Exploring Cognitive Spare Capacity:

Executive Processing of Degraded Speech

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Linköping Studies in Arts and Science No. 611

Studies from the Swedish Institute for Disability Research No. 58

Department of Behavioural Sciences and Learning

Linköping 2014

Linköping Studies in Arts and Science • No. 611

Studies from the Swedish Institute for Disability Research • No. 58
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Distributed by:
Department of Behavioural Sciences and Learning
Linköping University
SE-581 83 Linköping
Sweden

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Edition 1:1
ISBN 978-91-7519-386-1
ISSN 0282-9800
ISSN 1650-1128

Cover Design: Niklas Rönnberg

Printed by: LiU-Tryck, Linköping, 2014

"Karmany evadhikaras te
ma phalesu kadachana
ma karma-phala-hetur bhur
ma te sango ’stv akarmani"

“You have a right to perform your prescribed duty, but you are not entitled to the fruits of action. Never consider yourself the cause of the results of your activities, and never be attached to not doing your duty."

Bhagwat Gita: Chapter Two verse 47

Abstract

Cognitive resources, specifically working memory capacity are used for listening to speech, especially in noise. Cognitive resources are limited, and if listeners allocate a greater share of these resources to recovering the input signal in noise, fewer resources are available for interpreting and encoding its linguistic content. Although the importance of CSC for individual success in communicative situations has been acknowledged, this concept has not hitherto been explored experimentally. In this thesis, a CSC test (CSCT) was developed and administered to young adults with normal hearing and older adults with age-related hearing loss. CSCT required executive processing of speech at different memory loads with and without visual cues in different noise conditions. A free recall task using the same material was administered for comparison purposes and a battery of cognitive tests was administered to understand the relation between CSC and established cognitive concepts. The aims of the thesis were to investigate how CSC is influenced by 1) different executive demands and memory loads; 2) background noise; 3) visual cues; 4) aging and concomitant hearing loss. The results showed that 1) CSC was sensitive to memory load, and updating demands reduced CSC more than inhibition demands; 2) CSC was reduced in background noise compared to quiet; 3) visual cues enhanced CSC especially in noise; 4) CSC was reduced with ageing and concomitant hearing loss especially when visual cues were absent, memory demands were increased and background noise was speech-like. The main finding of this thesis was that visual cues enhanced CSC for older individuals with hearing loss, specifically in adverse listening conditions. This demonstrates the importance of audiovisual testing in audiological assessment. Further, specific cognitive resources depleted during listening in noise were at least partially compensated by other cognitive functions. This thesis is the first step towards a theoretical understanding of CSC and in future, tests of CSC may play a crucial role in planning rehabilitation of persons with hearing loss.

Keywords: Working memory, cognitive spare capacity, updating, inhibition

Lists of Papers

Paper 1

Mishra, S., Lunner, T., Stenfelt, S., Rönnberg, J., and Rudner, M. (2013). Visual information can hinder working memory processing of speech. *Journal of Speech Language and Hearing Research, 56*, 1120–1132.

Paper 2

Mishra S., Lunner T., Stenfelt S., Rönnberg J., & Rudner M. (2013). Seeing the talker's face supports executive processing of speech in steady state noise. *Frontiers in Systems Neuroscience,* **7**:96.

Paper 3

Mishra S., Stenfelt S., Lunner T., Rönnberg J., & Rudner M. Adverse listening conditions disrupt executive processing of speech more for older adults with hearing impairment than for younger adults with normal hearing. Under review.

Paper 4

Mishra S., Stenfelt S., Lunner T., Rönnberg J., & Rudner M. Updating ability reduces the negative effect of noise on memory of speech for persons with age-related hearing loss. Submitted manuscript.

Table of Contents

List of abbreviations

A-only	Auditory-only
ARCM	Age-related compensatory mechanisms
AV	Audiovisual
Cameq	Cambridge prescriptive formula
CSC	Cognitive spare capacity
CSCT	Cognitive spare capacity test
CRUNCH	Compensation-related utilization of neural circuits hypothesis
ELU	Ease of language understanding
fMRI	Functional magnetic resonance imaging
ICF	International classification of functioning, disability and health
ISTS	International speech testing signal
LTM	Long-term memory
PTA_4	Pure tone average threshold across 0.5, 1, 2 and 4 kHz frequencies
RAMBPHO	Rapid automatic multimodal binding of phonology
RMS	Root mean square
SNR	Signal-to-noise ratio
SSSW	Steady-state speech-weighted
TRT	Text reception threshold
WHO	World Health Organisation
WMC	Working memory capacity

Introduction

Research over the last few years has established the connection between cognition and listening in adverse listening situations. Adverse listening conditions refer to listening in the presence of background noise (Mattys, Davis, Bradlow & Scott, 2012), hearing loss (Stenfelt & Rönnberg, 2009) and when the cognitive demands of listening are increased (Mattys et al., 2012). Although there have been a number of studies examining the cognitive functions involved in speech understanding, there have been very few studies that have assessed the remaining cognitive resources available for interpreting and encoding linguistic content of incoming speech input while speech understanding takes place. These remaining cognitive resources are termed as cognitive spare capacity (CSC; Mishra, Lunner, Stenfelt, Rönnberg & Rudner, 2010; Rudner et al., 2011a, Rudner & Lunner, 2013). In everyday life, speech communication is not restricted to the perception of incoming speech input. Higher level cognitive functions such as working memory, executive functions and long-term memory (LTM) are involved in comprehension of incoming speech input as well as in preparation of an appropriate response to the incoming signal (Pichora-Fuller & Singh, 2006; Rudner & Lunner, 2013). Therefore, the success of an individual in daily communicative situations crucially depends on CSC. Although the importance of CSC in speech communication has been acknowledged (Pichora-Fuller, 2007), no studies have focused on developing a theoretical conceptualization of CSC or exploring CSC in adults with or without hearing loss.

This thesis investigates CSC in young adults with normal hearing and in older adults with hearing loss. The specific aims of this thesis were to investigate how CSC is influenced by factors such as 1) different executive demands and memory loads; 2) background noise; 3) visual cues; and 4) aging and concomitant hearing loss. To achieve these objectives, a CSC test (CSCT) was developed and then administered to young adults with normal hearing and to older adults with hearing loss. The CSCT systematically manipulates executive processing, memory load, modality of presentation and noise conditions to explore CSC in different listening conditions. Lists of items are presented and responses are made strategically. This contrasts with a free recall task in which the participant recalls as many of the presented items as possible. Hence, a free recall task, which made lower executive demands than the CSCT, was administered for comparison purposes, using the same material as used in CSCT. A battery of cognitive tests was administered to the participants to understand the relation between CSC and established cognitive concepts including working memory, executive function, linguistic closure and episodic LTM. This thesis explores CSC in young adults and in older adults with hearing loss and it also assesses the effects of aging and concomitant hearing loss on CSC. The findings of this research provide a theoretical basis for understanding CSC. These findings also have implications for rehabilitation of persons with hearing loss. For example, these findings could provide a basis for developing tests of CSC that can be used in audiological clinics.

Background

Working memory is the site of applied conscious mental effort. It is often defined as a mental workbench where information is encoded into meaningful chunks (Baddeley, 1992). Working memory is a limited resource which can be used for processing and temporary storage of incoming information. It is necessary for a wide range of complex cognitive tasks that also include speech understanding (Baddeley, 2003). Kiessling et al. (2003) outlined four processes that describe auditory functioning. These processes are hearing, listening, comprehending and communicating. Hearing is essentially a passive process directed towards unintentional detection of sound. Listening on the other hand demands mental effort and is the process of hearing with intention and attention. Listening is followed by comprehension, an unidirectional reception of meaning, intent and information, whereas communication is the bi-directional exchange of purposes of listening. Except for hearing all the other processes of auditory functioning demand involvement of cognitive resources. Greater demands on cognitive resources are made while listening in adverse conditions such as in noise or in the presence of hearing loss. In adverse listening conditions, listeners use their cognitive resources, especially the working memory, to recover the speech signal that is lost in adverse listening conditions. It has been suggested that the cognitive processes used for this recovery of the speech signal include attentional resources such as executive functions (Mattys et al., 2012) and other cognitive resources such as access to previous information stored in LTM (Rönnberg et al., 2013) and linguistic closure ability (Besser, Koelewijn, Zekveld, Kramer & Festen, 2013). Therefore, in order to understand the processes involved in speech understanding, an approach of integrating theories from the field of cognitive psychology and audiology is desired.

Cognitive resources, including working memory capacity (WMC) are limited (Baddeley, 2003) and vary from individual to individual (Daneman & Carpenter, 1980). In adverse listening conditions, if listeners allocate a greater share of these resources for recovering the degraded input signal, fewer resources are available for interpreting and encoding its linguistic content (Pichora-Fuller, 2003; Arehart, Souza, Baca & Kates, 2013). The success of an individual in daily speech communication does not only depend on the cognitive resources available for speech understanding, but also depends on the CSC that remains for comprehension and communication while speech understanding is taking place.

Cognitive spare capacity

Based on his studies using a dual task paradigm, Kahneman (1973) introduced a concept of spare capacity for the processes involved in attention. A dual task paradigm is a procedure in experimental psychology that requires an individual to perform two tasks simultaneously. Attentional processes were suggested to be constituted by a single capacity limited cognitive resource and in multiple task situations; each task competes for resources from this single cognitive resource (Kahneman, 1973). Similarly in studies on aging and brain damage, the concepts of cognitive reserve and brain reserve have been defined. In these studies, the differences in susceptibility to functional impairment as result of brain damage have been explained in terms of cognitive reserve, that is, individual differences in cognitive function (Barulli & Stern, 2013) or brain reserve, that is, individual differences in brain size (Satz, Cole, Hardy & Rassovsky, 2011). The concept of CSC for speech understanding explored in this thesis was first introduced by Mishra et al. (2010) for predicting individual success in daily communicative situations. Cognitive spare capacity is the remaining cognitive capacity a person possesses while listening to speech. These remaining cognitive resources or CSC is used to perform the higher level processing of speech that is important for speech communication. Such higher level of processing includes comprehension, inference making, gist formulation, temporary storage of information of the initial part of the message until the message is completed for a complete understanding to occur and also for preparing an appropriate response (Pichora-Fuller, 2007). The fundamental notion that drives this thesis is that in speech communication, a cognitive resource that is depleted while speech understanding occurs is no longer available if the same cognitive function is required at higher levels of communication. Individuals may compensate for information lost during signal degradation by using their WMC or specifically directing their attentional capacity towards understanding the signal (Mattys et al., 2012). The involvement of attentional capacity for speech perception involves the executive functions (Mishra et al., 2010; Rudner et al., 2011a; Sörqvist & Rönnberg, 2012; Rönnberg et al., 2013). Working memory capacity is used for speech understanding in degraded listening conditions. Moreover, the higher cognitive demands of communication also involve resources from WMC. Thus, CSC might be assumed simply as reduced WMC. However, during speech communication, it is likely that various executive functions may be employed differently in different signal degradation conditions. Therefore, CSC might be comprised of variable remaining resources for various executive functions. Moreover, increasing the memory load in speech understanding is likely to lead to a reduced CSC. Speech understanding demands more cognitive resources in the presence of noise (Mattys et al., 2012) and hearing loss (Pichora-Fuller & Singh, 2006). Hence, the starting point for this thesis was that CSC is reduced in the presence of noise and with hearing loss. On the other hand, cognitive demands for speech understanding are reduced by the presence of visual cues especially in noise (Frtusova, Winneke & Phillips 2013). Thus, CSC is likely to be enhanced by presence of visual cues.

Factors Influencing Cognitive Spare Capacity

In this section factors potentially influencing CSC such as, WMC, executive abilities, linguistic closure ability, LTM, hearing loss, signal degradation, aging and presence of visual cues, are discussed.

Working memory

Working memory has been conceptualized as a dual function cognitive system in which the information can be temporarily stored and processed until the input is either forgotten or consolidated into LTM (Baddeley & Hitch, 1974). Various studies have shown that working memory plays an important role in language comprehension (Daneman & Carpenter, 1980; Zekveld, Heslenfeld, Festen & Schoonhoven, 2006; Pichora-Fuller, 2008). In a listening situation when the signal is degraded, either due to the presence of noise (Mattys et al., 2012) or in the presence of hearing loss (Stenfelt & Rönnberg, 2009), listeners use their cognitive resources, especially the working memory to suppress the negative influence of noise. During listening in noise, individuals may store the fragments of information that are not masked by noise in their working memory. Speech understanding may be achieved by integrating these fragments of information. Recent work on memory for sentences heard in noise shows that memory performance correlates with WMC for individuals, both with normal hearing (Rönnberg, Rudner, Lunner & Stenfelt, 2014) and with hearing loss (Ng, Rudner, Lunner, Pedersen & Rönnberg, 2013). In two separate reviews, analyzing twenty studies (Akeroyd, 2008) and twenty-one studies (Besser et al., 2013), it was found that in most of the studies the speech recognition in noise was most reliably predicted by WMC as measured by the reading span test (Daneman &

Carpenter, 1980; Rönnberg, Arlinger, Lyxell & Kinnefors, 1989). In the domain of hearing aids, it has been shown that WMC correlates with aided speech recognition in noise performance (Foo, Rudner, Rönnberg & Lunner, 2007; Gatehouse, Naylor & Elberling, 2003, 2006a, 2006b; Lunner, 2003, Lunner and Sundewall-Thorén, 2007). The ability to derive benefit from digital signal processing algorithms in hearing aids is also associated with WMC (Arehart et al., 2013; Cox & Xu, 2010; Lunner, 2003; Lunner and Sundewall-Thorén, 2007; Rudner, Foo, Sundewall-Thorén, Lunner & Rönnberg, 2008; Rudner, Foo, Lunner & Rönnberg, 2009; Rudner, Lunner & Rönnberg; 2011b).

It has been suggested that the reliance on working memory for speech understanding depends upon the degree of degradation of the signal (Rudner et al. 2011a). Moreover, the higher levels of cognitive functions involved in successful communication require resources from working memory. These factors suggest that CSC may vary from individual to individual depending on WMC. Additionally, when memory demands are increased, CSC can be expected to be reduced. There are various models of working memory (Miyake and Shah, 1999), but only those models that have relevance to speech understanding are discussed here.

Capacity theory of working memory

Just and Carpenter (1992) introduced the capacity theory of working memory for language understanding. According to them, the processing and storage component of the working memory are recruited from a single cognitive resource and the capacity of this single resource is limited and varies from person to person. If there are more demands on processing, the cognitive resources directed towards storage of the incoming signals are reduced. The notion of CSC explored in this thesis is based on the capacity theory of working memory. Both assume that WMC is limited and when the cognitive resources that is available for two tasks occurring simultaneously are insufficient, the cognitive resources devoted to one task are reduced. One of the drawbacks of the capacity theory of working memory for speech communication is that it does not account for integration of information in more than one modality.

Component model of working memory

The component model of working memory (Baddeley & Hitch, 1974; Baddeley, 1996; 2000; 2012) provides for a component in the working memory that is dedicated to multimodal integration of information. It consists of a centre for attentional control, which is called the central executive. The central executive is assisted by the following three subsidiary slave systems: (1) the phonological loop; (2) the visuo-spatial sketchpad; and (3) the episodic buffer. The phonological loop provides temporary storage and processing of linguistically based information. The visuo-spatial sketchpad (Logie, Del Sala, Wynn & Baddeley, 2000) is used in the temporary storage and processing of visual and spatial information. The episodic buffer stores and integrates multimodal information from the sensory input and LTM (Repovs and Baddeley, 2006; Rudner, Fransson, Ingvar, Nyberg & Rönnberg, 2007; Rudner & Rönnberg, 2008). It can be suggested that when speech is presented in the audiovisual modality, the coding of speech stimuli in the phonological loop is assisted by the coding in the visuo-spatial sketchpad through the mediation of the episodic buffer. This mediation by the episodic buffer leads to a more stable representation of the incoming speech stimuli in working memory, which may lead to enhanced CSC.

Working Memory model for Ease of Language Understanding (ELU)

The working memory model for Ease of Language Understanding (ELU; Rönnberg, 2003; Rönnberg et al., 2008; Rönnberg et al., 2013) was developed to specify the role of working memory in language understanding. It incorporates the concepts of both the component model and the capacity theory of working memory. The ELU model recognises that language understanding is multimodal and it also postulates that the incoming language input is bound into multidimensional units of representation by an episodic buffer (Rapid, Automatic, Multimodal Binding of Phonology, RAMBPHO). According to this model, language understanding is automatic or implicit as long as the incoming signal matches with the stored representation in the LTM. But when the incoming signal does not match with the stored representation, mismatch arises. The conditions in which mismatch occurs include signal degradation (Mattys, et al. 2012), hearing loss (Stenfelt & Rönnberg, 2009) and using of amplification devices incorporating signal processing (Ng et al., 2013). In condition of mismatch, conscious or explicit processes are involved in language understanding. Rönnberg et al. (2013) argued that working memory influences LTM of speech, especially in the presence of speech noise and also the inhibitory function plays a key role for the long-term retention of speech. It has also been shown that with hearing loss there is a relative decline in LTM probably due to disuse (Rönnberg et al., 2011). As per the ELU model, in a mismatch condition, both explicit and implicit processing of speech takes place and the involvement of working memory in speech understanding is dependent on the degree to which explicit processing is involved for speech understanding (Rönnberg et al., 2010).

One of the most common ways of measuring WMC, especially in studies assessing the involvement of cognition in hearing, is by the reading span test (Daneman & Carpenter, 1980; Rönnberg et al., 1989). Reading span test is a dual task that assesses both the storage and processing component of the working memory. In the reading span test, the participants are presented with short lists of sentences and are asked to recall the first or the last words of each sentence. Simultaneously, the participants are required to judge the semantic correctness of each sentence immediately after its presentation. The numbers of correctly recalled words determine the individual's working memory capacity. The cognitive processes employed while performing the reading span test may be similar to those employed during perceiving speech sentences in presence of noise. During perceiving speech in noise, part of the signal may be masked by noise and the listener employ resources in working memory to fill in the information that is lost in the signal degradation (Rönnberg, Rudner, Lunner & Zekveld, 2010). At the same time, the listener may have to memorize the initial part of the speech input so that comprehension of the entire speech input may take place (Pichora-Fuller, 2007). Thus, the association of speech performance in noise and WMC can be expected. In particular, the reading span test is useful for assessing the WMC of persons with hearing loss as it involves testing through the unimpaired sensory channel of vision (Classon, Rudner & Rönnberg, 2012; Ng et al., 2013).

The distinction between working memory capacity and cognitive spare capacity

The association of speech recognition performance in adverse listening conditions with WMC suggests that persons with higher cognitive resources at their disposal are better at speech understanding. As discussed earlier, speech communication in real life is not restricted to mere speech understanding but involves higher level cognitive functions involved in communication, such as comprehension, gist formulation and preparation of appropriate response, which involves similar cognitive processes as used in speech understanding. Working memory capacity as measured by the reading span test may not predict CSC, especially when speech understanding takes place in adverse listening situations. This may be because the reading span is tested in visual modality in ideal presentation conditions so it is not confounded by the impaired modality for person with hearing loss and signal degradation due to noise. Reading span test provides a general measure of storage and processing, without separating out effects of memory load, executive function, visual information and background noise. For example, while listening in noise, a person with capacious working memory may be using his/her cognitive resources to a greater extent for speech understanding compared to a person with similar or lesser WMC and with same degree of hearing impairment. Therefore, in this situation, the person with higher WMC may have reduced CSC than a person with lower WMC, suggesting that CSC may be quantitatively different from working memory.

The sub-process view of working memory (Baddeley, 2012; Sörqvist, Ljungberg and Ljung, 2010) proposes that any relationship between working memory and another concept such as language understanding is actually a relationship between a specific part of the working memory construct and the other concept. The sub-process view suggests that during speech perception under adverse conditions, if demands are placed on a particular cognitive resource, such as executive function, then the executive function may be reduced in CSC, sparing other cognitive resources. This view can be interpreted as suggesting that the cognitive resources depleted during the perception of speech may not be available for higher level communicative functions. In such a case, if the depleted cognitive resource is required for higher level of communication functions, it may be either partially or completely compensated by another cognitive resource. For example, listening in noise demands inhibition (Janse, 2012). If the same inhibition skills are required at a higher cognitive level of functioning, the inhibition may be compensated by another cognitive function that achieves the required result by a different mechanism, for example, by the ability to make linguistic closure. Thus, CSC may be qualitatively different from working memory.

Executive Functions

It has been suggested that executive functions are used to segregate speech from noise (Sörqvist & Rönnberg, 2012; Rönnberg et al., 2013). Hence, the executive resources may be assumed to be reduced in CSC when speech perception takes place in adverse listening conditions. Interest in executive functions was renewed with the classic work by Miyake et al. (2000). In this study, it was shown that the higher level functions of planning and decision making rests on three basic underlying executive functions, namely, updating, shifting and inhibition. Updating refers to the monitoring and coding of information that is relevant to the task at hand (Miyake et al. 2000). It may involve appropriately revising the items held in the working memory by replacing the old, no longer relevant information, with newer, more relevant information (Morris & Jones, 1990). Shifting concerns shifting back and forth between multiple tasks, operations or mental sets (Miyake et al., 2000), which might be used to perform dual tasks in a series or parallel. Inhibition involves deliberate, controlled suppression of prepotent responses (Miyake et al. 2000). In working memory this involves ignoring task-irrelevant information. Carretti, Cornoldi, De Beni & Romano (2005) suggested that the relationship between executive function and working memory is mediated by the ability to control irrelevant information. Similarly, other studies have also shown that working memory capacity may be regulated by inhibitory abilities (Conway, Cowan & Bunting, 2001; Sörqvist & Rönnberg, 2012).

The executive functions may be involved in directing attentional resources to speech presented in noisy backgrounds. Furthermore, these executive functions may be required for integrating the fragments of speech information available in noise in order to achieve speech understanding. The executive functions of updating and inhibition have important relevance in speech understanding (Mishra et al., 2010; Rudner et al., 2011b). In a communicative situation, a listener is constantly comparing the incoming message with the stored representation in LTM to ascertain whether the incoming information is new. On the advent of new information, a person uses the executive function of updating to replace the old, no longer relevant information in working memory with the new information. On the other hand, the executive function of inhibition is used to selectively attend the incoming speech signal while ignoring the noise that may be present in the environment. Janse (2012) demonstrated that listening in modulated noise demands inhibition. It is likely that inhibition resources will be depleted while speech understanding takes place in modulated noise. Furthermore, inhibition resources will not be available if the higher communicative functions also require inhibition skills. Hence, in this thesis, it was assumed that the availability of executive resources in CSC will depend upon the extent of involvement of various executive functions in speech understanding.

Linguistic closure ability

During perceiving speech in noise, part of the signal may be masked by noise and the listener employs cognitive processing such as linguistic closure to fill in for the fragments of speech lost due to noise (Zekveld, Rudner, Johnsrude & Rönnberg, 2013; Rönnberg, et al., 2010). Besser, Zekveld, Kramer, Rönnberg & Festen (2012) compared the relationship among working memory, linguistic closure ability and speech perception in noise performance. They found that the linguistic closure ability is less susceptible to age-related changes and introducing a memory component to the linguistic closure ability did not appreciably change its ability to predict speech perception performance in noise. This finding suggested that WMC and linguistic closure ability tap into different processes relevant to speech perception in noise. Cued recall is when a person is given a list of items to remember along with a cue for each item. Memory performance is tested by providing the cue and the participants are required to recall the desired item. Zekveld et al. (2011) using a cued recall paradigm found that better WMC and linguistic closure ability performance was associated with better speech perception when unrelated cues were presented at higher noise levels. A follow-up fMRI study (Zekveld, Rudner, Johnsrude, Heslenfeld & Rönnberg, 2012) revealed that higher WMC was associated with greater benefit from related cues, whereas better linguistic closure was associated with greater ability to disregard information from irrelevant cues. Thus in relation to speech recognition in noise, linguistic closure ability has been shown to have predictive value separate from that of WMC. Therefore, better linguistic closure ability may influence CSC, if CSC is comprised of resources that are distinct from WMC.

Long-term memory (LTM)

Long-term memory is the ability to encode and store information over an extended period and then retrieve it (Tulving, 1983). Information is temporarily stored and processed in the working memory and if this new information is recognized to be useful for tasks in future, it is encoded into LTM (Baddeley & Hitch, 1974). Episodic LTM refers to the encoding and subsequent retrieval of personal happenings and doings, whereas the knowledge of the world independent of person’s identity and past is encoded in the semantic LTM (Tulving, 1983). Working memory plays an important role in speech understanding by acting as a bridge between bottom-up (implicit) and top-down (explicit) processes including drawing on the semantic resources in LTM (Rönnberg et al., 2013). It has also been suggested that listeners apparently retain non-linguistic information such as attributes of speech signal like speaker's gender, dialect, speaking rate and emotional state in the LTM (Pisoni, 1993). Recent work shows that age-related hearing loss is associated with decline in LTM (Lin et al., 2011; Rönnberg et al., 2011). The mechanism behind this association may be that hearing loss leads to more mismatch according to the ELU model due to poor audibility and distortion of the input signal and thus less access to and use of LTM (Rönnberg et al., 2011). In older adults, this is exacerbated by a general cognitive slowing that makes matching of input signal with representations stored in the lexicon more effortful and susceptible to errors (Pichora-Fuller, 2003). The episodic buffer of the working memory (Baddeley, 2000) mediates the matching of speech input with stored representations in semantic LTM with help of episodic LTM (Rudner et al. 2007; Rudner & Rönnberg, 2008). Hence, it can be assumed that an efficient episodic LTM may facilitate the processing of speech thus leading to lesser demands on CSC for speech understanding. On the other hand, efficient episodic LTM suggests better representation in working memory, which may be reflected as enhanced CSC.

Hearing loss

In developed countries, it is estimated that 10 to 15 % of the general population suffers from hearing loss that affects their daily speech communication (Kochkin, 2005; Stevans et al., 2013). The most common method used to assess hearing ability is by determining hearing thresholds by using pure tone audiometry. Pure tone thresholds are the lowest sound level where a repeatable detection occurs across different frequencies. Air and bone conduction hearing thresholds are determined in sound-treated rooms by using head phones and bone vibrator (Roeser, Valente & Hosford-Dunn, 2000). Pure tones at octaves and mid octaves in the frequency range of 125 Hz and 8 kHz are presented sequentially and the minimum sound level required to produce a sensation of hearing is determined. For bone conduction audiometry, the frequency range is restricted to 250 Hz to 4 kHz. The 0 dB HL in the audiometer is calibrated to the minimum sound pressure level required to cause a sensation of hearing at different frequencies for a young adult with normal hearing. Hearing thresholds are determined adaptively by procedure known as the modified Houghton-Westlake procedure. Here, the level of presentation is reduced by 10 dB each time the tone is audible and increased by 5 dB each time the tone is inaudible. Hearing loss is defined as a condition when the average pure tone threshold (PTA_4) across 0.5, 1, 2 and 4 kHz exceeds 25 dB HL for the better ear (World Health Organization; WHO, 2013). It has been estimated that about two thirds of the population in the age group of 70 years and above suffer from hearing loss in developed countries (Lin, Thorpe, Grodon-Slant & Ferrucci, 2011; Johansson & Arlinger, 2003). The term generally used for age-related hearing loss is presbycusis which encompasses all conditions that lead to hearing loss in the elderly (Gates & Mills, 2005). Schuknecht and Gacek (1993) have classified presbycusis into six major types. But clinically, the most common type of hearing loss associated with presbycusis is termed as sensorineural hearing loss (Pichora-Fuller, 2007). This type of hearing loss is caused by dysfunction of the inner ear, the cochlea or the sensory-neural interaction that transmits the impulses from the cochlea to the higher hearing centres in the brain where perception takes place. The most common reason for sensorineural hearing impairment is damage to the hair cells in the cochlea. In pure tone audiometry, sensorineural hearing loss manifests itself by a common elevation of the air conduction and bone conduction thresholds and the difference between both of these thresholds (Air-Bone gap) is less than 10 dB. Typically, age-related hearing loss is characterized by sloping high frequency hearing loss and the loss progresses towards lower frequencies (Gates & Mills, 2005). Sensorineural hearing loss leads to poorer speech recognition caused by reduced audibility, temporal and spectral smearing and abnormal growth of loudness (Moore, 1996).

Hearing aids

One of the most common ways to compensate for hearing loss is by using hearing aids that restores audibility by providing acoustic gain for declining hearing sensitivity. Digital signal processing was introduced in hearing aids nearly twenty years ago and moreover, now advanced signal processing algorithms are available. One of the signal processing algorithms is the noise reduction system. The noise reduction algorithm attenuates noise and provides selective amplification to the signal. Traditionally, hearing aid technology is based on a bottom-up approach to hearing which is concerned with the effects of hearing loss on the peripheral representation of the auditory signal and how hearing aids can improve this peripheral representation (Edward, 2007).

A vast majority of the older adults either underuse or abandon the use of hearing aids (Gates & Mills, 2005). The benefit of hearing aids varies from person to person and one of the reasons may be the individual differences in cognition (Lunner et al., 2009). It has been established that cognitive resources are often recruited to fill in the missing information due to hearing loss or signal degradation including the use of hearing aids implementing signal processing (Rönnberg 2003; Stenfelt & Rönnberg, 2009; Rönnberg et al., 2013). However, this comes at the cost of reduced cognitive resources, which is demonstrated as higher listening effort or fatigue (Edward, 2007; Picou, Ricketts & Hornsby, 2011). Recently, listening effort has been defined in cognitive terms, where it has been defined as the cognitive resources that are consumed for speech recognition (Picou, et al. 2011; Fraser, Gagné, Alepins & Dubois, 2010). From this definition it can be assumed that listening effort will be more pronounced when CSC for the individuals is reduced. The current assessment tools used in audiological clinics seem to be inadequate in predicting benefits of using hearing aids. However, new assessment tools that tests both aspects of cognition and hearing, for example CSC, may be more successful (Pichora-Fuller & Singh, 2006). Such new approaches will also be helpful in evaluating the various signal processing algorithms presently implemented in hearing aids (Edward, 2007).

Noise

In noisy situations, the speech signal may be partly masked by the presence of noise. As cognitive functions, such as working memory, are used to fill in the information lost in the background noise (e.g., Rönnberg et al., 2013), CSC can be expected to be reduced in noise. Noise may be either stationary or modulated. When modulated noise is presented at the same level as steady-state noise, fragments of speech information are masked to lesser extent in 'dips' of modulated noise compared to the steady-state noise. It is possible to take advantage of listening in 'dips' to aid in speech perception. This effect has been shown consistently for persons with normal hearing (Duquesnoy, 1983, George, Festen & Houtgast, 2006; Zekveld et al., 2013). However, individuals with hearing impairment do not always seem to benefit in the same way, possibly due to temporal and spectral smearing (Festen & Plomp, 1990; George et al., 2006; George et al., 2007; Lorenzi, Gilbert, Carn, Garnier & Moore, 2006; Wagener, Brand & Kollmeier, 2006). Alternatively, it has been proposed that benefit of listening in the dips of modulated noise decreases with increasing signal-to-noise ratio (SNR). As speech perception in noise is often tested at equated intelligibility levels, hearing-impaired participants are usually listening at higher SNRs that does not allow listening in the dips (Bernstein & Grant 2009).

Lunner and Sundewall-Thorén (2007) showed in older adults using hearing aids that WMC accounted for about 40% of the variance in speech recognition in modulated noise. Other studies have also suggested that speech performance in modulated noise compared to steady-state noise was associated to a greater extent with cognitive abilities such as working memory for older and young adults (Rudner, Lunner, Behrens, Thoren & Rönnberg, 2012; Zekveld et al., 2013) and linguistic closure ability (Zekveld, George, Kramer, Goverts & Houtgast, 2007). Along similar lines, Rönnberg et al. (2010) have suggested that persons with greater WMC have more resources to integrate fragments of speech that are recognized in dips. Speech recognition in modulated noise compared to steady-state noise is perceived to be more effortful by persons with hearing impairment in terms of subjective rating (Rudner et al., 2012) and physiological response in person with and without hearing loss (Koelewijn, Zekveld, Festen, & Kramer, 2012). However, recently Zion Golumbic et al. (2013) in an electro-physiological study in young adults showed that in the presence of modulated noise the target speech stimuli are dynamically tracked in the brain but the interfering noise is not tracked. This finding suggests that a mechanism of selective attention suppresses interfering modulated noise at the perceptual level and may provide richer representation of the target speech stimuli in working memory for young adults.

Memory for speech

The pioneering work on estimating the cognitive resources used for speech understanding has been based on evaluating memory for heard speech using free, paired-associate or cued recall. In free recall, the participants recalled as many words as possible, in any order. In paired-associate recall, pairs of words were presented and the participant recalled the second word in each pair when cued by the first word.

Free recall tasks

In free recall tasks, it has been observed that the recall scores are higher for early list items (primacy position) and late list items (recency position) compared to mid list items (asymptote). The items occurring in the primacy position are encoded into LTM (Glanzer & Cunitz, 1966; Murdock, 1974). The higher scores in the primacy position is attributed to the process that early-list items have larger rehearsal time. The performance in primacy position can be enhanced by increasing the presentation duration (Brodie and Mudrock, 1977). Higher recency scores are due to shorter retention interval of the late items (Salthouse, 1980). It has also been suggested that the late-list items are being retained in the working memory and hence are easily accessible during recall (Glanzer & Cunitz, 1966; Murdock, 1974). Unsworth and Eagle (2007) proposed a dual storage model of memory that can be used to predict performance in the immediate free recall task. In this framework, memory comprises of a dynamic attention component (primary memory) and a probabilistic cue-dependent search component (secondary memory). According to this model, individuals with low working memory suffer more from proactive interference and hence their performance is lower both in primary and secondary memory. As proactive interference selectively disrupts retrieval from the LTM, individual differences in working memory are likely to be more pronounced for pre-recency items than for recency items (Ng, 2013). Rönnberg (1990) conducted a free recall test on adults with and without hearing loss along with a battery of cognitive tests and concluded that performance in the asymptote is associated with processing speed and thus is sensitive to cognitive aging. Murphy, Craik, Li and Schneider (2000) compared the performance of young adults and older adults and found that in the presence of noise, the older adults recall performance was lower than the recall performance by the young adults, especially in the initial position of recall. Classically, it has been found that free recall performance in the verbal modality is better than the performance when visual texts are provided (Murdock and Walker, 1969; Rönnberg & Nilsson, 1987). However, when both female and male voices occur among the presented auditory stimuli, free recall performance is usually reduced due to dual streaming of male and female voice in a list of items (Hughes, Marsh & Jones, 2009).

Memory performance for speech heard in noise is reduced compared to performance in quiet. Pichora-Fuller, Schneider & Daneman (1995) showed that recall performance for sentence-final words was reduced in babble noise compared to performance in quiet for young adults with normal hearing and older adults with near-normal hearing at equated intelligibility levels. Similarly, paired-associate recall of spoken items is lower when the items are presented in babble noise than in quiet for both young adults and older adults with normal hearing (Murphy et al., 2000; Heinrich & Schneider, 2011). Furthermore, Murphy et al. (2000) showed that in the initial positions of recall, performance for older adults in quiet is similar to the performance of young adults in noise. Recently, there has been interest in evaluating whether noise reduction algorithms in hearing aids reduce the cognitive demands for speech understanding in noise by assessing memory for the final words in spoken sentences (Ng et al., 2013; Sarampalis, Kalluri, Edwards & Hafter, 2009). Sarampalis et al., (2009) found that by using noise reduction algorithms, recall performance in noise was improved in the primacy position for young adults with normal hearing. Using a similar paradigm, Ng. et al (2013) showed that noise reduction algorithms improved the performance in the recency position of recall for older adults with hearing loss who had good reading span performance.

To summarize, the findings of studies on memory for speech suggest that CSC is likely to be reduced by noise for adults with and without hearing loss. However, as adults with normal hearing take advantage of listening in the dips in modulated noise, the type of noise used may influence CSC differently in adults with normal hearing and in older adults with hearing loss.

Visual cues

It has been well-documented in the literature that speech recognition performance is higher with audiovisual (AV) compared to auditory (A-only) presentation in persons with normal hearing and persons with hearing loss (Erber, 1969; Grant, Walden & Seitz, 1998; Grant & Seitz, 2000; Bernstein & Grant, 2009). Observation of lips, teeth and tongue may provide disambiguating information that is complementary to less well-specified auditory information, by helping to determine the place and manner of articulation. While listening in noise, AV presentation can provide substantial benefits in terms of SNR compared to A-only (Campbell, 2009; Hygge, Rönnberg, Larsby & Arlinger, 1992). The advantage of AV presentation has even been observed for young adults when only a graphic representation of the movement of the articulators was shown during detection of syllables in noise (Tye-Murray, Spehar, Myerson, Sommers & Hale, 2011). However, in this study, a similar effect for older adults was not observed but they benefited from unambiguous visual cues. In the case of young adults, the graphic representation does not provide disambiguating information. Thus, the benefit in speech recognition was interpreted as suggesting that visual cues help the listener to direct their attentional capacities to the incoming signal at the most critical time to encode the target (c.f. Helfer & Freyman, 2005). It has been proposed that AV integration involves the episodic buffer of working memory (Baddeley, 2000; Repovs & Baddeley, 2006). Prabhakaran, Narayanan, Zhao and Gabrielli (2000) showed in an fMRI study that binding phonological and visual information involved the same prefrontal regions usually associated with executive function. Therefore, it was assumed that multimodal binding necessarily consumed cognitive resources. However, Allen, Baddeley & Hitch (2006) from five behavioural experiments concluded that although the presence of visual cues demands attention similar to unimodal stimuli initially, but AV integration does not require additional attentional resources. Moradi, Lidestam and Rönnberg (2013) found that the AV speech recognition in the presence of noise for young adults with normal hearing is faster, more accurate and less effortful than auditory-only speech recognition, and inferred that AV presentation taxes cognitive resources to a lesser extent by reducing working memory load. Yovel and Belin (2013) suggested that despite sensory differences, the neurocognitive mechanisms engaged by perceiving faces and voices are highly similar, facilitating integration of visual and speech information. Besle, Fort, Delpeuch and Giard (2004) in an electrophysiological study confirmed that the AV presentation decreased neural activity for young adults compared to A-only and visual-only when syllables were used as stimuli. Similarly, Frtusova, et al. (2013) demonstrated that the presence of visual cues improves behavioural performance on a working memory task demanding involvement of executive functions for both younger and older adults. Furthermore, older adults also showed decreased neural activation with visual cues, indicating a processing benefit in terms of less cognitive resources used in the presence of visual cues. Picou et al. (2011) found that the person with low WMC did not derive any benefit from the presence of visual cues whereas person with high WMC did derive benefit from the presence of visual cues in cued recall of words. Sommers, Tye-Murray and Spehar (2005) found that the AV integration for speech perception in noise was similar across young and older adults with normal hearing, but the young adults had better speech reading skills compared to older adults and hence had better performance in the AV modality.

However, other works have shown a disadvantage of presence of visual cues during speech recognition. Fraser et al. (2010) compared sentence recognition in noise in the A-only and AV modalities of presentation with a concurrent tactile pattern recognition task. When the A-only and the AV stimuli were presented at same SNR ratio, performance was better in the AV modality of presentation while performance was equal in the concurrent tactile task. However, when the noise was adjusted to equate speech recognition performance across modalities of presentation, performance in the tactile task was better when concurrent speech recognition took place in the A-only modality. This finding suggests that at equated performance levels, presence of visual cues increases listening effort and demands more processing capacity overall. Gosselin and Gagné (2011a) extended these findings by using the same experimental paradigm that included older adults with normal hearing in the study. It was found that the presence of visual cues at equated intelligibility level increased listening effort both for young and older adults, but recognition was more effortful for older adults compared to young adults.

The finding of these studies suggests that presence of visual cues reduced cognitive demands for older adults when the task involved executive functions. Hence, CSC for older adults is expected to be enhanced in presence of visual cues. However, when the executive demands are reduced, for example, in speech recognition tasks, although the older adults take advantage of visual cues but the advantage is reduced compared to that of young adults. Nevertheless, for young adults the advantage of presence of visual cues was dependent on the level of noise. At equated speech performance level for AV and A-only presentation, speech recognition performance has been found to be more effortful in young adults. Hence, it can be expected that the enhancement of CSC in young adults in the presence of visual cues may depend on the level of noise presented.

Aging

It has been observed that cognitive resources, especially WMC, are reduced with aging (e.g. Besser et al., 2013; Mattys, et al., 2012). Furthermore, aging is associated with hearing loss (Pichora-Fuller & Singh, 2006). When combined, aging and concomitant hearing loss may lead to reduced CSC compared to young adults with normal hearing. Although, cognitive resources are reduced with aging, still it does not apply to all the cognitive resources. Importantly, crystallized knowledge stored in long-term semantic memory is well preserved with aging, and age-related difficulties are confined to fluid knowledge including fast, moment-to-moment processing of information in working memory during language comprehension (Pichora-Fuller & Singh, 2006). Aging is associated with hearing loss which may lead to spectral resolution deficits (Smith, Pichora-Fuller, Wilson & MacDonald, 2012) in addition to temporal masking. It has been found that speech recognition performance of older adults even with normal hearing, especially in presence of noise, is reduced to greater extent in older adults than compared to young adults. It happens probably due to greater auditory temporal processing deficits (Mattys et al., 2012; Pichora-Fuller & Souza, 2003; Gordon-Salant, 2005; Pichora-Fuller & Singh, 2006). Other factors such as widening of auditory filters also may lead to worsened speech perception with presbycusis (Saremi and Stenfelt, 2013). The older adults because of their reduced speech recognition performance may not be active participants in their daily communicative situation (Hickson & Scarinci, 2007) that may lead to loneliness and depression in this population (Pronk, Deeg & Kramer, 2013).

Gosselin and Gagné (2011b) demonstrated that the older adults performed poorly in both speech recognition task and a secondary task of tactile recognition pattern. Hence, it can be concluded that not only the older adults have poorer speech recognition but they also use more cognitive resources for speech perception compared to the young adults. Pichora-Fuller et al. (1995) found that despite adequate recognition, the older adults recalled fewer items compared to the younger adults. It has been suggested that older adults deploy their cognitive resources for understanding speech in a different manner compared to younger adults (Wong et al., 2009). The lower memory performance of the older adults in the presence of the noise and even in quiet could be accounted for by allocating more cognitive resources to speech recognition, hereby, reducing resources available for memory processing (Pichora-Fuller et al., 1995). Despite adequate recognition (Pichora-Fuller et al., 1995; Heinrich & Schneider, 2011; Sörqvist & Rönnberg, 2012), this reduction in cognitive resources leads to an impoverished encoding of the target stimuli in the working memory. Reuter-Lorenz and Cappell (2008) in an fMRI study demonstrated that the older adults consumed greater neural resources compared to the young adults when the task demands were low, which was termed as compensation-related utilization of neural circuits hypothesis' (CRUNCH).

In summary, it can be suggested that CSC for the older adults can be expected to be reduced compared to that of the young adults. Older adults consume more cognitive resources for speech understanding and the representation of speech in working memory is impoverished to greater extent in noise. From these findings, it can be expected that CSC for the older adults to be reduced to greater extent compared to the young adults when memory demands are higher, especially in the presence of noise. Moreover, the older adults with concomitant hearing loss may not be able to take advantage of listening in modulated noise. Hence, CSC can be expected to be reduced to a greater extent compared to the young adults with normal hearing in presence of modulated noise. On the other hand, visual cues may reduce the influence of noise on CSC, especially in older adults with hearing loss.

Need for a test of cognitive spare capacity

A test for measuring WMC, such as reading span, may not predict CSC, especially in degraded listening situations. It has been argued that CSC may be quantitatively different from WMC as WMC varies from individual to individual. Moreover, different individuals employ their WMC to different extents for speech understanding. Furthermore, a cognitive resource that is depleted in the act of speech perception may be compensated for, fully or partially, by another cognitive function during further higher level of processing involved in communication. Hence CSC can be qualitatively different from working memory. Thus, it can be argued that a measure of WMC may not predict CSC and therefore there is a need for a separate test for CSC.

Another question that may arise here is that as there are so many test paradigms assessing the role of cognition in speech understanding then why is there a need for another paradigm. In fact, Ng (2013) has argued that performance in the free recall task provides an estimate of CSC. In free recall tasks, the participants recall speech items in any order. Hence, the free recall tasks can be assumed to be loaded on memory but the executive function demands in such tasks are reduced. It has been argued that cognitive functions such as executive functions and linguistic closure ability are essential for higher level of cognitive functions needed in communication (Rönnberg et al., 2013; Besser et al., 2013). As the free recall task does not operationalize such cognitive processes, it may not be considered as evaluating CSC for speech understanding. Studies in dual task paradigm may provide an estimate of the CSC, but the secondary task is usually in the visual or tactile modality and hence may not provide an estimate of the remaining cognitive resources that are essential for higher level cognitive functions involved in communication. Studies on listening effort where it is defined in cognitive terms can contribute to the concept of CSC in terms of identifying listening conditions which are cognitively demanding. It can be argued that these two concepts are distinct. Listening effort provides an estimate of the cognitive resources depleted during speech understanding and do not provide any information about the particular cognitive resources depleted during speech understanding or about CSC. Such information about the particular cognitive processes involved in speech understanding and remaining cognitive resources in CSC may help towards developing a theoretical understanding of CSC. In addition, in most of the studies assessing memory performance or listening effort involved in speech understanding, the modality of presentation is in the A-only modality (except for the study by Picou, et al. 2011), while communication in real situation is often multimodal.

In this thesis a test for CSC (CSCT) was developed and evaluated. CSCT has been designed to be an auditory working memory task that estimates CSC in different adverse listening conditions. It has been argued that executive functions and memory load may influence CSC (e.g. Rönnberg et al., 2013). Therefore, CSCT assesses performance in executive function tasks of updating and inhibition at different memory load, i.e., low load and high load conditions. As speech communication in real life is usually multimodal and visual cues may enhance CSC, CSCT was administered in AV modality also. The stimulus materials consist of two digits numbers and these were arranged in lists and presented in AV and A-only modality. These lists are presented in three different noise conditions including quiet (no noise), steady-state noise and speech-like noise conditions to verify the influence of different types of noise on CSC. The numbers were presented at high intelligibility levels in the presence of noise so that the participants could perceive most of the numbers, in order to perform the tasks in CSCT, but requiring effort. As cognitive resources were used while perceiving the numbers, especially in the presence of noise, it can be assumed that the performance in the CSCT task provides an estimate of CSC. A person with higher CSC is expected to have higher scores in CSCT. To verify whether the effects observed in CSCT are different when the executive demands in the task are reduced, a free recall task was also administered using the same material as used in CSCT. Along with CSCT and free recall task, a battery of cognitive tests was also administered to understand the cognitive underpinning of the CSC. The cognitive test battery included assessing working memory capacity, linguistic closure skills, updating and inhibition functions, processing speed and episodic LTM capacity. In a similar paradigm, Rönnberg et al., (2014) evaluated the processing and memory of sentences presented at high intelligibility levels in steady-state noise and at different levels of memory load in young adults with normal hearing. Although, the performance was reduced with increasing memory load, but surprisingly there was no effect of noise level. Presently, this test is being further developed to make it clinically feasible.

Methodological Considerations

Cognitive hearing science: An emerging field

There is a general consensus on the involvement of cognitive processes in speech understanding, especially in adverse listening conditions. However in the past, research in cognitive psychology and audiology had mostly occurred in isolation (Arlinger, Lunner, Lyxell & Pichora-Fuller, 2009). Recently, recognition of the interaction between cognition and hearing has led to development of a new interdisciplinary area called cognitive hearing science (Arlinger et al., 2009; Campbell, Rudner & Rönnberg, 2009; Rönnberg et al., 2009; Rönnberg et al., 2010). The pioneering work in cognitive hearing science was initiated by assessing the memory of heard speech in quiet and noise for both young and older adults with normal hearing (Pichora-Fuller et al., 1995; Murphy et al., 2000). Earlier, in the field of cognitive psychology, research in working memory and language comprehension was generally conducted on subjects with assumed normal hearing under ideal conditions of signal presentation with emphasis on the cognitive processes involved in speech understanding. In such studies, the effects of signal degradation including hearing loss were ignored. In the field of audiology, research on speech perception in person with and without hearing loss under different signal degradation was conducted. Here, relatively simple materials such as isolated words or simple sentences were used with an emphasis on controlling the acoustic parameters of the signal (Pichora-Fuller, 2007, Arlinger et al., 2009). The materials used in these studies can be considered to be too simplistic with regards to the cognitive demands of real-life communicative situation where performance was assessed on mere word or sentence repetitions without assessing the cognitive functions such as comprehension or communication. Hence, to predict the performance of an individual with and without hearing loss in real life communicative situation, research approaches used in the field of cognitive hearing science are important. The field of cognitive hearing science can be advanced either by using tests of cognition and hearing in the same study or by developing tests that measure both aspects cognition and hearing. In this thesis, CSCT has been developed that tests both aspects of hearing and cognition. In CSCT, cognitive tests used in the field of cognitive psychology are applied in the A-only and AV modality of presentation with emphasis on acoustic parameters of the stimulus material. Furthermore, CSCT was administered to young adults with normal hearing and to older adults with hearing loss. The finding of this thesis will help in devising better rehabilitative approaches for individuals with hearing loss. Hence, this thesis can be considered to be in the field of cognitive hearing science and disability research.

Disability research

Disability research is a discipline that deals with medical, psychological and social aspects of disability. Traditionally, disability research has been driven by the theoretical models of medical and social approaches (Bickenbach, Chattterji, Badley & Üstün, 1999). However, approaches to disability research restricted to one particular model or single dimension of knowledge does not provide a holistic view of disability (Thomas, 2004). Danermark (2003) suggested the need of multidisciplinary research in the field of hearing disability. To obtain a more holistic approach towards the issues of rehabilitation for person with hearing loss, approaches integrating knowledge from fields of audiology, psychology, sociology and others has been emphasized (Borg, 2003). A bio-psycho-social model called ICF (International Classification of Functioning, Disability and Health; WHO, 2001) has received a general acceptance in the field of disability research. The ICF model aims at integrating the medical and social model of disability. This thesis, investigates CSC in young adults with normal hearing and older adults with hearing loss to understand how this phenomenon may change over the lifespan. A horizontal dimension is achieved in this thesis by studying the two groups of participants, varying in terms of sensory and cognitive skills. CSCT was developed from the theoretical and experimental knowledge in the field of cognitive psychology and neuropsychology incorporating the concept of hearing impairment in the field on audiology. A vertical dimension to the thesis has been achieved by including various cognitive tests from the field of psychology and also emphasizing the effects of hearing loss, aspects of signal processing and intelligibility of stimuli material from the field of audiology. Thus, this thesis integrates horizontal and vertical dimensions of knowledge from the field of psychology and audiology at various levels. Although the primary purpose of this thesis was to gain theoretical insights into the concept of CSC, which may be further applied in the rehabilitation of persons with hearing loss. In the hearing aid industry, although the involvement of cognitive processes in speech understanding has been acknowledged recently, the focus of research has been based on improving signal processing aspects of hearing aids to enhance the peripheral representation of speech input. Due to lack of tools that test both cognition and hearing, we have little knowledge regarding whether improvement in speech understanding due to the advanced signal processing algorithms implemented in hearing aids comes at a cost of extra cognitive demands or relieves cognitive resources for other higher level functions of speech communication. The theoretical knowledge of CSC may serve as a tool to improve such rehabilitative approaches.

The ICF describes health domains and health related domains including 1) Body Functions and Structures, 2) Activities and 3) Participation, with health condition, environmental and personal factors interacting with activities. In accordance with the ICF, Kiessling et al. (2003) outlined four processes that describe auditory functioning, which are hearing, listening, comprehending and communicating. Comprehension and communication are both critical aspects of functioning according to the ICF at levels of both activity and participation (Pichora-Fuller & Singh, 2006).The work reported in this thesis involved recruiting persons with normal hearing and hearing loss by following a medical model. Hearing loss can be considered as an impairment of the body structure that leads to inadequate body function. Hearing loss restricts participation in conversation and thereby participation in society. Achieving the aims of this thesis will provide a better basis for audiological rehabilitation. In this way, the research may have a direct influence on environmental and participation factors for persons with hearing disability.

Aims

The present thesis investigates CSC for young adults with normal hearing and for older adults with hearing loss by developing and administering CSCT. The purpose of this thesis was to investigate the theoretical underpinning of CSC which would provide a baseline for devising new assessments tools. Such tools will help in devising better rehabilitation approaches for person with hearing loss. To investigate whether the effects of noise and modality would generalise to a memory tasks, a free recall task using the same material as used in CSCT was also administered. In the free recall task, memory load is maximised by retention of all the items but executive demands are minimised by allowing the participants to report the items they have succeeded in retaining in any order. In this thesis, CSCT, free recall task and a cognitive test battery was administered to two groups of participants; a) young adults with normal hearing and b) older adults with age-related hearing loss. In CSCT, at the end of the list the participants were asked to recall two or three numbers according to the instructions given. These instructions induced two different executive functions, updating and inhibition, at two different memory loads, low and high. In the free recall tasks, at the end of the lists the participant recalled as many numbers as they remembered. The aims of thesis were to investigate how CSC is influenced by the following factors 1) different executive demands and memory loads; 2) background noise; 3) visual cues; and 4) aging and concomitant hearing loss.

In the first Study, the CSCT was developed and assessed along with a free recall test in young adults with normal hearing in quiet. The aim of this study was to investigate whether CSC was distinct from WMC and whether the presence of visual cues enhanced CSC and memory performance in a similar manner. In the second Study, the CSCT was administered in quiet, steady-state and speech-like noise to the young adults. It investigated how noise influences CSC and whether the presence of visual cues moderated the effects of noise. The third Study involved administration of CSCT in the same condition as used in the second Study to older adults with age-related hearing loss and the performance of the participants of this Study were compared with performance of the young adults who participated in the second Study. The aim of the third Study was to investigate whether effects of noise and AV presentation on CSC was influenced by aging. In the fourth Study, free call task was administered to the young adults and to the older adults with hearing loss. The aim was to investigate whether background noise disrupts free recall of spoken items when intelligibility is still high, whether performance is restored by presenting visual cues and whether there were any effects of aging. Therefore, by conducting these four Studies, the main objectives of this thesis were accomplished.

General Methods

Participants

All participants were native Swedish speakers. The young participants with either continuing or completed university education in Linköping University were recruited through advertisements within the university. The older adults with hearing loss were recruited from the audiology clinic at Linköping University hospital. The same group of young adults participated in Studies 2 and 4, whereas the same group of older adults participated in Studies 3 and 4. The participants did not have any reported otological, psychological or neurological problems. Visual acuity after correction was normal for all participants as measured using the Jaeger eye chart (Weatherly, 2002). Hearing thresholds of the young participants were better than 20 dB HL in the frequency range of 125 Hz-8 KHz. An ethical approval for the studies was obtained from the regional ethical review board (Dnr-230-09).

Young adults

Study 1

Twenty young adults, undergraduates at Linköping University (Age: 22-54 years, M=29.5; S.D=8.2) completed the CSCT and cognitive test battery in this study. Additionally, ten undergraduates at Linköping University (Age: 21-33 years, M=27.8, SD=4.9), who did not take CSCT, participated in the free recall test.

Studies 2 and 4

The participants were twenty young adults with either continuing or completed university education in Linköping University. They were of 19-35 years of age (M=25.9; SD=4.4).

Older adults

Twenty-four participants (Age: 61-75 years, M=69, SD=4.7), 14 males and 10 females, with mild-to-moderate hearing loss and no reported tinnitus completed the testing in Studies 3 and 4. All participants had sensorineural hearing loss (Air-Bone gap <10 dB) and the mean PTA_4 was 34.5 dB HL (SD=3.6). The participants reported that their hearing loss was acquired post-lingually. An epidemiological study from a larger area in the same location showed that 73.1% of the individuals in the age range of 70-80 years and 42.1% in the age range of 60-70 years had mild hearing loss (Johansson & Arlinger, 2003). In the present study, all participants had mild (PTA_4: 26-40 dB HL; WHO, 2013) hearing loss, except for one participant aged 74 years who had moderate (PTA_4: 41-60 dB HL; WHO, 2013) hearing loss. Hearing thresholds of all participants at all four frequencies were within one standard deviation of population means for the age group reported by Cruickshanks et al. (1998). Thus, hearing status was representative for their age group.

Material

Stimuli

Recordings of the stimulus material for the CSCT in the AV modality were prepared in Swedish. Two native Swedish speakers, one male and one female, with no distinctive dialect were instructed to use the Swedish “Speaking clock” (Fröken ur), as a pronunciation reference during recording. At the same time an independent higher quality audio recording was carried out at the sampling rate of 44100 Hz with 16 bit resolution. The speakers wore dark colored clothes and were asked to maintain a neutral expression throughout the recording. Both speakers recorded the set of numbers from 13-99, spoken sequentially three times. A grey background was used and the speaker's neck and head were visible. The video was filmed using a digital camera (Sony HVR-V1E, PAL 25 fps) having a resolution of 720×576 pixels with 1536 bit resolution along with the audio track and digitized into AVI video format.

For each of the six separate recordings, the waveform of the independent higher quality audio recordings and the waveform of the audio track in the video of the entire sequence of numbers (13-99) were synchronized in Adobe Audition (Version 3) by matching the visual representation of the two waveforms at the onset of the auditory signal using the cursor. The synchronized audio tracks were imported into Adobe Premiere Pro (Version CS3) to make sure both the audio files and video file are of the same duration and the two waveforms were matched at the onset of auditory signal. The audio track in the video was removed and the higher quality audio recording was retained along with the video. From each sequence of numbers (13-99), 87 numbers were sampled out from the start to end of the articulator movements; hence, each AV and audio sample had 51-61 frames with maximum presentation duration of 2.5 seconds per sample. It was ascertained from a validation study that the audio and video recorded by the camera were in synchrony. Using Final Cut Pro, the placement of audio waveforms of simultaneous buzzer tones and blinks from an LED electronic electric-tension meter were compared. The blinks of about 30 ms in duration, with an interval of about 25 ms were recorded using the camera. Analyzing ten clips, each with eight blinks-and-tones, there was no average offset between blinks and tones. This validates that a hypothetical offset is less than 1/16 of the frame duration (40 ms) = 2.5 ms. Data obtained from the study showed that the potential synch errors are constant and that if there are synch errors, they are less than 2.5 ms.

Three native Swedish speakers rated these samples for naturalness of pronunciation. The final set of stimulus material was assembled from the highest rated sample of each number spoken by each of the two speakers. The quality of the items in the final stimulus set was checked by a practicing speech and language pathologist. The audio waveforms of all numbers were equalized to the same root mean square (RMS) level using MATLAB (Version 2009b). The numbers were arranged into lists, each containing thirteen numbers.

It is known that even after RMS equalization, there is lot of variation in intelligibility of different speech tokens. Therefore, in Studies 2, 3 and 4, the levels of the numbers were equated for 50% intelligibility in steady-state noise using a group of ten young adults with normal hearing. This was accomplished by increasing the SNR in steps of 1 dB for each number until a correct response was given in a procedure similar to that described in Hällgren, Larsby and Arlinger (2006). This was carried out to minimize the confounding factor of audibility while recalling numbers in noise.

Noise

The stationary noise was a steady-state speech-weighted (SSSW) noise, having the same long term average spectrum as the recorded numbers. It was created by filtering white noise with the same frequency characteristics as the stimulus material using MATLAB (Version 2009b). The modulated noise was the International Speech Testing Signal (ISTS; Holube, Fredelake, Valming & Kollmeier, 2010). The ISTS noise is designed to be speech-like but is unintelligible and is thus composed of concatenated speech segments of around 500 ms duration in six languages (American English, Arabic, Mandarin, French, German and Spanish) spoken by six different female speakers. Keeping the speech level constant, the noise levels were changed to obtain individualized SNRs.

Individualizing Signal-to- Noise Ratio (SNR)

The stimulus materials (numbers) in A-only modality and the SSSW noise were used in an adaptive procedure to determine the individualized SNR for presentation of the CSCT. In this adaptive procedure, the first stimulus was presented at an SNR of 5 dB and the participants were instructed to repeat the numbers they heard and were encouraged to guess if they were unsure. For the first run, for each new presented number that was repeated correctly, the noise was increased by steps of 3 dB until the participant's response was incorrect. Thereafter, the step size was changed to 1 dB and 30 numbers were randomly selected and presented consecutively to determine the 84% intelligibility level adaptively in a four-down/one-up procedure (Levitt, 1971). In the second step, the SNR obtained for 84% intelligibility was increased by 0.5 dB to give an approximate intelligibility level of 90% in SSSW noise. This 0.5 dB increment to yield an approximate intelligibility level of 90% in SSSW noise was verified in a piloting study using six participants with normal hearing. The 90% intelligibility level in noise was chosen so that the participants were able to perceive most of the numbers to perform the tasks in CSCT, but some effort was required for this perception. To verify the intelligibility at this new SNR, sixty numbers, again randomly selected from the stimulus material were used. These numbers were presented at the set SNR and the intelligibility with SSSW and ISTS noise was obtained independently. The same individualized SNR levels were applied in the SSSW and ISTS noise during CSCT presentation. The above tests were implemented in MATLAB (Version 2009b).

Amplification

To equate the audibility for older adults with hearing loss and young adults, the signal (number and noise) was presented with individualized amplification for the older adults with hearing loss in Studies 3 and 4. The signal for all speech in noise tests with auditory presentation was amplified using the Cambridge prescriptive formula (Cameq) for linear hearing aids (Moore & Glasberg, 1998). This amplification was implemented in a master hearing aid (MHA) system (Grimm, Herzke, Berg & Hohmann, 2006). The participant's audiogram was used to set the gain according to the Cameq fitting rule giving individual amplification for each participant.

Cognitive Spare Capacity Test

In the CSCT, the lists of thirteen two-digit numbers (13-99) were presented serially and after each list the participant was asked to report particular list items, depending on the condition. The stimulus materials consisted of two-digit numbers spoken by a male and a female speaker in Swedish. The lists were presented in quiet (no noise) in the first Study and in the subsequent three Studies, lists were presented in quiet, steady-state noise and speech-like noise with intelligibility levels approximating 90% in noise. The stimuli were presented with individualized amplification for person with hearing loss. The modality of presentation was either AV or A-only in all the Studies. The same lists were presented in all the Studies. Numbers were repeated between two and eight times over all lists but never within one list and the same condition. In all conditions the task was to remember at least two items specified according to certain predetermined criteria. Storage demands were manipulated in terms of working memory load. In the low load conditions, participants were asked only to recall the two specified items. In the high load conditions, they were asked to additionally recall the first list item (which is never one of the two specified items). Adding an extra to-be-remembered item is an established method of increasing working memory load (Braver, Cohen, Nystrom, Jonides, Smith & Noll, 1997). Processing demands were manipulated in terms of the executive function tapped by the working memory task. The two executive functions involved are updating and inhibition. In the updating task, the participants were asked to recall either the highest (in one version) or the lowest (in the other version) value item spoken by the male and female speaker in the particular list. Thus, in the updating conditions, the participant had to update working memory storage each time an item is presented that meets the criterion. There were either three or four updating occasion per list balanced across conditions. In the inhibition task, the participants were asked to recall either two odd numbers spoken by the male (in one version) or even numbers spoken by the female speaker (in the other version). Thus, in the inhibition conditions, the participant had to inhibit storage of items having the desired parity but spoken by the non-target speaker. Similar to the updating task, there was either three or four inhibition occasions balanced across conditions. In the two executive conditions, working memory storage load was taxed to a similar degree depending on whether the condition is low or high load. The serial position of the two target numbers was balanced across the lists. Additionally, in the updating conditions of CSCT, if the highest two numbers were asked to be recalled, the first number to be recalled in the high memory load condition was a number in thirties or lesser and similarly, if the lowest numbers were to be recalled, the additional number recalled in high memory load condition was in the seventies or higher. For the inhibition condition when odd numbers were recalled, the first number recalled in the high memory load was an even number spoken by the female and *vice versa* when even numbers were recalled. In the first Study, the lists were presented in quiet only, but in Studies 2 and 3, the lists were presented in quiet, SSSW and ISTS noise. Additionally, the presence or absence of visual information was manipulated. In AV conditions, a moving image of the speaker's face articulating the item was presented simultaneously with the A-only signal. For high memory load trials, the first number (dummy item) was not included in the scoring. Thus, all scoring in the CSCT was based on correct report, in any order, of two numbers.

Experimental design of CSCT

In the first Study, there were eight conditions of presentation with two executive function (updating, inhibition), two memory load (low, high) and two modalities of presentation (AV, A-only) in a 2x2x2 design. In Studies 2 and 3, the participants performed executive function in different memory load and modalities of presentation of CSCT with stimulus presentation in quiet, SSSW noise and ISTS noise in a 2x2x2x3 design.

Administration of CSCT

The CSCT was administered using the DMDX software (Forster & Forster, 2003). The participants performed the CSCT under four different conditions in Study 1 and twelve different conditions in Studies 2 and 3 per executive task in separate blocks. Hence, six lists per condition were assessed in Study 1 while in Studies 2 and 3, two lists per condition were tested. The order of the conditions was pseudo-randomized within the two task blocks and balanced across the participants. In Study 1, the visual stimuli were presented using a computer with a screen size of 14.1 inches and screen resolution of 1366 x 768 pixels. The video was displayed in 720 x 576 pixels resolution in the centre of the screen and the auditory stimuli were presented through speakers at the sound levels preferred by the listeners. For the noisy conditions in Studies 2 and 3, the noise sound files were played together with the AV and A-only stimulus files in DMDX.

The noise onset was one second prior to onset of stimulus and the noise offset was at least one second after the stimulus offset. The lists of numbers were always presented at 65 dB SPL and the level of the noise varied depending upon the individualized SNR level before individualized amplification for hearing loss. The same individualized SNR was used for all noisy trials. Across all the conditions (noisy or quiet), the duration of presentation of each number list was 33 seconds in AV and A-only modality. The visual stimuli in Studies 2 and 3 were presented using a computer exactly in same manner as used in Study 1 and the auditory stimuli were presented through Sennheiser HDA 200 headphones. Additionally, in Studies 3 and 4, the auditory stimuli were presented through headphones after individualized amplification through the MHA for the older adults with hearing loss.

The participants were provided with written instructions for the particular executive task before each of the blocks, and the instructions were also elaborated orally. In addition to this, before each list was presented, the participant was prompted on the computer screen as to which version of the executive task was to be performed, what was the modality and whether to remember two or three numbers (high or low load). The task prompt remained on screen until the participant pressed a button to continue for the test. At the end of each list, an instruction "Respond now" appeared on the screen and the participants were required to type the target numbers in Study 1, but oral responses were recorded in Studies 2 and 3. Corrections to reported numbers were allowed. The participant then pressed another button when they were ready to continue. All the participants practiced each task with two lists before performing the test. The participants were specifically instructed to keep looking at the screen during stimulus presentation. This instruction applied even during presentation in the A-only modality where a fixation cross was provided at the centre of the screen. If they looked away from the screen, the test was stopped after the presentation of the list and the participants were reinstructed to keep looking at the screen.

Free recall task

The free recall task used the same set of stimuli lists as used in the CSCT. In Study 1, the complete set of the materials used in CSCT was used in free recall task and in the same modalities of presentation (AV and A-only). In Study 4, each participant was presented with 24 of the 48 lists of the CSCT, 12 in AV and 12 in the A-only modality in three noise conditions (quiet, steady-state and speech-like noise). Allocation of the 48 lists was balanced across all the participants. At the end of each list the participants were asked to recall as many of the numbers given in the list as possible, in any order. The score was the mean percentage of correctly recalled numbers from primacy, asymptote and recency portions of the list. Primacy referred to the first two list items, recency referred to the last two list items and the asymptote was the remaining nine items.

Experimental design of free recall task

Altogether, with two modalities of presentation and three position of recall, the free recall test had a 2x3 experimental design in Study 1. Additionally, in Study 4 the lists were presented in three noise conditions, hence, the free recall had an experimental design of 2x3x3.

Administration of free recall task

The free recall test was administered using the DMDX software .The order of the noise conditions was pseudo-randomized within the two modalities of presentation and the order of modality of presentation was balanced across the participants. In Study 1, the administration of the free recall task was exactly carried out in the same manner as CSCT was administered in Study 1. In Study 4, the free recall task was administered exactly in the same manner as CSCT was administered for the young adults in Study 2 and for the older adults in Study 3.

Before the free recall test, the participants were provided with written instructions and the instructions were also elaborated verbally. First a prompt regarding the modality of presentation appeared on the screen and the participant pressed a button to begin the presentation of the list. At the end of the list an instruction "Respond" appeared on the screen and the participants were required to type the target numbers in Study 1, but oral responses were recorded in Study 4. The participant pressed another button to continue to the presentation of the next list. The participants were always encouraged to keep looking at the screen and even during the presentation in the A-only modality, a fixation cross appeared on the screen. If a participant was distracted, they were reminded to look at the screen.

Cognitive Test Battery

Reading span test

The reading span test provided a measure of WMC. In this test, the participants read a series of sentences which appeared on the computer screen one at a time (Daneman & Carpenter, 1980, Rönnberg et al. 1989). Each series consisted of three to six sentences presented in an increasing series length and each sentence consisted of three words. There was an interval of 50 ms between the words and each word was shown for 800 ms. Half of the sentences were coherent and the other half were absurd. After each sentence, the participant was given 1.75 seconds to judge the semantic coherence of the sentence before the next sentence appeared. The participant responded 'yes' (if the sentence was coherent) or 'no' (if the sentence was absurd). At the end of the presentation of each series of sentences, the participants were prompted by an instruction on the screen to recall either the first or the last word of all the sentences in the series in the order in which they appeared on the screen. All the participants practiced with a series of three sentences before the actual testing was carried out and if necessary, the practice was repeated. There were a total of 54 sentences in the actual test. The dependent measure was the total number of words correctly recalled in any order.

Text reception threshold (TRT)

The Text Reception Threshold (TRT) test taps the ability to make linguistic closure during speech processing (Zekveld et al. 2007). A Swedish version of the TRT test, using Hearing In Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994) sentences was employed (Hällgren, et al., 2006). The test consisted of presentation of three lists of 20 HINT sentences each, the first list being a practice list. The sentences appeared on the screen in red print masked by a pattern of vertical black bars. At the start of each trial, the bar pattern was first visible and then the sentence appeared. The timing of the appearance of each word was based on the audio files that were available for each of the sentences; the presentation rate of the words in each sentence was equal to the speaking rate in the specific speaker file (Hällgren et al. 2006). All the words remained visible on the screen until the sentence was complete. After the presentation of the last word of a sentence, the sentence remained visible for 3.5 seconds. Thus, first the black bars appeared on the screen and then the sentence appeared word by word in red, giving the appearance that the sentence was partially hidden by the black bars. The first sentence was presented with an unmasked threshold of 16% (i.e., 16% of the sentence was visible) and was repeatedly presented with an increased percentage of unmasked text (decreasing density of the bar pattern) until the participant was able to read the sentence correctly. For the first sentence a double step size (12%) was used, i.e., 12% more of the sentence was visible in each step and a step size of 6% was used for sentences 2-19, which were presented once and adapted to the response of the participants. The TRT is the average percentage of unmasked text for sentences 5-21 (the percentage of unmasked text of sentence 21 relied on the response to sentence 20). The average percentage of unmasked text from the two lists of sentences was used as the dependent variable.

Letter memory test

The letter memory test measures the updating skills of an individual. In the letter memory test (Morris & Jones, 1990; Miyake et al. 2000) lists consisting of 5, 7, 9 or 11 consonants were presented. In each of the list, the consonants appeared at the centre of the screen for 2 seconds each using the DMDX software. The participants were asked to remember the four most recent letters and then they were prompted to recall them at the end of each sequence. Sequence length was randomized across the trials to ensure that the participant followed the instructed strategy and continuously updated their working memory representation until the end of each trial. Two lists, each consisting of 7 and 9 letters were presented as practice. The testing consisted of 12 lists. The participants were asked to recall the letters in the order they appeared on the screen using the keyboard in Study 1. In Studies 2, 3 and 4, the responses of the participants were audio recorded. The score was the number of letters correctly recalled, irrespective of order.

Simon task

Simon task measures the inhibition skills. In this go/no go task (Simon, 1969; adapted from Pratte, Rouder, Morey & Feng, 2010), the red and blue rectangular blocks appeared at two second intervals either on the left or on the right of the computer screen. It was presented using the DMDX software. The participants were instructed to respond as quickly as possible to the red blocks by pressing a key present on the right side of the key board and the blue blocks by pressing a key on the left side of the keyboard in Study 1. In the subsequent Studies, external buttons were used. The participant had to ignore the spatial position in which the blocks appeared on the screen. Sixteen blocks were presented. There was no practice conducted for the test. When the spatial position of the stimulus and the correct response key coincided, the trial was termed as congruent; otherwise it was incongruent. The difference in the average reaction time between the incongruent and the congruent trials was taken as a measure of inhibition. The mean reaction time obtained on the congruent trials was taken as a measure of the processing speed.

Delayed free recall of reading span test

A delayed free recall of the reading span test was used to measure the episodic LTM of the participants. In this test the participants were asked to recall words or sentences remembered from the reading span test after approximately sixty minutes, without forewarning. During the sixty minutes, the participants performed the other tests in the cognitive test battery. The score in the delayed free recall of the reading span test was the total number of words recalled by the participant, irrespective of the order and the performance in the reading span test. The participants did not have any time restriction to recall the words or sentences. This test was not included in Study 1.

Procedure

The participants, on arriving in the laboratory, were fully briefed about the study and a consent form was signed. In Study 1, all testing were conducted in one session that lasted for almost two hours. All the participants underwent a hearing and vision screening in a room that had a low ambient noise. CSCT was administered first followed by the Simon task, the reading span test, the letter memory task, and finally, the TRT. For the free recall task, another experiment was conducted where the participants performed the free recall task in one session approximately of 90 minutes in duration.

In subsequent Studies, the testing was conducted in two sessions, each approximately of two hours in duration. The participants first underwent vision screening and audiometric testing in an audiometric test booth. The reading span test was administered first and then was followed by the Simon task, the letter memory test and the TRT test in a separate room. Individual SNRs for the CSCT and free recall test were determined in the audiometric test booth and the delayed recall of the reading span test concluded the first session. In the second session, the CSCT test was followed by the free recall test. The participants were allowed to take breaks after different tests were conducted, and also within different blocks of CSCT and free recall testing, whenever desired. Written instructions were provided for all the tests and the participants were given the opportunity to request an oral clarification.

Summary of the Studies

Study 1

Purpose

The purpose of this study was to determine whether the cognitive spare capacity as measured by CSCT was distinct from WMC as measured by the reading span test. This study was also performed to establish and evaluate CSCT. Another significant purpose of this study was to evaluate whether executive functions, memory load and modality of presentation, were successfully manipulated in CSCT. To determine whether the presence of visual cues benefited in recall performance with reduced executive demands, a free recall task was also administered. By administering a cognitive test battery along with the CSCT, the cognitive underpinning of CSC was evaluated that will serve as a baseline for understanding the construct of CSC, as CSCT was administered in quiet to young adults with normal hearing.

Methods

In this study, the CSCT and a cognitive test battery excluding the test for episodic LTM was administered to twenty young adults with normal hearing. In a separate experiment, a free recall task was administered to ten young adults. The CSCT and free recall task were administered in quiet condition only.

Results and discussion

The repeated measures analysis of variance (ANOVA) of CSCT data revealed main effects of the executive function, memory load and modality variables. There were no interactions. Performance was lower in the updating task than in the inhibition task, in the high memory load conditions than in the low memory load conditions and, surprisingly, lower in the AV than in the A-only modality of presentation. To ascertain that the better performance was due to the executive demands of the CSCT rather than driven by the stimulus material, ten different young participants performed a free recall task on the CSCT lists. The repeated measures ANOVA revealed a main effect of modality of presentation showing that free recall performance was better in the AV modality of presentation than in the A-only modality. The serial position effects were in expected lines and the interaction was also significant. Investigation of the interaction revealed better performance in the AV modality in the primacy and recency positions but not in the asymptote position. One possible explanation of poorer performance in the AV modality of presentation in the CSCT is that the loading executive function makes it difficult to prioritize task-related processing in the presence of low priority stimuli (Lavie, 2005). In this case the superfluous information in visual modality may be considered as low-priority stimuli for young adults with normal hearing as the task in CSCT could be performed based on A-only input only. The performance in CSCT in any of the condition was not associated with WMC as measured by reading span test. Thus, it suggests that CSC is quantitatively and qualitatively different from the working memory. The performance in the updating and inhibition condition of the CSCT was associated with the independent measure of executive function task. CSCT performance was associated with TRT, which is a measure of skills used for making linguistic closure.

Study 2

Purpose

The main purpose of this study was to investigate how noise influences CSC. It was predicted that noise would disrupt executive processing of intelligible auditory two-digit numbers leading to a lower CSCT performance compared to the performance in quiet. It was also expected that ISTS noise would be more disruptive than steady-state noise given the same SNR, particularly during the inhibition task. Seeing the talker's face would counteract the noise decrement by helping the listener segregate target from noise and generate richer cognitive representations. However, in quiet conditions, visual cues would act as a distractor and reduce performance.

Methods

In this study, CSCT and a cognitive test battery was administered to twenty young adults with normal hearing. In the noise conditions, the mean SNR for CSCT presentation was -2.17 dB (SD=0.85). The mean intelligibility level for the SSSW noise was 93.8% (SD=3.0) and for the ISTS noise was 92.3% (SD=2.9). There was no statistically significant difference in speech intelligibility performance in SSSW and ISTS noise (t (38) = 1.58, p =0.12).

Results and discussion

The repeated measures ANOVA of the CSCT scores revealed main effects of executive function, memory load, modality and noise. The main effect of executive function and memory load showed higher CSCT scores in inhibition than updating conditions and in low than high memory load conditions, replicating the results of the previous study. Furthermore, CSCT scores were higher in the AV than in A-only conditions. In addition, analysis of the main effect of noise revealed that the CSCT scores in quiet and ISTS noise was significantly higher than in SSSW noise but there were no significant difference between the performance in quiet and ISTS noise. The two-way interaction between noise and modality was significant. It was hypothesized that performance would be better in the A-only than in AV modality in quiet but the opposite was expected in noise. Planned comparisons revealed better performance was observed in A-only compared to AV in quiet, and better performance in AV compared to A-only in SSSW noise in line with the predictions. However, in ISTS noise there was no significant difference between performance in AV and A-only conditions. The better performance in A-only modality compared to AV has been reported in dual task paradigm studies as well (Fraser et al., 2010; Gosselin & Gagné, 2011). This may be because loading on executive functions makes it difficult to prioritize task-related processing in the presence of low-priority stimuli (Lavie, 2005). The presence of visual cues for young adults with normal hearing can be considered as a low-priority stimulus, if not a distractor for the participants. Higher CSCT performance in ISTS noise compared to SSSW noise may be explained by a selective attention mechanism that comes into play when speech stimuli are presented against a background of speech-like noise (Zion Golumbic et al., 2013).This finding suggests that selective attention at higher cortical levels suppresses interfering modulated noise at the perceptual level and may provide richer representation of the target speech stimuli in memory. In SSSW noise, it is likely that selective attention to the speech stimuli could not be achieved due to the lack of modulation in the interfering noise, thus, resulting in a failure to segregate the speech stimuli from the SSSW noise (c.f. Helfer and Freyman, 2005). There was no interaction between the executive function and the type of noise or memory load; hence, the data of present study did not provide any evidence that CSC was influenced differently by the executive function task in presence of different types of noise. There was no significant difference in performance in the AV modality between any of the noise conditions including quiet. These findings demonstrate that when noise disrupts executive processing of speech, seeing the face of the talker counteracts the disruptive effect of the noise.

The correlation between speech performance in ISTS noise and performance in the Simon task suggests that inhibition skills may come to the fore to suppress irrelevant information during memory encoding (Janse, 2012; Sörqvist, Stenfelt & Rönnberg, 2012). The association of speech performance in ISTS noise and TRT suggests a role for linguistic closure during speech perception performance in noise when irrelevant cues have to be disregarded (Zekveld et al., 2013). There was no overall correlation between CSCT performance and WMC as measured by reading span test, but CSCT performance in quiet conditions did correlate with WMC. CSCT in quiet conditions is likely to be more similar to independently measured WMC, which may explain the intercorrelation. The pattern of correlations between the CSCT and the cognitive test battery suggests that consistent demands were made on updating skills whereas inhibition skills had less impact. The explanation may be that during executive processing of numbers, updating skills compensated for the unavailability of inhibition skills already engaged in suppressing noise during perception of numbers.

Study 3

Purpose

In this study, CSC was assessed in older adults with hearing loss. The data of the present study and the previous study was reanalyzed to explore the effect of aging and concomitant auditory decline on CSCT performance.

Methods

Twenty-four older adults with mild to moderate hearing loss participated in this study. The hearing thresholds of the participants were similar to the hearing thresholds reported in population of same age group, hence the hearing loss was considered to be age-related. The participants performed the CSCT and the cognitive test battery. The mean SNR for CSCT presentation in noise was -0.17 dB (SD=1.39). The mean intelligibility levels for the SSSW noise was 94.5% (SD=3.0) and for the ISTS noise was 88.3% (SD=3.0). The difference between these levels was statistically significant, $t\ (46) = 7.05$, $p<0.01$.

Results and discussion

The repeated measures ANOVA of the CSCT scores of the older adults with hearing loss revealed main effects of executive function, memory load, modality and noise. The main effect of executive function and memory load showed higher CSCT scores in inhibition than updating conditions and in low than high memory load conditions, similar to the findings of young adults with normal hearing. The CSCT scores were higher in the AV modality compared to A-only modality and there was no interaction with noise, thus, indicating that even in quiet the performance was better in the AV modality. This finding suggests that even in quiet conditions, seeing the talker's face helps the older individuals with hearing loss to form better cognitive representations of spoken words, leading to higher performance in AV modality. Further, analysis of the main effect of noise revealed that CSCT performance in quiet was better than the performance in both noises, but there was no difference between performance in ISTS and SSSW noise. To test whether the difference in intelligibility influenced memory performance, difference in recall of the first list item in the high memory load conditions when items were presented in SSSW noise was compared to the recall in ISTS noise. Statistically, there was no significant difference, thus, suggesting that CSCT performance in SSSW and ISTS noise is not an artifact of intelligibility differences. It has been demonstrated that persons with hearing loss are poorer at segregating speech from noise than persons with normal hearing and that when the noise is modulated; this decrement is even greater (Festen & Plomp, 1990). Performance in CSCT was not significantly associated with performance in the reading span test, except in the ISTS noise conditions. Previous work has shown that speech recognition in modulated noise, especially in speech noise, is associated with WMC (Zekveld et al., 2013). This may be caused because listening in modulated noise involves integrating fragments of information available in the dips of the noise (Lunner, 2003). Moreover, better CSCT performance was associated with better episodic LTM. One interpretation of this finding is that higher scores in CSCT may be due to better representation in working memory that would also lead to higher LTM (Rönnberg et al., 2011). In addition, an efficient LTM may facilitate the processing of speech, therefore, leading to fewer demands on the cognitive resources (Rönnberg et al., 2013). Thus, LTM may form a processing bottleneck for this group.

Reanalysis

A reanalysis of the data of the present study and the previous study where CSCT was administered to young adults with normal hearing was conducted by a mixed repeated measure ANOVA on CSCT scores with the two groups of participants as a between subjects variable. A main effect of group revealed lower CSCT scores for the older adults with hearing loss compared to the younger adults with normal hearing. Examination of the two way interactions with the group factor revealed that the poorer performance of the older adults was driven mainly by performance differences in more challenging conditions: high memory load, A-only modality of presentation and in ISTS noise, where the performance of the older adults was significantly lower compared to the young adults. This finding suggests that CSC can be enhanced in older adults by reducing noise, providing visual cues and reducing the cognitive demands in listening tasks. The performance of the participants in the present study was significantly poorer in all the cognitive tests than that of the young adults. Furthermore, the correlation of CSCT performance and cognitive test battery revealed that age-related sensory and cognitive decline lead not only to a depletion of CSC but also to a redistribution of its individual cognitive components.

Study 4

Purpose

The purpose of the present study was to determine whether background noise disrupts free recall of spoken items when intelligibility is still high, and whether performance is restored by presenting visual cues. We examined this in young adults in Experiment 1 and in older adults with hearing loss in Experiment 2.

Method

The free recall task and the cognitive test battery were administered to young adults and the older adults.

Results and Discussion

Experiment 1

The repeated measures ANOVA of free recall scores of the young adults revealed main effects of modality, noise and serial position. There were no interactions. The recall scores were higher in the AV than in A-only conditions. Analysis of the main effects of noise revealed that recall scores in quiet was significantly higher than the scores in SSSW noise and there was no significant difference in performance in quiet and ISTS noise, or in SSSW and ISTS noise. The serial position effects were in expected lines. However, these three effects did not interact with each other, thus indicating that visual cues provide a general benefit in a free recall task when memory load is high and executive demands are minimised, irrespective of noise and serial position. The lack of association between free recall performance and the other cognitive tests used in this study suggests that free recall of highly intelligible auditory numbers by young adults with normal hearing does not require the cognitive abilities tested in this Experiment.

Experiment 2

The repeated measures ANOVA of free recall scores of the older adults with hearing loss revealed main effects of modality and serial position in a similar manner to that observed in the young adults. Analysis of the main effect of noise revealed that recall scores in quiet was significantly higher than the scores observed in both SSSW noise and ISTS noise, and there was no significant difference between the performance in ISTS noise and SSSW noise. The two-way interaction between noise and position of recall was significant. Post-hoc analysis revealed that it was only in the primacy position that the participants had significantly higher recall scores in quiet than compared to both SSSW and ISTS noise. Furthermore, performance on the letter memory test was negatively associated with the disadvantage of SSSW and ISTS noise in primacy position. These two findings suggests that participants with greater ability to update the contents of working memory showed less disruption in the ability to transfer the items to the long term memory. The recall performance from the asymptote position was associated with updating ability; the ability to make linguistic closure and episodic LTM. Successful performance in asymptote positions indicates an ability to encode items more durably in the working memory and it can be expected that this encoding ability can be associated with an ability to update working memory efficiently, good linguistic closure ability and efficient episodic LTM.

Reanalysis

In the reanalysis of the data, a mixed repeated measures ANOVA was conducted on the free recall scores with Experiment 1 and 2 as a between subject factor. There was a main effect of group which revealed that the young adults had higher recall scores than the older adults with age-related hearing loss. The interaction of modality and experiment was significant which revealed that the young adults had higher recall scores compared to older adults in AV modality but not in A-only modality. Moreover, the AV benefit was significantly better in young adults than compared to older adults. This finding suggests that the young adults took advantage of AV modality of presentation better than the older adults with hearing loss. This finding is in line with that of Sommers et al. (2005). Further, the older adults had lower reading span scores than young adults, indicating that they had lower WMC. Thus, the finding of greater benefit of visual cues by young adults is in line with that of Picou et al. (2011) who found that only persons with high WMC derived benefit from the presence of visual cues. This pattern of findings suggest that when executive processing demands are high, as found in the CSCT, visual cues compensate for the reduction in CSC attributable to noise. But on the other hand, when executive demands are low, as observed during free recall, visual cues provide benefit across the conditions, although less for older adults with poorer cognitive skills. The results also suggested that the older used updating skill, linguistic closure ability and episodic LTM to encode speech items durably in working memory unlike in young adults at high intelligibility of speech items.

General Discussion

In this thesis, the CSCT was developed and administered to young and older adults with hearing loss. The CSCT systematically manipulates executive processing and memory load. To verify whether the effects of noise and modality would generalise to a memory task, a free recall task using the same material as in the CSCT was also administered. In the free recall task, memory load is maximised by requiring the retention of all items but executive demands are minimised by allowing participants to report the items they have succeeded in retaining, in any order. Along with the CSCT and free recall task, a cognitive test battery was also administered. The main finding was that CSC in older adults was enhanced and made similar to that of young adults by adding visual cues, reducing the memory demands and reducing the negative effects of noise. Importantly, this could only be revealed by the new test of CSC and not by a traditional free recall task. The findings of this thesis contribute to develop a theoretical understanding for CSC and also have implications for the rehabilitation of persons with hearing loss. It suggests ways in which CSC can be enhanced to facilitate performance in daily communicative situations for persons with hearing loss.

Cognitive spare capacity and compensatory mechanisms

Speech understanding demands cognitive resources, especially in adverse listening conditions. CSC can be expected to be reduced in adverse listening conditions, such as when memory demands are higher, in background noise and in the absence of visual cues. Figure 1 depicts the various factors which affected CSC.

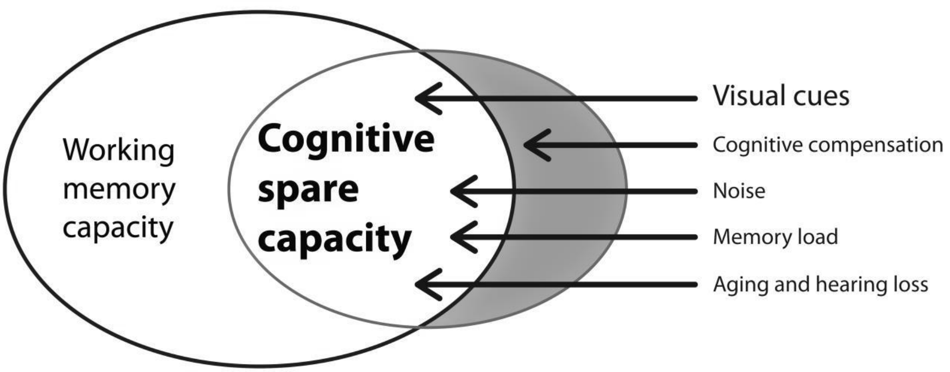

Figure 1: Factors affecting cognitive spare capacity. The grey area indicates the cognitive resources constituting cognitive spare capacity which are distinct from working memory capacity.

The results of this thesis showed that CSC reduces when memory load increases, suggesting that CSC is reduced when higher number of items are retained in working memory. CSC was decreased in noise compared to in quiet for young adults and older adults with hearing loss. Listening in noise led to impoverished representations of speech in working memory, thus more cognitive resources were needed to integrate stored information and accomplish executive function tasks. For younger adults, CSC was not reduced in speech-like noise. This is likely to be because younger adults with normal hearing were able to segregate speech from interfering noise better than older adults with hearing loss.

Visual cues reduced the effects of noise, especially for older adults with hearing loss. CSC for older adults with hearing loss was similar to that of young adults when visual cues were present. Visual cues enhanced CSC in older adults in adverse listening conditions, such as higher memory load and in the presence of speech-like noise. Importantly, the enhancement of CSC in the presence of visual cues in adverse listening conditions could only be revealed by the new test of CSCT and not by a traditional free recall task. Even in quiet, CSC in older adults with hearing loss was enhanced by presence of visual cues which suggests that the older adults consumed cognitive resources for speech understanding even in quiet. Visual cues reduced CSC only for young adults in quiet, where the superfluous visual information can be considered as a distraction.

Aging and concomitant hearing loss reduced CSC as expected. In the presence of hearing loss, representations of speech can be considered to be impoverished due to reduced audibility. The findings suggested that with aging and concomitant hearing loss, CSC was reduced in adverse listening conditions, namely, in the absence of visual cues, with higher memory load and in the presence of speech-like noise. The association of CSC with cognitive functions suggests that the older adults partially compensated for their reduced resources in working memory by using resources from episodic LTM, which is in agreement with cognitive ageing studies (Pichora-Fuller & Singh, 2006). Also, the benefit of the presence of visual cues in the quiet condition for older adults with concomitant hearing loss suggests that the older adults used their cognitive resources to greater extent compared to young adults in similar tasks. The use of greater cognitive resources by older adults is in line with the CRUNCH hypothesis (Reuter-Lorenz & Cappell, 2008) which suggests that when completing similar low level cognitive tasks, older adults recruit more cognitive resources compared to young adults.

Overall CSCT performance was not associated with performance in the reading span test which suggests that CSC is qualitatively different from WMC. Further, listening in noise depleted inhibition resources and when the tasks in CSCT demanded inhibition skills, young and older adults partially compensated for reduced inhibition skills by using linguistic closure skills. Also, CSC in older adults was associated with episodic LTM instead of updating skills as in young adults. This may be because older adults with hearing loss had reduced WMC and executive function skills compared to young adults. Therefore, it may be the case that as fluid intelligence is reduced in older adults, they compensate by utilizing more crystallized knowledge, like episodic LTM which is intact in older adults (Pichora-Fuller & Singh, 2006). Together these two findings suggest that when a cognitive resource is depleted while understanding speech, other cognitive functions which are separate from working memory, can partially compensate for the reduced cognitive resource. The findings suggest that CSC consists of two components, a component comprised of cognitive resources which are assumed to be included in working memory and another component which is comprised of cognitive resources which are distinct from working memory, like linguistic closure ability and episodic LTM. Since CSC was enhanced when the task involved inhibition and when memory load was lower, it may be assumed that CSC was affected by cognitive resources involved in executive functioning and the storage component of working memory.

Together, these findings suggest that the depletion of cognitive resources due to aging may be partially compensated for by the use of another cognitive resource or cluster of cognitive resources or additional cues, which may be termed “aging-related compensatory mechanisms” (ARCM). ARCM can be considered to be different from the CRUNCH hypothesis (Reuter-Lorenz & Cappell, 2008). The CRUNCH hypothesis suggests that in low load cognitive tasks, older adults use more cognitive resources to complete the tasks and when the task demands are higher this mechanism fails. In contrast, the findings of this thesis demonstrated that when memory demands were increased, older adults still used ARCM. In other words, older adults derived benefit from the presence of visual cues in the high memory load condition and in speech-like noise. Secondly, the findings suggest that the mechanism of ARCM did not only comprise of cognitive resources but also of additional sensory cues like visual cues. Thus, the results of this thesis suggest that aging and concomitant hearing loss does not only lead to reduced CSC, but also changes in the individual cognitive component predicting CSC.

Factors which affected cognitive spare capacity and memory performance

Effect of executive function and memory load on cognitive spare capacity

CSC was reduced for young adults and older adults in conditions of high compared to low memory load. It was shown in Study 3 that the CSC in older adults was reduced compared to that of young adults when the memory load was high. It has been shown that older adults with hearing loss use more cognitive resources compared to young adults for listening, especially in noise (Pichora-Fuller et al., 1995; Gosselin & Gagné, 2011). Also, the older adults have reduced cognitive resources compared to young adults (Pichora-Fuller & Singh, 2006). Both these factors may lead to impoverished encoding of speech stimuli in the working memory despite adequate recognition (Pichora-Fuller et al., 1995; Heinrich & Schneider, 2011; Sörqvist and Rönnberg, 2012). It is quite likely that when the task demands are increased, such as by increasing memory load, the older adults who already have reduced availability of cognitive resources, are likely to perform more poorly than young adults. In low memory load condition, the older adults may have employed ARCM for the tasks in CSCT and CSC for the older adults and young adults in low memory load was similar.

It has been shown that listening in speech-like noise demands inhibition (Janse, 2012). Thus, it was expected that CSC would be reduced to a greater extent when the tasks in CSCT involved inhibition rather than updating, especially when the memory load was high. Across both groups of participants in Studies 2 and 3, it was revealed that the type of executive processing and memory load influenced CSC as measured by the CSCT. The influence of executive function remained the same across memory load, modality of presentation and noise type for the young adults and older adults, and there were no interactions. This may be because performance in both groups was consistently higher in the inhibition tasks compared to the updating tasks. Therefore, the influence of speech-like noise on inhibition compared to performance on the updating task could not be observed in any of the groups. Thus, this thesis did not provide any evidence that executive function influenced CSC differently in different noise conditions. Additionally, there was no difference in influence of executive function with ageing and concomitant hearing loss.

Effect of noise on cognitive spare capacity

The results of Study 2 showed that CSC was reduced in steady-state noise compared to CSC in quiet for young adults with normal hearing. However, CSC in speech-like noise was similar to CSC in quiet. This high performance in speech-like noise may be explained by a mechanism of selective attention which comes into play when speech is presented in modulated noise (Zion Golumbic et al., 2013). However, the older adults with hearing loss had reduced CSC in both types of noise compared to the CSC in quiet. Furthermore, Study 3 revealed that CSC for the older adults was reduced compared to young adults in speech-like noise. This finding suggests that older adults with hearing loss were not able to take advantage of modulation in speech-like noise as young adults. One of the reasons for the reduced benefit from the modulations of speech-like noise in older adults may be hearing loss as persons with hearing loss derive less benefit from the modulation present in speech-like noise compared to persons with normal hearing. Another explanation may be that older adults do not have sufficient CSC to selectively attend to speech in the presence of modulated noise, while young adults have sufficient CSC to employ selective attention to speech. CSC may be reduced because the older adults, in addition to having reduced cognitive resources, require more cognitive resources to perceive speech in noise compared to young adults. These results demonstrated that the influence of noise on CSC differs in young adults and older adults with hearing loss. Additionally, they suggest that ARCM fail in speech-like background noise either because of hearing loss or reduced cognitive resources for older adults.

Effect of visual cues on cognitive spare capacity

In noise, the presence of visual cues consistently improved CSC for the young adults and older adults with hearing loss. The comparison of CSCT scores between young adults and older adults with hearing loss in Study 3 revealed that CSC for both groups was similar in the presence of visual cues but CSC was reduced for older adults compared to young adults in the A-only condition. Study 3 also showed that CSC was enhanced by the presence of visual cues in quiet for older adults with hearing loss. Enhanced CSC in the presence of visual cues suggests that even in quiet the older adults with hearing loss used their cognitive resources for speech understanding (Stenfelt and Rönnberg, 2009; Mattys et al. 2012) and the presence of visual cues helped to reduce the cognitive demands of listening (Frtusova et al., 2013).This finding is also supportive of ARCM hypothesis suggesting that the older adults used visual cues to enhance CSC. The results of Studies 1 and 2 demonstrated that the CSC of the young adults was reduced in the presence of visual cues when compared to the A-only condition. Young adults with normal hearing could perform the tasks in CSCT based on audition only. Hence, the superfluous visual information may have acted as distractor for the young adults (Laive, 2005).This suggests that the presence of visual cues enhanced CSC for young adults only in noise. On the other hand, for older adults with hearing loss, the presence of visual cues consistently enhanced CSC both in quiet and in noise.

Effect of listening conditions on cognitive spare capacity and memory performance

The data from Studies 2 and 4 suggest that both CSC and memory performance was reduced in steady-state noise compared to that in quiet for the young adults. CSC and memory performance in speech-like noise was similar to that in quiet for young adults. On the contrary, for older adults with age related hearing loss, both CSC and memory performance was reduced in each of the noise conditions compared to performance in quiet, as revealed in Studies 3 and 4. The results suggest that the type of noise used influenced CSC and memory performance differently with aging. But within each group of participants, the effects of different noise types was not influenced by the task administered, i.e., CSCT or free recall, where executive demands in the task varied.

However, Studies 3 and 4 revealed that AV benefit differed in both groups depending on the task administered. When the executive demands were higher in the CSCT, the older adults took advantage of the presence of visual cues and their performance was similar to that of young adults. When the executive demands were reduced and memory load was increased in the free recall task, the young adults had higher memory performance in the presence of visual cues. These results suggest that visual cues enhanced CSC for older adults with hearing loss, specifically in adverse conditions including executive processing of speech, in speech-like background noise and high memory load. On the contrary, in free recall task, older adults derived less benefit from the presence of visual cues compared to young adults. These findings are in line with the results of speech recognition tasks (e.g. Sommers et al., 1995) showing that older adults derived reduced benefit in the presence of visual cues compared to young adults.

This suggests that the CSCT provides a better or more ecologically valid estimate of the remaining cognitive resources. These resources can be used for higher cognitive functions involved in speech communication compared to the traditional free recall task or speech recognition tasks. Further, data from the CSCT in older adults suggests that ARCM are key mechanisms which enables the listener to compensate for cognitive and sensory decline by making use of cognitive resources and additional sensory cues, distinct from those used by young adults.

Cognitive underpinning of cognitive spare capacity

Overall, CSC was not associated with WMC as measured by the reading span test across both groups of participants. This finding provides evidence to support the assumption that CSC, as measured by the CSCT, is quantitatively and qualitatively different from WMC as measured by the reading span test. However, CSC for young adults in quiet was associated with WMC as measured by reading span in study 2. CSCT is designed to be an auditory working memory task. When the CSCT was presented to young adults with normal hearing in quiet, it is likely to be more similar to a test of WMC, which may explain the intercorrelation.

The updating subset of the CSCT was associated with the independent measure of updating as expected. The inhibition subset of CSCT was associated with the independent measure of inhibition only when the CSCT was administered in quiet to young adults in Study 1. In the subsequent Studies, the inhibition subset of CSCT was not associated with the independent measure of inhibition for young adults and older adults. In the rest of Studies, noise was introduced in two out of three lists unexpectedly. This means that the participants were likely to have allocated additional cognitive resources in anticipation of the potential onset of background noise. This allocation of additional resources is likely to have been restricted to the beginning of each list when the lists were presented in quiet. In other words, cognitive resources, probably inhibition skills (Janse, 2012), were likely to have been allocated, even when not specifically needed. This may have meant that participants had fewer inhibition resources available to engage in executive processing of the numbers. Hence, another cognitive function, in this case linguistic closure, was employed to aid performance in the inhibition task in the CSCT, in order to partially compensate for the reduced inhibition resources. This association suggests that the ability to make use of linguistic closure is related to the processing required to identify and keep in mind auditory two-digit numbers of a certain parity and voice. The common factor may be an underlying ability to generate a coherent response on the basis of diverse pieces of information.

CSC was consistently associated with updating skills in young adults. This association suggests that updating skills play an important role during the processing of encoded representations in working memory for young adults even when the task involves inhibition. When the task demands were increased, CSC in younger adults with normal hearing was associated with linguistic closure ability along with updating skills. On the other hand CSC in older adults with hearing loss was consistently associated with episodic LTM and, under higher task demands, it also correlated with performance in updating. One interpretation of this finding is that higher CSCT scores may be due to better representation in working memory, which would also lead to higher LTM (Rönnberg et al., 2011). Also, an efficient LTM may facilitate processing of speech leading to fewer demands on cognitive resources (Rönnberg et al., 2013). This finding also suggests that older adults compensated for reduced fluid intelligence by relying more on crystallized skills for encoding items stored in working memory (Pichora-Fuller & Singh, 2006).

Together, these findings suggest that age-related sensory and cognitive decline leads not only to a depletion of CSC but also to a redistribution of its individual cognitive components. This provides support for the ARCM hypothesis in that older adults use cognitive resources which are distinct from those used by young adults in order to complete the task.

Cognitive underpinning of memory performance

The memory performance of the young adults was not associated with any of the cognitive measures, suggesting that they did not use any cognitive functions tested, for free recall. But for older adults, better updating ability was associated with a lower performance disadvantage of noise in the primacy position. Overall performance in the asymptote was predicted by updating skill, linguistic closure ability and episodic LTM. Linguistic closure ability may help recall of two-digit numbers that have become partially encoded into LTM, thus improving performance in the asymptote position. Successful performance in asymptote position indicates an ability to encode items more durably in working memory and hence the association with updating ability and episodic LTM can be expected. The correlation of the cognitive measures with memory performance only for the older adults suggests that more cognitive resources were recruited by older adults for task completion compared to the young adults. This is in accordance with the CRUNCH hypothesis (Reuter-Lorenz & Cappell, 2008) which states that older adults recruit more neural resources at lower cognitive levels than young adults. The correlation patterns shown for free recall task performance demonstrated that older adults with hearing loss required more cognitive resources for performing the task, but did not provide specific information about the cognitive resources reduced due to aging. This may be because the free recall task is not sensitive enough to assess the specific cognitive resources reduced due to aging or because the free recall performance of young adults is not affected by the cognitive functions tested.

Implications of the thesis

The results of the present thesis showed that CSC in older adults with hearing loss could be enhanced by providing visual cues, reducing demands of memory and reducing the negative effects of noise, and thus providing support to ARCM. This thesis was the first step towards understanding the concept of CSC. The results demonstrated how CSC was affected by different conditions of signal degradation and how these effects differed with aging and concomitant hearing loss. Secondly, the theoretical knowledge derived from this thesis may serve as a foundation for devising clinical assessments tools which can be administered in audiological clinic. Such assessment tools can be used to verify the benefit derived from hearing aids, both in terms of speech understanding and cognition. Specifically, these tests may predict CSC when speech perception takes place through hearing aids and thus better predict hearing aid outcome. Thirdly, tests like CSCT may be useful in evaluating the cognitive benefit of the advanced signal processing algorithms presently being implemented in hearing aids. Finally, the findings of this thesis may have implications for audiologists working in clinics and the hearing aid industry. The findings suggested that persons with hearing loss benefit when the face of the speaker is visible in terms of reducing the cognitive resources involved in speech understanding. This reduction in cognitive demands may be reflected as reduced listening effort or less fatigue. However, the assessments of outcome of audiological rehabilitation, such as recommending hearing aids to persons with hearing loss, are conducted mostly in A-only modality. In order to estimate the outcome of audiological rehabilitation in real life situations, it is suggested that such testing may be carried out in AV modality. Further, this thesis provides empirical evidence that seeing the talker's face may reduce listening effort or fatigue for person with hearing loss. The importance of seeing the speaker's face while listening should be emphasized while counselling clients with hearing loss, especially for the clients who complain of listening effort or fatigue.

Conclusions

The aim of this thesis was to develop a theoretical understanding of the concept of CSC. CSC was evaluated in young adults with normal hearing and older adults with hearing loss to assess how ageing and concomitant hearing loss influenced CSC. In order to achieve it, a test for CSC (CSCT) was developed and administered to young adults and older adults with hearing loss. A free recall task, using the same material as used in CSCT, was administered for comparison purpose. A cognitive test battery was also administered to assess the cognitive underpinning to CSC. The findings suggested that CSC consists of two components. One component comprises cognitive resources which are considered to be part of working memory and another component comprises cognitive resources which are distinct from working memory, like linguistic closure skills and episodic LTM. The findings of the thesis demonstrated that aging and concomitant hearing loss did not only lead to reduced CSC, but also changed the individual cognitive component predicting CSC. Further, results on CSC in older adults suggest that ARCM are key mechanisms which compensates for cognitive and sensory decline. These mechanisms allow older adults to make use of visual cues by deploying their cognitive resources in a different way compared to younger adults. Importantly, this could only be revealed by CSCT and not by a traditional free recall task. The findings of this thesis have implications for rehabilitation of older adults with hearing loss. It is likely that CSCT performance may provide a snap-shot of how hearing-aid signal processing influences cognitive demands in communicative situations.

Methodological Discussion

Aging and concomitant hearing loss

The older adults included in this study had hearing loss which was appropriate to their age group (Cruickshanks et al., 1998; Johansson & Arlinger, 2003). Older adults with normal hearing were not selected in this study because such a group is not representative of the population of older adults. Aging is associated with sensory decline including hearing loss (Pichora-Fuller & Singh, 2006). Thus, in order to assess the effects of sensory and cognitive decline associated with aging on CSC, older adults with age appropriate hearing loss were selected. In future, studies may be conducted on age-matched young adults with and without hearing loss to verify the effects of hearing loss on CSC. Similarly, studies on young adults and older adults with normal hearing can be conducted to ascertain the effects of aging on CSC.

Cognitive test battery

One of the findings of this thesis is that CSC is both quantitatively and qualitatively different from working memory as measured by reading span. The reading span test uses sentences as test material and in CSCT digits were used as stimuli. Other tests assessing WMC, like the digit span test, use the same material as used in CSCT as stimuli. Test like digit span asses only the storage component of working memory and hence are not considered to reliably predict cognitive processing involved in speech understanding. It has been also pointed that both reading span and size-comparison span tests predicted comprehension of speech performance but size-comparison emerged as a stronger predictor (Sörqvist & Rönnberg, 2012). The reading span test was included in the present thesis because it has been widely used in previous studies assessing role of cognition in adverse listening conditions and has reliably predicted speech performance in noise (Akeroyd, 2008). The findings of this thesis suggest that CSC comprises of a component which is distinct from working memory. This finding can be verified further by including other tests of WMC like digit span and size-comparison span.

Slower processing speed has been associated with ageing and leads to difficulty in speech recognition (Pichora-Fuller, 2003) and memory performance (Rönnberg, 1990). But no such evidence was found in the present thesis as neither CSC nor the memory performance for the older adults correlated with the measure of processing speed used in the study. The reaction time for the congruent key press in the Simon task was used as a measure of processing speed. This may be verified in future by including an independent measure of processing speed.

Cognitive spare capacity test

In the current version of CSCT, two-digit numbers were used as stimuli material. Two-digit numbers were used because they provided an opportunity to devise the distinctive executive function tasks. Such distinctive tests are difficult to devise using the sentence material of same complexity. However, two digit numbers constitute a closed set material and there may be criticism that they do not relate entirely to the demands of everyday communication. In order to make tests like CSCT more ecologically valid, such tests may be designed by using sentences as stimuli material.

Future Direction

The four Studies included in this thesis are the first studies to provide a theoretical understanding of the concept of CSC. In these initial studies on CSCT, it was desirable to include many factors which are considered important for speech understanding in adverse listening conditions and explore their complex interaction. But once the interacting factors are identified it may be reasonable to reduce the number factors in later studies. The findings of this thesis may suggest directions for designing such tests in future. In such newer tests, the number factors manipulated may be reduced to make it feasible to be administered in audiological clinics. For example, in CSCT, there was no influence of type of executive function task either on memory load, modality or the type of background noise used. Also, performance in the inhibition subsets of CSCT was consistently higher for young adults and older adults with hearing loss. Hence, in later studies it may be appropriate to use only the executive function of updating.

CSCT used in this thesis had a long administration time and hence is not feasible to be administered in audiological clinic. In future studies, a simplified version of CSCT by reducing the number factors may be constructed and verified. For example a simplified version of CSCT may constitute an updating task administered in audiovisual modality in quiet and speech-like noise. The results of the present thesis showed that the CSCT may be a useful tool for evaluating CSC in person with hearing loss.

Acknowledgments

It would not have been possible to finish this doctoral thesis without the help and support of many people. First I would like to thank my main supervisor, Mary Rudner for giving me this opportunity to do my PhD research in Sweden. She motivated me to explore the area of cognitive psychology and enhanced my research skills immensely. It has been a privilege to work under her supervision. I will extend heartfelt thanks to Stefan Stenfelt, my co-supervisor, who has helped immensely in technical and practical aspects of my data collection and conceptualizing it. The expertise of my co-supervisor, Jerker Rönnberg, helped me in understanding and exploring the research findings conceptually. I would also like to thank Thomas Lunner, my co-supervisor, for sharing his expertise on a variety of topics, and his ideas on integrating fields of cognition and hearing. I truly appreciate the supervision that I have received over the past years.

I gratefully acknowledge the technical support I received from Mathias Hällgren, Björn Lidestam and my friend Niklas Rönnberg (including the design of the cover page). Björn Lyxell and Patrik Sörqvist have always helped me in learning and enriching my ideas in cognitive psychology. I would also like to thank Örjan Dahlström, Carine Signoret and Henrik Danielsson for sharing their expertise in statistics. I also extend my thanks to Tomas Bjuvmar for helping me in recruiting participants.

I would like to thank all my colleagues at the Disability Research Division, the HEAD graduate school, and SIDR for their warmth, kindness, and support. I would particularly like to thank Elaine Ng and Cecilia Henricson (my office-mate) for being very helpful through my journey as a PhD student. Jan Classon and Elisabet Classon, thanks for being the speakers in the stimuli material and also thanks to Elisabet and Håkan Hua for Swedish translation of my 'spikblad'. A special thanks to Pallavi Padhy for proof-reading this thesis. I am also very grateful to my colleagues Adriana Zekveld, Rachel Ellis, Vinaya Manchaiah, Josefine Andin, Cecilia Nakeva von Mentzer, Shahram Moradi, Lisa Kilman, Emelie Nordqvist, Amin Saremi, Victoria Stenbäck, Jakob Dahl, Emil Holmer and Wycliffe Yumba for their valuable inputs, encouragement and the laughter we shared. Most of you have also volunteered as participants in various stages of data preparation and collection. I take this opportunity to thank all the participants in the studies. A special thank you also goes to the administrators at the division for taking care of all PhD students, including me.

I acknowledge the contribution that has been made by my immediate and extended family in their support in all my professional and personal endeavors. I also acknowledge the influence of so many people who have helped me throughout my life both as friends and guides. My friends in Linköping, specially, TVK Chaitanya, Swadhin Mangaraj and Assmitra Dash, with whom I have shared the ups and downs in research. Last and most important, my special thanks to my wife, Sreeparna Mishra and my daughter, Shirina Mishra for their love, care and support.

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