Cognition in Hearing Aid Users:

Memory for Everyday Speech

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*“Now this is not the end.
It is not even the beginning of the end.
But it is, perhaps, the end of the beginning.”*

Winston Churchill

Abstract

Hearing impairment interferes with speech communication. Hearing aids are designed to provide amplification for individuals with poor auditory sensitivity. Signal processing algorithms are implemented in hearing aids to further improve speech understanding and to reduce listening effort in noise. When listening effort is reduced, fewer resources are assumed to be needed for speech perception and more resources would thus be freed for cognitive processing of speech. However, this effect has only been reported in young adults with normal hearing, not in hearing aid users. Cognitive abilities, which vary between individuals, have been shown to influence the ability to benefit from hearing aids. Specifically, it is not yet known how individual differences in cognitive abilities interact with signal processing to reduce listening effort. Also, the relationship between cognition and aided speech recognition performance, as a function of acclimatization processes in new hearing aid users, has not been studied previously.

This thesis investigated the importance of cognition for speech understanding in experienced and new hearing aid users. Four studies were carried out. In the first three studies (reported in Papers 1 to 3), experienced hearing aid users were tested and the aims were 1) to develop a cognitive test, called the Sentence-final Word Identification and Recall (SWIR) test, to measure the effects of a noise reduction algorithm on processing of highly intelligible speech (everyday sentences). SWIR performance is argued to reflect the amount of remaining resources upon successful speech perception; 2) to investigate, using the SWIR test, whether hearing aid signal processing would affect memory for heard speech; 3) to test whether the effects of signal processing on the ability to recall speech would interact with background noise and individual differences in working memory capacity; and 4) to explore the potential clinical application of the SWIR test by examining the relationship between SWIR performance and self-reported hearing aid outcome. In the fourth study (reported in Paper 4), the aim was 5) to examine the relationship between cognition and speech recognition in noise in new users using various models of hearing aids over the first six months of hearing aid use.

Results of the studies reported in Papers 1 and 3 demonstrated that, for experienced users, noise impairs the ability to recall intelligible speech heard in noise. Noise reduction freed up cognitive resources and alleviated the negative impact of noise on memory when speech stimuli were presented in background noise consisting of speech babble spoken in the listener's native language but not in a foreign language. The possible underlying mechanisms are that noise reduction facilitates auditory stream segregation between target and irrelevant speech and reduces the attention captured by the linguistic information in irrelevant speech. In both studies, the effects of noise reduction and SWIR performance were modulated by individual differences in working memory capacity, suggesting that hearing aid signal processing interacts with working memory. In the study reported in Paper 2, better performance on the SWIR test was related to greater reported

residual activity limitation. This seemingly contradictory finding can be explained in terms of the Ease of Language Understanding (ELU) model which proposes that high performers are more able to invoke explicit cognitive resources when carrying out a cognitively demanding task or when a listening situation is challenging. Such individuals would also experience greater activity limitation. Results of the study reported in Paper 4 showed that cognitive function, specifically working memory capacity, played a more important role in speech recognition in noise before acclimatization to hearing aid amplification, rather than after six months in new users.

This thesis demonstrates for the first time that hearing aid signal processing can significantly improve the ability of individuals with hearing impairment to recall highly intelligible speech stimuli presented in babble noise. It also adds to the literature showing the key role of working memory capacity in listening with hearing aids, especially for new users. By virtue of its relation to subjective measures of hearing aid outcome, the SWIR test can potentially be used as a tool in assessing hearing aid outcome.

List of Papers

Paper 1

Ng, E. H. N., Rudner, M., Lunner, T., Pedersen, M. S., & Rönnberg, J. (2013). Effects of noise and working memory capacity on memory processing of speech for hearing aid users. *International Journal of Audiology*, 52(7), 433–441.

Paper 2

Ng, E. H. N., Rudner, M., Lunner, T., & Rönnberg, J. (2013). Relationships between self-report and cognitive measures of hearing aid outcome. *Speech, Language and Hearing*. Advance online publication. DOI: 10.1179/2050572813Y.0000000013.

Paper 3

Ng, E. H. N., Rudner, M., Lunner, T., & Rönnberg, J. Noise reduction improves memory for target language speech in competing native but not foreign language speech. Submitted manuscript.

Paper 4

Ng, E. H. N., Classon, E., Larsby, B., Arlinger, S., Lunner, T., Rudner, M., & Rönnberg, J. Dynamic relation between working memory capacity and speech recognition in noise during the first six months of hearing aid use. Submitted manuscript.

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Introduction

Hearing aids, which are the most common treatment for hearing loss, typically provide amplification to increase audibility of sounds from everyday life. While hearing aid amplification improves speech clarity in quiet, listening to speech in noise remains difficult and cognitively taxing. It may be due to the fact that hearing aids amplify unwanted sounds as well as target speech signals. In this regard, signal processing algorithms are designed and implemented in hearing aids to further enhance speech intelligibility and to improve listening comfort by attenuating unwanted background noise. Sarampalis et al. (2009) showed that a hearing aid signal processing algorithm helped to reduce listening effort and free up cognitive resources, and thereby improved memory for heard speech in young adults with normal hearing. However, similar effects in individuals with hearing impairment have not been reported.

Individual differences in cognitive capacity are shown to be linked to differences in unaided and aided speech recognition performance in noise, success with hearing aid signal processing, and hearing aid benefit (for example, Davis, 2003; Foo et al., 2007; Gatehouse & Gordon, 1990; Gatehouse et al., 2003; Lunner, 2003; Lunner & Sundewall-Thorén, 2007; Moore, 2008; Picou et al., 2013; Rudner et al., 2009, 2011). Cognitive capacity has also been found to play a more important role in speech recognition performance when experienced hearing aid users are new to a hearing aid setting than when they are accustomed to it (Rudner et al., 2009). It is not known, however, whether the role of cognition in aided speech recognition would also decline over time in novice hearing aid users.

This thesis shows how cognition is related to speech processing with an unhabituated signal processing algorithm in experienced hearing aid users, and with (unhabituated) hearing aid amplification in new hearing aid users. The specific aims were: 1) to develop a cognitive test, called the Sentence-final Word Identification and Recall (SWIR) test, to measure the effects of a noise reduction algorithm on processing of highly intelligible speech. SWIR performance is argued to reflect the amount of remaining cognitive resources upon successful speech perception; 2) to investigate, using the SWIR test, whether hearing aid signal processing would affect memory for heard speech in experienced hearing aid users; 3) to test whether the effects of signal processing on the ability to recall speech would interact with background noise and individual differences in working memory capacity; 4) to explore the potential clinical application of the SWIR test by examining the relationship between SWIR performance and self-reported hearing aid outcome; and 5) to examine the relationship between cognition and speech recognition in noise in new users using various models of hearing aids over the first six months of hearing aid use.

Background

Hearing Impairment and Hearing Aids

Hearing impairment

Hearing impairment has a prevalence of approximately 10% in the general population (Stevens et al., 2013) and is a common chronic condition among the elderly. Disruption of any part along the auditory pathway (such as peripheral to central) may lead to hearing impairment. Problems in the outer ear (such as blockage of ear canal) or middle ear (such as ossicular chain discontinuity) cause conductive hearing loss, and problems in the inner ear (such as loss of outer and/or inner hair cells in cochlea) or in the auditory nerve to central auditory pathway (such as auditory neuropathy) result in sensorineural hearing loss.

Perceptual consequences of sensorineural hearing loss, especially hearing loss due to cochlear damage, include reduced audibility, abnormal growth of loudness, decreased frequency and temporal resolution, and impaired ability to discriminate pitch and localize sound sources (Moore, 1996). In particular, reduced spectro-temporal acuity (such as poorer frequency selectivity) makes perceptual separation of different component sources in a complex sound difficult. Therefore, daily listening abilities, such as detection and discrimination of sound and speech understanding, especially in complex listening environments with competing noise sources, are affected in individuals with cochlear hearing impairment. In conductive hearing loss, reduced audibility is the major consequence because the cochlea is functioning normally (i.e., frequency resolution, temporal resolution, and loudness growth are not affected).

Hearing aids and signal processing

Hearing aids represent the most common way of compensating for hearing impairment, and the primary goal is to restore audibility. Hearing aid outcome is usually satisfactory in quiet but not in noisy situations (Kochkin, 2000). Therefore, signal processing algorithms are implemented in hearing aids to further improve speech understanding and to reduce listening effort in noise (for example Dillon, 2001). Individuals with cochlear hearing loss usually find it difficult to listen in complex acoustic environments with competing noise. Shinn-Cunningham and Best (2008) suggested that this phenomenon is partly related to the limited ability to extract and selectively attend to the target auditory stream, and that noise reduction systems that suppress competing noise could potentially reduce the amount of listening effort required to achieve successful speech understanding in challenging listening situations.

Different signal processing schemes are designed to improve speech intelligibility using various techniques. Wide dynamic range compression with various types of implementations (such as fast- or slow-acting) aims to alleviate the problem of abnormal loudness growth. Directional microphones emphasize target speech that typically comes from the front by suppressing unwanted sounds coming from other spatial directions. Noise reduction systems, or more specifically, single microphone noise reduction systems, are designed to separate target speech from disturbing noise by using a separation algorithm operating on the input (Hendriks et al., 2013). This processing is most often intended to reduce gain, either in the low frequencies or in specific frequency bands, when steady-state noise (recognized as signal by the noise reduction system) is identified.

There are several approaches to noise reduction. One is long-term attenuation, a standard noise reduction system in current hearing aids, which analyzes the modulation of frequency in different frequency bands. Since speech (and/or music) components have much higher values of modulation frequency than noise (Plomp, 1994), frequency bands with higher frequency modulation are classified as the desired signal and amplified, while bands with less modulation are considered as noise and attenuated. In this way, frequency bands with very low signal-to-noise ratios (SNRs) are attenuated, and long-term SNR enhancement is achieved. However, this method is not effective in differentiating between the desired signal and noise that are located in similar frequency ranges, nor does it appear to improve speech recognition in noise (Bentler & Chiou, 2006; Lunner et al., 2009).

Another approach is based on short-term estimates of the desired signal and noise that are located in the same frequency ranges. This is achieved by estimating power spectral densities in brief pauses of the desired signal or by using statistical modeling of speech and noise components (such as a Wiener-filter-based model or similar statistical model, as proposed by Ephraim and Malah, 1984, 1985). Spectral subtraction is then performed based on the estimated power spectral density of the desired signal and noise, and short-term attenuation is applied to each frequency band. The problem with this approach is that the use of estimates causes distortion, which is known as the musical noise phenomenon (Berouti et al., 1979; Cappé, 1994; Takeshi et al., 2003). The Ephraim-Malah scheme yields a stronger noise reduction effect and generates less distortion when the background noise is steady-state in nature than strongly fluctuating (such as speech babble; Marzinzik, 2000).

The use of binary time-frequency masks is a recent approach aimed at separating the desired speech signal from speech-in-noise mixtures (Wang et al., 2009). Not yet available in commercial hearing aids, this noise reduction scheme involves the removal of noise dominant, spectro-temporal regions in the speech-in-noise mixture. For each

speech-in-noise mixture, time-frequency units are formed by applying a 64-channel gammatone filterbank followed by time-windowing. Comparisons are made between the estimated desired signal and the estimated noise, with different versions of binary masks reported in the literature. For the ideal binary masks used in Wang et al. (2009), complete information of both desired signal and noise are known to the algorithm. For the realistic version of binary masks (Boldt et al., 2008), the desired signal and noise are estimated using directional microphones. For each time-frequency unit in the binary matrix, noise is attenuated if the energy of the noise exceeds the energy of the target speech (i.e., has a local SNR of 0 dB or below). If the local SNR is above 0 dB, the unit is retained in the binary matrix to optimize the SNR gain with the binary masks (Li & Wang, 2009). Designed to enhance speech intelligibility, the binary masking noise reduction scheme has been proven to show substantial improvement in speech recognition in a background with irrelevant speech (Brungart et al., 2006; Wang et al., 2009).

Research in Hearing Disability: An Interdisciplinary Approach

This thesis applies the bio-psycho-social perspective established by the World Health Organization (WHO) (2001). Other approaches, representing individual or social perspectives, focus on one single dimension of disability and do not give a complete view of impairment and disability (Barnes et al., 1999; Samaha, 2007). The bio-psycho-social model, however, is an interdisciplinary approach in disability research and emphasizes the *interaction* between individual physical functions (such as medical conditions or body functioning) and social or environmental factors (like use of technology, socioeconomic status, and culture), together with a third, psychological component, comprising the individual's attitudes, motivation, awareness, and emotions. All of these together enable the bio-psycho-social model to describe disability in a holistic way. Based on this bio-psycho-social model, the International Classification of Functioning, Disability and Health (ICF) is a framework for such a description of function and disability as an outcome of interactions between health conditions and contextual factors.

The three ICF elements—*body functions and structures*, *environmental factors*, and *activity limitations and participation restrictions*—are considered in this thesis, which focuses on how the hearing-related body functions, such as hearing (b230), speech discrimination (b2304), memory function (b144), and mental functions of language (b167) might be improved by the wearing of hearing aids (environmental factor: assistive products and technology for communication, e1251) by individuals with sensorineural hearing impairment (body structure: inner ear, s260). Hearing aid technology may reduce experienced activity limitations and participation restrictions: for example, an individual with hearing impairment may feel left out in group situations (d3504, d750, d910)

because speech understanding is difficult in noisy environments (d310) (Hickson & Scarinci, 2007).

This thesis falls within the field of Cognitive Hearing Science, an interdisciplinary scientific study of cognition and hearing (Arlinger et al., 2009). This research field explores the balance between bottom-up and top-down information processing in different listening situations and demands. Research on language processing in adverse conditions and the use of auditory communication technologies (such as hearing aids and cochlear implants) are major topics within this field.

Theoretical Framework: Cognitive Mechanisms in Speech Understanding

Based on the ICF (WHO, 2001), Kiessling et al. (2003) outlined four processes involved in auditory functioning. These are 1) hearing, the detection of sound; 2) listening, the process of intentional and attentional hearing; 3) comprehending, the extraction of meaning and information that follows listening; and 4) communicating, which refers to an interactive and bidirectional way of exchanging meaning and information. While auditory processing is fundamental to all these functions, listening, comprehending and communicating depend to a great extent on cognitive processing.

The comprehension of speech involves a sequence of processes, ranging from acoustically-driven bottom-up processing (such as detection of auditory information) to cognitively-driven top-down processing (such as interpretation of speech signals with the help of prior knowledge, experience, and language proficiency) (Davis & Johnsrude, 2007; Rönnberg, 2003; Rönnberg et al., 2008, 2013). In quiet listening conditions, and with proper amplification for listeners with hearing loss, speech is mostly audible to the extent that 100% intelligibility is reached. Speech perception can be successfully achieved by bottom-up hearing, and use of contextual information is not necessary to a large degree. In noisy or adverse listening conditions, bottom-up hearing is difficult because the acoustic signal becomes distorted and/or less audible. Prior knowledge and contextual information are needed in order to fill in missing words in a sentence and to disambiguate alternative possible interpretations. This is referred to as remedial processing. Therefore, depending on the adversity of the listening situation, the balance of bottom-up and top-down processing varies.

A number of cognitive functions are related to general speech understanding, including speed of information processing and lexical access, phonological processing skills, and working memory capacity (Hällgren et al., 2001; Larsby et al., 2005; Lunner, 2003;

Lyxell et al., 2003; Rönnerberg et al., 2008). These functions are important because they are related to the accessing of information from semantic long-term memory. For instance, a high speed of lexical access allows efficient retrieval of information from the lexicon. Phonological processing skills are crucial in speech perception because they reflect the ability to detect, discriminate, and attend to speech sounds, and to maintain sounds in working memory.

Working memory

Working memory is the capacity for the simultaneous storage and online processing of information (Baddeley & Hitch, 1974). In working memory, task-relevant information can be maintained while complex cognitive tasks, such as speech understanding in adverse conditions, are performed. The above-mentioned remedial processes (use of prior and contextual knowledge to fill in the gaps when a word is inaudible) involve maintaining incoming information in the short-term store and retrieving relevant information from the long-term store (Lunner et al., 2009; Pichora-Fuller, 2003). Working memory is also highly associated with executive functions such as inhibition, the process involved in preventing irrelevant information from entering working memory (for example, Hasher et al., 1999), and attention, the process of selecting and limiting the amount of information entering or remaining in working memory (Atkinson & Shiffrin, 1968).

Working memory capacity varies between individuals. Individual differences in working memory, which are commonly measured using complex span tests, can predict performance on challenging linguistic tasks such as language comprehension, vocabulary learning, speech perception, and dichotic listening. Individual differences can be explained in terms of mental resources that can be divided up among processing and storage components in working memory. There are also several possible specific underlying mechanisms that explain the predictive power of complex span tests. These include individual differences in the ability to inhibit irrelevant information (Hasher et al., 1999; May et al., 1999), to divide/control attention (Kane et al., 2006), to selectively attend to target information (Conway et al., 2001), and to effectively retrieve items from the long-term store (Unsworth & Engle, 2007).

Baddeley's model of working memory

Baddeley's multi-component working memory model (Baddeley, 1986, 2000, 2012; Baddeley & Hitch, 1974) is one of the most widely cited working memory models in the literature. It consists of the central executive, which is an attentional control system, aided by three subsidiary slave systems, namely 1) the phonological loop, which deals with language-based verbal information, 2) the visuospatial sketchpad, which processes visual-spatial information, and 3) the episodic buffer, which provides temporary storage.

The episodic buffer also serves as an interface for binding information from different sensory sources, the other two subsidiary systems, and long-term memory. The phonological loop and episodic buffer, where phonological processing and lexical/semantic access take place, are responsible for speech perception. The phonological loop is comprised of a phonological store and articulatory or subvocal control processes. Speech or auditory-based input enters the phonological store directly and is maintained in working memory by the articulatory control processes. The episodic buffer serves as an interface between perception and long-term memory, where the phonological and semantic representations in the lexicon are stored.

Just and Carpenter's capacity theory of working memory

Just and Carpenter (1992) introduced a single-component, resource-limited working memory model for language comprehension. In this model, working memory capacity is expressed as the maximum total resources available for either storage or processing functions in the domain of language comprehension. In other words, these two functions compete for a common pool of resources when task demands exceed the capacity available. Working memory capacity varies between individuals and is related to age. For example, older adults have comparatively limited total resources, meaning that these individuals keep track of and process less amounts of information in a complex cognitive task (Salthouse, 1994). This model of working memory has been successful in explaining individual differences in language comprehension.

One of the classical tests of working memory capacity is the reading span test (Daneman & Carpenter, 1980). This is a complex span test, involving simultaneous processing (judging whether the visually presented sentences are sensible or not) and storage of information (to recall either the first or the final words of sentences). In this test, significant resources are devoted to language processing (judging the meaning of the sentences). This limits the resources remained for storing the to-be-remembered words. Individuals with a capacious working memory, who have more remaining resources upon successful language processing, are therefore better able to accomplish complex tasks than individuals with limited capacity.

The concept of individual differences in working memory capacity was applied throughout this thesis.

A working memory system for ease of language understanding (ELU)

The ease of language understanding (ELU) model (Rönnerberg, 2003; Rönnerberg et al., 2008, 2013) is closely related to the episodic buffer in Baddeley's model, but has a particular emphasis on multi-modal, phonological, and semantic aspects in language understanding (Rönnerberg et al., 2013). The ELU model illustrates the underlying

mechanisms of speech understanding in favorable and challenging listening situations and describes the phonological processing of speech input of both spoken and signed languages in a working memory system. Multi-modal inputs are bound together rapidly and automatically to form phonological streams of information (RAMBPHO) to unlock the lexical information stored in the semantic long-term memory. This processing can be implicit (automatic) or explicit (effortful). Implicit and effortless processing occurs when the listening conditions are favorable. In this case, the input is intact, clear, and non-distorted and matches readily with the phonological representation in long-term memory. When the listening condition is challenging and suboptimal, for example when the incoming speech signal is masked by noise or distorted, a mismatched situation occurs because the input signal cannot be readily matched with the phonological representation in the lexicon. This requires top-down remedial processing in order to make sense of the suboptimal input signal. The processing is then explicit and effortful.

As a perceptual consequence of cochlear damage, individuals with hearing impairment are exposed to distorted auditory inputs. Therefore, they may also tend to experience more explicit processing when compared to individuals with normal hearing. The ELU model predicts the engagement of explicit processing 1) when listening with hearing aids with advanced signal processing that distorts the original input signal, and 2) as the new hearing aid users become habituated to the device.

Listening to processed speech signals

Peripheral sensory degradation due to cochlear damage may demand extra cognitive resources during speech processing, which in turn restrains the amount of resources devoted to other cognitive functions (Edwards, 2007; Stenfelt & Rönnberg, 2009). Amplification and signal processing in hearing aids are designed to give a clearer (or more audible) auditory input, especially in challenging or noisy listening conditions. According to the ELU model, more explicit working-memory based processing is needed when auditory input is distorted or less audible, which leaves fewer resources available for the processing of auditory input. For instance, comprehending speech in noisy situations often requires contextual information because typically not all words are heard accurately in those situations.

However, advanced signal processing may also have undesirable side-effects, such as generating unwanted artifacts in the auditory scene or distorting the waveform of the target signal, which makes listening challenging. Listening to suboptimal incoming signal may recruit explicit processing and tax working memory resources (Lunner et al., 2009; Wang, 2008). Individuals with limited working memory capacity may have limited benefit from signal processing because the extra demand for working memory resources imposed by signal processing may exhaust their maximum total resources available. Thus,

whether a hearing aid user can take advantage from signal processing may be dependent on the individual working memory capacity (Rönnberg et al., 2013).

Unhabituated hearing aid amplification and settings

Processed or amplified speech signals may sound unnatural because of the presence of artifacts and/or distortions. For people who are not habituated to listening to processed or amplified speech, phonological representations of this kind of speech signal would not be congruent with those in the lexicon. When a person is newly fitted with hearing aids, a mismatched listening condition may arise because the processed speech signal could not be readily matched with the phonological representations in long-term memory. As a result, more explicit and top-down processing would be required for speech comprehension, related to which working memory capacity for explicit processing may play an important role. After using the hearing aid amplification and setting for a certain period of time, new phonological representations that are congruent with the processed speech signal are assumed to be established in long-term memory. Hence, less explicit processing would be engaged and the role of working memory capacity may become less important. In other words, the association between speech understanding and working memory capacity is expected to be the strongest when hearing aids are newly fitted (i.e., representing a mismatched listening condition), and this association should be weakened over time. Some studies have demonstrated this mismatch effect in experienced hearing aid users fitted with a new compression setting (Foo et al., 2007; Rudner et al., 2008, 2009). Similar effects in first-time users have not been documented.

Unsworth and Engle's dual-store model of working memory

Unsworth and Engle (2007) proposed a dual-store model of memory that is useful in predicting performance in memory or free recall tasks based on individual working memory capacity. In this framework, individual differences in working memory capacity are related to differences in the ability to maintain information in the short-term store (primary memory), and the ability to retrieve information from the long-term store (secondary memory), using a cue-dependent search mechanism. These two memory stores are regarded as independent of each other. In this model, individuals with low working memory capacity are generally poorer at retrieving information from both memory stores than individuals with high working memory capacity because these individuals tend to activate more irrelevant information during retrieval, which interferes proactively with the relevant information. Individuals with high working memory capacity are assumed to suffer less from proactive interference, resulting in better memory performance. However, proactive interference selectively disrupts retrieval for information from the long-term store only (Davelaar et al., 2005). Therefore, when the serial position effect in a free recall task is examined (Figure 1), individual differences in working memory capacity will be more pronounced for pre-recency items than recency

items. The probability of recall of pre-recency items (primacy and asymptote items) reflects retrieval of information from temporally early positions in a list of items presented for recall, and is assumed to measure retrieval from a long-term storage component. The probability of recency item retrieval reflects the retrieval of late items in the list, and is assumed to reflect retrieval from a short-term storage component.

Figure 1. A typical serial position curve for free recall.

Individual differences in cognitive abilities and speech recognition performance in hearing aid users: Empirical evidence

It is a well-known clinical phenomenon that hearing aid users with the same audiometric configurations and hearing aid fittings can demonstrate rather different outcomes (e.g., Saunders & Cienkowski, 2002; Saunders & Forsline, 2006; Saunders et al., 2004). Therefore, there must be other individual factors affecting the outcome of hearing aid amplification. While loss of sensitivity or elevated hearing thresholds have been equally compensated, apart from differences in peripheral origins of the hearing impairment, the difference in hearing aid fitting outcome may also partially be attributed to individual differences in higher-order cognitive abilities. Based on the ELU model, explicit cognitive processing is engaged when the listening situation is adverse or when the RAMBPHO-delivered representations suddenly change in character (Rönnberg et al., 2013). Having limited working memory capacity may constrain the engagement of the extra processing required to listen to distorted and processed speech signals. This may, in turn, reduce the benefit of hearing aid amplification. Likewise, hearing aid users with better working memory capacity tend to be more positively influenced by hearing aid

amplification and signal processing (for example, Foo et al., 2007; Gatehouse et al., 2003; Moore, 2008; Rudner et al., 2009, 2011).

Several empirical studies have successfully established the link between cognitive abilities and speech recognition performance in hearing aid users. Lunner (2003) found that scores for the reading span test and a rhyme judgment test, in which phonological processing speed was measured, correlated with the SNRs required to achieve 40% speech recognition using a Swedish version of the Hagerman test (Hagerman & Kinnefors, 1995). This held true for both aided and unaided conditions. In other words, hearing aid users with better cognitive functions demonstrated better speech recognition performance. Gatehouse et al. (2003) also studied how cognitive abilities and speech perception in noise were related. They found that listeners with better working memory, as measured by visual digit- and letter-monitoring tasks, performed better in a speech-recognition-in-noise test, especially in an amplitude-modulated noise background than individuals with poorer working memory.

The role of individual differences in cognitive abilities has also been investigated in studies comparing different hearing aid signal processing algorithms. For instance, fast- and slow-acting compression settings have differential effects on different listeners, depending on their cognitive abilities. Both compression settings have their own advantages. Fast-acting compression enables soft consonant sounds to become more audible, while slow-acting compression preserves speech naturalness and gives better subjective listening comfort (Gatehouse et al., 2006). The general conclusion of these studies is that people with better cognitive abilities can benefit from fast release time of compression in modulated noise, although this is not the case for those with poorer cognitive abilities (Foo et al., 2007; Gatehouse et al., 2006; Lunner & Sundewall-Thorén, 2007; Moore, 2008; Rudner et al., 2009, 2011).

Which cognitive function best predicts aided performance in noise?

As discussed, working memory capacity is an important factor in speech understanding. In a review of studies on speech recognition and cognitive abilities, Akeroyd (2008) concluded that hearing loss was the primary predictor of speech recognition performance, while individual cognitive ability emerged as the secondary factor. Among all the cognitive tests used in these studies, such as general scholastic achievements, IQ tests, working memory capacity tests, visual analogs of speech reception and rhyme judgment tests, the most effective predictor was working memory capacity measured by the reading span test. Given the mixed evidence available, however, the way in which general processes, such as processing speed and the ability to fill in missing words, may influence or relate to language- or speech-specific processes remains unclear. Humes (2007) also drew a similar conclusion in his review, finding that in addition to audibility, cognition

emerged as a predictor of speech recognition performance in older adults with hearing impairment. Besser et al. (2013) reviewed more than twenty recent studies examining the relationship between working memory measured using the reading span test and speech recognition performance in noise. A positive association between working memory capacity and speech recognition performance in both speech babble and steady-state noise was found across studies. Taken together, these three reviews indicate that working memory is a promising predictor of speech recognition performance.

Hearing Aids and Their Benefit

Hearing impairment has a negative impact on different levels of auditory functioning. Based on the auditory functioning outlined by Kiessling et al. (2003), three out of four processes (listening, comprehending, and communicating) depend to a great extent on cognitive processing. Therefore, the involvement of cognitive processing in these three processes may be affected by peripheral sensory degradation. Compared to intact peripheral sensory function, peripheral sensory degradation makes signal-based (bottom-up) perception less accurate and causes it to have a greater demand on top-down processing in order to achieve successful listening. Thus, it is possible that hearing aids, which presumably improve audibility of the speech signal, reduce the engagement of top-down processing, and hence, that cognitive resources would be freed up for other cognitive tasks (Edwards, 2007). The following sections discuss the interaction between listening situations, hearing aids, and performance on cognitive tasks.

Listening in adverse situations and performance on cognitive tasks

A number of studies have shown that memory for speech heard in noise is worse than in quiet, even when the to-be-remembered speech stimuli are recognized accurately (Heinrich & Schneider, 2011; Heinrich et al., 2008; McCoy et al., 2005; Murphy et al., 2000; Pichora-Fuller et al., 1995; Rabbitt, 1990; Sarampalis et al., 2009; Tun et al., 2002, 2009; Wingfield et al., 2005). One common explanation of this finding is that listening in challenging situations, such as with reduced hearing sensitivity and in the presence of noise, requires more effort than in easy listening situations (such as in quiet) (Mattys et al., 2012). In other words, listening effort, which is often conceptualized as the amount of cognitive resources devoted to speech recognition (Picou et al., 2013), increases as the situation becomes more challenging, and extra resources may be required to achieve successful speech recognition (Rudner et al., 2012). This may reduce the remaining resources available for other processing and thus have a negative consequence on cognitive performance, such as memory, attention, and speed of processing (Pichora-Fuller & Singh, 2006). In particular, Heinrich and Schneider (2011), Heinrich et al. (2008), and Murphy et al. (2000) investigated how noise affects memory for speech using

a free recall paradigm. The serial position curve was used to elucidate the loci of effects. Summarizing these studies, better memory for early serial speech items (i.e., primacy positions) was found in younger than older adults. Older adults, who often have limited working memory capacity (Nyberg et al., 2012), may have less efficient encoding of these items into their long-term store, and hence demonstrate a weaker primacy effect. Auditory segregation between speech and noise might be slowed down when speech is presented in competing speech babble. This may result in a negative impact on memory for late serial items (i.e., recency position) (Heinrich & Schneider, 2011). In other words, for older adults, the encoding of items into working memory may also become less efficient, which is in turn reflected in the recency positions.

Background speech in an intelligible language has a stronger masking effect on target speech than stationary noise (Mattys et al., 2009). The presence of irrelevant linguistic information is distracting and may make segregation and extraction of the target signal from noise more difficult (Rönnberg et al., 2010; Sörqvist & Rönnberg, 2012). According to Mattys et al. (2009), segregation of target speech from background noise is fundamentally driven by the differences in acoustic properties. However, segregation can also be driven by semantic and linguistic differences. When the background contains competing speech, segregation becomes cognitively demanding. Since working memory has a limited capacity, when more resources are demanded for segregation, fewer resources are left for higher-order processes, such as memory (Heinrich & Schneider, 2011; Heinrich et al., 2008; McCoy et al., 2005; Murphy et al., 2000; Rabbitt, 1990; Sarampalis et al., 2009; Tun et al., 2002; Wingfield et al., 2005). Thus, background speech in an intelligible language has an adverse effect on cognitive processes.

Hearing aids and cognitive benefit

As discussed, speech understanding engages both bottom-up and top-down processing. Having a hearing impairment would lead to less efficient bottom-up processing, and therefore more top-down processing would be recruited in order to achieve successful listening. A well-fitted hearing aid with appropriate amplification and signal processing enhances audibility and may make listening less effortful if the demand on top-down processing is reduced. This would in turn free up resources for higher-order cognitive processes. In other words, hearing aids may have a positive impact on the performance of cognitive tasks.

While aided speech recognition performance has been commonly used to quantify hearing aid outcome, other measures, such as changes in listening effort, have been used in the literature to show the cognitive benefits of hearing aid amplification (for example, Downs, 1982; Gatehouse & Gordon, 1990; Hornsby, 2013; Hällgren et al., 2005; Picou et al., 2013; Sarampalis et al., 2009). Gatehouse and Gordon (1990) evaluated the benefit of

hearing aids using word and sentence identification tests. Both accuracy (percentage correct) and response time (to identify target words) measures were used. In test conditions where no benefit of aided performance over unaided performance was shown using the accuracy measure, faster response time was obtained in the aided condition. Similarly, in test conditions where an amplification benefit as based on the accuracy measure was shown, a benefit based on the reaction time measure was also shown and was substantially greater in relative terms than that based on the accuracy measure. The authors concluded that the response time measure was sensitive and effective in demonstrating benefit, which could hardly be shown in the traditional accuracy measure. They argued that hearing loss demanded extra perceptual effort to decode a given speech signal and, consequently, prolonged response time. Speech perception performance should, therefore, not be the only way to measure hearing aid benefit.

Sarampalis et al. (2009) showed that a hearing aid noise reduction algorithm (Ephraim-Malah, 1984, 1985) improved memory for heard speech material and reduced listening effort for young adults with normal hearing. A dual task paradigm was used. Listeners were required to report the final words of sentences in a list, which were those originally used in the Speech Perception In Noise test (Kalikow et al., 1977), presented in four-talker babble and in quiet. After every list of eight sentences, the participants were cued to recall all the final words that they had previously reported (see Pichora-Fuller et al., 1995 for details of the recall paradigm). The results showed that in sentences with highly predictable final words presented at low SNR (-2 dB), recall performance was enhanced when noise reduction was applied. Rehearsal of the final words, especially those from earlier sentences in a list, was facilitated by noise reduction. Such enhancement was not observed in sentences with non-predictable final words, regardless of the SNRs and the use of noise reduction. The primacy effect was the strongest in quiet when compared to the conditions in noise, with and without noise reduction, and regardless of the predictability of the final words. Based on these results, therefore, the authors concluded that listening effort, as indicated by the magnitude of the primacy effect, increased when background noise was present. When noise reduction was applied, listening effort was reduced, and resources were freed up for rehearsal and encoding into long-term storage. However, similar benefits in listeners with hearing impairment have not hitherto been reported. This is the focus of this thesis.

Measuring hearing aid benefit

At present, the common ways to measure the outcome of hearing aid fitting include real ear measurement or functional gain measurement, speech audiometry, and self-report instruments. However, a good outcome using these clinical tests may not necessarily correspond to a satisfactory outcome in daily life (Taylor, 2007a). There are numerous factors that could explain the discrepancy. For example, test conditions in clinics do not

well represent the listening environments in real life. Thus, the test scores have limited predictive values in real-world hearing aid performance.

Traditional speech recognition tests, where repetition of speech heard is required, may not truly reflect the ability to process speech because other factors, such as use of prior knowledge, contextual information, and communication tactics, could affect real-life listening performance. In real life, we often listen in the presence of some adverse environmental noise, which leads to a heavy reliance on top-down processing and reallocation of cognitive resources to speech perception. Performance on traditional speech recognition tests (known as speech recognition threshold) indicates the SNR needed to achieve a certain level of speech intelligibility. However, this speech recognition threshold may not be sensitive to uncovering differences in the amount of extra resources engaged in speech perception. Many cognitive tasks may also be involved at the same time in an ongoing discourse, such as interpretation of information, decision making, turn-taking and retrieving events from memory, rather than just listening. Thus, a test that requires the simultaneous perception and processing of speech information could be a better way to evaluate hearing aid and signal processing algorithms.

Recent research has focused on ways in which hearing aid outcome can be evaluated on a dimension beyond speech recognition. Sarampalis et al. (2009) demonstrated the benefit of a noise reduction algorithm using a free recall test, where the participants were instructed to repeat and recall the final words of sentences. This kind of free recall paradigm requires simultaneous identification and memorization of heard speech and better resembles a daily communication situation than traditional speech recognition tests, which only require speech identification. Less cognitive resources would be required for speech perception in noise when an appropriate hearing aid signal processing algorithm is applied than when there is no processing, allowing for more remaining resources to be made available in order to remember target words, which will be reflected in the test performance. The cognitive capacity that remains once successful listening is achieved is known as cognitive spare capacity (Mishra et al., 2013). Ways in which noise and/or signal processing interact with serial position (which reflects recall of items from different memory stores) can also be studied using the free recall paradigm.

Another concern for the realistic measurement of aided performance in clinics is that conventional speech recognition tests are usually performed at undesirable SNRs. These speech recognition tests aim to obtain aided or unaided speech recognition thresholds at 50% intelligibility. This intelligibility level is commonly used because at 50% intelligibility, the slope of the psychometric function for speech intelligibility is the steepest. Thus, the speech recognition test measurement is most sensitive at the steepest part of the slope (where a change of 1 dB would cause typically a 10% to 15% change in

intelligibility). When this method is used, hearing aid users are typically tested at negative SNRs for both unaided and aided testing. According to Smeds et al. (2012), SNR test scores may be considered not to be an effective basis on which to evaluate hearing aid outcomes in the conditions experienced in daily life. Thus, there is a need to develop a test which measures performance at positive or realistic SNRs (i.e., between 0 and 15 dB SNR), where traditional speech recognition threshold measures are insensitive. Moreover, hearing aid signal processing algorithms are designed to be used in positive but not negative SNRs (Hendriks et al., 2013). It is important to include a test that allows for measurement at favorable SNRs in outcome assessment.

Theoretically, speech perception in negative SNRs is effortful and may exhaust cognitive resources in working memory (by means of engaging explicit cognitive processing). Speech is highly intelligible in favorable (positive) SNRs, and speech perception becomes less effortful because less top-down processing would be needed. Hence, there would be more cognitive resources remaining for other cognitive tasks. When speech is highly intelligible in the presence and absence of noise and/or hearing aid signal processing, significant differences in the cognitive task performance in varying test conditions may be associated with a change in listening effort. Therefore, a task paradigm which requires simultaneous processing and storage of information and the application of positive SNRs are the two crucial elements for the design of an outcome assessment tool that is complimentary to a traditional speech recognition test.

To summarize, working memory plays a crucial role in speech recognition. Based on different models of working memory, factors including listening situations and individual differences in working memory capacity predict effects on the processing and storage of speech. Although hearing aids work satisfactorily in quiet conditions, listening in noise remains problematic and cognitively taxing. Advanced signal processing algorithms may reduce listening effort in noise and therefore free up cognitive resources for other cognitive tasks. To measure the potential effects of signal processing on cognitive task performance, a free recall paradigm is used, which also enables testing at positive SNRs. Since the SNR used in the free recall paradigm better resembles realistic situations, good correlations are expected between the test results and self-reported hearing aid outcome.

Overall Aims

This thesis investigated the role of cognition in experienced and new hearing aid users. There were five aims. For experienced users, the effects of a hearing aid signal processing algorithm on the simultaneous processing and storage of speech heard in noise were studied. The aims were 1) to develop a cognitive test, called the Sentence-final Word Identification and Recall (SWIR) test, to measure the effects of hearing aid signal processing on the processing of highly intelligible speech; 2) to investigate, using the SWIR test, whether hearing aid signal processing would affect memory for heard speech; 3) to test whether the effects of signal processing on the ability to recall speech would interact with background noise and/or individual differences in working memory capacity; and 4) to explore the potential clinical application of the SWIR test by examining the relationship between SWIR performance and self-reported hearing aid outcome. For new users, using various models and different settings of hearing aids, the aim was 5) to examine the relationship between cognition and speech recognition performance in noise over the first six months of hearing aid use.

Papers 1 and 3 addressed the first three aims of this thesis. The SWIR test, which is a free recall test similar to the one described in Sarampalis et al. (2009), was developed to examine the effects of noise and a noise reduction algorithm on memory for speech in hearing aid users. Binary time-frequency masking, which is a noise-reducing signal processing scheme (Wang et al., 2009), was used in this thesis. This signal processing technique is designed to maximize speech enhancement and is effective when speech is masked by irrelevant information (Brungart et al., 2006). It improves speech intelligibility in noise for individuals with normal hearing and hearing impairment (Wang et al., 2009). Clearer speech input, as a result of noise reduction, may result in a better representation in working memory and hence improve recall performance. It is hypothesized that noise reduction may reduce the resources required for speech identification in noise. This might leave more resources for encoding the target speech items into memory. The prediction was also that this effect would be modulated by individual differences in working memory capacity, such that individuals with a capacious working memory could take greater advantage of the noise reduction algorithm than individuals with limited working memory capacity.

Paper 2 addressed the fourth aim. In order to explore the potential of using the SWIR test in clinics, specifically to determine ways in which knowledge of the individual's cognitive ability can be used during hearing aid fitting, the relationship between SWIR performance in an aided listening situation (obtained in Paper 1) and self-reported hearing aid outcome was examined in Paper 2.

The fifth aim was examined in Paper 4. As hypothesized by the ELU model, explicit processing is engaged when the listening situation is adverse. Listening with hearing aids may also create a suboptimal listening situation because the processed signal may introduce distortion and artifacts. In particular, first-time hearing aid users, who have had no prior experience with hearing aids, may not be accustomed to listening with hearing aids when they are first fitted. In Paper 4, the role of cognitive abilities in aided listening before and after six months of acclimatization was examined. Aided speech recognition performance was obtained at three different occasions over the first six months of hearing aid use. The prediction was that the role of working memory in speech recognition would decline over time because the engagement of explicit processing would be reduced as the new users were getting acclimatized to their hearing aids.

Empirical Studies

General Methods

Participants

All participants, who were native Swedish speakers, were recruited from the audiology clinic of the University Hospital of Linköping, Sweden. The data reported in Papers 1 and 2 shared the same pool of participants. Table 1 summarizes the details of the participants in each paper. None of the participants reported any history of otological problems or psychological disorders. Informed consent was obtained from all participants.

Tests administered

Table 1 shows the details of all tests reported in each paper.

Sentence-final Word Identification and Recall (SWIR) test

The SWIR test was developed in paper 1, and further modified in paper 3, to measure the effects of noise and noise reduction on memory for heard speech materials. The speech material for the test consisted of a subset of 140 sentences from the Swedish version of Hearing-In-Noise Test (HINT) (Hällgren et al., 2006). Since word recall performance is influenced by the syllabic length of the to-be-remembered words (the word-length effect in the phonological loop of working memory; Baddeley et al., 1975), all selected sentences ended in either a bi- or a tri-syllabic noun. The average frequency of occurrence of the sentence final words did not differ significantly between lists. All sentences were presented twice to yield 280 test trials in total. Thirty-five eight-sentence lists and 40 seven-sentence lists were employed as test lists in the studies reported in Papers 1 and 3, respectively.

Each participant listened to the lists of HINT sentences in different background noise and noise reduction conditions. Presentation levels of the sentence stimuli were individualized to optimize equality in listening effort across participants. An individualized SNR, which predicts 95% speech recognition in noise (in steady-state noise in Paper 1, and in Swedish four-talker babble in Paper 3), was applied to all test conditions for each participant. To estimate the individualized SNR predicting 95% speech recognition, the SNR that yielded 84% speech intelligibility in noise using the HINT test with a modified adaptive procedure (Levitt, 1971). Using all data points from the HINT test, an individual psychometric function was plotted. The SNR predicting 95% speech recognition was then estimated using this function.

Table 1. Details of the participants and tests reported in each paper.

Paper	Participants			Tests					
	N	Age (years)	Pure-tone average at 0.5, 1, 2, and 4 kHz (dB HL)	Hearing aid experience (years)	Sentence-final Words Identification and Recall test (SWIR)	Reading span test	Cognitive test battery	IOI-HA and SSQ	Speech-in-noise test (intelligibility level)
1	26 (F: 15, M: 11)	M=59, SD=7, range: 32-65	Symmetrical moderate to moderately-severe sensorineural hearing loss M=49.0, SD=5.9	M=9, SD=7, range: 1-20	• Thirty-five 8-sentence lists • SNR predicting 95% speech recognition in SSN • Noise reduction settings: NoP/ IBM/ NR • Background: Quiet/ SSN/ 4Tswc	Short version (max 24 items)	---	---	---
2						✓	✓	✓	HINT (84%)
3	26 (F: 13, M: 13)	M=62, SD=2, range: 56-65	Symmetrical moderate to moderately-severe sensorineural hearing loss M=51.4, SD=4.9	M=9, SD=8, range: 1-27	• Forty 7-sentence lists • SNR predicting 95% speech recognition in 4Tswc • Noise reduction settings: NoP/ NR • Background: 4Tswc/ 4Tchi	Short version (max 24 items)	---	---	---
4	27 (F: 7, M: 20)	M=66, SD=12, range: 42-84	Symmetrical mild to moderate sensorineural hearing loss M=42.8, SD=8.1	First-time users		Long version (max 54 items)	✓	---	Hagerman test (50%)

The original SWIR test (used in Paper 1) consisted of two tasks performed in sequence. First was the *identification task*, in which participants repeated the final word immediately after listening to each sentence; this was followed by the *free recall task*, in which participants recalled, in any order, the final words that have been previously repeated in the identification task. The modified SWIR test used in Paper 3 also consisted of the two tasks. Here, however, the identification task was only performed on half of the sentence lists (in order to check whether repetition of the final words would affect recall performance). The free recall task remained unchanged.

Binary masking noise reduction

There were three noise reduction settings: 1) without any noise reduction processing (NoP), 2) ideal binary masking noise reduction (IBM) (Wang et al., 2009), and 3) realistic binary masking noise reduction (NR) (Boldt et al., 2008). Both versions of binary masking were used so as to compare the idealized outcome and realistic implementation of this noise reduction scheme. The local SNR in each time-frequency unit was calculated based on known and complete information of speech and noise for IBM. For NR, the local SNR was estimated during recording from the output of directional microphones based on spatially separated speech (front) and noise (rear) sources (see Boldt et al., 2008 for details). An attenuation of 10 dB was applied to any time-frequency unit with a local SNR of 0 dB or below. Since the binary-masking noise-reduction algorithms are not commercially available, none of the participants had previous experience with this kind of signal processing.

Background noise

There were three types of background noise: 1) steady-state noise (SSN), 2) four-talker babble in Swedish (4Tswe), and 3) four-talker babble in Chinese (Cantonese dialect; 4Tchi). The SSN background was the stationary speech-shaped noise used in the Swedish HINT. The 4Tswe and 4Tchi backgrounds consisted of recordings of two male and two female native speakers in the corresponding languages reading different paragraphs of a newspaper text. Background noise started three seconds before the onset of each sentence stimulus and ended one second after sentence offset.

Reading span test

This test consisted of two tasks. First, the participants had to judge whether the three-word sentences shown on the center of a computer screen were sensible or absurd (Baddeley et al., 1985). The three-word sentences were presented word by word, at a rate of 800 msec per word with an inter-stimulus interval of 75 msec. Then, after each list of sentences, the participants were prompted to recall either the first or the final words of the sentences in the list. The test was scored by the total number of items correctly recalled irrespective of serial order.

There are two versions of the test, long and short. In the long version (Daneman & Carpenter, 1980; cf. Rönnerberg et al., 1989), lists of three, four, five, and six three-word sentences were presented in ascending order of length, with three lists for each length. A total of 54 sentences were presented. In the short version, lists of three, four and five three-word sentences were presented in ascending order of length, with two lists for each length. A total of 24 sentences were presented in the short version.

Cognitive test battery

All these tests were visually based and the stimuli were shown in the center of a computer screen.

Physical matching

The task was to judge whether the two tokens of the same letter shown on the screen were identical in physical shape (for example, A-A, but not A-a). This test measures general processing speed (Posner & Mitchell, 1967).

Lexical decision making

The task was to judge whether a string of three letters shown was a real (Swedish) word (for example, “kub”, meaning “cube” but not, for example, “tra”, which is meaningless in Swedish). The real words used were all familiar Swedish words according to Allén (1970). This test measures lexical access speed.

Rhyme judgment test

The task was to judge whether two words of equal length rhymed or not (Baddeley & Wilson, 1985). This test measures the quality of phonological representations in the lexicon (Lyxell, 1994).

Subjective measures of hearing aid outcome

International Outcome Inventory for Hearing Aids (IOI-HA)

There are seven domains of hearing aid outcome in IOI-HA (Cox et al., 2002), including 1) hours of daily use, 2) benefit, 3) residual activity limitation, 4) satisfaction, 5) residual participation restriction, 6) impact on others, and 7) quality of life. The Swedish version of IOI-HA (see Brännström & Wennerström, 2010; Öberg et al., 2007) was used in this thesis. (Appendix I)

Speech, Spatial and Qualities of hearing scale (SSQ)

The SSQ questionnaire (Gatehouse & Noble, 2004) consists of 50 items and covers three major aspects of hearing abilities: Speech hearing, Spatial hearing and Qualities of hearing. The participants were told to rate their aided hearing abilities.

Speech-in-noise tests

Hearing In Noise Test (HINT)

Speech recognition threshold at 84% speech intelligibility in noise was obtained using the Swedish HINT (Hällgren et al., 2006), with a modified adaptive up-down procedure suggested by Levitt (1971).

Hagerman test

This test was used to determine the speech recognition threshold at 50% speech intelligibility using an adaptive test procedure. The speech materials, which consisted of ten lists of low-redundancy five-word sentences, were presented in the presence of speech-shaped noise with a long-term frequency spectrum identical to that of the Hagerman sentences.

Procedure

Papers 1, 2, and 3

The experimental procedure was identical for the studies reported in Papers 1 and 2. The study reported in Paper 3 followed the same procedure, except where otherwise stated: There were two two-hour sessions. In the first session, audiometric measurements together with the reading span test, the cognitive test battery, and the subjective measures of hearing aid outcome were administered. In the second session, prior to the SWIR test, the individualized SNR, which predicts 95% speech recognition, was obtained for each participant and individually applied to all test conditions in the SWIR test.

Paper 4

There were four test sessions: Audiometric measurements, the reading span test, the cognitive test battery, and the Hagerman test (unaided) were performed in a pre-fitting session. The Hagerman test (aided) was administered in the hearing aid fitting session, and another two test sessions which took place at approximately 3 and 6 months after the hearing aid fitting session.

Summary of the Papers

Paper 1

Introduction

This study aimed to examine the effects of noise reduction on memory processing for speech perceived in quiet, in stationary noise, and in a competing speech background.

The role of individual differences in working memory capacity was also investigated. It was predicted that memory performance for speech heard in noise would be worse than in quiet. By introducing noise reduction, performance in noise would be restored. The two versions of binary-masking noise-reduction algorithm (IBM and NR) were also compared.

Method

The reading span test (short version, max score = 24) and the SWIR test were administered. In the SWIR test, there were 35 eight-sentence lists and seven test conditions: one in quiet, which was viewed as ideal noise reduction, and six in noise. The six conditions in noise comprised two types of background noise: SSN and 4Tswe; and three settings of noise reduction: NoP, IBM and NR. For all six test conditions in noise, the individualized presentation level was set at an SNR predicting 95% speech recognition in SSN. The average individualized SNR was 4.1 dB (SD = 1.9). For the quiet condition, speech was fixed at 65 dB A. Linear amplification with an individually prescribed frequency response was given.

Because the individualized presentation level estimated speech intelligibility below 100%, perceptual errors were still expected in the identification task. SWIR performance was scored according to the words correctly recalled in the free recall task calculated as a percentage of the total number of responses given in the identification task (rather than the total number of items in a list).

Results and discussion

There was no significant difference in memory performance between the two versions of noise reduction. Therefore, in order to optimize the variance in the following analyses of variance (ANOVAs), the IBM condition was removed from further analyses. The NR condition was included because it is a realistic estimation of the noise reduction algorithm and can be implemented in hearing aids. Two subgroups were formed ($n = 13$ in each group) based on the reading span test scores. The high and low reading span groups had mean test scores of 12.8 (SD = 2.2) and 7.8 (SD = 2.5) respectively. The reading span group was applied in the following ANOVAs as a between-group factor. The serial position (of presentation in the list of sentences) of the final words in each of the eight-sentence lists in the free recall task was also analyzed. The first to third, fourth to sixth, and seventh and eighth final words in each sentence list were partitioned into the primacy, asymptote, and recency positions, respectively.

Two repeated measures ANOVA were performed. The effect of noise reduction was examined in the first ANOVA by comparing recall performance in quiet, in 4Tswe/NoP, and in 4Tswe/NR. The results showed that recall performance was poorer in 4Tswe than in quiet. Noise reduction significantly reduced the adverse effect of noise on memory for

recency items and for the individuals in the high reading span group only. The effect of background noise on memory was examined in the second ANOVA by comparing recall performance in SSN and in 4Tswe. Recall performance was better in the high than the low reading span group in the presence of NR.

This study showed an effect of noise on memory for individuals with hearing impairment, such that recall of heard speech declined with background noise despite high intelligibility. Noise reduction reduced the adverse effects of noise on memory for individuals with good working memory capacity. The effect of noise reduction occurred in the recency positions. It is argued that the underlying mechanism may be related to facilitated segregation of target word from background noise when there is noise reduction. This would allow more rapid and accurate word identification and would enhance encoding of words into working memory. The results also demonstrated that competing speech was more detrimental to recall performance than stationary noise. Listening in a competing speech background is more cognitively demanding than listening in stationary noise because the lexical-semantic information in competing speech is more distracting (Sörqvist & Rönnerberg, 2012) and is harder to segregate from target speech (Mattys et al., 2009). The results of this study are in line with the prediction derived from the ELU model (Rönnerberg et al., 2013), that the effect of signal processing on memory is modulated by individual differences in working memory capacity.

Paper 2

Introduction

This study aimed to explore whether the SWIR test could potentially be applied in clinics to predict hearing aid outcome in real life. The aim was achieved by examining the relationships between SWIR performance and self-reported hearing aid outcome.

Method

Details of the participants were identical to those reported in Paper 1. In addition to the tests reported in Paper 1 (the reading span test and the SWIR test), Paper 2 included the following tests: subjective measures of hearing aid outcome (IOI-HA and SSQ), the cognitive test battery, and HINT.

Results and discussion

The overall percentage of items correctly recalled in the SWIR test in the five test conditions obtained in Paper 1 (i.e., quiet, SSN/NoP, SSN/NR, 4Tswe/NoP, and 4Tswe/NR) was used in the analyses. Recall performance in all test conditions, with the exception of the 4Tswe/NoP condition, correlated negatively with Item 3 of IOI-HA, which measures residual difficulty in adverse listening situations. There were also

significant correlations between speech recognition performance obtained using HINT and SSQ.

Item 3 of IOI-HA concerns a listening situation where one typically wants to hear better. This situation is assumed to be an adverse listening situation, resembling the situation where the target speech is degraded or competing noise is present. As hypothesized by the ELU model (Rönnberg et al., 2008, 2013), more explicit processing would be engaged to achieve successful understanding when the listening situation is suboptimal. Previous studies have also suggested that the engagement of remedial processing are associated with perceived effort in listening (Hällgren et al., 2005; Koelewijn et al., 2012; Pichora-Fuller, 2003; Rudner et al., 2012). Based on these two assumptions, Item 3, which focuses on the remaining difficulty experienced when hearing aids are used, could be interpreted as the amount of explicit processing *experienced* or how effortful it is to listen in challenging listening situations. In other words, individuals who experience more effort or explicit processing in adverse listening situations tend to report more remaining difficulties.

High performers on the SWIR test had more capacious working memory (as measured by the reading span test) and thus probably had more remaining cognitive resources to engage in more explicit kinds of processing in challenging listening situations than low performers. Therefore, it is not surprising that they are more likely to find it to be more effortful to listen in such situations in real life and report more remaining difficulty, despite the fact that they had the ability to perform well. This result also suggests that as task demand increases, high performers are more able to invoke explicit resources than low performers. In other words, individuals with high working memory capacity may be explicitly aware of the increase in processing load, suggesting a possible relationship between working memory capacity and perceived effort (Rudner et al., 2012; Rönnberg et al., 2013).

The potential clinical implication of the results of this study is that individuals with good cognitive ability, who experienced more remaining difficulties, could be fitted with challenging signal processing algorithms so that they could gain more benefit in adverse conditions.

Paper 3

Introduction

The effects of noise reduction on memory found in Paper 1 were further investigated using a modified version of the SWIR test. The modifications were designed to make the test less cognitively demanding. In addition, the effects of masker language (native versus

foreign) were studied. As in Paper 1, the role of individual differences in working memory capacity was examined.

Method

The reading span test (short version) and the modified SWIR test were administered. Three modifications were made to the SWIR test: 1) there were seven instead of eight sentences in a list; 2) the individualized presentation levels were estimated using an SNR predicting 95% speech recognition in 4Tswe instead of SSN. The average individualized SNR was 7.5 dB (SD = 1.9); and 3) the identification task (repeating the final word after listening to each sentence) was required on only half of the test trials. This was done to check whether there was an effect of immediate repetition of the final word on recall performance. The free recall task remained unchanged.

In total, 40 seven-sentence lists were presented in eight test conditions: two types of background noise: 4Tswe and 4Tchi; two settings of noise reduction: NoP and NR; and two conditions of final word repetitions: repeating the final word verbally after listening to each sentence and not repeating any word in a list. None of the participants in this study were familiar with any dialect of the Chinese language. Two alternative methods of scoring the SWIR test were compared, based on the percentage of words correctly recalled in the free recall task out of the total number of responses given in the identification task, and based on the percentage of words correctly recalled from the total number of items in a list. Because both scoring methods gave the same result patterns and because the identification task was performed on four out of eight test conditions, SWIR performance was scored according to the latter scoring method.

Results and discussion

As in Paper 1, two subgroups were formed based on the reading span test scores. The mean scores of the high and low reading span groups ($n = 13$ in each group) were 12.5 (SD = 1.9) and 7.7 (SD = 1.8) respectively. The serial position of the final words in each of the seven-sentence lists in the free recall task was also analyzed. The first and second, third to fifth, and sixth and seventh final words in each sentence list were partitioned into the primacy, asymptote, and recency positions respectively.

An ANOVA with four within-subject factors (with/without noise reduction, type of competing speech, final word repetition yes/no, and serial position) and one between-subject factor (reading span group) was performed. There was no main effect of final word repetition, indicating that verbally repeating the final words did not affect recall performance.

There was a main effect of noise reduction, indicating that noise reduction improved memory for words heard in noise. In particular, the noise reduction x serial position interaction indicated that increased recall for recency was once again observed, which replicated the data in Paper 1. Interestingly, this effect was found irrespective of working memory capacity. Note that the modified SWIR test was relatively less demanding than the original SWIR test. It is argued that when the test is less demanding (fewer items to be remembered and more favorable individualized SNRs as compared to the original SWIR test), the impact of individual differences in working memory capacity on task performance becomes less important. For the individuals with limited capacity, the modified test presumably did not fully exhaust their cognitive resources, and therefore they had sufficient cognitive capacity to accomplish the task. Then, it was more likely for them to benefit from noise reduction. The noise reduction x serial position x reading span group interaction was also significant. Examination of the interaction demonstrated that the effect of noise reduction occurred in the recency position only in the low reading span group, while it seemed to be rather evenly distributed across serial positions in the high reading span group. The output order of the free recall, which is the probability that the first recalled item comes from a given serial position, was analyzed and the two reading span groups found to have different recall behaviors: the low reading span group focused on the items in the recency position while the high reading span group spread their attention across the list and did not focus on any particular position. This finding is supported by another significant two-way interaction, serial position x reading span group, which indicated that the high reading span group had significantly better memory performance in the primacy portion of the serial position curve than did the low reading span group.

Recall performance was more disrupted by the native language masker than the unintelligible foreign language masker. When noise reduction was applied, the effect of the native language masker was reduced to that of the foreign language masker. One possible mechanism is that noise reduction facilitated segregation of the target native speech from native speech babble (cf. Kilman et al., 2013). Again, noise reduction reduces resources required for speech perception and hence resources are freed up for encoding and consolidation of target words into memory.

Combining the results from Paper 1, the effect of noise reduction on memory was consistently found in the recency position, suggesting that noise reduction facilitated retrieval from short-term memory store. The findings of this study also suggest that the effect of noise reduction is modulated by individual working memory capacity.

Paper 4

Introduction

As hypothesized by the ELU model, because of the impoverished input to the brain by the hearing impairment and because of the eventual presence of distortion and artifacts in processed speech signal, listening with hearing aids would require more explicit processing resources than listening to natural speech in individuals with hearing loss. The ELU model also assumes that for novice users with no previous hearing aid experience, more explicit processing is needed before rather than after acclimatization to the aid has taken place. Auditory acclimatization is defined as the improvement in auditory performance over time as the listener learns to process acoustic signal more efficiently (Arlinger et al., 1996). The study reported in Paper 4 aimed to examine the relationship between aided speech recognition in noise and cognition in new users using various models of hearing aids over the first six months of hearing aid use.

Method

The data reported in this paper was originally collected for a study of quality control of hearing aid fitting in the audiology clinic, the University Hospital of Linköping, Sweden. All participants were first-time hearing aid users (N = 27). Audiometric measurements, the reading span test (long version), the cognitive test battery, and the Hagerman test (unaided) were performed in a pre-fitting session. The Hagerman test (aided) was performed in the hearing aid fitting session (0m) and at three months (3m) and six months (6m) post-fitting.

Results and discussion

Results showed that the correlation between reading span and aided speech recognition performance was significantly weakened over the first six months of hearing aid use. This finding is corroborated by the results of the multiple regression analysis, which indicates that performance on the reading span test was the main predictor of speech recognition performance at 0m, and that hearing thresholds were the main predictor at 6m.

Although hearing aid amplification greatly improves audibility, advanced signal processing may also introduce unwanted artifacts or distortions (Lunner et al., 2009; Wang, 2008). Extra processing resources would then be required to perceive the processed speech signal (Pichora-Fuller, 2003; Rönnberg et al., 2008). When a user is still not acclimatized to listening with hearing aids, there would be a greater need for explicit processing to perceive the processed speech signals; as the user becomes acclimatized to the processed speech signals, the engagement of remedial processing would decrease. Thus, the results of this study suggest that working memory capacity (as measured by the reading span test) plays a more important role in speech recognition in noise before than after acclimatization.

General Discussion

Main Findings and Empirical Conclusions

The results of the SWIR test (Papers 1 and 3) showed that noise reduction freed up cognitive resources and reduced the adverse effect of noise on recall performance. In particular, this effect occurred for recency items of the serial position curve and was found when speech stimuli were presented in a background of speech babble spoken in the listener's native language. The possible underlying mechanisms are that noise reduction facilitates auditory stream segregation between target and irrelevant speech in noise and reduces the attention captured by the linguistic information in irrelevant speech.

When the SWIR test was more cognitively demanding, the effect was shown in individuals with a capacious working memory only (Paper 1). With reduced task demands, the effect was demonstrated in all individuals regardless of individual differences in working memory capacity (Paper 3). However, individual differences in working memory were found to be associated with recall output order. The effects of noise reduction and SWIR performance were modulated by individual differences in working memory, which suggests that working memory capacity interacts with hearing aid signal processing.

SWIR performance predicted self-reported residual activity limitation such that high performers on the SWIR test reported greater remaining difficulty in an adverse listening situation than low performers (Paper 2). This result suggests that individuals with good cognitive ability are better able to utilize explicit resources than individuals with limited cognitive ability. The potential clinical implication is that individuals with good cognitive ability could be fitted with challenging signal processing algorithms so that they could gain more benefit and thus be more satisfied.

Cognitive function, specifically working memory capacity, was found to play a more important role in speech recognition in noise before acclimatization to hearing aid amplification than after six months in new hearing aid users (Paper 4). This pattern suggests that new hearing aid users deploy more explicit cognitive resources for remedial processing when they are not acclimatized to the processed speech signal. As the users become acclimatized to the processed speech signals, the engagement of explicit cognitive processing reduces.

The key role of working memory capacity in aided listening performance in noise, for both new and experienced hearing aid users, is demonstrated. This thesis shows for the

first time that hearing aid signal processing significantly improves memory for highly intelligible speech heard in speech babble presented at SNRs that have a minimal effect on speech perception in individuals with hearing impairment. By virtue of its relations to subjective measures of hearing aid outcome and its capability to measure cognitive benefit of signal processing, the SWIR test can be used as a cognitive measurement tool to assess hearing aid outcome.

Effects of Noise and Noise Reduction on Memory for Speech

Adverse effect of noise on recall performance

Noise has an adverse effect on memory for heard speech. Memory is most disrupted when competing speech spoken in an intelligible language is present. For instance, in Paper 1, speech babble in the listener's native language was more disruptive than stationary noise and quiet; and in Paper 3, speech babble spoken in a foreign (unintelligible) language was less disruptive than that spoken in the native language. It is known that speech babble in an intelligible language has a stronger masking effect than that in an unintelligible language or than stationary noise (Mattys et al., 2009). The results of the present work also suggest a similar conclusion: when the target speech is highly audible and identifiable, the background noise containing speech in an intelligible (the native) language has a more deleterious effect on memory for heard speech than that containing no linguistic information (stationary noise) or unintelligible linguistic information (see also Heinrich & Schneider, 2011; Heinrich et al., 2008; McCoy et al., 2005; Murphy et al., 2000; Rabbitt, 1990; Sarampalis et al., 2009; Tun et al., 2002; Wingfield et al., 2005).

There are two possible interpretations as to why a background containing intelligible linguistic information gives rise to additional difficulty in performing the free recall task. The first is that extra attentional resources are needed for auditory stream segregation in the presence of irrelevant speech information. When the background contains lexical-semantic information, it becomes more distracting and harder to separate the target speech from the background speech (Kilman et al., 2013; Rönnberg et al., 2010; Sörqvist & Rönnberg, 2012). Similarly, the linguistic-similarity hypothesis (Brouwer et al., 2012) proposes that the efficiency of auditory stream segregation is related to the similarities between the target and the masker speech. For example, English is more linguistically similar to Dutch than to Mandarin or Korean, so it would be more difficult to extract target speech in English from masker speech in Dutch than from masker speech in Mandarin. This implies that more attentional and processing resources are drawn from the limited pool of cognitive resources to extract and identify the target speech; this reduces

the remaining resources for the recall task, which involves rehearsing and encoding words into memory (Heinrich & Schneider, 2011).

The second possible interpretation as to why a background containing intelligible linguistic information gives rise to additional difficulty in performing the free recall task is that the irrelevant speech may be processed involuntarily in working memory. Processing of the phonological and lexical-semantic information in the irrelevant speech background may consume some resources and interfere with the rehearsal and encoding of target words (Hasher et al., 1999; May et al., 1999). The irrelevant information, which is encoded into memory, may also compete with the target items during retrieval. Hence, recall performance is impaired.

Effects of noise reduction on recall performance

The general finding here is that the effects of noise reduction were found in a competing native speech background, in which segregating the target speech stream from noise and inhibiting irrelevant speech are required (Robert et al., 2009). When the recall performance was analyzed as a function of serial position, the results of Paper 1 showed that noise reduction restored memory for speech heard in speech babble in the listener's native language for recency items, and for individuals with good working memory capacity only. Similar results were found in Paper 3, where a less cognitively demanding test was used. Noise reduction improved memory for speech heard in speech babble in the native language irrespective of working memory capacity. In particular, the effect of noise reduction was once again found to be significant in the recency portion of the serial position curve. The effect of noise reduction was thus consistently found in the recency portion in both Papers 1 and 3.

One possible explanation for why memory for recency items is improved by noise reduction is that when the background noise is attenuated by noise reduction, the extraction of target words from interfering noise may become more accurate. Hence, words are identified in the lexicon more accurately and with greater speed. This would leave more processing time to be devoted to the encoding of words into working memory, which is reflected in items in the recency serial position (Heinrich & Schneider, 2011; Tun et al., 2009). This finding suggests that noise reduction improves the recall of items from the short-term but not the long-term store. In the framework of Unsworth and Engle (2007), recency items are actively maintained in the short-term store by attention. With noise reduction, less attention may be captured by the distracting irrelevant information, so items can be more efficiently maintained in the short-term store. For pre-recency items, retrieval is based on the search for relevant items activated by contextual cues in the long-term store. The efficiency of the cue-dependent search depends on different factors, such as the search set size, the ability to monitor possible errors in retrieval, and the ability to

recover degraded representations stored in long-term memory (Unsworth, 2009). Attention is also needed for the search, for instance to decide how to search and to determine which cues to use (Unsworth & Engle, 2007), but it appears to play a less central role. Thus, noise reduction seems to have a relatively smaller effect on the recall of pre-recency items.

This finding also agrees with Rönnerberg et al. (2011), who reported that hearing loss is negatively associated with episodic long-term memory but not with short-term memory. The authors predicted that, based on the ELU model, hearing loss would cause an increase in the number of phonological mismatches between the RAMBPHO-delivered phonological representations of the input signal and phonological representations in the lexicon or semantic long-term memory. This gives rise to constant active engagement of explicit processing in the short-term (or working) memory, which keeps short-term memory from disuse. At the same time, under this mismatched condition, lexical access is impaired, less information is encoded into episodic long-term memory, and disuse increases. Such disuse, caused by hearing loss, would lead eventually to a decline in episodic long-term memory. Thus, any potential benefit of noise reduction on recall performance would be more prominent for short-term memory, which is reflected in recall performance in the recency serial position, than for long-term memory. This also provides a plausible explanation as to why the effect of noise reduction was found in the recency position for hearing aid users in Papers 1 and 3, while Sarampalis et al. (2009) demonstrated an improvement in recall for primacy items for individuals with normal hearing. Hearing loss may have a negative impact on episodic long-term memory (Rönnerberg et al., 2011). This suggests that the effect of noise reduction is relatively limited in the primacy serial position for individuals with hearing loss than individuals with normal hearing.

The current results did not suggest that noise reduction has any effect on a noise masker that contains no intelligible linguistic information. In other words, noise reduction is most effective when background noise has a strong masking effect, where segregation or streaming is driven not only by the acoustic differences, but also by the presence of irrelevant linguistic information. Further investigations in this research area may focus on the effect of irrelevant speech spoken in the listener's second language or in an unintelligible language which is linguistically (such as phonetically and acoustically) similar to the listener's native language. How this effect interacts with the proficiency in the listener's second language should also be investigated.

In summary, the results showed that speech babble has an adverse effect on memory for heard speech when both target speech and babble noise are spoken in the listener's native language, and this effect is reduced by noise reduction. In particular, the effect is

observed in the recency serial position. This implies that the retrieval of items from the short-term but not the long-term store is facilitated by noise reduction, which possibly enhances auditory stream segregation between the target and irrelevant speech noise and reduces the attention captured by the linguistic information in irrelevant speech.

Individual Differences in Working Memory Capacity

In Paper 1, the effect of noise reduction on memory was found in individuals with good working memory capacity only. The relationship between the ability to make use of hearing aid signal processing and good cognitive function has been reported in previous studies (for example, Foo et al., 2007; Gatehouse et al., 2003; Lunner, 2003; Lunner & Sundewall-Thorén, 2007; Moore, 2008; Rudner et al., 2011). In Paper 3, the SWIR test was modified (fewer items to be remembered and more favorable individualized SNRs applied) so that it became less cognitively demanding. With the modified SWIR test, noise reduction had effects on memory irrespective of working memory capacity. In other words, the task demand in Paper 1 was sensitive to demonstrating the effect of noise reduction in some but not all participants. To illustrate the effect for all participants, the task demand in Paper 3 proved to be more effective and appropriate. The potential benefit of noise reduction in Paper 1 could have been cancelled out by the excessive task demand for individuals with limited cognitive capacity. However, individual differences were observed when the effect of noise reduction was analyzed as a function of serial position. For individuals with limited capacity, the effect of noise reduction was localized to the recency items, whilst for those with good capacity, the effect was evenly distributed across serial positions. This result may be explained by the differences in recall output order observed in these two groups of individuals. In short, individual differences in working memory modulated SWIR performance in these two studies. These results agree with the predictions based on the ELU model, which proposes that working memory capacity interacts with signal processing (Rönnerberg et al., 2013).

Working memory capacity varies between individuals, and the processing and storage components of working memory compete with each other when the task demand exceeds the limit (Daneman & Carpenter, 1980; Just & Carpenter, 1992). As predicted by the ELU model (Rönnerberg et al., 2013), signal processing and/or the artifacts in the processed signal may introduce phonological mismatch, which in turn requires extra resources to perceive and identify the target speech (i.e., greater demand on the processing component).

The results of Papers 1 and 3 suggest that it is necessary to have sufficient resources to first overcome the demand in listening to the processed speech signals (processing

component) before the potential benefit of noise reduction (leaving more remaining resources for the recall task, storage component) can be utilized. In the original SWIR test (Paper 1), the average individualized SNR was lower (4.2 dB) and a certain amount of processing resources might have been required to identify sentence-final words. For individuals with low working memory, it might be the case that the processing component has already reached the limit of working memory. The resources remaining for the free recall task (storage component) would be minimal, so any potential effect of noise reduction would not be able to be sufficiently demonstrated. Individuals with high working memory capacity would have relatively large resources devoted to the recall task, so the effect of noise reduction could be shown.

In the modified SWIR test (Paper 3), the average SNR was more favorable (7.5 dB), and the resources required for the identification task were presumably reduced. Thus, fewer resources were needed to overcome the extra demand in listening to processed signals, and more resources were freed up for the recall task. This allowed sufficient storage resources for noise reduction to elicit its potential effect on memory for all participants regardless of individual differences in working memory capacity. In Paper 3, the effects of noise reduction were found across all serial positions for individuals with high working memory capacity, while this effect was located in the recency serial positions for individuals with low working memory capacity. This observation is line with the results reported by Unsworth et al. (2011), who indicated that in completing free recall tasks, individuals that focus on both primacy and recency items have a higher working memory capacity than individuals who focus on recency items.

The memory model proposed by Unsworth and Engle (2007) may offer an alternative theoretical explanation. Based on their model, individuals with low working memory capacity suffer from proactive interference, which mainly disrupts information retrieval from long-term memory (Davelaar et al., 2005). Therefore, these individuals may rely more on the short-term store to complete the recall task. The effect of noise reduction was only found in the recency serial position in Paper 3. For individuals with high working memory capacity, information retrieval is assumed to be not affected by proactive interference, so these individuals may rely on both long- and short-term memory. Hence, noise reduction could enhance retrieval from both memory stores and the effect was found across all serial positions. In Paper 1, there were more items to be remembered in the recall task than in Paper 3 (i.e., the task was more demanding). The capacity of the short-term store is assumed to increase with task demand until the maximum capacity is reached (Cowan, 2004; Davelaar et al., 2005). In other words, it could be the case that more items are maintained in short-term memory, and retrieval from short-term memory is prioritized for all individuals. The effect of noise reduction might therefore be more localized to the recency serial positions. This applies to the individuals with high working

memory capacity. As for those individuals with low working memory capacity, they may have had their attention, which is crucial in maintaining items in short-term memory, exhausted by the excessive task demands. Thus, no effect of noise reduction was demonstrated in these individuals.

Relationship between Self-reported Hearing Aid Outcome and SWIR Performance

The two self-reported hearing aid outcome measures chosen in this thesis have different emphases. IOI-HA is a brief questionnaire covering seven major dimensions of hearing aid outcomes, while SSQ is an extensive questionnaire evaluating hearing abilities in everyday life.

One may expect a positive correlation between SWIR performance and self-reported outcome on the basis that the high test performers have a high cognitive capacity and are therefore more likely to receive benefit from hearing aid amplification and signal processing (for example, Foo et al., 2007; Gatehouse et al., 2003; Moore, 2008; Rudner et al., 2009, 2011). However, an inverse relationship (high performers reported more remaining difficulty in an adverse listening situation) was found in Paper 2. Several possible explanations based on different hypotheses or assumptions could account for this counterintuitive finding. The major argument in Paper 2 is based on the cognitive resources hypothesis. It is argued that reported remaining difficulty in adverse listening situations is related to *experienced* explicit processing. In such a listening situation, remedial or explicit cognitive processing is required to match the suboptimal (distorted or noise-masked) speech signal with the phonological representations in long-term memory (Rönnberg, 2003; Rönnberg et al., 2008). This hypothesis suggests a positive relationship between reported remaining difficulties and the remedial processing engaged.

SWIR performance can be viewed as a measure of cognitive spare capacity, such that high performers have a more capacious residual cognitive capacity to remember the target sentence-final words. As a result, these individuals, who are also likely to experience more explicit processing when listening in challenging conditions, tend to report more remaining difficulty. In other words, it is suggested, more vigorous remedial processing is engaged to achieve successful listening due to the greater availability of remaining cognitive resources among high than low performers. This, however, should not be interpreted as the higher absolute levels of difficulty reported by high performers.

Paper 2 showed that cognitive capacity is negatively related to self-perceived residual difficulty and residual activity limitations. This result extends the hypothesis introduced

by Rönnberg et al. (2013), that working memory capacity is related to perceived effort. This hypothesis is based on the assumption that individuals with high capacity are able to invoke more brain resources as task demand or cognitive load increases (Grady, 2012), and is supported by the results reported in Koelewijn et al. (2012), which showed that high performers used more effort (measured in terms of pupil dilation) than low performers to recognize speech in noise.

Expectation of hearing aid outcome could also have explained the current finding. Greater hearing aid benefit has been found to be associated with greater expectations of successful listening (Akeroyd, 2008; Cox & Alexander, 2000; Saunders et al., 2009). High performers of the SWIR test, who have better cognitive capacity and are supposed to have greater hearing aid benefit, may also have greater expectations. They may be aware of their ability to make use of top-down processing to achieve successful listening in unfavorable conditions. Low performers, on the other hand, may have lower expectations because they may be more aware of their limitations in adverse listening conditions. Hearing aid benefit in challenging listening situations is limited when compared with that in quieter listening environments. Expectations for adverse listening situations that go unmet may lead to disappointment. High performers, who are assumed to have greater expectations, may report considerably more remaining difficulties in adverse listening situations, while low performers, who are assumed to have lower expectations, may conversely report less remaining difficulties. How these possible explanations, including the cognitive resources hypothesis, expectation, and self-perception, affect self-reported hearing aid outcome and how these factors interact with each other should be explored in future studies.

The SWIR test is associated with reported remaining difficulty only. No significant correlations were found between SWIR performance and the self-reported outcome measured by other items in IOI-HA and SSQ in Paper 2. The (original) SWIR test, which is considered to be cognitively demanding, resembles a difficult listening situation and might be unrealistically challenging, at least for some participants. This could be the reason why no statistically significant relationship was found with other IOI-HA items or SSQ, which measure or reflect listening experience in real life. It would explain why only Item 3 of IOI-HA, which measures the remaining difficulty in an adverse situation, was significantly associated with SWIR performance.

In summary, the relationships between self-reported hearing aid outcome and SWIR performance have been demonstrated. The results presented here further illustrate the importance of having a cognitive measurement of aided performance and testing at favorable SNRs (Smeds et al., 2012), so that the test results obtained in clinics and the laboratory are associated with subjective outcome. The clinical implication of these

results could be that individuals with high cognitive ability might be fitted with a more challenging signal processing, which may enable them to gain more benefit from and thus be more satisfied with their hearing aids. In other words, knowledge of the individual's cognitive ability could be used during hearing aid fitting to improve satisfaction.

Relationship between Cognition and Speech Recognition in First-time Hearing Aid Users

The results of Paper 4 suggest that when a user is still not acclimatized to listening with hearing aids, there is a greater need for explicit cognitive processing because the processed speech signal cannot be readily matched with the phonological representations in the lexicon. As the user becomes acclimatized to the processed speech signal, the engagement of explicit cognitive processing decreases. Therefore, explicit processing capacity plays a more important role for new than for accustomed users. Rudner et al. (2009) also found that for experienced users fitted with a new hearing aid compression setting, working memory capacity (measured by the reading span test) was the main predictor of aided speech recognition performance in noise before, but not after, acclimatization. Taken together, these results suggest that working memory plays a more important role when users are new to a hearing aid setting or amplification than when they are accustomed to it, which is in line with the general mismatch prediction based on the ELU model. In addition, the findings of Paper 4 extend the conclusion drawn by Rudner et al. (2009) showing that this prediction is applicable to unhabituated hearing aid users using different models of hearing aids and is not tied to particular hearing aid amplifications or signal processing.

Clinical observations and many research studies suggest that there is a positive change in hearing aid benefit over time as new hearing aid users become acclimatized to their devices (see Taylor, 2007b for a review). The change in hearing aid benefit over time is often measured by means of subjective (such as self-report questionnaires) and objective (such as speech audiometry) outcome measures. As aided speech recognition performance improves over time, listening can be more successfully achieved after acclimatization. The matching process between the processed speech signals and the phonological representations in long-term memory may become less explicit. This is probably due to learning and the successive build-up over time of new representations in the lexicon, which become more and more congruent with the processed distorted signals (Rudner et al., 2009). This may also indicate that less explicit processing is engaged when listening with hearing aids to which the users are acclimatized than when listening with hearing aids that the users are new to.

The results of Paper 4, which showed the need for additional engagement of explicit cognitive processing in achieving successful listening in the early stage of acclimatization, may be related to the clinical phenomenon in which new users typically find the processed sounds from the device unnatural and uncomfortable to listen to. The idea that the cognitive hearing system becomes adapted to the processed sounds thus offers a new explanation as to why listening may get easier over time for new users.

Feasibility of Applying the SWIR Test in a Clinical Setting

In this thesis, the SWIR test was developed. The SWIR test measures cognitive spare capacity (Mishra et al., 2013). Like the test used by Sarampalis et al. (2009), in which sentences in English were used, the SWIR test measures the effects of hearing aid signal processing on memory for heard speech. In addition, individualized SNRs were applied in the SWIR test, so as to make the test suitable for testing individuals with varying degrees of hearing impairment.

Traditional speech recognition tests are mostly administered at unfavorable (negative) SNRs. These tests require the repetition of words or sentences, which do not represent daily listening and communication situations. Test performance alone does not always satisfactorily predict subjective hearing aid outcome (Taylor, 2007a). Speech recognition tests may not be the most desirable tools to assess hearing aid outcome if the test results cannot be translated to real-life performance.

The SWIR test is unique and has advantages over the conventional assessment tools in at least in two ways. First, positive SNRs (4.2 and 7.5 dB SNR in Papers 1 and 3 respectively) are applied in the test, and still the effects on memory for heard speech are clear and replicable. This is important because hearing aid signal processing algorithms are designed for listening in real life, in which SNRs are typically positive (Smeds et al., 2012). Moreover, when speech stimuli are highly intelligible (close to 100% speech intelligibility), the SWIR test is still sensitive to the effects of a hearing aid signal processing algorithm. Conventional speech recognition tests may not be sensitive enough to show the potential cognitive effects of advanced signal processing algorithms. For example, Sarampalis et al. (2009) showed that the Ephraim-Malah noise reduction scheme did not have any significant effect on speech recognition performance in noise but did improve memory for heard speech. The second advantage of the SWIR test is that it can also be viewed as a cognitive measure of hearing aid outcome. The SWIR test is inherently more complex than speech recognition tests because it better resembles real-life listening situations, where turn-taking and repetition of speech elements are convolved in the ongoing discourse. SWIR performance is also associated with self-

reported hearing aid outcome. Thus, the SWIR test is a relevant tool for use in clinics to assess hearing aid fitting outcome. This test can potentially be used to compare listening performance between different hearing aid signal processing algorithms, features, and even models.

In Paper 1, the effects of noise reduction were limited to high performers in the SWIR test. In Paper 3, where the SWIR test was modified, the effects of noise reduction were shown in all participants. This illustrates the importance of adequate task demands in assessing the potential effect of any hearing aid signal processing algorithms. Although the current form (modified version) of the test appears to be an appropriate assessment tool to evaluate the binary-masking noise-reduction algorithm, the test should be further fine-tuned for clinical application and use in the assessment of other hearing aid signal processing algorithms.

Theoretical Implications

Noise reduction and the short-term memory store

Sarampalis et al. (2009) found that in young adults with normal hearing, the Ephraim-Malah noise reduction algorithm improved retrieval from the long-term store because noise reduction reduced the resources required for speech identification and freed up more resources for the encoding of target items into the long-term store. This thesis offers a contrasting view, which proposes that the binary-masking noise-reduction algorithm facilitates the retrieval of items from the short-term store for hearing aid users (Papers 1 and 3). The possible underlying mechanism suggested is that noise reduction allows more rapid encoding of items into short-term memory (due to easier segregation of target speech from noise) (Heinrich & Schneider, 2011). Moreover, noise reduction may also allow better maintenance of items in memory because less attention is captured by the distracting, irrelevant information in background noise. Since items in the short-term but not the long-term memory store are actively maintained by attention (Unsworth & Engle, 2007), the retrieval of recency items is enhanced.

There are other factors that could have contributed to the different results between this thesis and Sarampalis et al. (2009). For example, age and/or hearing sensitivity of the sample and the use of different noise reduction algorithms are also possible candidates. Further research is needed to deepen our understanding of whether different signal-processing algorithms would differentially affect recall performance (retrieval from different memory stores) and whether the effects of these algorithms vary among people with normal hearing and hearing impairment.

Working memory and explicit awareness of speech processing

It is argued in Paper 2 that individuals with high working memory capacity are more able than individuals with low working memory capacity to recruit and to utilize cognitive resources in adverse listening conditions. These individuals could therefore experience more remaining difficulty (or may be more aware of the engagement of explicit processing in listening). In Paper 4, the results support the hypothesis (based on the ELU model) that new hearing aid users have a greater need for explicit processing before than after acclimatization. Clinically, these users usually find it uncomfortable, or even effortful, to listen with hearing aids when these are first fitted. Putting these results together, it could be hypothesized that in adverse listening situations, where a person *most wants to hear better* (Paper 2) and is unhabituated to hearing aid amplification (Paper 4), cognitive resources or working memory capacity is explicitly engaged in speech perception. Since explicit processing is assumed to be effortful, listeners may then be aware of such explicit processing during speech processing in adverse conditions. In short, the more the engagement in explicit processing, the greater the difficulty that a listener experiences. Individuals with a capacious working memory may also be more likely to experience more difficulty than individuals with a limited working memory capacity. This support the hypothesis stated in Rönnberg et al. (2013), that perceived effort is related to *experienced* explicit processing.

Methodological Discussion

Dichotomization of the quantitative reading span measure

Although there are potential shortcomings with this analysis technique (in Papers 1 and 3), dividing the groups by their median reading span scores enables further investigation of the interaction effects of individual differences on recall performance. For instance, the results of analyses using this technique showed that there was an interplay between different factors including individual differences, and that noise reduction and background noise had differential effects for some, but not all, participants. However, the point at which the groups were split (into high and low performers on the reading span test) was entirely data-driven: the cut-off point should not be applied clinically. An alternative choice of statistical analysis might be regression analysis with interaction terms. This method of analysis, however, requires a larger sample size.

Sentence stimuli in the SWIR test

The stimuli used in the SWIR test (Papers 1 and 3) consisted of 140 sentences selected from the Swedish HINT sentences. Each sentence was presented twice to yield a total of 280 sentences. The reasons the sentences were used repeatedly were that 1) there is a limited number of HINT sentences that end with a bi- or tri-syllabic noun, and 2) five

sentence lists are needed for each of the test conditions in the SWIR test in order to obtain stabilized serial position curves. The shortcoming of presenting the sentences twice is that there may be a learning effect in the free recall task, such that recall performance for the second presentation of the sentences may be better than for the first presentation. ANOVAs were performed to compare recall performance obtained from the first and the second presentation of the stimuli. The learning effect was found in Paper 1, $F(1, 316) = 4.24, p < 0.05$, and but not in Paper 3, $F(1, 175) = 3.27, p > 0.05$. Nevertheless, the learning effect did not interact with test conditions in either of the two studies, $F(4, 621) = 0.48, p > 0.05$ and $F(7, 175) = 0.29, p > 0.05$, respectively. Therefore, the learning effect did not influence on the interpretations of the results.

Age of participants

The participants recruited in these studies were 60 years of age on average. Although a major decline in episodic memory is expected to begin at the age of 65 (Nyberg et al., 2012), the participants here might still have been at risk of such decline. In all studies, however, hearing aid users with age-related sensorineural hearing loss are the target population. Therefore, it is inevitable that these also belonged to this age range.

Cognitive tests were administered in the studies. The results of these tests suggest that the participants demonstrated age-appropriate cognitive performance. For instance, the reading span test scores, as well as the cognitive test battery performance, were similar to those reported in previous studies, in which the participants' age ranges were similar (e.g., Foo et al., 2007; Lunner, 2003; Rudner et al., 2012; Rönnerberg, 1990). Moreover, working memory capacity in general is strongly related to cognitive functioning such as fluid intelligence and reasoning (Kane et al., 2004; Schmiedek et al., 2009). Thus, the participants in the current studies (Papers 1–4) were believed to have age appropriate cognitive performance. In order to better determine the general mental status of participants, relevant assessment or screening tools, such as the Montreal Cognitive Assessment (Nasreddine et al., 2005), should be included in future studies.

Future Directions

Cognitive Measure as a Hearing Aid Evaluation Tool

This thesis looks at the importance of using cognitively based clinical assessment tools to evaluate hearing aid outcome in a realistic manner. Further investigations should focus on the development of cognitive assessment tools. As discussed previously, it is crucial that the task demand is set at an appropriate level because individual differences in cognitive abilities mean that any potential effect of hearing aid signal processing on memory cannot be uncovered when the task demand is excessive.

In order to apply the SWIR test clinically, the following three aspects of the current version should be further fine-tuned. First, attention needs to be given to the number of to-be-remembered items in a list; alternatively, an adaptive test procedure could be considered (that is, increase the number of to-be-remembered items if all given responses in a list are correct, and vice versa), so that the task demand is adapted according to individual cognitive capacity. Second, the choice of background noise is important; for instance, an effect of noise reduction was found here only in speech babble (four-talker) spoken in the native language. Third, the choice of individualized presentation level is sensitive in any cognitive measure.

Long-term Effect of Signal Processing on Memory for Speech

The study presented here demonstrated an immediate effect of noise reduction. It is therefore valuable to know whether the hearing aid signal processing used in this work will have a long-term effect on recall performance obtained using the SWIR test. Two aspects related to long-term effects are hypothesized here that can be tested in future research. Firstly, it is a clinical phenomenon that aided speech recognition performance improves over time (i.e., acclimatization). It is expected that there is a similar effect of acclimatization on memory for heard speech after using the signal processing algorithm for a longer period of time. Investigations to confirm this are indicated.

Secondly, as suggested in Paper 4 and by Rudner et al. (2009), the role of cognition in speech recognition in noise declines as acclimatization progresses because the explicit processing required to listen to the processed speech signal decreases. A similar trend is expected when the effect of noise reduction (or any kind of advanced signal processing algorithm) on memory for heard speech is examined over time. When the users are new

to a signal processing algorithm, individual cognitive capacity may play a more important role because more explicit remedial processing is required to listen to the distorted speech signal processed by signal processing. As the users become accustomed to that specific signal processing algorithm, it is assumed that new phonological representations congruent to the processed signal are developed in the lexicon. As a result, the engagement of explicit processing in listening to the processed signal should decline over time. Thus, the role of individual differences in working memory capacity observed in Papers 1 and 3 would be attenuated over time. In addition to further investigation of this, it would be interesting to see how these two hypotheses (acclimatization of cognitive effect of hearing aid signal processing and declining role of cognition in listening to processed signal) interact with each other over time.

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Appendix

Appendix I. International Outcome Inventory for Hearing Aids (IOI-HA).

INTERNATIONAL OUTCOME INVENTORY – HEARING AIDS (IOI-HA)

1. Think about how much you used your present hearing aid(s) over the past two weeks. On an average day, how many hours did you use the hearing aid(s)?

none

☐

less than 1
hours a day

☐

1 to 4
hours a day

☐

4 to 8
hours a day

☐

more than 8
hours a day

☐

2. Think about the situation where you most wanted to hear better, before you got your present hearing aid(s). Over the past two weeks, how much has the hearing aid helped in that situation?

helped
not at all

☐

helped
slightly

☐

helped
moderately

☐

helped
quite a lot

☐

helped
very much

☐

3. Think again about the situation where you most wanted to hear better. When you use your present hearing aid(s), how much difficulty do you STILL have in that situation?

very much
difficulty

☐

quite a lot of
difficulty

☐

moderate
difficulty

☐

slight
difficulty

☐

no
difficulty

☐

4. Considering everything, do you think your present hearing aid(s) is worth the trouble?

not at all
worth it

☐

slightly
worth it

☐

moderately
worth it

☐

quite a lot
worth it

☐

very much
worth it

☐

5. Over the past two weeks, with your present hearing aid(s), how much have your hearing difficulties affected the things you can do?

affected
very much

☐

affected
quite a lot

☐

affected
moderately

☐

affected
slightly

☐

affected
not at all

☐

6. Over the past two weeks, with your present hearing aid(s), how much do you think other people were bothered by your hearing difficulties?

bothered
very much

☐

bothered
quite a lot

☐

bothered
moderately

☐

bothered
slightly

☐

bothered
not at all

☐

7. Considering everything, how much has your present hearing aid(s) changed your enjoyment of life?

worse

☐

no change

☐

slightly
better

☐

quite a lot
better

☐

very much
better

☐

English Version

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