the present study encourage further studies, especially with hearing-impaired subjects.

The results of the PMTF with ipsilateral masker were in accordance with the Lindblad & Hagerman (1999) study. Age effects at a stimulus frequency of 4000 Hz were also expected, as the peripheral hearing in this frequency region might be slightly worse for the older subjects. We cannot explain, why gender effects occurred within the ipsilateral but not the bilateral masker situation of the PMTF. In this respect, more subjects would be needed, especially as the important feature of the PMTF is related to the shape of the threshold curves rather than to

absolute threshold levels (Lindblad & Hagerman, 1999). The PMTF results might therefore have to be interpreted in terms of general parameters in future studies with hearing-impaired subjects. Suitable parameters can be shifts of curve maxima under bilateral masking conditions compared with ipsilateral or increasing/decreasing average values of the threshold curves under the different masking conditions.

The principle and the results of the PMTF can be compared to intensity discrimination studies on the “severe departure” from Weber’s Law and the “mid-level hump” (Carlyon & Moore, 1986; Zeng, 1998; Nizami et al, 2002). Generally, these experiments show level dependant threshold curves for short signals in simultaneous and temporary shifted masking conditions. The effect is especially interesting, as it is speculated how much of the effect is related to peripheral hearing and how much on central auditory functions (Zeng, 1998). When applying the tests on hearing-impaired persons in order to evaluate benefit of unilateral or bilateral amplification, both functions are important observables.

The dichotic digits test showed clear ceiling effects, which was expected and is in accordance to Noffsinger et al (1994), Hällgren et al (1998) and Mukari et al (2006). The two oldest subjects showed a somewhat decreased performance for the DR right condition. This might be interpreted as an age effect in accordance to the results by Jerger et al (1994), who showed decreasing performance for subjects from age 60. As these two subjects showed better results in the FR condition than in the DR condition, the deficit can be interpreted as mainly an auditory problem and not a cognitive one (Carter et al, 2001). Nevertheless, this single digits test was obviously quite easy for normal-hearing subjects with normal cognitive function. However, as speech perception is correlated to both hearing impairment (e.g. Hagerman, 1984; Moore, 1996), and cognitive performance (e.g. Lunner, 2003), we find it important to proceed with the dichotic digits test in ongoing studies on the benefit of hearing aids.

Similarly to the dichotic digits test, the results for the dichotic CV test were not surprising. The results for both FR and DR were very similar to the results of the Hällgren et al (1998) study, at least in the left ear. The results for the right ear in the present study were slightly better, resulting in a bigger REA, in the present study. In the Hällgren et al (1998) study, the stimuli were presented at a level of 60 dB SPL (C-weighted equivalent level), in the present study at 70 dB SPL re 20  $\mu$ Pa. It can be speculated if this higher level might have enhanced the REA. As this test turned out to be demanding for the normal-hearing subjects, it’s applicability to test hearing-impaired subjects is to be proven.

#### **6.4 BINAURAL PERFORMANCE OF SUCCESSFUL AND UNSUCCESSFUL USERS OF BILATERAL HEARING AIDS – DIFFERENCES AND SIMILARITIES (PAPER IV)**

The goal of the present study was to examine two groups of bilaterally hearing-impaired persons, who were initially fitted with bilateral hearing aids and who had developed a preference for one or two hearing aids. Each group consisted of 11 persons. The hypothesis was, that measurement results and answers to relevant questionnaires would differ between persons preferring two hearing aids and persons preferring one.

Measurements included both an examination of presumably mainly peripheral functions by means of hearing thresholds and PMTF, and mainly central auditory functions as well as cognitive abilities by means of speech-in-noise and dichotic tests. We took a closer look on the



gain provided by the participants' hearing aids and completed the test battery with a questionnaire. The significant differences between the results in psychoacoustical measurements of the two groups regarded mainly speech-in-noise and dichotic tests. There were some correlations between HA preference and aspects of spatial listening in the questionnaire. There were no significant differences in hearing thresholds and PMTF.

The unilateral amplification group was provided with slightly higher gain in their HAs. Even if this difference, also after a comparison with the NAL-formula (Byrne & Cotton, 1988), was not statistically significant, it might contribute to a rejection of bilateral hearing aids. There is evidence, that hearing aid users prefer less than normal loudness with aided listening (Smeds, 2004; Smeds et al, 2006). Because of binaural loudness summation, two hearing aids might provide the user with too much overall loudness.

Although the number of subjects in the present study is small, the general results show clear differences and similarities between auditory and cognitive performance of unsuccessful and successful users of bilateral hearing aids. In some points, differences between the groups might have been clearer with more subjects, e.g. regarding the speech-in-noise test, and the PMTF measurements.

It has been shown earlier, that speech recognition in noise is a task involving the efferent auditory system (Giraud et al, 1997; Kumar & Vanaja, 2004; Kim et al, 2006). Thus it requires a combination of peripheral auditory function, as the OHCs have to be able to react on the signals from the efferent system (the brain), as well as good central auditory functions. In former studies, speech-in-noise measurements were primarily used to investigate the effects of bilateral versus unilateral hearing aid amplification and not in a diagnostic approach (Festen & Plomp, 1986; paper II; Hällgren et al, 2005; Walden & Walden, 2005). In the case report by Chmiel et al (1997), speech-in-noise in terms of a cued listening task (Jerger & Jordan, 1992) is used in a more diagnostic approach, similar to the present study. The subject described in the case report showed better results for the right ear in unfavorable signal-to-noise conditions. Also the subjects performing better with unilateral amplification in speech-in-noise in the Walden & Walden (2005) study, showed a strong advantage for the right ear in this task. In our study, none of the two groups (preferring bilateral or unilateral hearing aids) showed a difference between the ears for the speech-in-noise test. However, the average S/N for 40% correct reported words was three to four dB worse in the unilateral amplification group than in the bilateral amplification group. This result was almost statistically significant ( $p=0.06$ , SM noise;  $p=0.05$ , FUM noise). Obviously, speech signals in noise were processed better for the group of persons preferring bilateral hearing aids.

In the speech-in-noise task, both groups showed release of masking when the ipsilaterally masked measurement was compared with the bilaterally masked one. For normal-hearing subjects in this task, a BMLD of about 5 dB can be expected (paper III). The BMLD results for hearing-impaired persons are typically worse (Jerger et al, 1984) and have also been reported to be related to more central auditory dysfunctions (e.g. Olsen & Noffsinger, 1976). The BMLD for both groups in the present study was 3-4 dB, with no significant difference between the groups. Thus, the obtained results are in accordance with the earlier studies cited, but the BMLD effect does not seem suitable to explain individual preferences for one or two hearing aids.

For the dichotic tests, Hällgren et al (1998) showed in an earlier study that normal-hearing subjects achieved scores near 100% for the digits and 65-80% for the CVs with a significant REA of 10-15% for the test material also used in the present study. Former studies also showed,

that older adults with symmetrical hearing losses obtained worse results in dichotic tests, mainly manifested as a bigger REA, which appears to be more related to cognitive function and age than to hearing sensitivity (Jerger et al, 1994; Humes, 2005; Roup et al, 2006). Studies on unsuccessful users of bilateral hearing aids have demonstrated the same performance in both ears in dichotic test situations (Walden & Walden, 2005), as well as substantial REAs with normal to almost normal function in the right ear and substantial deficits in the left ear (Chmiel et al, 1997; Carter et al, 2001). In the present study, the total number of correctly identified signals was reduced for both amplification groups compared to normal-hearing subjects (paper III), despite presentation at the most comfortable level. We found REA in both groups only for the CV test, which is in accordance with Hällgren et al (1998). The most striking result in our study was the big difference between the amplification groups concerning the dichotic digits test. As the test consists of single digits, this test is considered as quite easy, which is also demonstrated by the ceiling effects on this task for normal-hearing subjects (Hällgren et al, 1998; paper III; Mukari et al, 2006). The bilateral amplification group scored much better than the unilateral amplification group in this test, both during FR and DR conditions. For the digits test, only the unilateral amplification group showed a substantial difference between FR and DR conditions with better results during DR especially for the left ear. Compared to normal-hearing subjects, the unilateral amplification group showed significantly worse results in both the FR and the DR condition (Hällgren et al, 1998; paper III). This indicates, that the deficit of binaural processing in this group should rather be correlated to auditory factors, than cognitive ones (Carter et al, 2001), even if the substantial difference between the results during FR and DR also could indicate a slightly worse cognitive function. We therefore suggest, that this group might have a declined function of the corpus callosum. The corpus callosum has been shown to influence dichotic performance of the stimulus-driven component of the signals, favoring the input to the right ear. But there is also an influence of the corpus callosum on the attentional effect allowing to primarily process signals from the left ear in the DR-left condition (e.g. Clarke et al, 1993; Westerhausen et al, 2006). Problems in interhemispheric transfer could also partly explain the worse speech recognition in noise for the unilateral amplification group. Symmetrical general degeneration of the central auditory system can, however, not be excluded as a possible causative factor for the differences in auditory performance of the two groups studied.

As already mentioned, investigations of advantages and disadvantages with bilateral and unilateral hearing aid amplification most often measured the effect of the different fitting strategies (see Noble, 2006, for a summary). The present study used the SSQ as a tool to find aspects of listening situations, where users who prefer unilateral and users who prefer bilateral amplification differ. We were looking for questions with a significant correlation between score and amplification preference. We consider the scores for 'listening unaided' as the more important part of the results of the SSQ in this study, as those could work as a predictor for the chances to succeed with bilateral amplification. The only five questions, showing a significant correlation with amplification preference under the condition 'listening unaided', were found within the 'spatial' domain of the SSQ. This is in accordance with Noble & Gatehouse (2006) and Gatehouse & Akeroyd (2006), who found the strongest correlations between benefit of bilateral amplification/binaural processing and subjective scores of the SSQ within this domain.

To summarize, the obtained results show differences between successful and unsuccessful users of bilateral hearing aids manifested in both cognitive, central auditory, and possibly also peripheral auditory function. This is manifested in better speech-in-noise results, better results in the dichotic digits task as well as better subjective abilities in spatial listening for the group

preferring two hearing aids. However, we cannot totally exclude worse peripheral auditory functions in the unilateral amplification group.

The technical equipment is of course of utmost importance for a hearing-impaired person. In the present study, we tried to exclude test subjects with more practical issues such as occlusion and irritation in ear canals as reasons to reject bilateral hearing aids. Another reason for the rejection might be binaural loudness summation. Not all clinically used fitting software seems to include the option to choose bilateral or unilateral fitting routines. A bilateral fitting might then result in too much overall amplification as discussed before.

However, most of the results in the present study suggest, that unsuccessful users of bilateral amplification have degraded function of central auditory pathways. Peripheral hearing and slightly too high hearing aid amplification might contribute to a minor degree to problems using two hearing aids for those individuals.

## 7 CONCLUSIONS AND OUTLOOK

As shown in paper I, the majority of hearing-impaired persons who are provided with bilateral HAs also use them to a high degree. There was no audiometric explanation, why one third of the population rejected bilateral HAs. Bilateral amplification was appreciated especially for recognising speech, for sound localisation and for superior sound quality. The most appreciated situations when two HAs were preferred were when attending lectures and theatre performances and for communication in smaller and larger groups of persons. The ability of sound localisation seems to be improved by two HAs compared to one HA only.

The study described in paper II showed that speech recognition in noise was improved by using one HA and an even greater improvement was achieved with bilateral HAs. Horizontal localization could not be improved by hearing aid amplification. However, bilateral amplification preserved the subjects' horizontal localization abilities, whereas unilateral amplification decreased the subjects' ability of aural orientation.

The test battery to measure binaural performance described in paper III was evaluated with normal-hearing subjects and showed feasibility for the purpose of measuring binaural performance.

In the final step of this work (paper IV), the measurement methods developed in paper III were used for two groups of symmetrically hearing-impaired persons. All of the participants had initially been fitted with bilateral HAs. Persons preferring only one HA formed one group, those preferring to use both formed another group. The preference of the unilateral amplification group was based on hearing related problems, with unspecific explanations from the subjects.

According to the results obtained, we assume a dysfunction of central auditory pathways and possibly also in peripheral auditory function in the group preferring one HA, since there were substantial differences in performance for the two groups for speech-in-noise and an easy dichotic digits test. A disadvantage in spatial abilities for the unilateral amplification group when listening unaided was revealed by the answers to the SSQ questionnaire. This also indicates worse binaural central auditory processing abilities in the unilateral amplification group. However, slight contributions to the result from worse inner ear function as well as slightly too high hearing aid amplification for the unilateral amplification group cannot be excluded.

Interestingly, using BMLD-modifications of the psychoacoustical tests did not result in a difference between the two groups. Already clinically used speech-in-noise tests and a simple dichotic digits test should improve the diagnostic scheme for persons unsuccessfully fitted with bilateral HAs.

Our suggestion for future rehabilitation plans for bilaterally hearing-impaired persons in a shorter perspective would be to offer to try two hearing aids, as most symmetrically hearing-impaired persons seem to benefit from binaural amplification. The results of the study indicate, that it might be an advantage to include questions on spatial abilities in interviews with presumable first-time hearing aid users, to include a simple dichotic digits test in the diagnostic test battery, and to be attentive to abnormally bad performance in speech-in-noise tests. In case of an unsuccessful initial bilateral fitting, the results of these tests can be used to possibly change to a unilateral fitting.

In a longer perspective, future research should aim to further improve the diagnostic possibilities before rehabilitation with HAs. A goal has to be to find reliable measures to predict a successful or unsuccessful bilateral fitting without starting rehabilitation with bilateral amplification. Speech-in-noise and dichotic tests have shown to be useful tools in this respect. Special concern has to be put on the fitting of the hearing aids. Here, better methods for a bilateral fitting instead of two independent unilateral ones have to be developed. Instead of questionnaires, focus groups (“group interviews”) could be used to find a better understanding of problems that the hearing-impaired persons encounter in real-life listening situations.

The present study showed, that there might be a correlation between speech-in-noise tasks, cognition and spatial listening on the one hand as well as these three factors and the ability to benefit from bilaterally HA processed signals on the other. Further basic research is necessary to understand those connections.

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