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Assessing cognitive spare capacity

as a measure of listening effort using the Auditory Inference Span Test

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Abstract

Hearing loss has a negative effect on the daily life of 10-15% of the world's population. One of the most common ways to treat a hearing loss is to fit hearing aids which increases audibility by providing amplification. Hearing aids thus improve speech reception in quiet, but listening in noise is nevertheless often difficult and stressful. Individual differences in cognitive capacity have been shown to be linked to differences in speech recognition performance in noise. An individual's cognitive capacity is limited and is gradually consumed by increasing demands when listening in noise. Thus, fewer cognitive resources are left to interpret and process the information conveyed by the speech. Listening effort can therefore be explained by the amount of cognitive resources occupied with speech recognition. A well fitted hearing aid improves speech reception and leads to less listening effort, therefore an objective measure of listening effort would be a useful tool in the hearing aid fitting process.

In this thesis the Auditory Inference Span Test (AIST) was developed to assess listening effort by measuring an individual's cognitive spare capacity, the remaining cognitive resources available to interpret and encode linguistic content of incoming speech input while speech understanding takes place. The AIST is a dual-task hearing-in-noise test, combining auditory and memory processing, and requires executive processing of speech at different memory load levels. The AIST was administered to young adults with normal hearing and older adults with hearing impairment. The aims were 1) to develop the AIST; 2) to investigate how different signal-to-noise ratios (SNRs) affect memory performance for perceived speech; 3) to explore if this performance would interact with cognitive capacity; 4) to test if different background noise types would interact differently with memory performance for young adults with normal hearing; and 5) to examine if these relationships would generalize to older adults with hearing impairment.

The AIST is a new test of cognitive spare capacity which uses existing speech material that is available in several countries, and manipulates simultaneously cognitive load and SNR. Thus, the design of AIST pinpoints potential interactions between auditory and cognitive factors. The main finding of this thesis was the interaction between noise type and SNR showing that decreased SNR reduced cognitive spare capacity more in speech-like noise compared to speech-shaped noise, even though speech intelligibility levels were similar between noise types. This finding applied to young adults with normal hearing but there was a similar effect for older adults with hearing impairment with the addition of background noise compared to no background noise. Task demands, MLLs, interacted with cognitive capacity, thus, individuals with less cognitive capacity were more sensitive to increased cognitive load. However, MLLs did not interact with noise type or with SNR, which shows that different memory load levels were not affected differently in different noise types or in different SNRs. This suggests that different cognitive mechanisms come into play for storage and processing of speech information in AIST and for listening to speech in noise. Thus, the results suggested that a test of cognitive spare capacity seems to be a useful way to assess listening effort, even though the AIST, in the design used in this thesis, might be too cognitively demanding to provide reliable results for all individuals.

List of publications

I. Rönnberg, N., Stenfelt, S., & Rudner, M. (2011). Testing listening effort for speech comprehension using the individuals' cognitive spare capacity. Audiology Research, 1(1S). doi: 10.4081/audiores.2011.e22

II. Rönnberg, N., Rudner, M., Lunner, T., & Stenfelt, S. (2014). Assessing listening effort by measuring short-term memory storage and processing of speech in noise. Speech, Language and Hearing, 17(3), 123-132. doi: 10.1179/2050572813Y.0000000033

III. Rönnberg, N., Rudner, M., Lunner, T., & Stenfelt, S. (2014). Memory performance on the Auditory Inference Span Test is independent of background noise type for young adults with normal hearing at high speech intelligibility. Submitted to Frontiers in Psychology, hosting specialty: Frontiers in Auditory Cognitive Neuroscience .

IV. Rönnberg, N., Rudner, M., Lunner, T., & Stenfelt, S. (2014). Adverse listening conditions affect short-term memory storage and processing of speech for older adults with hearing impairment. Manuscript.

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List of abbreviations

AIST	Auditory Inference Span Test
AMN	Amplitude modulated noise
CSCT	Cognitive Spare Capacity Test
dB	Decibel, the measure of sound level
HINT	Hearing In Noise Test
HL	Hearing level
Hz	Hertz, the unit of frequency
ISTS	International Speech Test Signal
kHz	Kilohertz
LM	Letter Memory Test
LTM	Long-term memory
MLL	Memory load level
MP3	MPEG-1 or MPEG-2 Audio Layer III, encoding format for digital audio using lossy data compression
PTA4	Pure tone average threshold (across 0.5, 1, 2, and 4 kHz)
RS	Reading Span Test
RT	Response time
SICSPAN	Size-comparison span test
SNR	Signal-to-noise ratio
SPL	Sound pressure level
SQ	Sentence questions
SSN	Steady-state speech-shaped noise
SWIR	Sentence-final Word Identification and Recall test
UA	Updating ability, referring to the executive function of updating
WAV	Waveform Audio File Format, audio file format standard for storing an audio bitstream
WMC	Working memory capacity
WHO	World Health Organization

Introduction

It is estimated that between 10 to 15% of the general population suffers from hearing loss that to some extent affects their daily life (Stevens et al., 2013). Having a hearing impairment negatively influences physical, cognitive, behavioral and social functions, and quality of life (Arlinger, 2003). The most common way to treat an individual with a hearing loss is to fit hearing aids. Hearing aids provide amplification to increase audibility but do not restore hearing. Even though hearing aids improve speech reception in quiet, listening in noise might still be difficult and stressful. Individual differences in cognitive capacity have been shown to be linked to differences in speech recognition performance in noise. For example, individuals with higher cognitive capacity have better speech recognition ability at poor signal-to-noise-ratio (SNR) compared to individuals with less cognitive capacity. The relation between speech in noise performance and cognitive capacity applies to individuals with normal hearing as well as to individuals with hearing impairment both aided (when using a hearing aid) and unaided (Foo, Rudner, Rönnberg, & Lunner, 2007; Gatehouse, Naylor, & Elberling, 2003; Lunner, 2003; Lunner & Sundewall-Thoren, 2007; Moore, 2008; Rudner, Foo, Rönnberg, & Lunner, 2009; Rudner, Rönnberg, & Lunner, 2011). However, although we are starting to understand the relation between cognition and the functionality of modern hearing aids, they are still commonly fitted based on the individual's hearing thresholds and personal preference. Not only speech recognition performance, but also the ability to benefit from digital signal processing algorithms in hearing aids is related to differences in cognitive capacity (Lunner, 2003; Lunner, Rudner, & Rönnberg, 2009; Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013a; Ng, Rudner, Lunner, & Rönnberg, 2014; Sarampalis, Kalluri, Edwards, & Hafter, 2009). However, the individual's cognitive capacity is seldom considered in the fitting process today.

Evaluating a hearing aid fitting with a speech-in-noise test may not provide a reliable measure of hearing aid benefit, since individuals may successfully compensate for increased task demands by increasing the amount of effort. One individual might consequently perform equally well with two different hearing aid fittings, but more cognitive resources will be required and more listening effort will be experienced in a less optimal fitting compared to an optimal fitting. Therefore, it has been argued that audiologists should involve measurements of cognitive capacity when assessing hearing aids (Pichora-Fuller & Singh, 2006). However, even if an individual's cognitive capacity were to be measured along with the fitting process, it is not obvious how this information could be used. When listening in adverse conditions, cognitive resources are consumed for listening which leaves fewer resources to remember and process the auditory information (Mishra, Rudner, Lunner, & Rönnberg, 2010). The residual cognitive capacity left after successful listening is called an individual's cognitive spare capacity (Rudner & Lunner, 2014; Rudner, Lunner, Behrens, Thoren, & Rönnberg, 2012; Rudner, Ng, et al., 2011). If the individual's cognitive spare capacity could be measured, this would be an indication of how well hearing aids are fitted. When the hearing aid is not optimally fitted more cognitive resources would be allocated to decode speech leaving fewer resources for other tasks, which in turn would result in more fatigue and greater listening effort.

This thesis investigates the use of cognitive spare capacity as an objective measure of listening effort on young adults with normal hearing as well as older adults with hearing impairment. The specific aims were:

1) to develop a dual-task hearing-in-noise test, the Auditory Inference Span Test (AIST), which combines auditory and memory processing. AIST performance is argued to reflect the degree of cognitive spare capacity left after successful listening;

2) to investigate how different signal-to-noise ratios (SNRs) affect memory performance for perceived speech for young adults with normal hearing;

3) to explore if this performance would interact with cognitive capacity, i.e. working memory capacity (WMC) and updating ability (UA);

4) to test if different noise types would interact differently with memory performance for young adults with normal hearing; and

5) to examine if these relationships would generalize to older adults with hearing impairment.

Background

In life, sound is all around us, bringing meaning and pleasure; the sound of birds singing in the spring, of the symphony orchestra playing, and of the voices of our children. Sound can bring us understanding of the environment and tell us that the key is left in the car, that the elevator has arrived, or that the light has shifted to green and it is safe to cross the street. And of course it brings us the opportunity to speak and communicate using spoken language. But, the environment is also full of sounds that distract and disturb us, like the power drill hammering the concrete outside, an agitated conversation on the other side of the subway car, or the clink of crockery and cutlery in the restaurant. Some of these sounds we hear, some we listen to, and some we comprehend, but all of them are to some extent part of a communication situation.

These abilities, hearing, listening, comprehending, and communicating can be categorized as different functions (Kiessling et al., 2003; Pichora-Fuller & Singh, 2006). Hearing is the passive function that gives access to the sounds in the world around us. Hearing might be described as automatic auditory processes; such as sensing the presence of sound, or discriminating location, pitch, loudness, or the quality of a sound. We hear the sound of the crickets on a summer evening, but we do not necessarily pay attention to them. Listening on the other hand is the function of hearing with intention and attention. Accordingly, listening can be called an activity, as people actively engage in hearing for a purpose. Listening consequently involves cognitive processes beyond the fundamental functions of hearing, and listening might therefore require the expenditure of effort (Kiessling et al., 2003; Pichora-Fuller & Singh, 2006). We hear the crickets in the background, but we listen to our spouse telling us about their day (Johnsrude et al., 2013).

Comprehending is an activity undertaken beyond the functions of hearing and listening. Comprehending is the ability to receive information, meaning, and intent. It is to understand the information in the message that we have heard, to follow and experience the story we are being told. With that in mind it seems likely that comprehending needs more concentration and expenditure of effort than listening or just hearing (Rudner, Karlsson, Gunnarsson, & Rönnberg, 2013). Communication, finally, is the exchange of information, meaning, or intent between two or more individuals. Communication assumes that the individuals taking part in the communication are hearing, listening, and comprehending (Kiessling et al., 2003; Pichora-Fuller & Singh, 2006). While listening to our spouse talking about their day we simultaneously compose an answer, involving our knowledge and experiences, while keeping conversational details in memory and continuously update this information to be able to give a contextually valid answer.

It is clear that comprehending and communicating involves many more processes than hearing alone. These processes are called top-down processes, while the perception of sound and the ability to hear is rather referred to as bottom-up processes (Avivi-Reich, Daneman, & Schneider, 2014; Besser, Koelewijn, Zekveld, Kramer, & Festen, 2013; Davis & Johnsrude, 2007; Zekveld, Heslenfeld, Festen, & Schoonhoven, 2006). For example, the acoustic analysis and intensity coding of speech are, more or less, unconscious and automatic bottom-up processes, while linguistic processes and the use of internal speech representations to facilitate speech identification are top-down processes (Zekveld et al., 2006). Top–down processes are also used to infer what has been said especially if listening in a noisy and troublesome listening situation

(Pichora-Fuller, Schneider, & Daneman, 1995).

Listening in noise

As in the examples depicted above there are often sounds that disturb or interfere with what an individual actually wants to listen to. The target sound, whether it is a specific voice or another sound, is called the signal. The masking sounds, which are often unwanted, are called noise. When an individual is listening to a signal in the presence of noise, they are listening in adverse listening conditions. These adverse conditions may arise not only due to signals masked by competing background noise, but also by signals that are incomprehensible due to an unfamiliar accent or dialect, or distorted by the signal processing in the hearing aid (Mattys, Davis, Bradlow, & Scott, 2012) or by a hearing impairment (Stenfelt & Rönnberg, 2009). The difference in magnitude between the signal and the noise is called the signal-to-noise ratio (SNR).

In favorable listening conditions the speech signal is intact and understanding is implicit and automatic (Rönnberg, 2003; Rönnberg et al., 2013; J. Rönnberg, Rudner, Foo, & Lunner, 2008). However, noise masks the signal, even if only partly, and reduces the fidelity of the acoustic information of the signal. This requires a higher degree of attentional investment at the perceptual level, and consequently more top-down processing to compensate for the poor bottom-up representation of the signal (Avivi-Reich et al., 2014). Therefore, more cognitive processes are occupied when listening in noise than in quiet (Akeroyd, 2008; Edwards, 2007; Larsby, Hällgren, Lyxell, & Arlinger, 2005; Mishra, Lunner, Stenfelt, Rönnberg, & Rudner, 2013a; Ng et al., 2013a; Pichora-Fuller & Singh, 2006; J. Rönnberg et al., 2013), and the use of these cognitive resources might be perceived as effortful (Picou, Ricketts, & Hornsby, 2011; Rabbit, 1968, 1991; Rudner et al., 2012; J. Rönnberg, Rudner, & Lunner, 2011). Thus, individuals experience listening in noise to be more effortful than listening in quiet (Pichora-Fuller et al., 1995).

The cognitive processes involved in listening in adverse conditions may include working memory and executive functions (Rönnberg et al., 2013; Rönnberg, Rudner, Lunner, & Zekveld, 2010). Working memory is the ability to store and process information on a short-term basis (Baddeley, 2000) while executive functions include, for example, updating of information in working memory. The multi-component model of working memory (Baddeley, 2000) suggests that the working memory consists of the central executive which is an attentional control system that involves the phonological loop, the visuospatial sketchpad, and the episodic buffer. The phonological loop deals with language-based verbal information, while the visuospatial sketchpad processes visual-spatial information, and the episodic buffer provides temporary short-term storage and processing of multimodal representations. Phonological processing and lexical and semantic access take place in the episodic buffer, and the episodic buffer and the phonological loop are used for speech perception (Rönnberg et al., 2013). Phonological and semantic representations in the lexicon are stored in long-term memory (LTM), and the episodic buffer serves as an interface between perception and episodic LTM. The executive function of updating may be understood as the ability to update working memory with new information and simultaneously remove old information (Miyake et al., 2000). For example, when the bill is to be split after a dinner at the restaurant, the prices for the dishes are held and processed in working memory. However, when it is discovered that two persons at the dinner have mixed up their starters, the prices held in working memory are updated and then processed again. And since this calculation is done in the restaurant with disturbing sounds around, it will be more effortful and cognitive demanding to do compared to a quiet condition.

It has been suggested that both working memory and updating processes are involved in disambiguating degraded speech and inferring absent information when listening in adverse conditions, and consequently compensating for speech understanding difficulties (Mishra et al., 2013a; Rudner, Rönnberg, et al., 2011; J. Rönnberg et al., 2013; J. Rönnberg et al., 2008). The cognitive processes store unidentified fragments of the speech signal in working memory until they can be disambiguated. Meanwhile, processing continues and the information held in working memory is continuously updated and old bits of information are removed (Rudner, Rönnberg, et al., 2011). Thus working memory and the executive function of updating facilitate speech recognition.

Young adults with normal hearing can obtain the same level of speech recognition, i.e. speech reception thresholds (SRTs), in worse SNRs in modulated noise compared to steady-state noise (Duquesnoy, 1983; Gatehouse, Naylor, & Elberling, 2006; Zekveld, Rudner, Johnsrude, & Rönnberg, 2013). Individuals with higher working memory capacity (WMC) can achieve the same speech intelligibility level in worse SNRs as individuals with less WMC achieves in better SNR, and the relation between speech perception in noise and WMC is generally stronger when speech is masked by a fluctuating or modulated noise compared to steady-state noise (Gatehouse et al., 2003; George et al., 2007; Koelewijn, Zekveld, Festen, & Kramer, 2012; Lunner & Sundewall-Thoren, 2007; Rudner et al., 2009; Rudner, Ng, et al., 2011; J. Rönnberg et al., 2010; Zekveld et al., 2013). Steady-state noise, usually speech-shaped, is referred to as energetic masking since it competes with the signal in sound energy. Modulated noise competes with the signal in temporal as well as spectral properties, e.g. amplitude modulated speech-shaped noise. The amplitude modulation might be generated by a low frequency sinusoid or by an envelope extracted from a speech signal. However, a modulated noise may also consist of one or more competing voices, and might then be referred to as information masking. An explanation for the stronger relation between WMC and modulated noise is that individuals with greater cognitive capacity are better able to utilize the short periods with increased SNR to infer information that is masked when the noise level is louder (Duquesnoy, 1983) which would give rise to release from masking (Festen & Plomp, 1990), but it is possible that these individuals also have a better ability to inhibit the distracting effect of the noise.

When the background noise contains linguistic information it causes distraction and adds to speech understanding difficulties (Sörqvist & Rönnberg, 2012). An explanation for this is that linguistic information in background noise makes it more difficult and cognitively demanding to segregate target speech, i.e. the signal an individual wants to hear, from the masking speech (Mattys, Brooks, & Cooke, 2009). The listener must also spend more cognitive resources to inhibit irrelevant lexical-semantic information (Rönnberg et al., 2010). This might be particularly problematic when the masking speech is in the same language as the target speech, since the masker then will interfere at several different linguistic levels (Brouwer, Van Engen, Calandruccio, & Bradlow, 2012; Tun, O'Kane, & Wingfield, 2002). However, if the masking speech is not in the same native language as the target speech (Ng et al., 2014), and if the nonnative language is linguistically dissimilar the masking effect becomes less pronounced (Brouwer et al., 2012). Two languages that belong to the same language family, will be more alike because these languages will have similar temporal and spectral properties (Calandruccio, Dhar, & Bradlow, 2010). It is also of importance if the speaker of the signal and the speaker of the masker are of the same sex, since male and female voices are less confusable (Freyman, Balakrishnan, & Helfer, 2004).

Furthermore, the number of voices in the masker will change the balance between energetic masking and information masking. The individual that is listening in an adverse condition attempts to attend to the signal and simultaneously ignore the masker. When there is two masking talkers it is likely to be greater competition for attention than with one masking voice. As the number of competing maskers increases these will start to mask each other, and as a result they will become less like individual signals and consequently compete less with the target signal for attention. Also, as the number of competing masker voices increases, the temporal and spectral gaps will be filled which will shift the balance from informational masking towards energetic masking (Freyman et al., 2004), consequently the modulation diminishes with more speakers.

Even a modulated noise with limited semantic content like the International Speech Test Signal (ISTS) (Holube, Fredelake, Vlaming, & Kollmeier, 2010), which is largely non-intelligible, may contain strains of informational masking (Francart, van Wieringen, & Wouters, 2011). In ISTS the informational masking is not primary the semantic content but other cues such as pitch, temporal fine structure, and voice timbre which may confuse the listener and lead to worse speech recognition. Of course, these problematic cues may also be present when the background masker consists of semantic content.

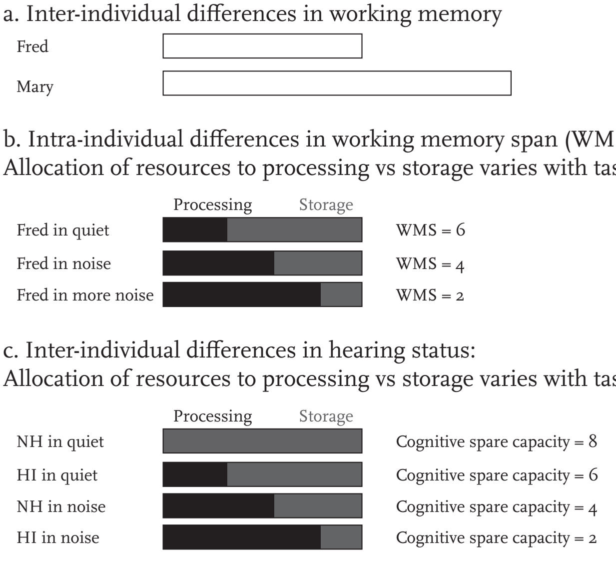
It seems that having a greater cognitive capacity facilitates speech understanding, especially when listening in adverse situations. However, the extent of advantage a greater cognitive capacity gives appears to be related to the type of background masker.

Cognitive spare capacity

An individual has limited WMC, and the amount of WMC is different between individuals (Pichora-Fuller, 2007), see Figure 1 (a). The WMC is gradually consumed by increasing processing demands for example due to adverse listening conditions, see Figure 1 (b). This suggests that, an individual that is listening in a noisy situation will have fewer cognitive resources to process and store information compared to when listening in quiet (Pichora-Fuller & Singh, 2006; Rudner & Lunner, 2013; Schneider, 2011). Therefore, an individual with higher WMC is likely to cope better with worse SNR, than an individual with lower WMC (Foo et al., 2007; Larsby et al., 2005; Lunner, 2003; Pichora-Fuller, 2007; Pichora-Fuller & Singh, 2006; Rudner et al., 2009; Schneider, 2011). This applies for individuals with normal hearing as well as for individuals with hearing impairment, aided or unaided (Gatehouse et al., 2003; Ng et al., 2013a).

One approach to measuring the ability to manipulate intelligible information assumes that cognitive resources are consumed in the very act of listening, which in turn leaves fewer resources to process the auditory information (Rudner et al., 2012; Rudner, Ng, et al., 2011). This assumption is supported by studies showing a decreased memory performance for sentences heard in noise compared to performance in quiet (Heinrich & Schneider, 2011; Pichora-Fuller et al., 1995; Sarampalis et al., 2009). If the residual cognitive resources after successful listening has taken place is referred to as cognitive spare capacity, then listening in an adverse conditions leads to less cognitive spare capacity compared to when listening in quiet conditions (Mishra et al., 2010; Rudner & Lunner, 2013; Rudner, Ng, et al., 2011; N. Rönnberg, Rudner, Lunner, & Stenfelt, 2014b). It has been shown that cognitive spare capacity is sensitive to processing load relating to both memory storage requirements (Mishra et al., 2013a; Mishra, Lunner, Stenfelt, Rönnberg, & Rudner, 2013b; N. Rönnberg et al., 2014b) and background noise (Mishra et al., 2013a; N. Rönnberg et al., 2014b), while other studies have shown an effect of improved memory performance for hearing impaired individuals when noise level was attenuated by noise reduction algorithms (Ng et al., 2013a; Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013b).

Mishra et al. (2013a; 2013b) used the Cognitive spare capacity test (CSCT). The CSCT is a test of the ability to process heard speech, in which an individual listens to lists of numbers between 13 and 99 presented in different modalities (audiovisual and auditory-only), and performs a working memory task that loads, at different levels, on one of two executive functions (updating or inhibition). These studies showed that for young adults with normal hearing the cognitive spare capacity was reduced when task demands was increased by higher level of storage load as well as executive processing. Interestingly, cognitive spare capacity was not related to WMC. This suggests that the CSCT captures cognitive aspects of listening related to sentence comprehension, and that these are quantitatively and qualitatively different from WMC. Another reason for this might be that the CSCT rather involves storage in and updating of information



in memory, rather than processing of information in memory. Consequently, the CSCT does not load on working memory storage capacity to such a degree as it is measurable with the CSCT but rather affects executive functions that manipulate information held in working memory.

Figure 1. The figure is adapted with the author's permission from Pichora-Fuller (2007) and shows inter-individual differences in working memory capacity showing that two individuals might have different working memory capacity (a); and intra-individual differences showing that for an individual the allocation of the individual's limited capacity to the processing and storage functions of working memory is gradually consumed by increasing processing demands due to adverse listening conditions (b); and inter-individual differences in hearing status showing that an individual with hearing impairment (HI) might have reduced cognitive spare capacity compared to an individual with normal hearing (NH) after successful listening (c).

Ng et al. (2013a) used the Sentence-final word identification and recall (SWIR) test. In SWIR an individual listens to the Swedish Hearing In Noise Test (HINT) sentences (Hällgren, Larsby, & Arlinger, 2006) in different listening conditions, in quiet as well as in different noise types, with and without noise reduction enabled in the hearing aids. The individual was requested to report the final word of each sentence immediately after listening to it, this was used as a measure of speech intelligibility. After reporting the final word of a list of sentences, the individual was requested to recall all the words that had previously been reported, in any order. The study showed that when background noise consisted of four-talker babble speech intelligibility decreased, and recall performance decreased as well. When noise reduction was enabled this improved speech intelligibility and also reduced the adverse effect of noise on memory for individuals with good WMC. This might suggest that for individuals with better WMC noise reduction frees memory resources and consequently results in more cognitive spare capacity. But also that good speech intelligibility level is essential for storing auditory information in memory. Ng et al. (2013b) showed that when task demands were less, the cognitive spare capacity was increased by the use of noise reduction system that improved speech intelligibility for individuals with less good WMC.

The concept of cognitive spare capacity has been proposed to be a useful measure of listening effort by measuring the amount of cognitive engagement (Rudner, Ng, et al., 2011). The cognitive spare capacity is measured with performance on a second task, and therefore reveals the amount of demand that the first task, i.e. listening in noise, strains the cognitive system with.

Hearing impairment and age

When we listen, sound arrives at the ear as pressure waves, which in turn causes the eardrum to vibrate. The eardrum transmits the vibrations to the ossicular chain, consisting of the malleus, the incus, and the stapes. The ossicular chain conveys the mechanical vibrations to the oval window. The motion of the stapes in the oval window generates a sound pressure in the cochlear fluid that creates a traveling wave on the basilar membrane. As the basilar membrane moves, the organ of Corti on the basilar membrane moves, and the inner hair cells convert this motion by the release of neurotransmitters to neural impulses on the auditory nerve. These auditory neural information are sent via brainstem to the auditory cortices for further processing (Moore, 2003).

According to the World Health Organization (WHO) 360 million people worldwide, which is more than 5% of the world's population, have a hearing loss. This is defined as worse than 40 dB HL in the better hearing ear in adults, and worse than 30 dB HL in the better hearing ear in children (World Health Organization, 2014). It is estimated that up to 15% of the general population to some extent are affected negatively in their daily life and everyday communication situations by a hearing loss (Stevens et al., 2013). Physical, cognitive, behavioral and social functions, as well as quality of life are negatively affected, and hearing loss is also clearly related to depression and dementia (Arlinger, 2003). A lesion in the auditory system might lead to various forms of impairment, most commonly hearing loss, tinnitus, or hyperacusis. The most common form of hearing impairment is sensorineural impairment, which primary involves the cochlea and the function of hair cells. The hearing impairment can lead to attenuation and distortion of a heard sound (Plomp, 1978), a decrease in the ability to detect sounds, deficits in spectral and temporal processing (Pichora-Fuller & Singh, 2006; Pichora-Fuller & Souza, 2003), and worse speech recognition performance (Arlinger, 2003; Moore, 1996; Pichora-Fuller et al., 1995).

The presence of background masker, whether it is steady-state noise or competing speech, makes speech understanding more effortful, as discussed above, especially for persons with hearing impairment (Rudner, Rönnberg, et al., 2011). A common complaint from individuals with a hearing impairment is that they often find it stressful and tiring to listen, and even more so in noise (Edwards, 2007; Kiessling et al., 2003). Since hearing impairment is associated with a decreased speech understanding, background noise further decreases this ability. As discussed previously the modulation in noise can give release from masking and improved speech in noise performance. However, individuals with hearing impairment do not always benefit from the modulation in noise (Festen & Plomp, 1990; George, Festen, & Houtgast, 2006; George et al., 2007; Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006). A hearing impaired individual will have poorer representation of the speech signal (Rabbit, 1991) as well as a greater cognitive load due to more top-down processes compared to normal hearing individuals, which will lead to less cognitive spare capacity in noise, regardless of noise type, than in quiet, see Figure 1 (c).

Aging is often associated with hearing impairment (Strawbridge, Wallhagen, Shema, & Kaplan, 2000). In the developed countries almost two thirds of the population over seventy years has a sensorineural hearing loss (Johansson & Arlinger, 2003; Lin, Thorpe, Gordon-Salant, & Ferrucci, 2011). The most common type of age related hearing loss, also called presbycusis, is sensorineural hearing loss (Pichora-Fuller, 2007). In general, age related hearing loss is characterized by a sloping high frequency hearing loss (Schmiedt, 2010).

Speech recognition performance decreases with hearing impairment. For older adults with hearing impairment the decrease in speech recognition performance is worse compared to younger adults with hearing impairment. As SNRs become less favorable, speech recognition performance decreases even further. The difference between older adults with hearing impairment and young adults with hearing impairment becomes more apparent in adverse listening conditions (Pronk et al., 2012). A reason for this might be presbycusis, another reason for this might be that cognitive resources are used to achieve speech recognition (Rönnberg, 2003; J. Rönnberg et al., 2013; J. Rönnberg et al., 2008), and because cognitive abilities decline with age (Besser et al., 2013; Mattys et al., 2012; Nyberg, Lovden, Riklund, Lindenberger, & Backman, 2012) the younger hearing impaired adults have better ability to achieve better speech recognition in adverse conditions. In addition, listening in noise makes higher demands on cognitive processes which reduces resources available for higher level processing, and as a consequence there is worse memory performance on tasks that requires speech recognition in noise (Mishra et al., 2013a, 2013b; Ng et al., 2013b; N. Rönnberg et al., 2014b). Consequently this affects older adults with hearing impairment more than younger normal hearing adults (Mishra, Stenfelt, Lunner, Rönnberg, & Rudner, 2014). Even when speech recognition is high, despite a possible hearing impairment, speech understanding might be reduced due to decline of cognitive resources with age (Heinrich & Schneider, 2011; Pichora-Fuller et al., 1995).

A hearing impairment might also imply that the hearing impaired individual refrains from interactions with other people, something that might lead to a withdrawal from social activities and in the long run reduced intellectual and cultural stimulation (Arlinger, 2003). This in turn, might imply further cognitive decline and therefore it is of importance to prevent and treat this highly prevalent condition (Strawbridge et al., 2000).

Hearing aids and hearing aid fitting

Fitting hearing aids is one of the most common rehabilitations for hearing loss. A hearing aid typically restores audibility by amplifying the acoustic signal for reduced hearing sensitivity. Digital signal processing algorithms in the hearing aids enables noise reduction, feedback cancelation, and various dynamic compression settings. However, the benefit of hearing aids varies between individuals, which might partly be explained by individual differences in cognitive capacity (Lunner et al., 2009). Also, speech reception in noise performance is related to cognitive abilities in individuals using hearing aids (Foo et al., 2007; Humes, 2007; Lunner, 2003; Rudner et al., 2009; Rudner et al., 2012).

If the acoustical signal is degraded by a hearing impairment, the sound perception or the bottom-up processes will be less accurate which in turn will force more top-down cognitive processes for successful listening. Hence, a well fitted hearing aid, which improves audibility of the speech signal (Edwards, 2007), will reduce the amount of top-down processing needed, and consequently lead to more cognitive spare capacity, see Figure 1 (c). As a result, an improved speech reception would also reduce the listening effort. Therefore the fitting process is of great importance for the hearing aid outcome (Edwards, 2007), and measures of an individual's cognitive capacity should be considered in the fitting process (Edwards, 2007; Lunner et al., 2009; Lunner & Sundewall-Thoren, 2007; Pichora-Fuller & Singh, 2006; Rudner & Lunner, 2013; Rudner, Rönnberg, et al., 2011; Stenfelt & Rönnberg, 2009), however, there is no consensus how to use this information in the fitting process.

Today the hearing aid fitting process is primarily based on an individual's hearing thresholds using different prescription formulas. Even though hearing aid amplification reduces cognitive processes needed for hearing by restoring audibility (Gatehouse & Gordon, 1990; Hornsby, 2013; Humes, 2007; Hällgren, 2005; Picou, Ricketts, & Hornsby, 2013; Sarampalis et al., 2009), hearing thresholds alone are an insufficient measure of an individual's hearing system considering bottom-up as well as top-down processes. Studies have shown that individuals with a greater WMC benefits from fast-acting wide dynamic range compression compared to slow-acting compression, while individuals with poorer WMC perform worse with fast-acting compared to slow-acting compression (Gatehouse et al., 2003, 2006; Lunner & Sundewall-Thoren, 2007). A reason for this is that fast compression in modulated noise may increase the output SNR at negative input SNRs, but decrease the output SNR at positive input SNRs (Rudner, Rönnberg, et al., 2011). Individuals with high WMC can achieve the same speech intelligibility in negative SNRs as an individual with less WMC achieves in positive SNRs. Consequently, fast-acting compression would result in a more favorable SNR for an individual with high WMC listening in negative SNRs, while for an individual with lower WMC listening in positive SNRs would result in a less favorable SNR. Thus, the individual with high WMC would probably benefit from fast compression, but for the individual with lower WMC fast compression would be a disadvantage. Even though fast acting compression leads to increased audibility it also leads greater processing demands due to distortion of the signal, which also might explain why individuals with lower WMC do not benefit from fast acting compression in the same way as individuals with greater WMC. Therefore, it is necessary to have knowledge about the individual's cognitive capacity when adjusting compression of the dynamic range in a hearing aid.

A noise reduction system in the hearing aid attenuates background masker sounds, which in turn might increase the amount of cognitive spare capacity. This is typically measured by an increase in memory performance, even if the noise reduction has no positive effect on speech reception thresholds (Sarampalis et al., 2009). However, the improvement in memory performance might be dependent on the listeners working memory capacity (Ng et al., 2013a; Rudner, Rönnberg, et al., 2011). Ng et al. (2013a) argues that a noise reduction system allows faster word identification and consequently facilitates encoding of heard material into working memory for individuals with good WMC. However, a noise reduction algorithm might add distortion to the signal, thus leading to greater demands on the cognitive systems (Lunner et al., 2009). For individuals with less good WMC the extra demands the distorted signal adds to the cognitive system might cancel out the benefits from the noise reduction system. Never the less, a noise reduction system attenuates background noise which might lead to a decrease in listening effort, even if there is no measurable increase in speech recognition performance (Sarampalis et al., 2009). Thus, evaluating the fitting with a speech-in-noise test would not reveal the benefit of noise reduction, but knowledge about the individual's cognitive capacity is necessary for the highest hearing aid benefit.

If a hearing aid is not fitted optimally for an individual, regarding amplification levels, compression settings and noise reduction algorithms, even more cognitive resources will be allocated to decode speech, especially in adverse listening conditions. This suggests that an individual might score equally well on a speech-in-noise test with one optimal and one suboptimal hearing aid fitting, but more cognitive resources will be required with the suboptimal fitting than with the optimal fitting. This in turn will lead to more fatigue, less cognitive spare capacity, as well as a greater listening effort.

Listening effort

Listening effort can be explained by the amount of cognitive resources occupied with speech recognition (Picou et al., 2013), or in other words; listening effort can be described as the amount of cognitive spare capacity (Rudner, Ng, et al., 2011), i.e. if cognitive spare capacity is low, listening effort is high. In ideal listening conditions when speech recognition is good, understanding is implicit and automatic, but in adverse listening conditions there might be a mismatch between the heard signal and the phonological representations in LTM. Then explicit cognitive resources are allocated to facilitate speech recognition (Rönnberg et al., 2013; J. Rönnberg et al., 2008; J. Rönnberg et al., 2010). The amount of explicit cognitive processes that are involved is assumed to reflect listening effort.

In the hearing aid fitting process, an objective measure of listening effort would be a useful tool to evaluate the fitting. Yet, no such tool is used in the clinical situation. Instead audiologists and hearing aid dispensers need inquire and ask the hearing aid user about their experienced listening effort. Many studies have involved a subjective measure of listening effort (Anderson Gosselin & Gagné, 2011; Fraser, Gagné, Alepins, & Dubois, 2010; Hicks & Tharpe, 2002; Larsby et al., 2005; N. Rönnberg et al., 2014b; Zekveld, Kramer, & Festen, 2010; Zekveld, Kramer, Kessens, Vlaming, & Houtgast, 2009). However, consistent for these studies is the lack of correlation between the objective and the subjective measure listening effort, regardless of experimental conditions or participants. It might be expected that cognitive capacity and perceived effort would interact since cognitive capacity facilitates listening in noise. Rudner et al. (2012) showed a relation between rated effort and SNR, but this relation was not dependent of WMC. However, Rudner et al. (2012) showed a relation between WMC differences and rating in different noise types. Age might also affect the amount of rated listening effort, Larsby et al. (2005) found that older adults tended to report less listening effort compared to young adults despite measurable differences in performance. It seems plausible that personality also might affect ratings of listening effort. It can be questioned if individuals use the same criteria when making their subjective judgments. It might even be questioned whether an individual is judging their perceived listening effort or if the subjective rating rather indicate their ability to discriminate noise levels. This discussion implies that subjective rating of effort might not be a good measure of listening effort, and that subjective ratings and objective measurements do not tap into the same mechanism.

Various attempts have been made to measure listening effort objectively (McGarrigle et al., 2014). A common approach is to use a dual-task test where listening effort is measured by performance on the secondary task, either in terms of accuracy or reaction time (Downs, 1982; Gatehouse & Gordon, 1990; Hicks & Tharpe, 2002; Rakerd, Seitz, & Whearty, 1996; Tun, McCoy, & Wingfield, 2009). The AIST, used in the studies within this thesis, is a dual-task test that measures cognitive spare capacity by memory performance on the secondary task, why the following text will discuss some dual-task setups for measuring listening effort.

Rakerd et al. (1996) measured listening effort on young adults with normal hearing, young adults with congenital/early-onset hearing loss, as well as older adults with mild to moderate sensorineural hearing loss. Listening effort was estimated using a memory test where individuals had to memorize digits presented visually while simultaneously listening to either noise or speech. When the individual was listening to speech, understanding of the speech was later probed by questions regarding information in the speech signal. However, this was not the case when listening to noise. The listening effort was measured as the number of forgotten digits. The results suggest that remembering a sequence of digits was more demanding and effortful when listening to speech than when listening to noise. This was more noticeable for participants with hearing impairment, and especially so for older participants. However, there are probably different demands on the cognitive capacity when memorizing digits in background noise compared to memorizing digits and speech information. Two simultaneous memory processes is deemed to be more cognitive demanding compared to one. The test might therefore rather reflect cognitive effort than listening effort. Speech intelligibility might explain the effect of decreased performance for participants with hearing impairment. The presentation level for participants with hearing impairment was adjusted for most comfortable listening level but was not tested for speech intelligibility. If speech intelligibility level was not sufficient, i.e. the participant did not hear all the words of the speech information, remembering that information would be difficult. Also, it seems likely that more effort would be spent in trying to hear the information, while fewer cognitive resources would be available for memorizing the digits. The effect of age might be explained by a cognitive decline with age, why the older participants performed worse than the younger participants.

Tun et al. (2009) assessed listening effort with a dual-task paradigm consisting of word recall and visual tracking on four groups of younger and older adults with normal hearing and with hearing impairment. The listening effort was measured as a reduction in visual tracking accuracy during word recall. They found a greater reduction in tracking accuracy for older individuals, as well as for individuals with hearing impairment. The study showed the cost of dividing attention while recalling words, and a higher cost suggested extra effort at the bottom-up processes. This was found to be due to hearing loss, which in turn was magnified by increased age. Even if both groups with hearing impairment were matched across the primary speech frequency range, other parts of the hearing system might have declined due the effect of age, for example the fidelity of the auditory stream. Also, the cognitive capabilities might also decline as a function of age. The effect of hearing impairment was most prominent when comparing older adults with good hearing and older adults with poor hearing. This might indicate that, even when speech intelligibility is good, a decline in hearing status as well as a decline in cognitive capability due to older age leads to greater cognitive demands with worse visual tracking accuracy as a result. Unfortunately, this test was not administered in adverse listening conditions why an effect of different listening conditions could not be examined. However, theoretically the addition of background noise should have decreased tracking accuracy, and this would have been an effect of adverse listening condition which leads to higher cognitive demands and higher listening effort.

Hicks and Tharpe (2002) measured listening effort using repetition of words from word lists in quiet as well as three different SNRs (+20, +15, and +10 dB), and measured reaction time of responses to a flashing light as a secondary task, similar to Downs (1982). This was tested on school children with and without hearing impairment. The results suggested that children with hearing impairment had longer reaction times, and consequently experienced more listening effort, than children with normal hearing. Also, children with hearing impairment had poorer word repetition performance compared to children with normal hearing. The difference in listening effort between the two groups might be explained by differences in hearing status. Since the children with hearing impairment had less good speech recognition performance in all listening conditions, compared to the children with normal hearing, they were cognitive loaded and had longer reaction times as a result of this. Furthermore, the children with hearing impairment might have had poorer language skills and therefore experienced more cognitive demands to repeat the words with worse second task performance as a result. Despite that speech intelligibility decreased for both groups with decreasing SNR, reaction times for none of the groups showed an effect of SNR. Nevertheless, according to Hicks and Tharpe (2002) the reaction times were measures of listening effort. But a measure of listening effort should be expected to show an effect of noise level which was not found to be the case. Since there was no significant difference in reaction times between listening conditions for either of the groups, the measure of listening effort suggests that none of the children experienced greater listening effort with worse SNR.

The study by Anderson Gosselin and Gagné (2011) investigated the impact of age on listening effort, using young and older adults with normal hearing. The primary task was sentence recognition in noise in one SNR and the participant had to respond to certain key words in the sentences, while simultaneously identify a tactile pattern as the second task. Listening effort was measured as the decrease in accuracy on the tactile pattern recognition task. The results suggested that older adults experienced more listening effort than young adults, not only when SNRs were held constant between participants but also when speech intelligibility level was individually equalized for the older adults. However, it is possible that hearing status and cognitive factors were mediated by age and that this explained that listening effort at the same speech intelligibility level was an effect of age.

In the above mentioned studies, secondary task performance might not provide a reliable measure of listening effort since individuals may successfully compensate for increased task demands by increasing the amount of effort (Anderson Gosselin & Gagné, 2011; Hicks & Tharpe, 2002; Zekveld et al., 2010). In this case, one individual might perform well without experiencing much effort, while another individual might perform equally well but at the expense of high experienced effort. However, the test of listening effort will indicate the same degree of listening effort. This is because differences in cognitive abilities affect the results. Listening effort is a result of using more cognitive capacity to achieve better speech understanding in adverse conditions. Hence, an individual with greater cognitive capacity is likely to experience less listening effort.

Sarampalis et al. (2009) assessed listening effort as the number of remembered and correct repeated last words after a list of eight sentences for young adults with normal hearing using head phones with and without noise reduction. The results suggested that the presence of background noise had negative consequences on listening. This also applied to the individual's ability to perform simultaneous cognitive activities measured by memory accuracy as well as reaction times. Thus, the decreased performance indicated a higher perceived listening effort. However, the results also showed that noise reduction frees cognitive resources and thus improved memory performance even if not making speech more intelligible. Consequently, noise reduction systems might lead to less listening effort. For individuals with hearing impairment, where a decrease in the peripheral auditory system loads the cognitive system by requiring more top-down processes, noise reduction system would lead to less listening effort and more cognitive spare capacity. Ng et al. (2013a) used a similar test setup as Sarampalis et al. (2009) on adults with hearing impairment, and also involved measurements of cognitive capacity. Ng et al. (2013a) showed a decreased speech intelligibility as well as an impaired recall performance when listening in four talker babble noise, which suggested an increase in listening effort with the addition of background noise. However, when listening with noise reduction system enabled speech intelligibility and memory performance increased for individuals with higher WMC and consequently decreased listening effort. A similar effect was shown for individuals with less WMC when task demands was made easier (Ng et al., 2013b).

In this thesis listening effort is assessed with the AIST. As in the above-mentioned studies, the AIST measures listening effort on secondary task performance: accuracy and reaction time. Like in the study of Sarampalis et al. (2009), the secondary task in AIST is a memory task. However, instead of memory storage alone the AIST involves different levels of cognitive engagement. By having different levels of cognitive involvement differences between individuals with greater and worse cognitive abilities would, theoretically, be more lucid. Hence, it is hypothesized that the AIST would show a more nuanced difference between individuals with different cognitive capacity.

To summarize, working memory and executive functions play an important role in speech recognition, especially in noise. As listening demands increase more cognitive resources are occupied in listening, which in turn leads to less cognitive spare capacity. Consequently, the amount of cognitive spare capacity reflects the amount of listening effort. Hearing impairment is often associated with worse speech recognition compared to individuals with normal hearing, and this difference is even greater when listening in adverse conditions. The most common way to rehabilitate a hearing impairment is to fit a hearing aid. An optimal hearing aid fitting is likely to reduce listening effort and leave more cognitive spare capacity for other tasks. Therefore, a reliable measure of listening effort would be a useful tool in the hearing aid fitting process. However there is no consensus on how to measure listening effort. In this thesis it is suggested that cognitive spare capacity could be useful as an objective measure of listening effort, and that this could be assessed using the AIST.

Overall aims

This thesis investigates if cognitive spare capacity as measured by the AIST can be used as an objective measure of listening effort. The aims were:

1) to develop and evaluate a test, the AIST, that assessed listening effort by measuring the cognitive spare capacity;

2) to investigate, using the AIST, whether worse SNR would increase listening effort as measured by decreased cognitive spare capacity;

3) to explore the role of WMC and UA when assessing listening effort by measuring cognitive spare capacity using the AIST;

4) to test if different background noise types would affect cognitive spare capacity and consequently listening effort differently; on young adults with normal hearing; and

5) to examine whether these relationships would generalize to older adults with hearing impairment.

The first study addressed the first aim, and the AIST test was developed with a series of development versions to the final version used in study 1, where the AIST was administered in SSN at an SNR targeting about 100% speech intelligibility. The second study addressed aim 1, aim 2, and aim 3 by further developing the AIST test and evaluating the test in SSN with three different SNRs targeting 90% speech intelligibility or better, on young adults with normal hearing. Study 2 also analyzed memory performance on AIST related to measurements of WMC and UA. The third study addressed aim 2, aim 3, and aim 4 by administering the AIST in three noise types (SSN, AMN, ISTS) in matched SNRs targeting 90% speech intelligibility or better, on half of the study population from study 2. Memory performance on AIST was analyzed in relation to measurements of WMC and UA. Study 4 addressed aim 3, aim 4, and aim 5, by administering the AIST to older adults with hearing impairment in three listening conditions (Quiet, SSN, ISTS). Memory performance on AIST was analyzed in relation to hearing thresholds, age, and measurements of WMC and UA.

Ethical consideration

The study was approved by the Regional Ethical Review Board in Linköping (Dnr: 230-09).

Empirical studies

General methods

To assess cognitive spare capacity as a measurement of listening effort a new test, the Auditory Inference Span Test (AIST), was developed and evaluated together with measurements of the participants cognitive abilities and hearing function. The cognitive abilities assessed were working memory capacity (WMC) and the executive function of updating (UA), and these were measured with the Reading span test and the Letter memory test respectively.

Stimuli

The AIST used the Swedish Hagerman sentences (Hagerman, 1982, 1984, 2002; Hagerman & Kinnefors, 1995). These are five-word matrix-type sentences in Swedish, based on a closed set of 50 words in a structured sequence: name, verb, number, descriptor, and item. For example (translated from Swedish): Britta has eight black rings. These sentences have low redundancy which prevents guessing of a word that is not heard from the context provided by the rest of the sentence. Another advantage with the structured sequence of sentences is that it was possible to automatically create balanced questions and answers using Matlab.

The original speech-material was transferred to computer and each sentence was stored as an individual sound file, in WAV format using 44.1 kHz sampling frequency and 16 bit resolution, with 1.5 seconds silence before and after each sentence. The sound files were in stereo format with the original speech-shaped steady-state noise in one channel and the speech signal in the other channel.

Noise types and SNRs

The studies in this thesis used three types of noise: speech-shaped steady-state noise (SSN), speech-shaped amplitude modulated noise (AMN), and voices (ISTS). The SSN was the original stationary speech-shaped noise developed by Hagerman (1982) that has the same long-term average spectrum as the speech material. The AMN was the same noise as SSN but amplitude modulated by a sinusoid with a modulation frequency of 5 Hz and a modulation depth of 20 dB. The amplitude modulation was performed using Matlab (R2013a). The International Speech Test Signal (ISTS) (Holube, Fredelake, Vlaming, & Kollmeier, 2010) consists of six female voices reading a story in six different languages. The recordings of these voices were cut into 500 ms segments, which were then randomized and put into a serial order one voice at a time. This method ensures a largely non-intelligible natural speech signal.

It was hypothesized that even at a fairly good SNR the noise would add some demands on the cognitive system to achieve good speech recognition, thus leaving fewer resources to remember and process heard information which would be measureable on memory performance using the AIST. However if the SNR was not demanding enough it might not affect the cognitive system to such a degree that it would lead to a measurable decrease in memory performance. On the other hand, if the SNRs were too poor a decrease in memory performance is expected due to the decreased audibility and that may dominate the decreased memory performance.

In study 1 SSN was used at an SNR of 0 dB. According to Hagerman (1982) this would give a speech intelligibility of just under 100% for young adults with normal hearing. Theoretically this would load on cognitive resources and simultaneously provide a good speech intelligibility level. For study 2 it was decided that the speech intelligibility level should be 90%. This would still ensure reasonably good speech recognition, while the noise level would cause a relatively challenging listening situation. According to Hagerman (1982) 90% speech intelligibility was achieved at approximately -3.7 dB when using SSN. To measure the effect of SNR on AIST memory performance, the SNRs used in study 2 were -2, -4, and -6 dB. These SNRs resulted in average speech intelligibility levels of 97%, 96%, and 91%. In study 3 the effect of different noise types on AIST performance was investigated. To do that, the speech intelligibility levels for AMN and ISTS was matched to those for SSN using ten young adults with normal hearing. The absolute SNRs as well as the amount of change in SNR differed between noise types, but average speech intelligibility levels were approximately the same. The SNRs used for AMN were -8, -11, and -14 dB, and for ISTS the SNRs used were -5, -9, and -13 dB. Study 4 examined the effect of noise on AIST performance for older adults with hearing impairment using hearing aids. AIST was tested in quiet, in SSN, and in ISTS. To ensure audibility as well as avoid differences between individuals' hearing aid fittings, amplification was individually adjusted to compensate for the participants hearing loss. This was done using a master hearing aid system (Grimm, Herzke, Berg, & Hohmann, 2006) with NAL-RP gain prescription (Byrne & Dillon, 1986). Also, the SNRs were individually adjusted to target 90% speech intelligibility in both noise types using a speech recognition test. In all studies, the speech level was held constant while altering the noise level changed the SNRs.

Development of the AIST

The AIST was developed using four development versions (see Table 1), before the AIST test was evaluated in study 1. In all versions of AIST the participant heard a number of Hagerman sentences and was then required to remember, and to some extent process, this information.

In the first development version the participant's task was to judge statements about the sentences by inferring from the information given in the sentences. These statements were based on categories, like round things, angular things, soft things, or hard things, for example "Did Britta have round things?". This question was answered with Yes or No. However, it was difficult to create categories. First, if a category was too wide it allowed many of the items to fit into the same category. For example: rings, balls, hats, bowls, and baskets can all belong to the category round things, but gloves and pens might also be described as round. Second, many of the items could be placed in more than one category; a basked can be square shaped as well as round, a ball might be described as round, soft, or hard. Finally, the two alternative forced-choice questions had a chance level at 50%, which was deemed to be too imprecise. Therefore, the use of categories and inferring from the information was abandoned.

Instead, it was decided to create questions concerning names, numbers, and items given in the sentences. The use of these three specific words and the matrix-set of sentences enabled automatic generation of questions and answer alternatives. The questions were designed to engage three levels of cognitive processing, called memory load levels (MLL), from memory storage, via memory storage and updating of memory, to memory storage and cognitive processing. Instead of inferring from the information a similar level of cognitive processing was achieved by mathematical comparisons. The test procedure was changed to a three alternative forced-choice procedure, where the chance level of a correct response is 33%.

The simplest memory load level, MLL 1, tapped into memory storage by asking the participant to recall which of three given words occurred in the sentences presented. This level of questions could be answered by a scan of the information held in working memory. The questions were:

1. Which of the following names were used in the sentences?

2. Which of the following numbers were used in the sentences

3. Which of the following items were used in the sentences?

The order of these questions as well as the order of answer alternatives was randomized. Answer alternatives were selected from other sub-lists of sentences, and the procedure made sure to avoid two valid or two identical answer alternatives.

The next memory load level, MLL 2, tapped into memory storage as well, but also required updating. This level of questions could be answered by scanning the sentences held in memory to find the correct word, updating working memory to maintain the relevant sentence and then scanning the sentence to find the second relevant word. Consequently, MLL 2 made greater cognitive demands on working memory storage as well as updating than MLL 1. The questions used were:

1. Who had <number> of items?

2. How many <item> where there?

3. What item did <name> have?

The words in brackets were automatically changed to the corresponding word given in the sentences. Answer alternatives were selected from the same sub-list of sentences. As for MLL 1 questions, the order of questions and answer alternatives was randomized.

The most cognitively demanding level was MLL 3. It required storage and updating of information in working memory, as well as processing of the information from all three sentences presented. This level of questions could be answered by scanning the sentences in working memory for the relevant words and comparing them to find the one that met the criterion. After that, memory could be updated to retain the relevant sentence of the scanned sentences to identify the answer. Thus, MLL 3 made higher cognitive demands than MLL 2, specifically on working memory storage, comparing characteristics, and updating. These questions were:

1. Who had the <most/fewest> <odd/even> number of items?

2. How many <more/fewer> items had <name1> compared to <name2>?

3. Of which item were there <most/fewest> of?

The words in brackets were automatically changed to valid words. For the first question, most or fewest were used randomly, but odd or even were depending on the content of the sentences. For the second question, two of the sentences were randomly selected, the number of items was compared between these and more or fewer derived from this comparison. For the last question, most or fewest were randomly used. Answer alternatives were selected from the same sub-list of sentences. As for the other MLLs, the order of questions and answers was randomized.

Development versions

The AIST was developed in four development versions (see Table 1), first as a simple PowerPoint presentation (tested on 13 participants), and then in three web-based versions using PHP and Java-scripts (all tested on 25 participants). The first three development versions used list lengths of five sentences. However, the use of five sentences was deemed to be too memory demanding, while development version 4 used list lengths of three sentences. Additionally, for development version 4 a practice list was added to improve test reliability. The number of MLL questions was reduced from six to three questions for development version 4 to decrease memory load and increase accuracy. In the final version of AIST, used in studies 1 to 4, only one MLL was tested after each list of sentences. A measurement of response time (RT) was added for the last two development versions (3 and 4).

The first three development versions were performed without background noise, but the last development version used SSN at an SNR of 0 dB. As described previously, the audio files with the Hagerman sentences were stereo files with the noise in one channel and the speech material in the other channel. The easiest way to mix these two channels together was by using java script to control an audio player developed in Adobe Flash. However, this restricted the use of audio formats to mp3 files. For highest audio quality the mp3 files were encoded using variable bitrate and 44.1 kHz. A three seconds mp3 file with SSN was analyzed and compared to a corresponding wave file in Matlab (R2010a), regarding amplitude at each sample and spectral power for frequencies between 25 Hz and 12 kHz. The differences in amplitude and spectral power were small, approximately between 0.026 and 0.15 dB. However, the mp3 file did not contain any information at frequencies over 16 kHz, where some information was present in the wave file. The audio content in the frequencies above 16 kHz was not considered as particularly important for the outcome of the test. There might have been other aspects of the mp3 encoding that was not considered in the analysis, but any differences between the file formats were assumed negligible considering other uncertainties that might differ more between test occasions, such as type of headphones, sound devices, and listening environments, even if these were instructed to be held constant during the tests.

Sentence questions

After each sentence there was a control question to verify speech perception and force processing of the auditory stimuli, as well as preventing the participant from focusing on word storage alone. In the first two pilot versions the question was if any of the five words in the sentence began with a certain letter. However, due to possible pronouncement or dialectal differences this was changed to a question probing which of three alternative words that was in the sentence. This also improved reliability as the chance level decreased from 50% to 33%.

Drawbacks when testing over the web

AIST was during the development implemented as a web-based test. This proved to be an easy way to reach participants. However, there were also drawbacks. The web-based test was conducted in an uncontrolled environment with several possible uncertainties. Some of these uncertainties were controlled for. The audio formats were considered as discussed previously, and the web-based test versions were tested for robustness and accuracy of the time measurement between different web-browsers and different operating systems; the differences found were small and were considered unimportant for the reliability of the test. However, the web-based tests were conducted in an uncontrolled environment with several uncertainties, e.g. choice of sound card and headphones, if subjects took a short break during the test, or even made notes despite the instructions at the beginning of the test.

Version	Length	P. list	Questions	Answers	Control	SNR	n	Code	RT	Audio
1	5	0	6 statements	2	Letter	--	13	PPT	No	wav
2	5	0	6 MLL	3	Letter	--	25	PHP, Java	No	wav
3	5	0	6 MLL	3	Word	--	25	PHP, Java	Yes	wav
4	3	1	3 MLL	3	Word	0 dB	25	PHP, Java	Yes	mp3

Table 1. The AIST test was developed in four versions, with slightly different setups. The table shows development version (Version), list length with number of sentences (Length), if a practice list was used (P.list), the number of questions (Questions), the number of answer alternatives (Answers), type of sentence question (Control), SNR, number of participants (n), implementation environment (Code), if response time was measured (RT), and type of audio format (Audio).

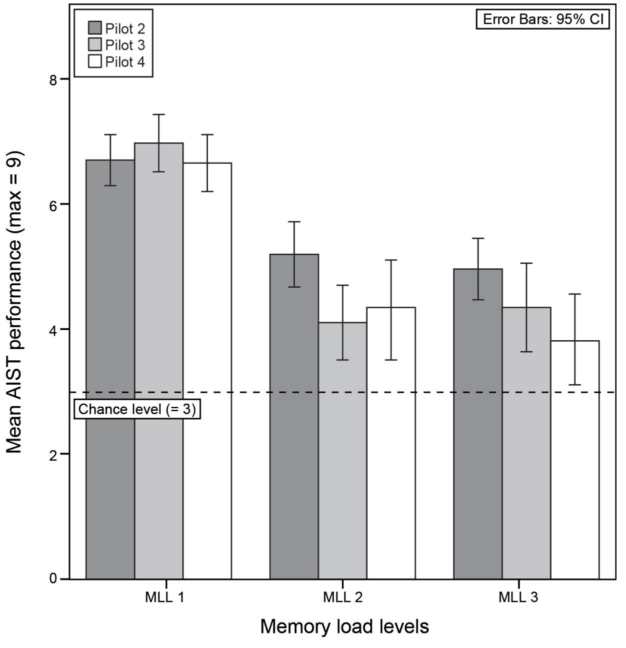


Figure 2. Mean AIST performance in each MLL for development version 2 (Pilot 2), development version 3 (Pilot 3), and development version 4 (Pilot 4). Maximum score for each MLL was 9.

Version	MLL	MLL 1/MLL 2	MLL 1/MLL 3	MLL 2/MLL 3
2	$F(2,48) = 18.84$, $p < 0.001$	$p < 0.001$	$p < 0.001$	No statistically significant difference
3	$F(2,48) = 34.89$, $p < 0.001$	$p < 0.001$	$p < 0.001$	No statistically significant difference
4	$F(2,48) = 34.84$, $p < 0.001$	$p < 0.001$	$p < 0.001$	No statistically significant difference

Table 2. The table shows the effect of MLL for each of the development versions, as well as p-values from post-hoc tests with Bonferroni correction for multiple comparisons.

Results from the development versions

Development version 1 was not considered good enough or useful why no results or analysis will be presented. The following development versions were compared in a repeated measures ANOVA. There were no statistically significant differences between the development versions regarding age, gender, educational level, or self-rated hearing acuity. The repeated measures ANOVA with two within group variables development version (development versions 2, 3, 4) and MLL (MLL 1, MLL 2, MLL 3) showed a significant effect of development version ($F(2,48) = 3.52$, $p = 0.038$) (see Figure 2). Post-hoc tests with Bonferroni correction for multiple comparisons did not show any significant differences between test versions, but studying mean performances and 95% confidence intervals suggested that performance was poorest in development version 4. This suggested that the addition of noise might have affected AIST performance negatively. There was also a significant main effect of MLL ($F(2,48) = 74.17$, $p < 0.001$). Post-hoc tests with Bonferroni correction showed a significant difference between MLL 1 and MLL 2 ($p < 0.001$), and between MLL 1 and MLL 3 ($p < 0.001$), but nog between MLL 2 and MLL 3 (see Figure 2, and Table 2 for individual analyzes of MLLs for each development version).

Conclusion from the development versions

The results from the development versions suggested that AIST performance was a function of MLL with decreased performance with increasing MLL. This show that when MLL questions were more demanding, memory performance decreased, i.e. the cognitive spare capacity decreased. Performance on AIST was also a function of test version with worse performance on the test version with background noise. The decrease in AIST performance in noise suggested that the addition of background noise was adding more cognitive demands which affected memory performance and reduced cognitive spare capacity as measured by AIST. These results indicated that the AIST measured cognitive spare capacity in noise as well as in quiet.

Cognitive measurements

The Reading span test

The Reading span (RS) test (Daneman & Merikle, 1996; J. Rönnberg, Arlinger, Lyxell, & Kinnefors, 1989) is a well-established test of working memory capacity (Unsworth & Engle, 2007). A short version in Swedish, with a maximum score of 28, was used in the present study. The working memory capacity is measured by presenting three-word sentences, one word at the time, on the computer screen. These are grammatical correct sentences, however half of the sentences are absurd. After each sentence the participant is asked to judge, within 1.75 seconds, whether the sentence was absurd or not. After a list of sentences, from two and up to five sentences long in increasing set size, the participant's task is to recall either the first or the last words of the sentences, in serial order. The Reading span was implemented in Matlab (R2013a), and the RS score was measured as the number of correctly recalled words regardless if the participant recalled these in serial order or not.

The Letter memory test

The Letter memory (LM) test (Miyake et al., 2000; Morris & Jones, 1990) is a test of the executive function of updating. The updating ability is assessed by presenting lists with capital letters that are shown one letter at a time on the computer screen. Each letter was presented for 2 seconds. The participant's task is to recall the last four letters in a list in the correct serial order. The length of the lists is either five, seven, nine, or eleven letters long, but the order of these is randomized. The LM test was implemented in Matlab (R2013a), and the LM score was the number of letters that were correctly recalled in serial order for each series.

Participants

Study 1

Forty-one adults (mean age = 32, range = 23 to 59), 18 women and 23 women were recruited at Linköping University, Sweden. One participant had self-reported hearing impairment, while 40 participants had self-reported normal hearing.

Study 2 and 3

Forty-two young adults were invited to the study. Three of these did not meet the inclusion criteria and were excluded from the study. Consequently, 39 young adults (mean age = 31.6, range = 22 to 45), 22 women and 17 men, with normal hearing (hearing thresholds better or equal to 20 dB HL for the frequencies 250 to 4000 Hz on both ears) participated in the study. They were students and employees at Linköping University, Sweden, and all were native Swedish speakers. Twenty of these participants accepted to take part in study 3 as well. The participants in study 3 had a mean age of 35 years (range = 28 to 42), 11 were women and 9 were men.

Study 4

Twenty-one older adults (mean age = 74.1, range = 67 to 80), 7 women and 13 men, were recruited from the audiology clinic at Linköping University Hospital, Sweden. One of these did not meet the inclusion criteria and was excluded from the study. The twenty participants included in the study were all native Swedish speakers and had an average pure-tone threshold (PTA4) of 38 dB HL at 500, 1k, 2k, and 4k Hz across both ears. They were hearing-aid users, and had self-reported normal visual acuity (after correction) and no tinnitus problems.

Procedure

In study 1 the testing time was approximately 30 minutes. In the beginning of the test the participant had to fill in a form regarding their age, sex, educational level, and if they rated themselves as having a hearing impairment or not. This was then followed by the AIST. In study 2 the total testing time was at most 90 minutes, and the order of the tests was: baseline audiometry, Speech recognition test, AIST administered in SSN, Perceived listening effort test, Reading span test, and Letter memory test. In study 3, which was a continuation of study 2, the testing time was about 30 minutes, and AIST was administered in two background noises, AMN or ISTS. The order of background noises was balanced between participants. In study 4 the amount of testing time was 90 minutes and the order of tests was: baseline audiometry, speech recognition and individualizing of SNRs, Trail making test to assess that the participants had age-appropriate cognitive performance, Reading span test, Letter memory test, and AIST administered in three listening conditions, quiet, SSN, and ISTS. The order of listening conditions was balanced between participants.

Study 1

Aim

The aim of this study was to develop and evaluate the AIST as a test that taps into the different cognitive aspects of listening effort.

Method

The AIST version used in study 1 was implemented as a web-based test. The test was conducted in SSN at 0 dB SNR. In this version of the AIST, after each list of sentences and MLL questions the participants were asked to rate their listening effort on a ten-point fixed scale, from “No effort” to “Greatest possible effort”.

Results and discussion

As expected, the results showed that memory performance on AIST decreased with increasing MLL, and that reaction time was longer for MLL 3 than for MLL 1 and 2 questions. The decrease in AIST performance with increasing MLL suggested that a higher degree of involvement of cognitive resources was demanded for higher MLLs. This resulted in a decrease in memory performance, and thereby also a decrease in cognitive spare capacity. The increased reaction time for MLL3 questions indicated that a greater amount of processing of the information was needed to give an answer at this level compared with MLL 1 and 2. Consequently, the AIST was considered to be a test of cognitive spare capacity. There were differences in subjectively rated listening effort between participants, but there were no significant differences in individual listening effort between memory load levels. Since the SNR was the same throughout the test, the results suggested that subjective listening effort was not affected by different cognitive loads due to the different MLLs. However, the large variations of subjective listening effort indicated that the participants experienced the same SNR differently, which may be explained by individual differences in auditory as well as cognitive capacities.

The results suggested that AIST was sensitive to different memory loads. However, if AIST could be used to measure listening effort it should be sensitive to differences in SNR. Therefore, it was decided that in the following study AIST should be tested in different SNRs, and be analyzed with measures the participants’ cognitive abilities.

Study 2

Aim

The aim of this study was to evaluate the AIST as an objective measure of listening effort in different SNRs, and to investigate the effects of WMC and UA on this measurement.

Method

The AIST was conducted in SSN at three SNRs, -2, -4, and -6 dB. Two additional tests were used to collect data on speech recognition as well as individually rated listening effort at these SNRs. The Reading span test assessed WMC, and the Letter memory test was used to measure UA.

Results and discussion

The results showed that AIST performance was a function of cognitive capacity. The analyses were performed using repeated measures ANOVAs with WMC or UA as between subjects factors. The participants were divided into High and Low groups via a median split for each cognitive measurement. However, Table 3 shows correlations with the RS score as well as the LM score, and not median split groups. Participants with greater WMC had higher AIST performance at better SNRs than those with low WMC. The addition of background noise added substantial demands on working memory, and memory performance decreased with worse SNR for participants with high WMC. For the low WMC group, a decrease in SNR did not affect AIST performance. Therefore, the AIST was considered to be too cognitive demanding for this group. Participants with high UA performed better on MLL 2, which made particular demands on UA, than participants with low UA.

Measure		WMC	UA	SRN	LE
AIST	Total AIST	0.208	0.254	0.083	-0.140
	SNR1	0.390*	0.030	0.353*	-0.025
	SNR2	0.380*	0.207	0.118	-0.136
	SNR3	0.124	0.203	0.269	-0.016
	MLL 1	0.317*	0.341*	--	--
	MLL 2	0.235	0.277	--	--
	MLL 3	0.371*	-0.151	--	--
Speech in noise	SNR1	0.270	0.043	--	0.148
	SNR2	0.115	-0.051	--	0.203
	SNR3	0.252	-0.134	--	0.174
Listening effort	SNR1	0.062	-0.193	0.148	--
	SNR2	0.057	-0.060	0.203	--
	SNR3	0.048	0.030	0.174	--

Note: *p < 0.05

Table 3. The table shows correlations between AIST performance and cognitive measurements (WMC and UA), speech recognition in noise (SRN) for the corresponding SNR, and subjectively rated listening effort (LE) for the corresponding SNR. AIST performance is shown as the total AIST performance (pooled over SNR, and MLL), AIST performance in each SNR (pooled over MLL), AIST performance in each MLL (pooled over SNR). As well as correlations between speech in noise performance and cognitive measurements, and between subjectively rated listening effort and cognitive measurements.

Speech recognition scores were a function of SNR, but not associated with any of the cognitive measurements (see Table 3). This suggested that speech recognition in SSN at these SNRs was fairly undemanding, which is probably why having a greater cognitive ability did not improve speech recognition performance. Furthermore, there was no correlation between speech recognition scores and AIST performance, except at the easiest SNR, which implied that factors other than speech intelligibility alone affected AIST performance (see Table 3). Consequently, it was assumed that the decrease in SNR increased cognitive demands resulting in a decrease in memory performance on AIST. Subjectively rated listening effort was a function of SNR as well, but correlated neither with AIST performance, nor with speech in noise performance, nor with any of the cognitive measurements (see Table 3). Consequently, subjective rating of effort is not a good measure of listening effort when speech intelligibility is high. Therefore it was assumed that subjectively rating and AIST performance as an objective measure of listening effort did not tap into the same mechanisms. Memory performance on AIST was also, as expected, a function of MLL with decreased AIST performance with increasing MLL. The results from study 2 showed that the AIST tapped into cognitive functions necessary for understanding speech in noise. The results suggested that for young adults with normal hearing and greater WMC the cognitive spare capacity was reduced when SNRs worsened. Consequently, the listening effort increased for participants with higher WMC in SSN and decreasing SNRs.

Study 3

Aim

The aim of this study was to use the AIST to investigate how memory performance was affected by different background noise types and noise levels, and the influence from WMC and UA. The relationship between speech in noise performance and WMC tend to be stronger when the background noise is modulated, why study 3 was a follow up study 2 and tested the AIST in modulated noise.

Method

The AIST was conducted in three noise types (SSN, AMN, and ISTS) and at three SNRs. The three SNRs for the noise types targeted the same speech intelligibility levels. The Reading span test was used as a measure of WMC, and the Letter memory test as a measure of UA.

Results and discussion

The results showed that AIST performance was not affected differently by the three noise types. Consequently, the type of noise was not important for memory performance in young adults with normal hearing in SNRs targeting 90% speech intelligibility or better. Furthermore, memory performance on AIST was not affected by three different SNRs for SSN or for AMN. However, AIST performance decreased with decreasing SNR when ISTS was used as background noise. The results indicated that ISTS did put additional strains on the cognitive processes required to listen. This can be explained by the speech signal in ISTS. Although unintelligible, it may cause informational masking due to its similarity to real speech. Consequently, since ISTS added more cognitive load, AIST performance in ISTS was more sensitive to decreased SNR compared to the other noise types. Memory performance on AIST was a function of WMC for the easiest SNR in SSN and for the worst SNRs in AMN and ISTS (see Table 4). This indicated that having a greater WMC facilitated listening in SSN in easy listening conditions, but not when the signal was masked due to worse SNRs. However, in the modulated noise types, a greater WMC facilitated listening, with better AIST performance as a result. Memory performance was also a function of UA for the easiest SNR in AMN and ISTS, but not in SSN or at worse SNRs (see Table 4). This suggested that a greater UA facilitated performance on AIST when listening is fairly undemanding. However, in worse SNRs WMC was more important for listening. AIST accuracy was also, as expected, a function of MLL, where performance decreased with increasing

MLL. The results from study 3 showed that when speech intelligibility levels were kept constant and above 90%, different masker types did not have different effects on cognitive spare capacity as measured with the AIST for young adults with normal hearing. However, the cognitive spare capacity was reduced when background noise consisted of voices and the SNR decreased. Consequently, the listening effort increased with the decreased SNR when ISTS was used as background noise.

Measure		WMC	UA
AIST	Total AIST	0.712**	0.319
	Total SSN	0.460*	0.199
	Total AMN	0.616**	0.210
	Total ISTS	0.623**	0.391
	Total SNR1	0.603**	0.495*
	Total SNR2	0.569**	0.237
	Total SNR3	0.715**	0.149
	MLL 1	0.495*	0.186
	MLL 2	0.638**	0.374
	MLL 3	0.656**	0.214
	SSN SNR1	0.637**	0.185
	SSN SNR2	0.108	0.200
	SSN SNR3	0.391	0.093
	AMN SNR1	0.389	0.477*
	AMN SNR2	0.636**	0.118
	AMN SNR3	0.605**	0.000
	ISTS SNR1	0.340	0.512*
	ISTS SNR2	0.602**	0.218
	ISTS SNR3	0.665**	0.283

Note: *p < 0.05, **p < 0.01

Table 4. The table shows correlations between AIST performance and cognitive measurements (WMC and UA). AIST performance is shown as the total AIST performance (pooled over noise type, SNR, and MLLs), AIST performance in each noise type (pooled over SNR and MLL), AIST performance in each SNR (pooled over noise type and MLL), AIST performance in each MLL (pooled over noise type and SNR), as well as AIST performance in each SNR in each noise type (pooled over MLL).

Study 4

Aim

The aim of this study was to use the AIST to investigate the effect on memory performance by different listening conditions, as a function of WMC and UA, for older adults with hearing impairment.

Method

The AIST was conducted in three listening conditions (Quiet, SSN, and ISTS). The background noise was administered in individually adjusted SNRs targeting 90% speech intelligibility levels. The Reading span test was used as a measure of WMC, and the Letter memory test as a measure of UA.

Results and discussion

The results showed that AIST performance decreased with the addition of background noise. This suggested that background noise decreased the cognitive spare capacity and consequently memory performance on AIST. However, speech recognition performance also decreased with the addition of noise. For MLL 1, the decrease in AIST performance was greater than the decrease in speech recognition performance, but for MLL 2 and MLL 3 they were similar. This suggested that for MLL 1 questions the noise did not only affect speech intelligibility but also put additional demands on the cognitive capacity why memory performance decreased. However, for the more cognitive demanding MLLs, the decrease in performance in noise might completely be explained by decreased speech intelligibility. The reason for this might be floor effects where the overall poor performance on the more demanding MLLs did not leave any cognitive spare capacity to store the information. Also, more of the words were needed to be heard to be able to give a correct response on the more demanding MLLs, which is probably why these questions were more sensitive to decreased speech intelligibility.

Measure		WMC	UA	Age	PTA4
Speech recognition	Quiet	-0.077	-0.006	0.544*	-0.233
	SSN	-0.143	0.110	0.330	-0.583**
	ISTS	-0.487*	-0.146	0.424*	0.360
AIST	Total AIST	0.329	0.578*	-0.520*	-0.025
	Total Quiet	0.086	0.552*	-0.295	0.094
	Total SSN	0.383	0.306	-0.583**	-0.202
	Total ISTS	0.293	0.337	-0.251	0.027
	Total MLL 1	0.430	0.495*	-0.630**	-0.172
	Total MLL 2	0.083	0.322	-0.216	0.100
	Total MLL 3	0.160	0.288	-0.185	-0.024

Note: *$p < 0.05$, **$p < 0.01$

Table 5. The table lists correlations between speech recognition performance and cognitive measurements (WMC and UA), age, and hearing thresholds (PTA4), as well as AIST performance and cognitive measurements, age, and hearing. AIST performance is shown as the total AIST performance (pooled over listening conditions and MLLs), AIST performance in each listening condition (pooled over MLLs), as well as AIST performance in each MLL (pooled over listening conditions).

As in the previous studies, memory performance on AIST was also a function of MLL, with decreased AIST performance with increasing MLL. The UA was related to AIST performance, where a greater UA increased AIST performance on MLL 1 (see Table 5). In study 2, this effect was found between UA and MLL 2 and not between UA and MLL 1. In study 4 the UA was lower overall than in study 2. Therefore, the participants with better UA in study 4 probably did not have sufficient UA to improve performance on MLL 2. Another effect of UA was found in AIST performance in quiet, where participants with higher UA performed better on AIST than participants with lower UA. However, having a greater UA was not sufficient to manage the cognitive demands that the addition of background noise put on the cognitive system. Consequently, all participants, regardless of UA, performed at about the same level in the presence of background noise. Contrary to the results in studies 2 and 3, there was no effect of WMC on AIST performance (see Table 5). This might be explained by the rather low performance on the Reading span test, and even participants with higher WMC might not have had enough WMC to make a difference on AIST performance. The results from study 4 showed that the addition of background noise reduced the cognitive spare capacity as measured by AIST performance on MLL questions that did not tax the cognitive system too much. Consequently, the listening effort increased with the addition of background noise. However, the type of background noise did not affect AIST performance differently for speech intelligibility levels at 90% for older adults with hearing impairment. Response times on SQs increased with the addition of background noise, and consequently reflected a higher degree of processing of the auditory information and a higher degree of listening effort.

Discussion

In this thesis the AIST was used to assess listening effort by measuring short-term memory storage and processing of speech in different listening conditions. The AIST manipulates executive processing and memory load by varying difficulty levels on questions about heard information. The AIST was administered to young adults with normal hearing as well as older adults with hearing impairment. The main finding was that memory performance on AIST decreased with increasingly more adverse listening conditions, i.e. worse SNR and/or more taxing noise types (speech-like signals compared to steady-state speech-shaped noise in young adults, and background noise compared to quiet in older adults with hearing impairment). Memory performance on AIST was also a function of cognitive capacity with increased memory performance for individuals with greater cognitive capacity compared to individuals with less cognitive capacity. This observation was independent of the measure of cognitive capacity WMC or UA. However, this was only true for young adults with normal hearing. For older adults with hearing impairment, AIST performance was a function of UA only. The work in this thesis explores the concept of listening effort and cognitive spare capacity. Moreover, it suggests a way to measure listening effort that, with further development, might be a useful instrument to assess listening effort when fitting or evaluating hearing aids.

AIST performance and individual differences in cognitive capacity

In this thesis, memory performance on AIST among young adults with normal hearing was generally better for those with greater cognitive capacity. This was regardless of whether the cognitive capacity was measured as WMC using the Reading span test or as UA using the Letter memory test. This suggests that among young adults with normal hearing, the individuals with the greatest cognitive capacity to start with had most cognitive spare capacity after successful listening and consequently performed best on AIST.

For young adults with normal hearing, WMC was the strongest predictor for AIST performance. In study 2, both WMC and UA were associated with AIST performance. Having a greater WMC implies having more short-term memory storage of the information in the sentences, but also better possibilities to process this information. Consequently, having a greater WMC improved AIST performance regardless of MLL. An interaction revealed that UA was more strongly associated with MLL 2, where memory storage and updating of information in memory was needed. In study 3, AIST performance correlated with WMC regardless of noise type, SNR, or MLL. However, contrary to expectations AIST performance did not correlate with UA.

However, these results were for young adults with normal hearing. When administering the AIST to older adults with hearing impairment in study 4, WMC did not, contrary to expectations, correlate with AIST performance. Even if performance on RS in study 4 was low, it was comparable to other studies using an elderly study population (Classon et al., 2013). Nevertheless, the overall limited RS performance and the small variance may have prevented a statistical significant relation between RS and AIST performance. Furthermore, the poor performance on the RS suggested that the RS might not be a good tool to evaluate WMC in older adults with hearing impairment. On the other hand, UA correlated with AIST performance on MLL 1 questions. Based on the findings in study 2, this correlation was expected to be found between

UA and memory performance on MLL 2, since MLL 2 questions are designed to require more updating of information. The results suggested that participants with low UA did not manage to perform well even at the lowest level (MLL 1), while the older participants with higher UA did not have sufficient UA to perform well at the higher levels (MLL 2 & 3). The results from study 4 might indicate that the overall difficulty level on AIST is too demanding for older adults with hearing impairment.

MLL questions and response time

In study 1 there was a significant effect of MLL on response time. The response time was statistically significantly longer for MLL 3 questions than for MLL 1 and MLL 2 questions. This was interpreted as more processing of the auditory information was needed before an answer could be given. This longer response time can be an indication of increased effort. However, in study 2, the response times on MLL questions were not included in the analyses. The reason for this was that the measure of response time started when the question was presented on the computer screen and continued until an answer had been given, and the test had continued to the next question. Consequently, the time it took to read and comprehend the question was part of the response time measurement. The results from study 1 suggested that there was no statistically significant difference in response times between MLL 1 and MLL 2 questions, but there was a decrease in accuracy between these MLLs. This suggested that MLL 2 was more difficult to answer correctly but that answering did not take longer time. MLL 3 questions are more complex to read and to understand before an answer can be given, and this is likely to increase the response time. Nevertheless, response time on MLL questions might be analyzed when pooled over all three MLLs. It is expected that this response time depend on noise types and/or SNRs. However, this was not found. Pooled response times on MLL questions did not change with listening conditions. Consequently, response time was not deemed as a useful measure when the results of study 2, 3, and 4 were analyzed.

In AIST there is no time limit for the MLL questions. The question is read, the answer alternatives are read, the answer is given, the answer might be changed, and the participant has time to contemplate before giving answers or continuing the test. As time progresses it is likely that cognitive spare capacity to some extent is restored. Either by involving LTM and thus free WMC, or by allowing executive functions to facilitate working memory. It is likely that a longer time to give an answer will facilitate and allow necessary cognitive processes to take place. Mishra et al. (2014) showed an association between cognitive spare capacity and LTM for older adults with hearing impairment. This association showed that for individuals with lower cognitive skills, who are more sensitive to increased demands on processing of speech, LTM may be used to overcome the cognitive weaknesses and free up cognitive capacity. Piquado et al. (2012) also showed a relation between memory performance when young adults with hearing impairment had better memory performance when they were allowed to self-pace the speech input. The listening effort associated with hearing impairment might slow processing operations and increase demands on working memory, with negative memory performance as a result. However, when presentation time was longer this allowed for more inferential processing time of the auditory information and a better memory performance (Piquado, Benichov, Brownell, & Wingfield, 2012). As longer response times diminishes the disadvantage the background noise adds in AIST, the effect of background noise might not show in the measured response time, even if the effect of noise was noticeable in accuracy with decreased memory performance in more adverse listening conditions. Also the effect of cognitive capacity might to some degree be diminished by allowing long answering times, since all participants would have time to scan memory for the answer, regardless of cognitive capacity. However, participants with greater cognitive capacity was overall better to keep the relevant word in memory why there was an effect of cognitive capacity on accuracy on MLL questions. In the data from study 3, there was a tendency towards a significant positive correlation between WMC and response times, which might suggest that individuals with greater cognitive capacity tried to further improve performance by having longer response times to recap the sentences. However, if the word necessary to answer the question was not in memory, it could not be retrieved from memory regardless of the amount of time spent.

There were no statistically significant differences in response time between individuals with high or low WMC, or between individuals with high or low UA. Having a greater cognitive capacity might indicate that information retrieval from memory is faster and more efficient. It is likely that the individual with greater WMC would manage to do more processing of the information held in working memory in the same amount of time as an individual with less WMC. Therefore, the individual with greater WMC would achieve a higher accuracy but spending the same amount of time pondering the question as the individual with less WMC. Consequently, no statistically significant effects of WMC were found on response times on MLL questions in any of the studies, despite there were statistically significant effects of cognitive capacity on accuracy on MLL questions. Therefore, the response time on MLL questions did not measure cognitive spare capacity. Accuracy, on the other hand, was a measure of cognitive spare capacity.

Another possible explanation is that the time it takes from hearing the first sentences until the last question is presented on the computer screen does not only reflect the amount of WMC but also the ability to encode from working memory to LTM. Neither the ability to encode to LTM or a measure of episodic LTM was used in any of the studies within the work of this thesis. If the time to answer all MLL questions reflects encoding to LTM, there might not be an effect of WMC or of UA on response times.

If the time for answering a MLL question had been limited, there might have been an effect of listening condition on response time. The adverse effects of noise might be overcome by long response times since this may free cognitive resources. Consequently, limiting the time available to give an answer would force the answer to be given while working memory still is affected by the listening condition. There might also have been an effect of cognitive capacity on response times as the need for speed would strain the cognitive system to a higher degree than in the present test design. The individual with higher cognitive capacity would likely be better able to give accurate answers even when under time pressure, compared to an individual with less cognitive capacity.

Sentence questions and individual differences in cognitive capacity

The accuracy on the sentence questions was affected by listening condition. In study 3, where the study population was young adults with normal hearing, SQ accuracy was worse in ISTS compared to the other two noise types. There was also an effect of SNR when ISTS was used, with decreased SQ accuracy with worse SNR. In study 4, where the study population was older adults with hearing impairment, SQ accuracy decreased with the addition of background noise. SQ accuracy might be recognized as a measure of speech intelligibility level. Consequently, the results from study 3 suggested that speech intelligibility levels might not have been perfectly matched between noise types since SQ accuracy decreased in ISTS. However, even if ISTS is largely non-intelligible (Holube et al., 2010), it may cause additional informational masking (Francart et al., 2011). Such masking would add to the cognitive load since the masker interferes with the speech material at different linguistic levels (Brouwer et al., 2012; Tun et al., 2002).

Consequently, ISTS adds more cognitive load compared to speech-shaped noise. However, this should have been compensated for when matching speech intelligibility levels between noise types. Consequently, the results suggest that the speech intelligibility levels may not have been perfectly matched between noise types. The results might also imply that there are different cognitive mechanisms or different amount of cognitive engagement involved when repeating words heard in noise compared to when answering a SQ question, and therefore there was a decreased SQ performance in ISTS. In study 4, 90% speech intelligibility level was achieved at statistically significant better SNR for ISTS compared to SSN, suggesting that ISTS was more demanding to listen to compared to SSN. It might also explain why the effect of SNR was only present in ISTS and not in the other noise types. In study 4, SQ accuracy decreased with the addition of background noise. This decrease is considered an effect of decreased speech intelligibility level due to the background noise and hearing impairment.

In study 3 there was no effect of WMC or of UA on SQ accuracy, and there was a ceiling effect on the SQ accuracy measurement. This suggested that for young adults with normal hearing, listening was undemanding why having a greater cognitive ability did not further improve speech intelligibility. Thus, since task demands were low, having a greater WMC did not give an advantage in answering SQ questions. Reading the three answer alternatives and keeping the relevant position for the correct answer in memory, did not seem to load on the UA for it to be visible in the SQ accuracy. Consequently, no effect of WMC or of UA was seen on SQ accuracy.

In study 4 WMC or UA did not influence SQ accuracy. According to the results in study 3, the lack of effect from WMC was expected. Since speech intelligibility levels were individually adjusted, any differences in cognitive capacity needed for speech perception had already been compensated. Therefore, the decreased speech intelligibility could not be overcome by having a greater WMC or UA. Consequently, the decrease in SQ accuracy was a function of speech intelligibility.

Sentence questions and response time

Accuracy on SQs is a measure of intelligibility, why response times on SQs reflects the amount of processing required to listen and give the answer.

In study 4, when presentations were in noise, response times to SQs were significantly longer, statistically, for incorrect answers than for correct answers. To avoid the effect of longer response times for incorrect answers, only response times for correctly answered questions were included in the analyses. These data would indicate the effect of noise on SQ response times when the word was heard. Consequently, the difference in SQ response time between listening in quiet and listening in noise show the additional processing needed when listening in noise. Hence, SQ response time on correct answered SQs in study 4 measure listening effort for older adults with hearing impairment.

In study 4 there was a tendency towards a significant negative correlation between WMC and response time on SQs, indicating that individuals with a greater WMC had faster response times. The negative correlation between response time and WMC found in study 4, suggests that having a greater WMC facilitated faster responses. This could be the result of a more efficient working memory with faster access time to information stored in the working memory. As a consequence, the individuals with greater WMC might be more efficient to scan the three given answer alternatives, store these in working memory, and retrieve the position of the correct answer alternative faster than an individual with less WMC. However, there was also a tendency towards positive correlation between response time and age indicating that older individuals took longer time to give an answer than the younger individuals. It has been shown that aging is often associated with cognitive decline (Besser et al., 2013; Mattys et al., 2012; Nyberg et al., 2012), why the effect of WMC on SQ response time might be a result of age and cognitive decline. However, within none of the studies in this thesis there was an effect of age on the measure of WMC or on the measure of UA. Nevertheless, there were statistically significant differences in WMC and in UA between the young adults with normal hearing (the participants in study 2 as well as the participants in study 3) and older adults with hearing impairment (the participants in study 4), where the young adults had better WMC as well as UA.

In study 3, the number of incorrect answered SQ questions was low and there were no significant difference in SQ response time between correct and incorrect answered questions. Therefore, all SQ response time measurements were used in the analysis. This suggests that for older adults with hearing impairment, task demands was higher than for the study population in study 3 with young adults with normal hearing. There was a statistically significant effect of noise type as well as of SNR found in study 3. SQ response times were longer in ISTS compared to SSN and AMN, and SQ response times were also longer in SNR3 compared to SNR1. The results suggested that more processing of the auditory information was needed in ISTS compared with the other noises and in the more demanding SNR compared with easier SNRs. Hence, there was a higher degree of listening effort in ISTS and SNR3 compared to the other listening conditions.

In study 3, SQ response times correlated positively with WMC showing that individuals with higher WMC had longer SQ response times than individuals with poorer WMC. It was expected that having a greater WMC would imply faster access time to information stored in working memory and a shorter time to retrieve the position of the correct alternative. Instead, the results suggested that individuals with greater WMC spent more time reading the answer alternatives and giving the answer. Despite this, they did not gain from this extra time spent when considering accuracy on SQ questions. Since task demands were low, having a greater WMC did not add an advantage. However, these individuals used more time, perhaps being more careful, giving the answers.

According to the statistical analysis, updating ability did not affect response time on SQs in any of the studies. The results suggested that a greater UA did not improve SQ accuracy, and it did not affect response times.

The speech material

All auditory tests in this thesis used the Hagerman sentences (Hagerman, 1982, 1984, 2002; Hagerman & Kinnefors, 1995). Since these are matrix-type sentences with a structured sequence it was possible to automatically create balanced questions and answer alternatives in Matlab. The software scanned all sentences used within a test and rendered questions, answer alternatives, as well as kept track of the correct answer. The multiple-choice response procedure gave experimental advantages since answer data could be recorded automatically using three-alternative answers to each question, and eliminating manual errors. These advantages could not have been achieved using open-set material, such as the Hearing in Noise Test (Hällgren et al., 2006). However, the Hagerman sentences are artificial and might not be as ecologically valid as an open-set material. Consequently, the Hagerman sentences might be more difficult to memorize than a more natural speech material. Furthermore, using a closed set of 50 words can result in additional difficulties. There might be list intrusion where participants were unable to distinguish words used in the present list of sentences from words used in a previous list of sentences, still being held in memory. Having a greater cognitive ability would probably increase the ability to inhibit words from previous sentences and update the memory with new words. This might add to the effect of greater cognitive capacity leading to improved overall AIST performance. Another issue is the learning effect associated with the Hagerman sentences. However, this effect is assumed negligible for speech-in-noise tests after using 20 practice sentences (Wagener, 2003). In the studies included in this thesis all participants heard more than 20 Hagerman sentences before the AIST test.

Speech intelligibility and SNRs

Study 2 and 3 had a study population of young adults with normal hearing. The SNRs were chosen to produce a speech intelligibility level of 90%, and +2 dB and -2 dB relative to that SNR. According to Hagerman (1982), 90% speech intelligibility was achieved at approximately 3.4 dB above the 50% intelligibility threshold for normal hearing listeners. Accordingly, the SNR for 90% speech intelligibility was at a SNR of approximately -3.7 dB. The SNRs used in study 2 were therefore rounded to -2, -4, and -6 dB. However, the speech recognition test used in study 2 showed a speech intelligibility level of 97%, 96%, and 91% at these SNRs. Differences in test setup between study 2 and the Hagerman study (1982) could explain these differences. In the Hagerman study (1982) stimuli were presented monaurally while stimuli in the studies in this thesis was presented binaurally which would improve speech recognition There were also differences between the studies regarding number of practice lists where the Hagerman study used 10 sentences as practice, while 20 sentences were used in the studies in this thesis. The speech intelligibility levels were not individually adapted since young adults with normal hearing have similar psychometric functions. The SNRs were deemed to give reasonably good speech recognition, while the noise level theoretically caused a relatively challenging listening situation (Mishra et al., 2013a; Ng et al., 2013a). The same speech intelligibility levels were decided to be used in study 3 as well, thus making comparisons between noise types possible.

In study 3, ten young adults with normal hearing were used to equate intelligibility levels between noise types. First, SNRs were roughly adjusted after other studies using similar noise material. Then these SNRs were tested on two participants using 20 sentences in each SNR in each noise type after 20 initial practice sentences in quiet. The SNRs were then adjusted to the mean speech recognition score and tested on four other participants using the same procedure. Then the SNRs were adjusted again and verified using four additional participants. When the speech intelligibility levels were matched, the final SNRs differed between the noise types, both in absolute values and in step sizes between intelligibility levels. However, considering the accuracy on SQ in study 3, the speech intelligibility levels might not have been perfectly matched, but the ISTS might have caused a slightly poorer speech intelligibility level.

The study population in study 4 was older adults with hearing impairment. The speech intelligibility level when listening in noise was set to 90%. The speech intelligibility level was individually adjusted for each participant in each noise type. However, the participants were required to have a speech intelligibility level of 95% or better in quiet. Otherwise, the AIST performance could be a result of hearing loss solely and not of the additional noise. One participant did not meet this criterion and was excluded from the study.

AIST measures the effect of noise on memory performance, and the optimal intelligibility level is not obvious. To be able to answer a MLL question the information must have been heard. Consequently, to measure listening effort using the AIST or another test that measures memory performance as listening effort, it must be ensured that the individual has heard the information. If intelligibility levels are too good, the effects of noise on the cognitive system might be too small to measure. On the other hand, if intelligibility levels are too poor, the measured effect might be a result of masking, since the word might not have been heard. Thus, using more than one intelligibility level when assessing the AIST gives experimental advantages, as memory performance data can be analyzed over intelligibility levels. Furthermore, the SNR step size might be considered. The changes in SNR, as used in study 2 and 3, could have been larger aiming for example at 95%, 90%, and 85% intelligibility levels. However, as intelligibility levels decrease the AIST accuracy can be expected to decrease as well. When SNR thresholds targeting 90% speech intelligibility are applied, the probability to hear the target word decreases from 100% (in quiet or in SNR thresholds targeting 100% speech intelligibility) to 90% for MLL 1 questions. Consequently for MLL 1 questions a decrease in AIST accuracy of 10% can be expected. For target words on MLL 2 and MLL 3 questions the probability to hear two words in quiet is 100% and in noise 81%, hence an expected decrease in AIST accuracy of 19%. Consequently, SNRs must target reasonable good speech intelligibility levels.

The design of AIST makes it possible to detect interactions between difficulty level (MLL) and SNR. Such an interaction would reveal if the noise level would load working memory and executive functions to such a degree that accuracy on one or more of the more difficult MLLs decreased. This allows the AIST to be more sensitive to changes in SNR than if only one memory load level was used. However, no such interaction was found in any of the studies within this thesis. The results suggested rather that the effect of SNR and MLL was independent of each other. When SNR was decreased and AIST performance decreased as well, AIST performance decreased generally equally over all MLLs. This might suggest that the SNRs used (or with other words the speech intelligibility levels used) were such cognitive loading that even the simplest MLL was affected.

Interestingly, Ng et al. (2013a; 2013b) showed an effect of noise reduction algorithms on memory performance in favorable SNRs for adults with hearing impairment. At the individualized SNRs used, speech intelligibility levels were not improved by the use of noise reduction. However, there was an improvement in memory performance when noise reduction was used. This suggests that speech intelligibility levels might be around 100%, and background noise still affects cognitive processes. Consequently, if AIST would be tested at better intelligibility levels, AIST performance might still be an effect of noise type and SNR. As a consequence, the results on memory performance might be more reliable, then those obtained in this thesis, since the measured effect would be due to the influence of noise on the cognitive system only and not a result of intelligibility level.

Subjective measure of listening effort

In study 1 there was a question about listening effort after each sub-list of three sentences and MLL questions. All sentences were presented in SSN and at the same SNR, and the rated subjective listening effort did not change between MLLs. In study 2, the question about listening effort was removed from the AIST. Instead, there was a test of subjectively rated listening effort using the same three SNRs as used in the AIST. The rated listening effort increased with decreasing SNR, but there was no correlation between AIST as the objective measure and the subjectively rated listening effort. Also speech perception in noise decreased with decreasing SNR, but there was no correlation between speech-in-noise performance and rated listening effort. Thus, stated effort did not reflect speech-in-noise performance or memory performance on AIST, and consequently ratings and performance did not tap into the same mechanisms. Furthermore, in good listening conditions when speech intelligibility is high, it is expected that cognitive capacity and listening effort should go hand in hand (Pichora-Fuller & Singh, 2006; Rudner & Lunner, 2013; Rudner, Ng, et al., 2011; Schneider, 2011). However, this was not the case in study 2. There was no correlation between rated listening effort and cognitive abilities, neither WMC nor UA, while AIST performance correlated with cognitive abilities. Consequently, this implied that subjective rating is not a good measure of listening effort when speech intelligibility is high. In hindsight, it was not surprising that there was no correlation between subjectively rated listening effort and the objective measure of effort, since this also had been reported in other studies (Anderson Gosselin & Gagné, 2011; Fraser et al., 2010; Hicks & Tharpe, 2002; Larsby et al., 2005; Zekveld et al., 2010; Zekveld et al., 2009). As a result, subjectively rated listening effort was not used in study 3 or in study 4.

AIST as a measure of cognitive spare capacity

In study 2 (N. Rönnberg et al., 2014b) we assessed cognitive spare capacity using the Auditory Inference Span Test (AIST) developed in study 1 (N. Rönnberg, Stenfelt, & Rudner, 2011) on young adults with normal hearing. This test is designed to measure the ability to apply different levels of cognitive processing of auditory information, which theoretically load on working memory and the executive function of updating. The results showed an effect of memory load level with a decrease in memory performance for questions with increasing cognitive demands. The result suggested that putting the cognitive system under higher demands decreases the amount of cognitive spare capacity. There was also an effect of SNR showing that when background noise level increased memory performance decreased as well. This suggests that more cognitive resources were engaged in listening when background noise level increased, which reduced residual resources needed to remember the auditory information. This was however only true for individuals with greater WMC, which indicated that the test might have been too cognitive demanding to show this effect for individuals with less WMC. In study 3 (N. Rönnberg, Rudner, Lunner, & Stenfelt, 2014c) cognitive spare capacity was assessed using the AIST in three noise types in three matched speech intelligibility levels. Different noise types did not affect cognitive spare capacity differently, but when background noise was speech-like memory performance decreased with worsening SNR. This suggests that different noise types, when speech intelligibility levels are equal, do not load the cognitive system differently, when tested on young adults with normal hearing. However, the cognitive system seems nevertheless to be more sensitive to changes in intelligibility level in speech-like noise. A reason for this might be due to the extra level of informational masking caused by the speech-like noise. In study 4 (N. Rönnberg, Rudner, Lunner, & Stenfelt, 2014a) cognitive spare capacity was tested on older adults with hearing impairment. A similar effect of SNR as in the previous studies was found when comparing memory performance when listening without background noise and when listening in background noise. As in the study 3 (N. Rönnberg et al., 2014c), there were no differences between noise types.

Cognitive spare capacity and WMC

As listening becomes more demanding due to adverse listening conditions, more cognitive resources are needed for speech comprehension (Akeroyd, 2008; Edwards, 2007; Larsby et al., 2005; Mishra et al., 2013a; Ng et al., 2013a; Pichora-Fuller & Singh, 2006). Consequently, the cognitive spare capacity is reduced when listening in adverse conditions (Rudner et al., 2012; Rudner, Ng, et al., 2011). In this thesis, both WMC and UA were generally associated with cognitive spare capacity for young adults with normal hearing. This suggests that cognitive capacity as reflected by WMC or by UA is important for speech comprehension in demanding conditions and affects the cognitive spare capacity. However, this was not seen in studies by Mishra et al. (2013a and 2013b), where cognitive spare capacity was different from WMC. This is intriguing since both the studies by Mishra et al as well as the studies within this thesis measured WMC with RS and measured UA with LM. The results from these studies suggest that the Cognitive spare capacity test (CSCT) used by Mishra et al (2013a; 2013b), and the AIST measures different aspects of cognitive spare capacity.

Mishra et al. (2013a; 2013b) used lists of numbers between 13 and 99 and involved processing of this information by requesting the participant to keep track of the highest odd (or even) number spoken by a male (or female) voice, involving different executive functions such as updating of (or inhibition of) information. The CSCT was structured to assess how visual clues, memory load, and executive functions affect recalling performance of semantically poor stimuli (two digit numbers) in different listening conditions for individuals with normal hearing as well as individuals with hearing impairment. AIST, on the other hand, was designed to assess how cognitive load (working memory as well as executive function) affects memory performance and identification of a target word among three words in different listening conditions (both different noise types as well as different SNRs) for individuals with normal hearing as well as individuals with hearing impairment. Even if the CSCT most certainly loads on the cognitive processes by requiring updating and inhibiting of information, it might not load working memory storage and processing to such a degree as the AIST. Instead the CSCT involves processes to update and maintain a few number of items in working memory or to inhibit irrelevant items from entering working memory. This may explain the general lack of an association between the measure of cognitive spare capacity and WMC. However, within the work of this thesis, the results from AIST suggest that cognitive spare capacity is associated with WMC as well as executive functions. As working memory as well as executive functions has been shown to be associated with speech recognition in noise (Akeroyd, 2008; Edwards, 2007; Larsby, Hällgren, Lyxell, & Arlinger, 2005; Mishra, Lunner, Stenfelt, Rönnberg, & Rudner, 2013a; Ng et al., 2013a; Pichora-Fuller & Singh, 2006; J. Rönnberg et al., 2013) the AIST seem to be more of relevance in a clinical situation compared to the CSCT, for example when evaluating a hearing aid fitting.

The AIST in a clinical setting

For a clinical test it is required that the test used is fast, easily administered, and reliable. The AIST is easily administered with written instructions in the test setup and automatic registration of data. Furthermore, if the AIST is used with individualized speech intelligibility levels the test will assess listening effort by measuring memory performance for individuals with normal hearing as well as for individuals with hearing impairment. However, the difficulty levels of the MLL questions need to be considered when administering AIST to older adults, for whom a decline in the cognitive abilities might be expected. This is of uttermost importance to consider, since the majority requiring hearing aid rehabilitation is older adults. A future, finalized and verified, version of AIST could be used in the hearing aid fitting process, to adjust and evaluate the hearing aid fitting. The AIST would then be used in different listening conditions: in quiet, as a baseline measurement, and in a modulated speech-like noise, as this noise type showed a greater impact on AIST performance. In this setting the AIST would take about 20 minutes. The measurements from AIST, performance on MLL questions as well as response time on SQ questions would show the cognitive spare capacity and thus the listening effort. This would be a useful tool when evaluating the hearing aid fitting, and adjusting the parameters in the noise reduction system and the time constants for the compression. A well fitted hearing aid would improve performance on the AIST with more cognitive spare capacity and less listening effort as a result. However, the AIST, in the versions used in this thesis, is not yet a useful instrument in the hearing aid fitting process, but in need of further development and refinement. Nevertheless, the knowledge that has been gained within the work of this thesis will be of use for future development and testing, using the cognitive spare capacity as a measure of listening effort.

Conclusions

The aim of this thesis was to develop a test, the AIST, to assess cognitive spare capacity as a measure of listening effort. The AIST was administered to young adults with normal hearing as well as older adults with hearing impairment. Two tests of cognitive ability, WMC and UA, were used to determine the associations between these cognitive abilities, cognitive spare capacity, and listening effort.

For young adults with normal hearing and at high speech intelligibility, AIST performance decreased and thus cognitive spare capacity was reduced when task demands required more cognitive processes. However, rated listening effort was not affected by changed task demands at the same SNR. Thus, different MLLs did not affect rated listening effort. Also, for young adults with normal hearing the cognitive spare capacity was a function of WMC and of UA. Consequently, AIST tapped into cognitive functions necessary for understanding speech in noise. Cognitive spare capacity was higher overall for individuals with higher WMC, but also for individuals with better UA on tasks that specifically required updating of information in working memory. Accordingly, having a greater cognitive ability implied also having a greater cognitive spare capacity, and thus less listening effort.

Cognitive spare capacity was sensitive to SNR, when SSN was used in study 2 and when ISTS was used in study 3, and tested on young adults with normal hearing. AIST performance decreased and cognitive spare capacity decreased when SNRs decreased. A similar result was found in study 4 on older adults with hearing impairment when AIST performance was compared between quiet listening condition and when background noise was used. In the presence of noise, AIST performance and cognitive spare capacity decreased. This suggested that there were fewer cognitive resources left for storage and processing of information when listening conditions became poorer, even though speech intelligibility was high, better than 90%. Consequently, when more cognitive resources were involved in listening due to decreased SNR, there was a higher listening effort.

However, at these high intelligibility levels and when intelligibility levels were matched between noise types, the type of noise did not affect cognitive spare capacity differently for young adults with normal hearing. Consequently, the results suggested that at these rather easy listening conditions, there was no difference in listening effort with different types of noise. Despite this, an interaction between noise type and SNR showed that cognitive spare capacity decreased more in speech-like noise when SNR decreased. This suggests that as SNR becomes worse, cognitive spare capacity becomes more vulnerable to interference from other voices compared to non-speech-like noise, even when intelligibility is held constant.

Furthermore, performance on SQs decreased and response times increased in adverse listening conditions, when background noise was present for older adults with hearing impairment and when background noise was speech-like compared to speech-shaped noise or when SNRs decreased for young adults with normal hearing. Consequently, this reflected a higher degree of cognitive processing of the auditory information when listening condition became more adverse and thus a higher listening effort. This was explained by decreased speech intelligibility which theoretically decreased cognitive spare capacity since listening in more adverse conditions would have required more cognitive resources. The increased response times also supported this interpretation, since more processing of the auditory information to maintain speech comprehension would take more time and therefore a higher degree of listening effort.

The research done within the frame of this thesis demonstrates that cognitive spare capacity is related to individual differences in cognitive functions including WMC and UA. The results also suggest that LTM could be used to free up cognitive spare capacity, a relation that has been shown in other research, but other executive functions, like shifting and inhibition, are most probably also of importance for speech recognition in noise as well as for cognitive spare capacity. The results showed an interaction between UA and MLL, for questions that made particular demands on UA. Future work should investigate whether having a better inhibitory function results in better AIST performance in worse listening conditions.

AIST seems to be a useful way to assess listening effort. However, this objective measure of listening effort does not correlate with subjectively rated listening effort. AIST is an objective measure of cognitive spare capacity, or with other words the cognitive effort caused by task demands and listening conditions. Using AIST, it is possible to measure effects of listening condition on memory performance at high speech intelligibility levels where changes in SNR have a negligible effect on speech recognition.

The AIST is a new test of cognitive spare capacity which uses existing speech material that is available in several countries, and the AIST simultaneously manipulates cognitive load and SNR which makes it possible to discover and identify interactions. The interaction found between noise type and SNRs show that decreased SNR reduces cognitive spare capacity more in speech-like noise compared to speech-shaped noise, even though speech intelligibility levels are similar between noise types. Task demands, MLLs, interacted with cognitive capacity, consequently, individuals with less cognitive capacity are more sensitive to increased cognitive load. However, MLLs did not interact with noise type or with SNR, which shows that different memory load levels were not affected differently in different noise types or in different SNRs. This suggests that different cognitive mechanisms come into play for storage and processing of speech information in AIST and for listening to speech in noise.

In summary, cognitive spare capacity seems to be a useful way to assess listening effort, but that AIST in the form used in this thesis might be too cognitively demanding for older adults in general and for young adults with less good WMC. The findings in this thesis have nonetheless implications for further studies of listening effort as well as of cognitive spare capacity. Further findings will be valuable to provide knowledge for evaluating a hearing aid fitting by assessing hearing aid settings and cognitive abilities simultaneously.

Future directions

The AIST that has been developed, evaluated, and assessed in this thesis provides a test of listening effort, considering memory storage and also processing of information as well as updating of information in working memory. The AIST has not been substantially altered between the studies within the frame of this thesis. The reason for this is to more easily understand how different changes in the test setup, like SNR or noise type, affect memory performance on AIST. The findings of this thesis therefore suggest directions for future developing the AIST or of similar tests.

Future developments of the AIST

There are several ways that the AIST might be adopted and improved. The most cognitive demanding level, MLL 3, might be omitted. This would most probably increase AIST accuracy but also shorten the administration time. This would leave time to add questions at the easier MLLs to further improve accuracy. Furthermore, without MLL 3 questions, reaction time might be a valid measure to use together with accuracy. These two measurements might show interactions that can further develop and extend the understanding of AIST performance. The number of sentences within a list could be reduced. Two sentences compared to three sentences, as used in this thesis, would free cognitive capacity and might improve AIST performance. Using two sentences would lead to less demands on memory storage with less information from the sentences, and the information heard would be closer in time to the MLL questions. This could be tested with variable list lengths as well. The amount of time to give answers on MLL questions could be limited. This might show an effect of listening condition on response times, but also an effect of cognitive capacity on response times. A free recall task could also be included in the AIST setup. For example, after answering the MLL questions the participant could be asked to recall the final words from the sentences. After the second list the participant would be asked to recall the final words from the current list as well as the previous list, and so on for each SNR in the test. This free recall measurement could give information about the effect of noise on the participant's WMC as well as ability to encode information to LTM. Finally, other intelligibility levels than those used in this thesis would be interesting to investigate. For example, at 100% there might be an effect of background noise on memory performance when comparing with and without noise, even if there would not be a measurable difference in intelligibility levels between the two listening conditions.

The AIST and measurements of cognitive abilities

In this thesis cognitive spare capacity has been investigated in relation to WMC and UA, as measured with the RS test and the LM test respectively. For young adults with normal hearing cognitive spare capacity was associated with WMC, but not for older adults with hearing impairment. The overall RS performance for the older adults was poor. Thus, another and more sensitive measurement of WMC would be more useful. For example the size-comparison span test (SICSPAN) (Sörqvist, Ljungberg, & Ljung, 2010) might provide an interesting addition to the AIST, since SICSPAN is related to WMC as well as, and contrary to the RS test, episodic LTM (Sörqvist & Rönnberg, 2012). Furthermore, the SICSPAN has been shown to be more strongly connected to speech in noise performance than the RS test (Sörqvist et al., 2010). Also, other executive functions than UA might be interesting to investigate and add to the analysis, like shifting and inhibition (Miyake et al., 2000), since shifting facilitates selection of individual speakers and inhibition slows control of interference from background noise (Rudner, Rönnberg, et al., 2011). Furthermore, linguistic closure ability could be interesting to involve in the AIST test setup. Linguistic closure is suggested to be one of the cognitive processes involved when listening in adverse conditions (Besser et al., 2013; J. Rönnberg et al., 2010; Zekveld et al., 2013). Also LTM would be interesting to include in a future AIST setup, for example as suggested above, as Mishra et al. (2014) showed a correlation between LTM and performance on the CSCT on older adults with hearing impairment. The episodic buffer in the working memory (Baddeley, 2000) enables matching of heard speech with phonological representations in LTM (Rudner & Rönnberg, 2008). Consequently, an efficient episodic LTM may facilitate processing of speech, which in turn might lead to less demands on the cognitive capacity to understand speech, leading to more free cognitive spare capacity.

The AIST and hearing aid settings

The aim with this thesis was to assess cognitive spare capacity as a measure of listening effort, and to develop a test that might evolve as a clinical tool. Within the work in this thesis, the AIST was administered to young adults with normal hearing as well as older adults with hearing impairment. In study 4, the AIST was administered to older adults with hearing impairment using a master hearing aid system (Grimm et al., 2006) with NAL-RP gain prescription (Byrne & Dillon, 1986). This eliminated the effect of different hearing aid types, gain prescriptions, and other hearing aid settings. However, for the AIST to be a useful tool in the hearing aid fitting process, the test must be sensitive to different hearing aid settings. Therefore, the AIST should be evaluated with regards to hearing aid settings. First, the AIST should be tested with regards to noise reduction algorithms, similar to Sarampalis et al. (2009) but with participants with hearing impairment, similar to Ng et al. (2013a; 2013b). Second, AIST should be administered with fast as well as slow dynamic range compression, in a similar way as Lunner (2003) and Lunner and Sundewall-Thoren (2007). This would most probably provide new knowledge and further extend our understanding about listening effort and cognitive spare capacity in connection to hearing aid fittings, but also about hearing aids and cognition (Lunner et al., 2009).

Finally, for the AIST to be a useful test in a clinical setting it is required that it is fast and easily administered. Once the above suggestions have been further analyzed and an optimized AIST set-up has been found, the test would be a useable instrument for testing listening effort by assessing the individual's cognitive spare capacity.

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> *For the strength and courage, that in me I've never known.*
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> *(VNV Nation - Gratitude)*

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