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Hearing and cognition in speech comprehension

Methods and applications

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HEARING AND COGNITION IN SPEECH COMPREHENSION
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To Karoline, Ida and Moa

Abstract

Central auditory processing is complex and can not be evaluated by a single method. This thesis focuses on assessment of some aspects of central auditory functions by the use of dichotic speech tests and cognitive tests that tax functions important for speech processing.

Paper A deals with the cognitive effects in dichotic speech testing in elderly hearing-impaired subjects. It was found that different listening tasks in the dichotic tests put different demands on cognitive ability, shown by a varying degree of correlation between cognitive functions and dichotic test parameters. Age-related cognitive decline was strongly connected with problems to perceive stimuli presented to the left ear.

Paper B presents a new cognitive test battery sensitive for functions important for speech processing and understanding, performed in text, auditory and audiovisual modalities. The test battery was evaluated in four groups, differing in age and hearing status, and has proven to be useful in assessing the relative contribution of different input-modalities and the effect of age, hearing-impairment and visual contribution on functions important for speech processing.

In Paper C the test battery developed in Paper B was used to study listening situations with different kinds of background noise. Interfering noise at +10 dB signal-to-noise ratio has significant negative effects on performance in speech processing tasks and on the effort perceived. Hearing-impaired subjects showed poorer results in noise with temporal variations, and elderly subjects were more distracted by noise with temporal variations, especially by noise with meaningful content. In noise, all subjects, particularly those with impaired hearing, were more dependent upon visual cues than in the quiet condition.

Hearing aid benefit in speech processing with and without background noise was studied in Paper D. The test battery developed in Paper B was used together with a standard measure of speech recognition. With hearing aids, speech recognition was improved in the background condition without noise and in the background condition of ordinary speech. Significantly less effort was perceived in the cognitive tests when hearing aids were used, although only minor benefits of hearing aid amplification were seen. This underlines the importance of considering perceived effort as a dimension when evaluating hearing aid benefit, in further research as well as in clinical practice.

The results from the studies contribute to the knowledge about speech processing but also to the search for more specific evaluation of speech understanding, incorporating both sensory and cognitive factors.

Original articles

This thesis is based on the following papers which will be referred to as Paper A, B, C and D in the text.

- A. Hällgren, M., Larsby, B., Lyxell, B. & Arlinger, S. 2001. Cognitive effects in dichotic speech testing in elderly persons. *Ear & Hearing*, 22:120-129.
- B. Hällgren, M., Larsby, B., Lyxell, B. & Arlinger, S. 2001. Evaluation of a cognitive test battery in young and elderly normal-hearing and hearing-impaired persons. *Journal of the American Academy of Audiology*, 12:357-370.
- C. Larsby, B., Hällgren, M., Lyxell, B. & Arlinger, S. 2005. Cognitive performance and perceived effort in speech processing tasks: effects of different noise backgrounds in normals and in hearing-impaired subjects. Accepted for publication in *International Journal of Audiology*.
- D. Hällgren, M., Larsby, B., Lyxell, B. & Arlinger, S. 2005. Speech understanding in quiet and noise, with and without hearing aids. Accepted for publication in *International Journal of Audiology*.

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Chapter 1

Introduction

Every oral communication is dependent on information being correctly received and understood. Detection of isolated acoustic sounds or words, integration of sounds, words and sentences into meaningful units are included in this speech understanding process. This involves the peripheral sense organ as well as central auditory pathways and cognitive functions such as working memory capacity, selective attention and speed of information processing. If the acoustic signal is limited or distorted because of a hearing impairment or because of distracting signals, noise, from the environment, many people have problems with communication. These speech understanding problems become even more pronounced in the elderly (CHABA (Committee on Hearing Bioacoustics and Biomechanics), 1988; Pichora-Fuller, 1997). The mechanism behind this is related to limited and distorted auditory information, but also to a decline in cognitive functioning. It has been suggested that the extra problems in the elderly are caused by age-related changes in cognitive functions in general (Birren and Fisher, 1995). Further, it has been suggested that aging also occurs in central pathways specific for hearing in the brainstem and the auditory cortex (Humes, 1996). Central auditory functions are complex and not known in detail. However, it is well known that elderly subjects with disorders in central auditory processing rate themselves as significantly more handicapped than those without such disorders (Jerger et al, 1990), and they also have difficulties to make use of amplification in hearing aids (Chmiel & Jerger, 1996).

Due to the complexity of central auditory functions, there is no single measurement available which completely describes these functions. Nevertheless, different kinds of tests, ranging from electrophysiological measurements (e.g. Larsby et al, 2000) to behavioral measurement of cognitive

abilities, can give different aspects and angles of approach and together contribute to the understanding of these functions (Musiek, 1999). In this thesis different kinds of procedures for the measurement of central auditory function are described and evaluated.

Dichotic speech tests have been widely used for evaluation of central auditory functions, for both research and clinical purposes (Musiek & Lamb, 1994; Mueller & Bright, 1994; Willeford & Burleigh, 1994). However, most material has been in English and experiences with dichotic speech tests in Swedish have been limited. A Swedish test battery was therefore developed (Hällgren et al, 1998) and evaluated. The test was used in Paper A to investigate the effects of cognition and age on dichotic speech listening.

Cognitive tests which tap functions important for speech processing have mainly been performed in the text modality, e.g. the cognitive test battery used in Paper A, which is a limitation (Rönnberg et al, 2000). To obtain a more complete picture of a person's cognitive abilities in relation to speech understanding processes, auditory and audiovisual versions have been added to the text version in a battery called SVIPS (Speech and Visual Information Processing System). The SVIPS battery has provided new possibilities to study the relative contribution of different input signals and the effect of for example age, hearing impairment and visual contribution on functions important for speech processing (Paper B).

In many situations in today's society we are exposed to a variety of sounds which make communication more difficult. Previous studies have shown that speech understanding in noise is affected by the characteristics of the background noise (Bronkhorst & Plomp, 1992; Gustafsson & Arlinger, 1994; Bacon et al, 1998) as well as by peripheral hearing (e.g. Festen & Plomp, 1990; Hygge et al, 1992) and cognitive ability (Gatehouse et al, 2003; Lunner, 2003). In Paper C the cognitive test battery developed in Paper B (SVIPS) was used to study effects of different kind of background noises on speech understanding processes in hearing-impaired and elderly subjects.

It is a well known fact that the use of amplification (hearing aids) improves speech recognition in situations without background noise. In noise, however, there are both reports of benefit (Haskell et al, 2002; Larson et al, 2002; Shanks et al, 2002; Alcantara et al, 2003) as well as of no benefit (e.g. Gustafsson & Arlinger, 1994) of hearing aid use in speech processing tasks. In Paper D the effects of hearing aid use on speech recognition and speech understanding processes (SVIPS) were evaluated, in silence and in background noise.

When the signal-to-noise ratio becomes unfavorable and the processing goes from being easy and automatic to being difficult and cognitively demanding, the degree of perceived effort is likely to increase (Pichora-Fuller et al, 1995). A

measure of perceived effort has been used in Papers C and D to complement the objective measure of speech recognition and understanding. This dual approach was intended to give a more complete picture of the person's ability to handle different listening situations and to make use of amplification.

In conclusion, two different methods to investigate central auditory functions have been developed: a dichotic speech test battery and a cognitive test battery. The purpose was to validate these measurements and their possibilities to generate new information in the field of central auditory processing. Studies have been performed with the aim to assess speech understanding processing in different kinds of background conditions and with/without hearing aid amplification, in groups of hearing-impaired and elderly subjects as well as young normal-hearing listeners.

Chapter 2

Theoretical background

2.1 The hearing system

The hearing organ can be divided into a peripheral and a central part (overview, Purves, 1997). The peripheral part consists of the outer ear, middle ear and inner ear. The outer ear, i.e. the pinna and the ear canal, transfers the signal to the middle ear, and has an acoustic amplifying effect on the signal. The ossicular chain in the middle ear transfers the movements of the tympanic membrane to the oval window of the cochlea in the inner ear. The signal now is represented as movements of fluid in the cochlea. Hair cells along the basilar membrane are of two types. Inner hair cells carry information via afferent nerve fibers to the central auditory system. Outer hair cells respond to the incoming sound, amplifying the vibrations of the sensory organ, and, in addition, respond to efferent information from the central auditory system. They are important for high sensitivity processing of sound. The frequency of the signal is coded by the position of the hair cells as well as by the temporal pattern of the nerve impulses. At the apex of the cochlea the hair cells are sensitive for low frequencies and at the base for high frequencies. The intensity of the signal is primarily coded by the firing rate of the nerve impulses and the number of nerve cells being activated.

The central auditory function is complex, the information in the 30.000 nerve fibers in the auditory nerve is converted into millions of nerve fibers at the level of the auditory cortex (Bredberg, 1981). The information from the peripheral part of the auditory system is transferred via both ipsi- and contralateral

pathways to the auditory cortex, but the primary route is contralateral (Zimmerman, 1994; Bellis, 1996). At several levels of the central auditory system information is transformed and decoded in different nuclei. These nuclei contain nerve cells, which react to different properties and combinations of incoming nerve impulses and refine the information that is important for speech understanding. For example, one nucleus codes for frequency bands, rather than pure tones, which is essential for the perception of vowels, and another for stimulus onset, change and termination, which is essential for the perception of formant transitions and stop consonants. Information from both ears are integrated in the nuclei and used to give a representation of auditory space (Purves, 1997), where sound-localization is an essential part. Thus, before speech information reaches the cerebral cortex, it has already been processed in sub-cortical centers. In the cortex the signals first reach the temporal lobes and the primary auditory cortex, which shows a topographical map of the cochlea. This is the site of auditory sensation and perception. Then the information is passed on to the associative auditory cortex, of which Wernicke's area is a part. This area is important for recognition of linguistic stimuli and comprehension of spoken language.

2.2 Cognitive functions in speech understanding

The speech process yields not only the sensation of an incoming stimulus, but also its processing and interpretation in the context of previous experiences. Information about how things are related and categorized, for example contextual, lexical, syntactic and semantic information, is stored in a long-term memory. Controlling top-down processes work in parallel with stimulus-driven bottom-up processes in every information-processing stage. Thus, hearing includes both audition and cognition.

The information available from perception and cognitive processing has to be available for conscious manipulation. In theoretical models (e.g. Baddeley, 2003) the working memory is responsible for the active part in language comprehension, as well as for the transfer of information into long-term memory. The central unit in the working memory (the central executive) is in control of directing attention and mental resources and uses slave systems for limited short-term storage of information (the phonological loop and the visuospatial sketchpad).

Any kind of distortion or limitation of an incoming stimulus, i.e. in difficult listening situations or because of a hearing impairment, makes the process more dependent on top-down processing. The situation becomes more cognitively demanding than normally. Functions like rapid access to semantic and lexical

knowledge, working memory capacity, selective attention, and high speed of information processing become thus more critical for the understanding of spoken language.

It has been shown that cognitive functions decline with increasing age (Park, 1999). Poorer results on highly demanding working memory tasks as well as decreased speed of performance have been noticed in the elderly (e.g. Birren & Fisher, 1995; Salthouse, 1996; Li et al, 2001; Wingfield & Tun, 2001). It has also been verified that some cognitive functions deteriorate as a consequence of hearing impairment in severely hearing-impaired and deaf people. More precisely, it has been proven that the phonological ability decline when auditory stimulation is reduced during a longer period (Andersson & Lyxell, 1998; Andersson, 2001) for severely hearing-impaired and deafened adults.

The extra problems with speech understanding in the elderly population, especially in noisy situations, are often discussed in connection with a poorer peripheral hearing. Previous studies have reported that peripheral auditory impairments account for most of the variance in speech recognition scores among older listeners (e.g. van Rooij & Plomp, 1992; Schneider et al, 2000). But a decline in peripheral hearing is not the only explanation. Decline in higher order abilities, cognitive and/or central auditory functions, has also been discussed as an explanation to the problems in the elderly (e.g. Jerger et al, 1989; Humes, 1996; Paper A; Pichora-Fuller, 2003). That is, the cognitive abilities are never the entire explanation but always a part of it. However, the relative effect on speech understanding of the different ageing processes has been difficult to verify, because of the problems in isolating the different components.

2.3 Hearing impairment

Hearing impairments are classified according to their anatomical localization. Lesions affecting the transformation of sound in the outer and middle ear are called conductive hearing losses and cause an attenuated but otherwise intact auditory signal. These kinds of lesions can be treated in many cases, and if not, they are relatively easy to compensate for with hearing aids. Sensorineural hearing impairments comprise defects in the cochlea and/or the auditory nerve. The most frequent type of sensorineural impairment is caused by damage to hair cells in the cochlea (cochlear hearing loss). The outer hair cells are generally more vulnerable to damage than the inner hair cells (Borg et al, 1995). Presbycusis, a hearing impairment caused by aging of the auditory system, affects mainly the basal part of the cochlea, giving rise to a hearing loss in the high frequency range. Sensorineural hearing impairment causes in addition to

poorer hearing threshold levels also reduced spectral and temporal resolution (Humes, 1983; Tyler, 1986; Larsby & Arlinger, 1999). The response of the basilar membrane to sound in the healthy cochlea is sharply tuned, highly non-linear and compressive. In hearing-impaired listeners the response becomes broadly tuned and linear, which means that the high sensitivity of the basilar membrane to weak sounds disappears. Oxenham & Bacon (2003) pointed out that a number of aspects of temporal processing in the hearing-impaired can be explained in terms of this loss of cochlear non-linearity.

This has great consequences in everyday listening situations. Normal-hearing subjects are able to take advantage of temporal and spectral “dips” in the interfering sound to achieve an improved speech recognition threshold (SRT) (for a review, see Moore, 1996). The SRT is 7 to 18 dB lower when the background is a single talker compared to when the background is continuous speech-shaped noise. However, people with cochlear damage appear to be less able than normal-hearing people to take advantage of the temporal and spectral dips. For hearing-impaired subjects, SRTs are not greatly different for a steady noise background compared to a single talker background.

Lesions central to the auditory nerve are classified as central impairments. The additional handicap for the elderly compared to younger subjects with comparable peripheral hearing status can partly be attributed to aging in the central auditory system (Jerger et al, 1989, Paper A).

2.4 Outcome measures

Measurement of the peripheral auditory function is standardized and well established in clinical use. However, a variety of tests have been used to evaluate central auditory function and cognitive functions important for speech comprehension. Another dimension in addition to the objective results from those methods is the subjectively perceived listening effort.

2.4.1 Dichotic speech tests

Dichotic speech tests are psychoacoustic tests sensitive for central auditory functions (Bellis, 1996). In these tests the two ears are stimulated simultaneously with different speech sounds (overview see Hugdahl, 1995). The task of the subject is to report what is being heard, either in both ears or in one of the ears, either left or right. This is a difficult listening situation, in which the brain has to process a lot of competing information in a short time. Furthermore, the simultaneous presentation of stimuli to both ears makes the signals from the ears depend on contralateral pathways to a higher extent than normally. The

ipsilateral pathways are suppressed by the competing stimulus situation. This means that the stimuli from the left ear have a longer way to the speech-dominant left hemisphere, since these signals are conveyed via the right hemisphere and the corpus callosum (see figure 1). The stimuli from the right ear, on the other hand, have direct access to the left hemisphere. This leads to a right ear advantage (REA), a typical finding in dichotic speech tests.

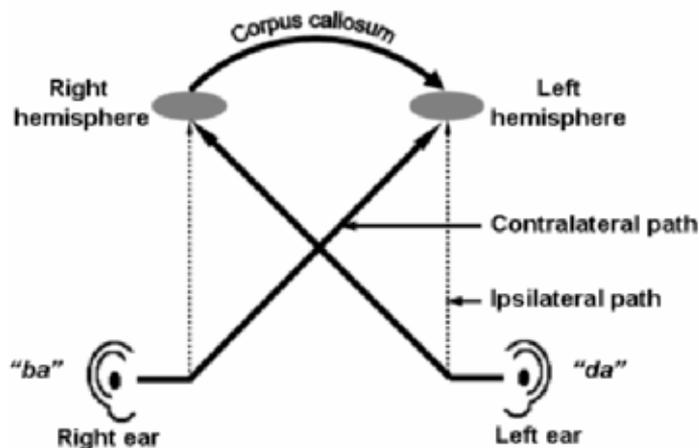


Figure 1. The pathways in the hearing system underlying right ear advantage in dichotic listening.

2.4.2 Cognitive tests

The first studies on age-related cognitive decline and speech recognition focused on general cognitive functions and idealized listening conditions (review see Sommers, 1997). It is only during the last decade that focus has been changed to speech-specific cognitive capacities in natural listening environments. Studies have been published about for example the ability to use semantic context (Wingfield et al, 1994) and the role of lexical discrimination in speech recognition (Sommer, 1996). How working memory relates to speech understanding in individuals with hearing loss has been studied (Lunner, 2003), but has received surprisingly little attention in the research literature (Lyxell et al, 2003).

Traditionally hearing evaluation and rehabilitation has been based on the pure tone audiogram which primarily represents the peripheral hearing in stimulus driven bottom-up processing. This assumes that two persons with the same audiogram have the same communicative ability, which is not the case. It is also important to consider the ability to make use of cognitive processing in order to compensate for a limited and distorted sensory signal and in order to make use

of amplification in modern hearing aids with advanced signal processing. In recent studies it has been convincingly argued that individual cognitive prerequisites interact with different signal processing algorithms in determining the benefit obtained from hearing aids (Gatehouse et al, 2003; Lunner, 2003).

The cognitive tests used in this thesis were based on a cognitive test battery called TIPS (Text Information Processing System; Ausmeel, 1988), which captures functions like working memory capacity, selective attention, phonological ability and speed of information processing. Results from the TIPS tests have been shown to be related to various kinds of communicative performance for populations of hearing-impaired subjects (e.g. Lyxell et al, 1998; Lyxell & Holmberg, 2000; Andersson, 2001). It is important to notice that these studies used text stimuli for measurement of cognitive functions. Thus, the modality specific parts in speech comprehension are not present.

In order to obtain a more complete picture of a person's cognitive abilities a system for presentation of the tests in TIPS in auditory and audiovisual modalities was developed (SVIPS, Speech and Visual Information Processing System, Paper B). This opened for studies of natural communication in normal hearing and hearing-impaired subjects both in easy and in adverse listening situations (Rönnberg et al, 2000).

2.4.3 Perceived effort

Listening to speech in noise requires more cognitive resources and puts higher demands on top-down driven processing to restore the distorted sensory signal. It is thus likely that listening in noise requires more effort (Pichora-Fuller et al, 1995). The degree of effort one has to exert in difficult speech understanding tasks when deprived of the full auditory signal is a dimension that will add valuable information about the auditory capacity that can not be obtained in traditional audiometric tests. One way to assess perceived effort is to use some kind of rating scale directly in connection with a given listening situation. In this thesis a version of Borg's CR-10 scale (Borg, 1990) was used. This scale is a combination of ratio and category scaling where verbal expressions and numbers are used congruently on a scale ranging from 0= "none at all" to 10="extremely great".

Chapter 3

Contribution of the present work

The purpose of this thesis is to study the role of hearing and cognition in speech understanding processes, in silence and in noise. The first two papers focus on development and evaluation of measurements. Paper A is about dichotic speech testing and Paper B about cognitive tests presented in auditory and audiovisual modalities (SVIPS). In Paper C and D the SVIPS tests are used to study effects of different kinds of noise on speech understanding processes in relation to hearing and age (Paper C) and to age and use of hearing aids (Paper D).

3.1 Paper A – Cognitive effects in dichotic speech testing in elderly persons

3.1.1 Method

Dichotic speech tests and cognitive tests in the TIPS-battery were performed on a group of 30 hearing-impaired subjects in the age-range 42-84 years. The subjects were divided into a younger and an older group, each comprising 15 subjects. The dichotic test material comprises digits, low-redundancy sentences and consonant-vowel-syllables (Hällgren et al, 1998). The subjects reported stimuli heard in both ears (free report) or in one ear (directed report to left or right ear). In the TIPS tests, both accuracy and reaction time were recorded for all tests except the reading span test, where only accuracy was measured.

3.1.2 Results

The dichotic speech tests and the text-based cognitive tests in TIPS reveal two major findings. First, there is an overall decrement with age in both dichotic and cognitive test results. In the dichotic test with syllables as stimuli the elderly group had more difficulties in focusing on stimuli presented to the left ear compared to younger subjects, while no age effects were seen in the right focusing condition. Age effects in the cognitive tests were seen in the speed of performance and in the reading span test. Secondly, there were significant correlations between the performance in the left focusing condition (directed report to the left ear) in the dichotic syllable test and the cognitive parameters speed of performance and working memory capacity. These correlations were not seen in the right focusing condition.

3.1.3 Discussion

The finding of a general age effect in the dichotic tests is discussed assuming a model of three mechanisms underlying the speech understanding process in the elderly (Humes, 1996). These effects are aging in a) peripheral hearing, b) central auditory functions, and c) cognitive functions. The difference in peripheral sensitivity between the two age groups might explain the age effect found in overall results in all dichotic speech tests. However, an impaired ability with age to correctly perceive stimuli presented to the left ear was not related to the degree of peripheral sensitivity, thus indicating a component of central aging.

The overall results in the dichotic tests correlate with the cognitive parameters, but also with age. Therefore, these results can not separate the influence from the age-dependent peripheral hearing component and the central components. However, the scores for the left focusing condition correlate to a much higher extent with the cognitive parameters than the scores for the right focusing condition. As the peripheral hearing is not a confounding factor, the correlation between results in dichotic tests and in cognitive tests points to a true aging of cognitive mechanisms important for dichotic listening.

3.2 Paper B - A cognitive test-battery based on text, auditory and audiovisual stimuli. Evaluation in young and elderly, normal-hearing and hearing-impaired subjects

3.2.1 Method

A cognitive test battery sensitive for processes important for speech understanding was developed and investigated in three modalities, namely text, auditory and audiovisual modality (SVIPS – Speech and Visual Information Processing System). The task in all tests in the battery, independent of presentation modality, is to answer yes or no in different cognitive tasks by pressing predefined buttons. The cognitive tests capture functions such as phonological processing and verbal information-processing. Accuracy and speed of performance measured as percent correct answers and reaction times, respectively, were recorded. The test battery was performed at two occasions to study the test-retest variability. At the second occasion the tests were also carried out in noise (+10 dB S/N). Four groups, each including 12 subjects, participated in the study. The groups were young normal-hearing, young hearing-impaired, elderly normal-hearing and elderly hearing-impaired subjects.

3.2.2 Results

The results show an age effect in speed of performance in the text, auditory and audiovisual modalities. A comparison of the auditory and audiovisual modalities shows that hearing-impaired subjects have more difficulties without visual cues than the normal-hearing subjects, apparent in both accuracy and speed of performance parameters. The effect of hearing-status is not seen in the text-based version. Performing the test battery in noise made the tasks more difficult, especially in the auditory modality and for the elderly subjects, both in accuracy and speed of performance. Test-retest measurements were performed and the variability was established for the different tests.

3.2.3 Discussion

In order to function in daily life, hearing-impaired subjects, to a much higher degree than normal-hearing subjects, have to depend upon non-auditory information and compensation mechanisms. It has been shown that the visual contribution (lipreading) is essential to the hearing-impaired subjects even in

relatively easy listening situations. The results from the condition with noise show that the visual contribution is even more important in more difficult listening situations and that elderly have an impaired ability to manage these tasks, due to age-related cognitive decline. The cognitive test battery in three different modalities has proven to be useful in assessing the relative contribution of different input signals on functions important for speech processing. The test-retest variability indicates that SVIPS in the present form mainly should be used for group comparisons and not for individual assessments.

3.3 Paper C – Cognitive performance and perceived effort in speech processing tasks: effects of different noise backgrounds in normals and in hearing-impaired subjects

3.3.1 Method

The SVIPS tests were presented as text, or in auditory or audiovisual modality, in silence and in three types of noise, varying in temporal structure and meaningfulness (four background conditions).

The included noises were:

- ICRA noise. Random noise signals with speech-like spectral and temporal characteristics (corresponding to one female voice) (Dreschler et al, 2001).
- Hagerman noise (HN). A slightly amplitude-modulated noise which is spectrally matched to Hagerman's original sentences read by a female speaker (Hagerman, 1982).
- Speech. The voice of a female speaker reading a continuous story from the novel 'Nils Holgerssons underbara resa genom Sverige' (The Wonderful Adventures of Nils) by Selma Lagerlöf.

Perceived effort was rated after each listening situation with a version of Borg's CR-10 scale (Borg, 1990). Four groups, young/elderly with normal hearing and young/elderly with hearing loss, 12 subjects each, participated.

3.3.2 Results

The performance in the SVIPS tests in the text modality was in some situations affected by background condition, despite no masking in the auditory channel. In the semantic test the elderly subjects had longer reaction times in the background condition of speech compared to the meaningless noises, while the young subjects did not. It was also found that performing SVIPS in the text modality caused a higher degree of perceived effort in noise than without noise.

Introduction of noise in the auditory and audiovisual modalities resulted in fewer correct answers, longer reaction times and higher degree of perceived effort. In noise, the visual information contributes more to the number of correct answers than in silence. A lower degree of perceived effort was observed in the audiovisual compared to the auditory modality.

Differences between the three background conditions of noise were found. Hearing-impaired subjects performed worse in noises with temporal variations (ICRA and speech), and reported a higher degree of perceived effort than normal hearing subjects. Elderly subjects performed worse in noise with temporal variations, and especially in noise with meaningful content. Elderly did not report a higher degree of effort than the young subjects.

3.3.3 Discussion

This study focuses on effects of interfering noises with different degrees of speech-like characteristics on cognitive abilities critical for speech processing. The results from the SVIPS tests performed without disturbing noise agree in general with those found in Paper B. Furthermore it can be concluded from this study that interfering noise even at a relatively favorable signal-to-noise ratio has significant negative effects on performance in speech processing tasks and perceived effort. How the disturbing noises interact with the speech understanding process is dependent on the characteristics of the noise as well as the individuals' capacity to process information, which is sometimes limited by a hearing impairment and/or reduced cognitive abilities due to age.

The objective measures of accuracy and speed of performance in the SVIPS tests were supplemented with a subjective measure of the degree of effort that the individual had to exert when performing the different tasks. This method for scoring perceived effort proved to be sensitive enough to verify differences between the background conditions, between hearing-status groups and between modalities.

3.4 Paper D – Speech understanding in quiet and noise, with and without hearing aids

3.4.1 Method

The SVIPS tests and Hagerman speech test for determination of speech recognition threshold (Hagerman, 1982) were performed in silence and in two noises (three background conditions).

The included noises were:

- Hagerman noise (HN). A slightly amplitude-modulated noise which is spectrally matched to Hagerman's original sentences read by a female speaker (Hagerman, 1982).
- Speech. The voice of a female speaker reading a continuous story from the novel 'Nils Holgerssons underbara resa genom Sverige' (The Wonderful Adventures of Nils) by Selma Lagerlöf.

Perceived effort was rated for each test situation. The tests were performed with and without hearing aids. One young and one elderly group of 12 hearing-impaired subjects each participated.

3.4.2 Results

In the Hagerman speech test there was a hearing aid benefit of 7 dB in silence, a hearing aid benefit of 2.5 dB (S/N) with speech as background, and no hearing aid benefit in the Hagerman noise. In the scores of perceived effort no effect of hearing aid use was seen in the Hagerman test. Despite the adaptive procedure, there was a main effect of background condition, where speech as background condition was more demanding than Hagerman noise. Least demanding was the condition without noise.

In the SVIPS tests performed with background noise there was no hearing aid benefit in the objective measures. In silence, positive effects of hearing aid use were found in tasks with low redundancy test items in the auditory modality without background noise. In the scores of perceived effort there was an effect of hearing aid use - subjects reported less effort with hearing aids. The subjective benefit of hearing aid was highest in silence and decreased in background noise.

3.4.3 Discussion

The purpose of this study was to investigate the effect of hearing aid use on speech recognition threshold and cognitive functions important for speech understanding, in silence as well as in two different noises with different cognitive load. Despite minor benefits of hearing aid amplification in the objective measures, above all in the cognitive tests, significantly less effort was perceived when hearing aids were used. In the Hagerman speech test, however, where we measure around 40% correctly recognized test words, we saw a hearing aid benefit in noise, which was most evident in the background condition of speech. The fact that there was no effect of hearing aid use on perceived effort in the Hagerman speech test is probably due to the adaptive process of signal-to-noise adjustment to reach 40% correct responses.

All hearing aid benefit measurements depend on methodological circumstances and outcome measure used. They are for example dependent on level and presentation mode of noise and speech stimuli, the test material used, and the hearing aid settings. In daily life we are sometimes listening at threshold, but most of the time we are listening above threshold where persons with moderate hearing loss can function quite well if they make use of context and visual support.

It was concluded that obtaining measures of perceived effort adds valuable information when evaluating hearing aid benefit.

3.5 General discussion

The purpose of this section is to provide a comprehensive discussion of the methods and results of all the papers included in the thesis. Finally, the clinical relevance and the implications for future research are discussed.

3.5.1 Methods

To evaluate the ability to perceive and understand spoken language there are different measurements, more or less dependent on functions on different levels of speech processing, ranging from *identification* of words in noise (for example Hagermans test, used in Paper D), to *speech understanding* (SVIPS). The cognitive load varies with the demands on central processing. This dependence can be tested in difficult listening situations with competing speech, such as in dichotic speech tests.

Dichotic speech tests are indicators of both peripheral and central processes related to hearing (Paper A). The two ways in reporting the presented stimuli,

free and directed report conditions, reveal different and complementary information. In the free report condition, when focus is on stimuli presented to both ears, the results are affected by central processes as well as by peripheral sensitivity. These mechanisms can not be quantified separately. In the directed report condition, when focus is on either left or right ear, the effect of peripheral hearing can be neglected in the case of symmetrical hearing loss. The comparisons of the results from the left and the right ear are thus indicators of central auditory and cognitive processes.

The stimuli used in the dichotic speech tests have different sensitivity. All tests except those with syllables (CV's) revealed ceiling effects in this study (Paper A). In other groups of subjects with different peripheral hearing and/or cognitive abilities, other stimuli may be the most sensitive.

With the text-based TIPS it is possible to study cognitive functions essential for speech processing and understanding (Paper A). By performing the cognitive tests in TIPS also in the auditory and audiovisual modalities (SVIPS, Paper B) a more complete picture of a person's cognitive abilities is obtained, and in addition, the role of the peripheral hearing is considered. The modalities can be compared and, especially, the comparison of the auditory and audiovisual modalities gives an opportunity to verify the visual contribution in speech processing.

To investigate different aspects of the cognitive abilities involved in the speech understanding process five tests with varying demands on cognitive or information-processing activity were included in SVIPS at the first stage (table 1; for details see Paper B). The results from Paper B showed that the two different rhyme tests presented in auditory and audiovisual modalities resulted in ceiling effects. In Papers C and D the test battery was therefore reduced to three tests.

Test	Task	Activity
Semantic decision	To decide whether a word belongs to a certain pre-defined semantic category or not	Verbal information-processing speed of category related information
Lexical decision	To judge whether a combination of three letters is a real word or a non-word	Verbal information-processing speed of word related information
Name matching	To judge whether two presented letters are the same (e.g., A - A) or not (A - B)	Verbal information-processing speed of letter related information
Rhyme-judgment 1	To decide whether two presented words rhyme or not	Phonological processing of familiar words
Rhyme-judgment 2	To decide whether two presented bisyllabic non-words rhyme or not	Phonological processing of non-words

Table 1. Tasks and activities in the different tests in SVIPS.

In the SVIPS battery two major mechanisms interact: word recognition, which to a high degree reflects peripheral hearing, and decision-making, which depends more on cognitively demanding top-down driven speech understanding processes. Incomplete word recognition complicates the decision-making, which can be compensated for by higher redundancy in the test situation. In the semantic test for example, it is known that the target item belongs to a predefined category which facilitates the decision making (semantic redundancy). In the lexical test however, where the task is to judge whether the item is a real word or a non-word, the non-words have very low redundancy (lexical) and are hard to identify if the word recognition is incomplete. This makes it possible to study the effect of different levels of redundancy on speech understanding.

Both accuracy and speed of performance are assessed in TIPS as well as in SVIPS. The inclusion of speed of performance as measurement gives additional and complementary information about the individual's skills of processing spoken stimuli. Even though the subject's ability to perform is unaffected, longer reaction times will lead to difficulties in maintaining that performance. The results from the Papers included in this thesis show that group differences

sometimes are reflected by poorer results in accuracy or in longer reaction times, or in both.

In real life, speech is typically present in a more or less noisy acoustic environment. The effects of different noises on speech processing and comprehension tasks are due to masking of the target stimuli as well as to distraction of the cognitive decision making. It can be concluded that interfering noise at the relatively favorable signal-to-noise ratio used in this thesis still has significant negative effects on performance in speech processing tasks and perceived effort. For clinical diagnostic and rehabilitation purposes it is also important to use tests with high face validity to mimic the subject's difficulties in daily life situations.

A difficult listening situation, such as in background noise, does not necessarily mean that performance drops. Sometimes only the degree of effort required is affected (Paper D). The relatively simple method for scoring perceived effort used in Papers C and D proved to be sensitive enough to verify differences between background conditions, hearing-status groups, modalities of presentation and hearing aid usage. It is concluded that rating perceived effort is a valuable tool to complement the objective measure in the SVIPS tests, both within and between groups.

The Borg's CR-10 scale (Borg, 1990) used in Paper C and D is a combination of ratio and category scaling where verbal expressions and numbers are used congruently on a scale ranging from 0= "none at all" to 10="extremely great". The scale is logarithmic which means that the resolution is higher at lower levels. This has proven to be an appropriate method, but other kinds of scales and tools may have better specificity and sensitivity in other experimental tasks.

In conclusion, different tests have been used in different listening environments in a multimodal approach to study effects on different levels of speech understanding. A standardized test of peripheral hearing and speech recognition (Hagermans test) involving primarily bottom-up processing, have been used in combination with cognitively demanding test requiring more top-down processing.

3.5.2 Results

In the papers included in this thesis we have studied effects of *age* and/or *hearing impairment* on the speech understanding process. The main effects and some interactions with background condition, modality and hearing aid use are presented.

Age

Dichotic listening is a difficult listening situation reflecting peripheral as well as central auditory function. In Paper A it has been shown that there is an overall decrement in results in dichotic listening with age which has been shown also in previous studies (Gelfand et al, 1980; Jerger et al, 1994; Wilson and Jaffe, 1996). The reduced ability to focus to the left ear in the elderly agrees with the results from Alden et al (1997) and indicates a decreased central auditory function with increasing age. This is supported by the correlations with cognitive functions. The peripheral hearing is not a confounding factor since the test subjects had symmetrical hearing losses.

In Paper A and previous studies with the text-based TIPS (Rönnberg, 1990) a general effect of age was found in the reaction time parameter. The same age effect is seen in the auditory and audiovisual modalities in easy listening situations without background noise (Paper B). But when noise is used as background condition (Paper B, C and D) there is an age effect in accuracy. This effect remains even when analyzed with hearing threshold level average (PTA4=mean of 500, 1000, 2000 and 4000 Hz) as covariate. Previous studies assessing primarily correlations between speech recognition and cognitive functions in general, like memory and attention (see review by Sommers, 1997) have shown that cognitive factors made only minimal contribution to the speech recognition difficulties in the elderly. In our studies, however, there are obvious age effects in cognitively demanding listening tasks.

In difficult listening situations, such as in noise, there are higher demands on compensatory mechanisms to perceive verbal information. Results from both Papers B and C show an interaction between age and background condition (silence, noise) indicating that the elderly have relatively more problems than young subjects when noise is introduced (figure 2). This effect remains when analyzed with hearing threshold level average (PTA4) as covariate. This finding agrees with Schneider et al (2002) and CHABA (1988) who concluded that elderly people compared to young have additional difficulties in adverse listening situations, such as noise. In both Papers B and C the extra problems in noise for the elderly subjects appeared in the lexical test only. In this difficult test there is little redundancy in the auditory signal, which puts high demands on both sensory and cognitive processing. Sommers (1997) showed that older listeners compared to younger exhibited larger reductions in identification performance for lexically difficult items but not for easy items.

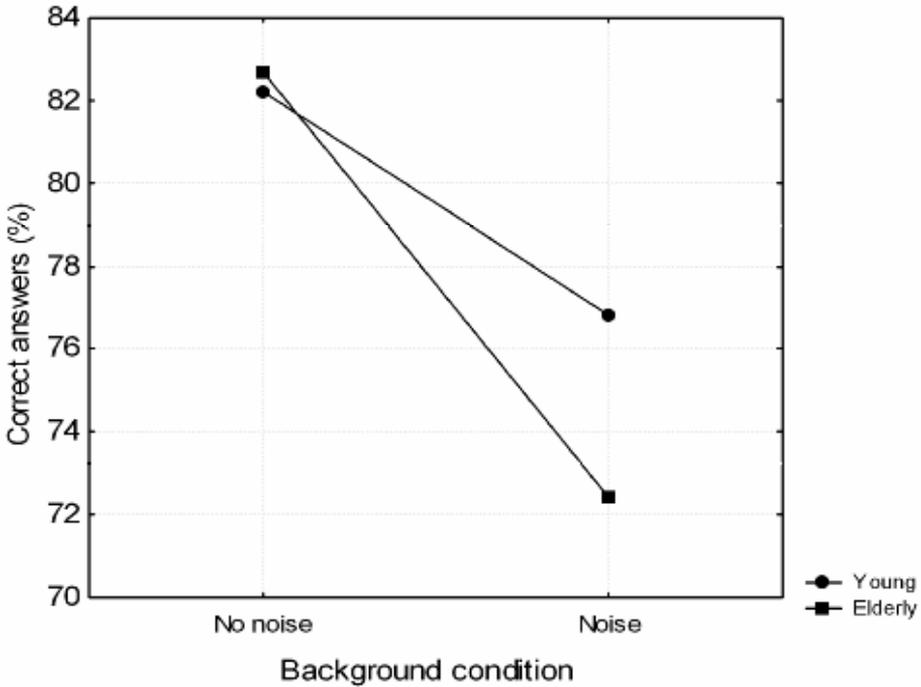


Figure 2. Mean correct answers (%) in the no noise and noise condition for the young (●) and elderly (■) groups in the lexical test. Paper C.

Speech as background noise is special in many respects. It provides context and conveys a meaningful message. It is thus likely that it interferes more with a speech processing task than noise without meaning. When comparing Hagerman noise and speech as background noise there was a significant interaction between background noise and age in the semantic test, showing that the young group performed equally well in the two noise conditions, while the elderly performed worse in speech background (Paper C). This might be explained by differences of the background noises in acoustical characteristics – older listeners benefit less from listening in the gaps of a competing voice (Duquesnoy, 1983; Snell et al, 2002) – as well as by meaningfulness (Tun et al, 2002) – elderly were more impaired by a meaningful distracter.

The effect of age on performance parameters is not verified by a higher degree of perceived effort in the elderly (Papers C and D). One explanation to this might be that the elderly are less prone to complain.

We have concluded that the elderly have more problems when noise is introduced (figure 2), especially if the noise has temporal variations and

meaningful content. The problems for the elderly in cognitively difficult listening situations were also seen in Paper A, where the elderly had extra problems when the task was to attend to the left ear in a dichotic speech test. In the task of attending to one ear in a dichotic listening situation, two main mechanisms are involved. The first uses a stimulus driven “bottom-up” processing with low cognitive demands. The second uses controlled cognitive processing in a “top-down“-manner with higher cognitive demands. In the right focusing condition these two mechanisms work in synchrony, since most subjects perform better when attending to stimuli heard in the right ear (REA). In the left focusing condition the two mechanisms are in conflict, since stimuli from the left ear are naturally suppressed by stimuli from the right ear. In order to attend to the left ear, the top-down processing has to be active to a much greater extent. Difficult listening situations, in general, require more top-down processing, exemplified by the results from attending to the left ear in dichotic listening and by the performance in the SVIPS tests in noise. A general decline in speed of performance is a result of old age and can contribute to the problems for the elderly with top-down processing. Every single task takes longer time and this finally becomes critical in the complicated speech understanding process. A decline in working memory function with increasing age is seen in the reading span test both in Papers A and B. This means that the elderly on average have reduced capacity to simultaneously store and process information. These age-related declines in cognitive abilities are even more critical in hearing-impaired subjects.

Hearing impairment

Both Papers B and C show poorer results and longer reaction times for the hearing-impaired compared to the normal-hearing groups in the SVIPS tests. This is an expected effect since the hearing-impaired subjects have to deal with limited and distorted auditory information in the auditory or audiovisual modalities. With a limited auditory input signal it is also likely that extra time is required to process the signal before making a decision.

When noise interferes with the target signal both normal-hearing and hearing-impaired subjects perform worse (Papers B and C). The hearing-impaired subjects had more problems in noise with temporal variations compared to normal hearing subjects, a phenomenon not seen in noise without temporal variations (Paper C). This result agrees with several studies. Bronkhorst & Plomp (1992) varied the number of interfering talkers and showed that hearing-impaired subjects performed significantly worse than normal-hearing subjects, with larger differences between the groups for one talker than for multi-talker babble. Festen & Plomp (1990) and Hygge et al (1992) showed that the differences in speech-recognition-threshold between hearing-impaired and

normal-hearing subjects increased going from steady-state noise to one interfering voice. The extra problems for the hearing-impaired subjects in noise with temporal variations are probably due to impaired temporal and spectral resolution (Moore, 1996).

There are no general benefits of hearing aid amplification in the SVIPS tests (Paper D). This might be explained by the fact that the SVIPS tests were performed at favorable signal levels or S/N ratio, which clearly allows the hearing-impaired subjects to hear most of the test items and also to utilize redundant information. However, in tasks with low redundancy test items without visual support, where the decision making is highly dependent on acoustic information, there was a hearing aid benefit in situations without background noise. In noise, the positive effect of amplification on the target signal did not occur. To recognize low redundancy stimuli one has to identify every speech sound in the test word/pair of letters, and any kind of noise is likely to disturb this. These results agree with previous studies (e.g. Gustafsson & Arlinger, 1994; Cord et al, 2000) showing that the hearing aid benefit is much smaller or nonexistent in a background condition of noise.

A compensatory mechanism often used in verbal communication is the visual support from lip reading. The results in SVIPS improved by up to 15 percentage points with support from visual information (Papers B, C and D). The importance of visual support increases in difficult listening situations and/or if other individual prerequisites are limited. The results from SVIPS studies show that the hearing-impaired subjects performed worse than the normal-hearing subjects without visual support, but produced approximately the same results as the normal-hearing subjects with visual support in the audiovisual modality (figure 3a). It is worth noting, however, that the results from the normal-hearing subjects show longer reaction times in the audiovisual modality compared to the auditory modality (figure 3b). It can be concluded that an audiovisual task requires more time and effort than auditory alone in order to process the additional visual information. Additional information from a second input channel presumably requires additional resources and reduces speed of performance. Neuropsychological research has shown that audiovisual stimuli activate multimodal brain regions including the motor cortex to a larger extent than auditory-alone stimuli, which facilitate speech perception (Skipper et al, 2005).

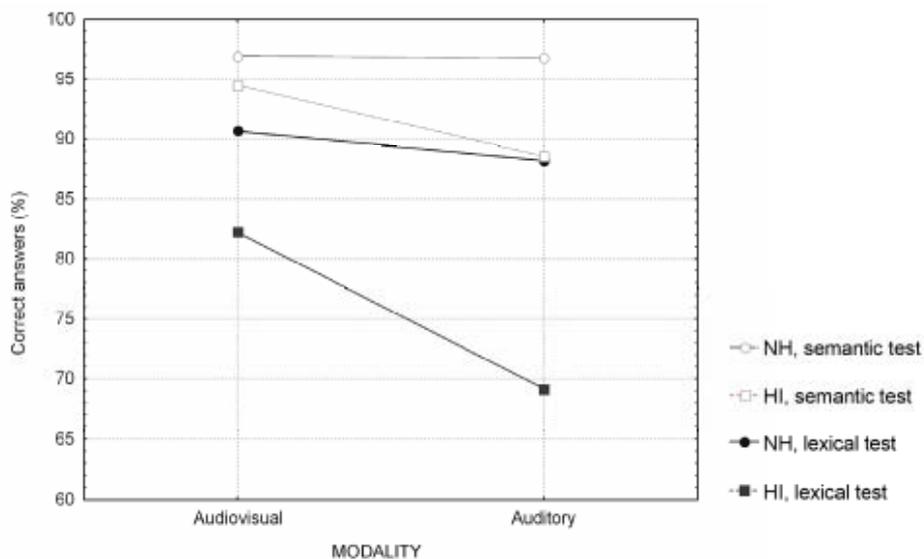


Figure 3a. Correct answers (%) as a function of modality for the NH and HI groups in the lexical (filled symbols) and semantic (unfilled symbols) tests. Paper B.

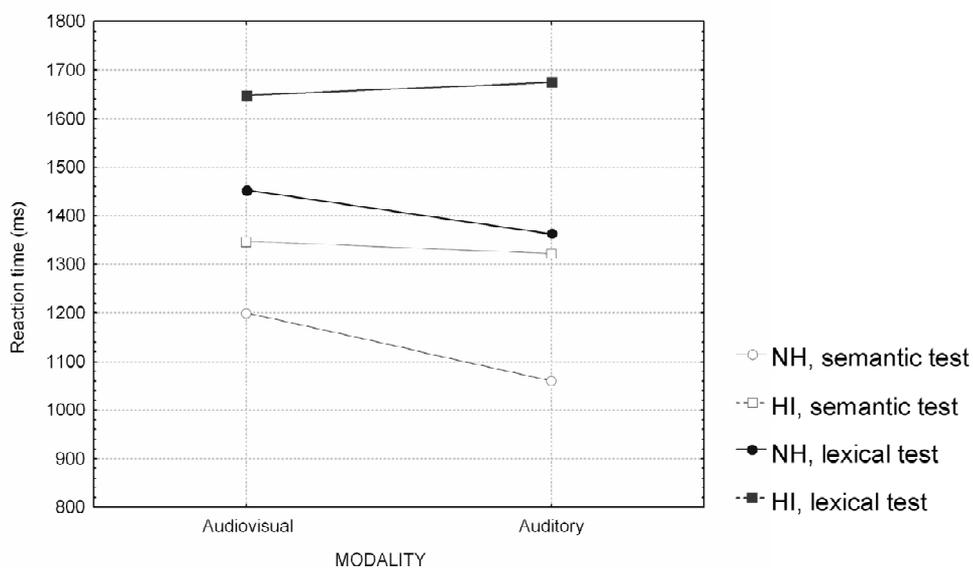


Figure 3b. Reaction time (ms) as a function of modality for the NH and HI groups in the lexical (filled symbols) and semantic (unfilled symbols) tests. Paper B.

Hearing-impaired subjects, in addition to reduced performance in the SVIPS tests, also reported a higher degree of perceived effort than normal-hearing subjects (Paper C). Despite the fact that there is no hearing aid benefit in objective performance, the perceived effort is significantly reduced (Paper D). The interaction between hearing status and modality (figure 4) shows that the higher degree of effort perceived by the hearing-impaired compared to normal-hearing subjects was more pronounced in the auditory modality, in a similar way as seen in the objective measures.

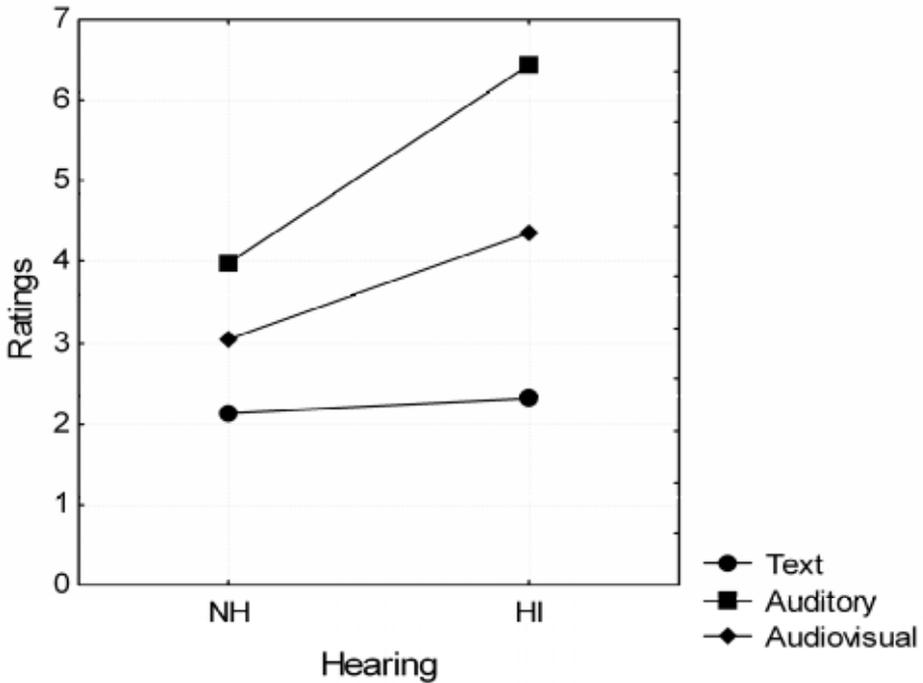


Figure 4. Mean ratings of perceived effort for normal-hearing and hearing-impaired subjects in the text (●), auditory (■), and audiovisual (◆) modalities. Paper C.

3.5.3 Clinical relevance and future research

Like in all measurements, the outcome of audiometry depends on methodological circumstances and the outcome measure used. Hearing aid benefit measured as improved speech recognition threshold in Hagerman's test was not at all comparable with improved speech understanding measured with

SVIPS with a more favorable signal-to-noise ratio (Paper D). The important question is what one wants to measure - changed speech recognition around the threshold or differences in a more complex cognitively demanding speech understanding process in every-day-like situations. In SVIPS the tests were performed at +10 dB S/N and in Hagermans test the average S/N for 40% correct answers was -5.5 dB S/N. Thus the tests differ both regarding task and S/N ratio. A further and necessary step to understand the mechanisms underlying the differences between the results from the SVIPS and the Hagerman tests is to perform SVIPS with less favorable S/N ratios. This would give a more complete picture of a person's ability to both recognize and understand a spoken message, with and without hearing aids.

Recent studies have shown that an integrated approach incorporating both cognitive and sensory factors is likely to be of greatest benefit in designing hearing aid strategies for improving speech recognition (Gatehouse et al, 2003; Lunner, 2003). The results from the SVIPS tests should be seen as contributions to the development and refinement of test methods for both sensory driven bottom-up and cognitively demanding top-down processing. The results from SVIPS are dependent on many factors involved in the speech understanding process that are difficult to separate. The clinical relevance increases if tests are developed that tap functions at different well defined stages of speech processing. Such tests will, in addition, add to our knowledge about the effect of different adverse listening environments on speech understanding processes.

In measurements of speech recognition the outcome measure usually is expressed as percentage of correct answers or signal-to-noise ratio. However, the results from the SVIPS tests have shown that both the reaction time parameter and the subjective score of perceived effort have contributed with complementary and important information. Gatehouse & Gordon (1990) used response time as an estimate of ease of listening in a study on speech recognition tasks in noise. Humes (1999) pointed out the importance of including a measure of subjective listening effort in measures of hearing aid outcome. The high degree of perceived effort will negatively affect fatigue and the ability to concentrate, which affect speech understanding. Salthouse (1996) pointed out that "if relevant processing operations are not successfully completed within a particular temporal window, then the quality of the final product is likely to be impaired because later processing operations would be either less effective or only partially completed" (p.404). Both perceived effort and reaction time should be taken into account in studies of speech recognition and understanding in different listening situations, with and without hearing aids. The goal for hearing aid fitting must be to optimize speech understanding and to minimize the degree of perceived effort.

Chapter 4

Conclusion

This work has contributed with methods for evaluation of central auditory processing and cognitive functions important for speech processing. Furthermore, applying the test methods has contributed new knowledge about speech processing, especially in hearing-impaired and elderly subjects. The results prove that it is necessary with an integrated approach in measurements of speech recognition and understanding, incorporating both sensory and cognitive factors. In difficult listening situations, when the auditory signal is limited and/or distorted or masked by background noise, other compensatory mechanisms are used. Visual information through lip-reading, prior knowledge about the semantic and lexical rules in the language, context etc are used in a cognitively demanding top-down process. These compensatory mechanisms are among other things dependent on individual cognitive abilities. Both sensory limitations and the cognitive load affect the effort perceived by the individual. The results from the methods used in this thesis should be seen as contributions to the development and refinement of test methods for both sensory driven bottom-up and cognitively demanding top-down processing. This may hopefully lead to better individual rehabilitation and alternative communication strategies when the auditory input signal is limited and/or distorted.

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