Representing sounds and spellings

Phonological decline and compensatory working memory in acquired hearing impairment

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Pursue one great decisive aim with force and determination.

Carl von Clausewitz "On war"

Abstract

Long-term severe acquired hearing impairment (HI) is associated with a deterioration of phonological representations in semantic long-term memory that negatively affects phonological awareness (Andersson, 2002). The primary aim of this thesis was twofold: to use electrophysiological and behavioral measures to examine phonological processing in adults with moderate-to-profound, postlingually acquired HI, and to determine whether explicit working memory processing of phonology and individual working memory capacity (WMC) can compensate for phonological decline in this group. The secondary aim was to provide reference data for a Swedish test of WMC that is frequently used in the field of cognitive hearing science and to examine the relation between test performance and speech recognition in noise in a larger sample of individuals with HI.

In papers I-III, non-auditory tasks were used to examine input and output phonological processing, episodic long-term memory, and WMC in individuals with HI as compared to a reference group with normal hearing. Text-based rhyme judgments of word pairs with matching or mismatching orthography and letter fluency were used to assess phonological processing. In papers II-III, the relation between phonological task performance and tests of WMC (papers II-III) and episodic long-term memory (paper II) were examined. In paper I, electrophysiological indices of phonological processing under conditions that either allowed for, or limited, involvement of explicit processing were investigated. While the overall purpose was to test if working memory processing of phonology and individual differences in WMC could compensate for phonological decline in individuals with HI, paper II also tested a proposal made by the Ease of Language Understanding (ELU) model (Rönnberg et al., 2013). The ELU postulates that individual differences in WMC will modulate task performance under conditions with increased occurrence of phonological mismatch, as in rhyme judgment of written words with mismatching orthography by individuals with degraded phonological representations.

Paper IV examined performance on the reading span test (RST; Rönnberg, Lyxell, Arlinger, & Kinnefors, 1989), the measure of WMC used in papers I-III, in a larger sample of individuals with HI who had participated in different projects from our laboratory and its collaborators. The test is theoretically anchored in the capacity theory of working memory (Just & Carpenter, 1992) and plays an important role in the ELU model. Test performance in two different age groups were compared (50-69, 70-89), and the original version of the test was compared to a shortened version. Examination of the relation between test performance and speech recognition in noise was also conducted.

The results replicated previous findings of phonological processing declines following acquired moderate-to-profound HI (papers I-III) and found that WMC (papers II-III) and explicit working memory processing of phonology (paper I) could be employed to compensate for degraded phonological representations. However, this compensation may come at the cost of interfering with episodic memory encoding (paper II). Further, paper I found an electrophysiological marker of HI in text-based rhyme judgments. Finally, paper IV

provided reference data for RST performance in individuals with HI. Examination of the relationship between speech recognition in noise and RST performance also suggested that WMC may be differentially predictive of speech-in-noise recognition in different age groups of older adults with HI.

The clinical implications of the present results concern the double disadvantage of individuals with lower WMC and HI. A structured assessment of WMC in rehabilitative settings would help to identify these individuals and tailor treatment to their needs. The RST is suggested as a suitable future candidate for clinical WMC assessment.

List of papers

This thesis is based on the following papers, referred to in the text by their Roman numerals.

- I. Classon, E., Rudner, M., Johansson, M., & Rönnerberg, J. (2013). Early ERP signature of hearing impairment in visual rhyme judgment. *Frontiers in Psychology*, 4:241. doi: 10.3389/fpsyg.2013.00241
- II. Classon, E., Rudner, M., & Rönnerberg, J. (2013). Working memory compensates for hearing related phonological processing deficit. *Journal of Communication Disorders*, 46(1), 17-29. doi: 10.1016/j.jcomdis.2012.10.001
- III. Classon, E., Löfkvist, U., Rudner, M., & Rönnerberg, J. (2013). Verbal fluency in adults with postlingually acquired hearing impairment. *Speech, Language and Hearing*. Advance online publication. doi: 10.1179/2050572813Y.0000000019.
- IV. Classon, E., Ng, E. H. N., Arlinger, S., Kilman, L., Larsby, B., Lyxell, B., Lunner, T., Mishra, S., Rudner, M., & Rönnerberg, J. Reading span performance in 339 Swedish 50-89 year old individuals with hearing impairment: Effects of test version and age, and relation to speech recognition in noise. Manuscript.

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List of abbreviations

CI	Cochlear implant
CRUNCH	Compensation-related utilization of neural circuits hypothesis
EEG	Electroencephalogram
ELU	Ease of Language Understanding model
ERP	Event-related potentials
fMRI	Functional magnetic resonance imaging
HI	Hearing impairment
IFG	Inferior frontal gyrus
ISI	Interstimulus interval
NH	Normal hearing
PTA	Pure tone average
RAMBPHO	Rapid automatic multimodal binding of phonology
RST	This abbreviation is specifically used to denote the Swedish version of the reading span test (Rönnberg et al, 1989). A number of reading span tests have been developed and when these tests are referred to in general, no abbreviation is used.
SNR	Signal-to-noise ratio
STG	Superior temporal gyrus
WHO	World Health Organization
WMC	Working memory capacity

Introduction

This thesis examines how phonological processing and working memory capacity (WMC) interact in adults following moderate-to-profound, postlingually acquired hearing impairment (HI). Previous research has shown that severe postlingually acquired HI is associated with phonological processing declines due to a deterioration of phonological representations in semantic long-term memory (Andersson, 2002; Andersson & Lyxell, 1999). Other studies have found that individual WMC can support speech recognition in noise when hearing is impaired (e.g. Akeroyd, 2008; Arehart, Souza, Baca, & Kates, 2013; Lunner, 2003; Rudner, Foo, Sundewall-Thorén, Lunner, & Rönnberg, 2008; Rudner, Rönnberg, & Lunner, 2011). Phonological processing and working memory are closely intertwined. However, any specific interactions between these two functions in individuals with HI have not been directly studied. The primary aim of this thesis was to do so, taking a special interest in whether explicit working memory processing of phonology and WMC can help to compensate for phonological declines. A second aim was to provide reference data for a test of WMC, the Swedish version of the reading span test (RST; Rönnberg et al., 1989) and to examine the relation between RST performance and speech recognition in noise in a larger sample of individuals with HI belonging to different age-cohorts.

Framework

The overarching framework of this thesis is *disability research*, an area that covers biological, psychological, social and cultural aspects of functioning, impairment and disability. In disability research, functioning and disability are typically conceptualized as a complex interaction between an individual's health condition, contextual factors of the environment and personal factors (WHO, 2001). More specifically, the present research belongs to the field of *cognitive hearing science*. Cognitive hearing science is an interdisciplinary area that aims to merge knowledge from a range of different disciplines, including biology, physiology, medicine, engineering, audiology, linguistics and psychology. The purpose is to generate knowledge of the interaction between hearing and cognition, particularly when hearing is compromised. An ultimate goal is to improve rehabilitative interventions given an increased understanding of the intricate interplay between the auditory and cognitive systems (Arlinger, Lunner, Lyxell, & Pichora-Fuller, 2009). The primary perspective taken in the present thesis is that of cognitive psychology and the focus is on memory systems and mental representations of language.

Elements of this thesis

The population studied in the current thesis consists of adults aged 45-89 years who are native Swedish speakers with sensorineural, postlingually acquired, moderate-to-profound HI (papers I-III), or a range of mild-to-severe sensorineural HI (paper IV) of different etiologies. This work examined the effect of hearing loss on phonological processing in visual, non-auditory tasks, that is, on hearing-related changes in the representation of speech sounds, and how these interact with explicit working memory processing of phonology and WMC in tasks of input and output phonology (papers I-III). In addition, RST performance in two versions of the test was examined in terms of mean performances, frequency distributions, percentile

scores and relations to speech recognition in noise in adults with mild-to-severe HI in different age cohorts (paper IV).

Definitions and main concepts

In accordance with the WHO (2013) guidelines, *HI* is here measured as the best ear pure tone average (PTA) across 500, 1000, 2000 and 4000 Hz. Degree of HI is graded into 4 levels: mild, PTA 26-40 dB HL; moderate, PTA 41-60 dB HL; severe, PTA 61-80 dB HL and profound, PTA >81 dB HL. Further, *WMC* is in the present thesis defined as the general capacity of the individual working memory system for carrying out multiple storage, processing and retrieval functions simultaneously or close to simultaneously during a brief period of time. *Explicit working memory processing of phonology* refers to the storage, maintenance and other processing functions applied to phonological material in working memory, without reference to the general capacity of the system as a whole. The term *explicit* is used to denote conscious processing that requires some degree of attentional and/or working memory resources while the term *implicit* refers to processing, perceptual or cognitive, that does not require conscious awareness. Importantly, a specific process, for example speech recognition, may be either implicit or explicit depending on the circumstances. For example, if the speech signal is clearly perceived, speech recognition may proceed implicitly. If the signal is degraded, explicit processing may be required for successful speech recognition. Further, implicit processing is typically conceived of as being fast and effortless, while explicit processes are relatively slower and more effortful. Finally, *phonological representations* are here conceptualized as structural units stored in semantic long-term memory, while *phonological processing* refers to functional operations applied to those units.

Background

Hearing impairment

The present research focuses on adults with long-term postlingually acquired moderate-to-profound sensorineural HI. HI is a partial or total loss of hearing that may arise from many different causes including certain diseases, noise exposure, aging and genetic factors. Depending on which part of the auditory system is damaged, HI can be roughly divided into conductive and sensorineural HI. Conductive HI is due to damage in the outer and/or middle ear and typically causes a generalized, frequency independent reduction in hearing acuity. In most cases the problem can be resolved by surgery or medical management. If those measures are not sufficient to restore hearing, the benefit of hearing aids is usually good. Sensorineural HI is due to damage to the cochlea, the auditory nerve, the brainstem or the brain. Together with the loss of acuity, auditory function may be disrupted across a wide range of specific perceptual processes such as discrimination of frequency and timing, and detection of gaps in the signal. Speech perception and recognition are affected and the benefit provided by hearing aids is often unsatisfactory (Arlinger, 2007).

The site of lesion is thus one factor that influences the consequences of hearing loss in daily life. Another factor is the degree of HI that can be roughly divided into mild, moderate, severe or profound. In moderate HI a hearing aid is usually needed to follow a conversation in background noise. Individuals with severe-to-profound HI typically need to rely not only on hearing aids but also on speechreading, and perhaps sign-language (WHO, 2013). Age at onset of HI is also important. The effects of HI on language development differ markedly depending on whether the onset is prelingual or postlingual (Giraud & Lee, 2007; Lyness, Woll, Campbell, & Cardin, 2013). Prelingual HI develops before the acquisition of speech and language is complete, usually defined as around the age of six, and disrupts language learning and the development of phonological abilities even when the degree of HI is relatively mild (Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007; Park, Lombardino, & Ritter, 2013). In most cases however, hearing loss onset is postlingual and thus acquired after the establishment of spoken and written language. This means that phonological skills and other language abilities have usually had the chance to develop normally. With declining auditory function, changes may nevertheless occur in the neural processing and representation of sounds, as well as in articulation. Such effects may be almost coincident with hearing loss onset (Lee, Truy, Mamou, Sappey-Mariniér, & Giraud, 2007; Sharma, 2013) or progress over time (Andersson & Lyxell, 1999; Lyxell, Rönnerberg, & Samuelsson, 1994). Thus, the duration of HI also has an influence on the degree of associated disability.

Partial or total loss of hearing affects communication and may impact psychosocial functioning and experienced quality of life. HI may also affect, and be affected by, cognitive functions.

Psychosocial effects

The impact of HI at the psychosocial level is multifaceted, spanning emotional reactions to the stigma of hearing loss, interpersonal consequences such as loss of intimacy in relationships, activity limitations and physical problems in the form of headaches and muscle tension (Nachtegaal et al., 2009; Preminger, 2007). As a result, perceived quality of life is lower in individuals with HI than in individuals with normal hearing (Chia et al., 2007; Dalton et al., 2003). They, for example, report experiencing more energy loss, emotional distress, depression and social isolation (Dalton et al., 2003; Ringdahl & Grimby, 2000). Performance at work is negatively affected and sick-leave due to stress-related factors more common (Kramer, Kapteyn, & Houtgast, 2006). Most likely, these effects are to a large part mediated by the hallmark of HI, communication difficulties due to impaired speech recognition. Indeed, inadequate communication has been found to be more associated with depression, social introversion, loneliness and social anxiety in persons with acquired severe HI than the HI as such (Knutson & Lansing, 1990).

Hearing impairment and communication

Consequently, several programs have been developed to enhance communication, targeting the individual with HI, his or her significant others, or both, in either a group setting, a couples format or individually. Overall, communication training is seen as an essential part of

rehabilitation (Heine & Browning, 2002). Interventions typically include learning to use efficient repair strategies, how to ask for clarifications and coaching of helpful communicative behaviour (for example speaking at a slower rate and not covering the mouth), speech perception training and pedagogical information on HI, technical aids and hearing tactics. The most common intervention is the fitting of some type of hearing device, for example hearing aids or cochlear implants (CIs), with improved speech recognition as a primary aim. Nevertheless, even with well-fitted hearing aids all sound signals are distorted to some degree, and at all times (Mattys, Davis, Bradlow, & Scott, 2012). In everyday life, a range of factors other than the HI itself, such as noise, reverberation or cognitive load (for example when listening and driving at the same time) are often present and contribute to communication difficulties. Together with HI, such factors create adverse listening conditions.

Hearing impairment and cognition

Whatever the source, adverse conditions result in unsuccessful speech recognition, interference of irrelevant sounds and/or increased load on attentional and working memory networks (Mattys et al., 2012). Interference due to ambient sounds increases the demands on attentional resources to resist the interference and focus on the speech of one's conversational partner. Increased working memory load may be induced not just by ambient noise, but also by the need to listen while concurrently engaging in some other activity. However, exposure to adverse listening conditions may also lead to the engagement of implicit or explicit compensation. At the implicit level, recent findings suggest that cortical auditory association areas are recruited for visual processing at an early stage following hearing loss (Lee et al., 2007; Sharma, 2013) which may be associated with an enhanced receptiveness to visual language cues. At the explicit level, the semantic context can be used to infer words that were not clearly perceived, and a large vocabulary or world knowledge may be taken advantage of (MacCallum, Zhang, Preacher, & Rucker, 2002; Pichora-Fuller, 2008; Wingfield & Tun, 2007). There are indications that such explicit compensation is reflected in neural activation patterns (Cabeza et al., 2004; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Grady, 2012; Wingfield & Grossman, 2006). For example, increased engagement of brain structures involved with higher-order cognitive functions, such as the prefrontal cortex which plays a role in inhibitory control mechanisms, attention and phonological working memory, is associated with better speech in noise recognition in older adults (Wong, Ettlinger, Sheppard, Gunasekera, & Dhar, 2010; Wong et al., 2009).

Such findings support the decline-compensations hypothesis which states that sensory decline in aging is accompanied by compensatory recruitment of cognitive areas (Cabeza et al., 2004). Although the interpretation of relationships between differential neural activation and cognitive performance in aging as signs of compensation is not straightforward (Grady, 2012; Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010), the overall picture shows that speech understanding can be enhanced by calibrating the balance between top-down and bottom-up processes when the latter falters (Mattys et al., 2012; Pichora-Fuller, 2008; Rönnberg, Rudner, Foo, & Lunner, 2008).

Hearing impairment, cognition and aging

Deterioration of auditory function is part of normal aging. Loss of hearing sensitivity typically starts around middle adulthood and then progresses, particularly affecting the high-frequency ranges that are crucial to speech recognition (Pearson et al., 1995; Schneider, Pichora-Fuller, & Daneman, 2010). Outer hair cell damage and degeneration of the stria vascularis and the auditory nerve are main causes (Pichora-Fuller & Singh, 2006) and auditory processing, such as temporal resolution and duration discrimination, is negatively affected (Fitzgibbons & Gordon-Salant, 2010; Saremi & Stenfelt, 2013). In parallel, speech understanding gets increasingly challenging. This deterioration is most likely exacerbated by concomitant age-related changes in the cognitive system (Grady, 2012; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005). A variety of cognitive abilities tend to decline with increasing age, including processing speed (Salthouse, 1996), attention (Craig & Salthouse, 2000; Phillips & Lesperance, 2003), and WMC (Bopp & Verhaeghen, 2005; Salthouse & Babcock, 1991). Indeed, even older adults with normal pure tone thresholds have more difficulties with speech recognition than younger normally hearing individuals (Frisina & Frisina, 1997; Gordon-Salant, 2005).

Thus, changes in hearing and cognition go hand in hand in older adults (Baltes & Lindenberger, 1997; Lin, Ferrucci, et al., 2011; Lin et al., 2013; Pearman, Friedman, Brooks, & Yesavage, 2000; Rönnberg et al., 2011; Valentijn et al., 2005). The relative contributions of auditory and cognitive factors to speech recognition performance have been investigated in several large scale studies (Humes, 2002, 2005; Jerger, Jerger, Oliver, & Pirozzolo, 1989; Jerger, Jerger, & Pirozzolo, 1991). The general finding from these studies is that auditory factors account for around 50 to 60% of the variance in speech recognition and an additional 6-7% is explained by cognitive factors. However, this balance is dependent on perceptual clarity. When audibility is better, for example when the degree of HI is lower or the speech signal amplified, cognitive factors explain more of the variance than when audibility is poorer (Anderson, White-Schwoch, Parbery-Clark, & Kraus, 2013; Humes, 2007).

In addition, HI *per se* may have an impact on cognitive function. A very specific effect is that severe-to-profound postlingual HI is related to impairment in certain aspects of phonological processing, most likely due to a gradual loss of specificity of phonological representations (Andersson, 2002; Andersson & Lyxell, 1999; Lazard, Giraud, Truy, & Lee, 2011; Lazard et al., 2010; Lyxell, Andersson, Borg, & Ohlsson, 2003; Rönnberg et al., 2011). Recently, several large scale studies have indicated that HI is also associated with a much more general effect on cognition. For example, prospective studies have found accelerated cognitive decline and increased risk of dementia and Alzheimer's disease in individuals with HI (Lin, Metter, et al., 2011; Lin et al., 2013). Cross-sectional studies have shown that HI is associated with lower scores in tests of executive function and free recall (Lin, Ferrucci, et al., 2011) and has a negative effect on episodic and semantic long-term memory (Rönnberg et al., 2011).

The social isolation experienced by many individuals with HI may contribute to this picture. Social isolation is another factor that is in itself related to cognitive decline, possibly due to fewer opportunities to partake in cognitively challenging social relationships and activities

(Barnes, de Leon, Wilson, Bienias, & Evans, 2004; Crooks, Lubben, Petitti, Little, & Chiu, 2008). More direct mechanisms have however also been suggested to mediate the effect of HI on cognitive function. According to the disuse hypothesis, relatively less information is encoded into, and retrieved from, episodic and semantic long-term memory when hearing is impaired due to repeated disturbances (mismatches) in the matching of speech signals to phonological representations. Over time, this relative disuse is assumed to affect the efficiency of the episodic and semantic long-term memory system (Rönnberg et al., 2011; Rönnberg et al., 2013). This hypothesis helps to explain lower memory performance, but not the declines in executive functions (Lin, Ferrucci, et al., 2011). A related account, the information-degradation hypothesis, suggests that the online attentional effort required for the decoding of distorted sound signals occupies resources that would otherwise be available for memory encoding and other cognitive processes (Pichora-Fuller, Schneider, & Daneman, 1995; Tun, McCoy, & Wingfield, 2009). For example, mild-to-moderate hearing loss has been associated with reduced recall of spoken words even when cognitive load is low and the words have been correctly perceived (McCoy et al., 2005). However, the information-degradation hypothesis cannot readily explain that hearing-related reductions in cognitive function are also found when visually presented verbal tests are used (Lin, Ferrucci, et al., 2011; Lin, Metter, et al., 2011; Lin et al., 2013; Rönnberg et al., 2011). It is probable that the association between hearing loss and cognitive decline has multiple causes that vary between individuals. Nevertheless, the disuse and information degradation hypotheses point to a role for phonological functions and the type of storage and processing trade-offs that are typically associated with WMC in mediating the effect of hearing loss on long-term memory.

Working memory capacity

Working memory refers to a system of limited capacity that is responsible for the active storage, processing and retrieval of task-relevant information during a brief period of time that is necessary for online cognition and communication. This multifunctional system is essential for the ability to carry out complex cognitive tasks and individual differences in WMC predict, for example, reading comprehension (Daneman & Merikle, 1996; Kemper, Crow, & Kemtes, 2004), fluid intelligence (Kane, Hambrick, & Conway, 2005) and reasoning ability (Kyllonen & Christal, 1990).

Perhaps the most influential account of working memory is Baddeley's multicomponent model (Baddeley, 2000, 2012). This model proposes separate slave systems, the phonological loop and the visuospatial sketchpad, that are involved with temporary storage and maintenance of modality specific, that is, verbal and visuospatial, information. The model also include an episodic buffer which is capable of holding larger chunks of information from the slave systems and long-term memory bound into richer, multimodal (for example audiovisual) representations. Finally, there is the central executive which retrieves information from both the slave systems and the episodic buffer into conscious awareness for more elaborate processing and manipulation. Via its control over attentional resources, the central executive also directs which information is entered into the buffer.

A functional rather than modular perspective of working memory is taken by the capacity theory of working memory (Just & Carpenter, 1992). The focus here is shifted to individual differences in the capacity of the system as a whole. Working memory is proposed to be defined by the limit set by the resources, that is, the amount of neural activation, available for concurrent storage and processing of multimodal information. If task demands exceed the limit, resources need to be allocated between these two main functions. This processing-storage trade-off is assumed to be largely implicit and favor lower level, for example perceptual, processing. When capacity limits are reached in performing a task, storage and higher level processes will therefore suffer. Individual differences in either system storage capacity or efficiency of processing will thereby determine performance in complex tasks such as language comprehension (Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Just & Carpenter, 1992).

Apart from the modality specific storage systems of the multicomponent model, the two accounts are not irreconcilable and can be considered to belong to the same general framework (Baddeley, 2012). However, with its focus on prediction of language understanding and its emphasis on trade-offs between lower-level perceptual demands and higher level processes, capacity theory (Just & Carpenter, 1992) has been very influential in the field of cognitive hearing science.

Assessing working memory capacity

WMC is typically assessed by the dual storage and processing tasks that are together referred to as complex span tasks. In the verbal domain, reading span tests (Daneman & Merikle, 1996) are frequently used. In these tests, a sentence comprehension task is combined with a recall task (Daneman & Carpenter, 1980). Commonly, written sentences are presented in sets that progressively contain more sentences. After each sentence, a judgment as to whether it was absurd or not is required, and after each set of sentences, recall of, for example, the last word in the sentences is tested. Thus, the sentences need to be processed semantically in order to execute the absurdity judgment and at the same time, the to-be-remembered items must be maintained in working memory for later recall. The main dependent measure is recall performance; as task demands increase with increasing set sizes, less WMC resources will be available for storage of the to-be-remembered items, resulting in relatively lower recall (Just & Carpenter, 1992). A number of versions of the test have been reported in the literature and have proven to be reliable and valid measures of WMC (Conway et al., 2005; Redick et al., 2012; Unsworth, Redick, Heitz, Broadway, & Engle, 2009) capable of predicting performance in complex cognitive tasks such as language comprehension (Daneman & Merikle, 1996; Kane et al., 2005; Kyllonen & Christal, 1990).

Reading span tests are however multifaceted and taps not only processing, storage and trade-offs between processing and storage, but also executive functions such as attentional control, inhibition and task switching ability (Bayliss, Jarrold, Baddeley, & Gunn, 2005; Kane et al., 2004; Towse, Hitch, & Hutton, 2000; Unsworth & Engle, 2007). Some or all of the components of the multicomponent model of working memory (Baddeley, 2012) may therefore be involved in reading span test performance (Alloway, Gathercole, Willis, &

Adams, 2004; Rudner & Rönnerberg, 2008). Which of the functions tapped by reading span tests that drives the correlation with complex abilities is under continuous debate (e.g. Bayliss et al., 2005; Kane et al., 2005; Unsworth et al., 2009)

Hearing impairment and working memory capacity

WMC has been found to play the important role of supporting speech recognition in noise in individuals with HI (Akeroyd, 2008; Besser, Koelewijn, Zekveld, Kramer, & Festen, 2013; Gatehouse, Naylor, & Elberling, 2006; Lunner, 2003; Lunner & Sundewall-Thorén, 2007; Rudner et al., 2008; Rudner et al., 2011). This has been shown for speech recognition of low-redundancy sentences material in background noise that is modulated, unmodulated (Lunner, 2003; Rudner, Foo, Rönnerberg, & Lunner, 2009; Rudner et al., 2011) or modulated using competing speech (Desjardins & Doherty, 2013). In particular, WMC has been related to better speech recognition with different types of signal processing algorithms (Arehart et al., 2013; Gatehouse et al., 2006; Rudner, Foo, Rönnerberg, et al., 2009; Rudner et al., 2011). In speech recognition in noise, lexical access and retrieval need to be achieved based on degraded phonological input information. With a larger WMC there will be relatively more resources available for the maintenance of sentence content during the effortful decoding of the ongoing and ambiguous speech signal. The executive component of working memory may also be involved. For example, better ability to inhibit the distracting noise signal and update the to-be-remembered items held in working memory is likely to improve performance in speech recognition in noise (Rudner et al., 2011).

WMC has also been found to support visual (speechreading) and visual-tactile speech recognition (see Rönnerberg et al., 2013). On a more subjective level, high WMC has been linked to lower perceived effort when listening to degraded speech (Desjardins & Doherty, 2013; Rudner, Lunner, Behrens, Thoren, & Rönnerberg, 2012) and, from a slightly different perspective, those with a high WMC may be better able to discern and report differences between hearing aid settings, formulate their needs and use hearing aid controls more effectively than those with low WMC (Lunner, 2003). Taken together, this points not only to the relevance of cognitive assessment in hearing rehabilitation but also to the range of channels through which cognitive function may help compensate for HI.

As mentioned previously (section *Hearing impairment, cognition and aging*), HI has been associated with reduced episodic and semantic long-term memory and executive function in aging (e.g. Lin, Ferrucci, et al., 2011; Rönnerberg et al., 2011; Valentijn et al., 2005). Whether this is also true for WMC as measured by reading span tests has not been investigated, but seems likely. However, in the studies published so far that compare participants with HI to normally hearing reference groups, reading span test performance typically does not differ between groups although participants have not been explicitly matched on this variable (e.g. Andersson & Lyxell, 1999; Besser et al., 2013; Lyxell et al., 1998; Lyxell et al., 2003). Ongoing longitudinal studies will likely be in a position to answer this question in the near future.

Either way, using reading span tests to assess WMC in individuals with HI is suitable because the verbal storage and processing of the test mimics functions highly relevant to everyday situations. For example, in listening to a conversation when hearing is impaired, the impoverished quality of the auditory input means that speech recognition and understanding cannot be relied upon to proceed automatically. Rather, the listener needs to continually process the incoming auditory signal for disambiguation, while at the same time extracting the meaning of the ongoing speech stream and integrating it within the context given by previous sentences maintained in working memory. Further, reading span tests are text-based, minimizing the confounding influence of auditory function and the test is theoretically tightly associated with the ELU-model (Rönnberg, 2003; Rönnberg et al., 2013).

The Ease of Language Understanding model

The Ease of Language Understanding (ELU) model (Rönnberg, 2003; Rönnberg et al., 2013) is a working memory model aiming to describe the cognitive mechanisms behind language understanding in challenging conditions, for example when hearing is impaired. It incorporates elements from both the multicomponent model (Baddeley, 2012) and capacity theory (Just & Carpenter, 1992) and proposes a reciprocal relationship between implicit bottom-up and explicit top-down processes in language understanding that is modulated by a general limited capacity working memory system. It postulates an episodic buffer for the Rapid, Automatic and Multimodal Binding of PHOnological information (RAMBPHO) in which phonological information from different modalities is integrated and matched to phonological representations in semantic long-term memory. Under favorable conditions this process is assumed to be rapid and implicit, allowing for effortless lexical access or word decision making. When conditions are more challenging, for example when listening to speech in noise, the possibility of a mismatch between the input and the stored representations increases. When mismatches occur, the model proposes that explicit resources are recruited to resolve the ambiguity. The ELU model (Rönnberg, 2003; Rönnberg et al., 2013) is a model of language understanding, not language production and the RAMBPHO is thus described as an input buffer. In comparison to capacity theory (Just & Carpenter, 1992), the ELU model emphasizes the matching of incoming phonological information to semantic long-term memory and assumes that language understanding is implicit unless mismatches occur. The episodic buffer of the ELU model differs from that of the multicomponent model (Baddeley, 2012) in that it is specifically devoted to process phonological information. The ELU model also differs from the multicomponent model (Baddeley, 2012) in its aim to describe the functional role of working memory in ease of language understanding, rather than describing working memory mechanisms as such (Rudner & Rönnberg, 2008).

There is a relatively large literature on the role of WMC in speech recognition in adults with HI. Less is however known about how WMC may be involved in other important language functions, such as phonological processing, in this population.

Phonological processing

Phonology is a subdiscipline of linguistics concerned with “the function, behaviour, and organization of sounds as linguistic items” (Lass, 1984, page 1), while *phonetics* concerns the

study of speech sounds as physical phenomena, including their articulatory and acoustic properties. Phonetics and phonology interface at the level of *distinctive features*, the sets of phonetic properties that characterize and distinguish between the phonemes, that is, the smallest linguistic units that may carry a change of meaning, for example, *kiss-kill* (Lass, 1984).

In this thesis, the term phonological processing is used as a broad reference to the processing of speech sound information that is a fundamental part of language related activities (Anthony et al., 2010; Wagner & Torgesen, 1987). There are a number of specific phonological processes and abilities involved in language comprehension and production, for example, *phonological encoding*, retrieving the phonology of a word before articulation (Levelt, 2001) and *phonological decoding*, deriving a word's pronunciation from its orthography (Facoetti et al., 2010; Ziegler & Goswami, 2005). *Phonological awareness* refers to awareness of the sound structure of a language and the ability to access it, that is, to recognize, identify and/or manipulate sublexical units such as rhymes, phonemes or syllables (Anthony & Francis, 2005; Oakhill & Kyle, 2000; Wagner & Torgesen, 1987; Ziegler & Goswami, 2005). Most phonological processes have in common that they involve phonological representations in semantic long-term memory (Anthony et al., 2010; Hickok & Poeppel, 2007; Snowling & Hulme, 1994).

To put it simply, the language system in semantic long-term memory can be conceptualized as a network of abstract representations that are interconnected and organized in conceptual, semantic, lexical, phonological, orthographic and articulatory subsystems. Activation spreads in both a bottom-up and a top-down manner between representations in the subsystems. Language comprehension starts as a predominantly bottom-up mapping of incoming units of perceptual information, for example from a speech signal or text, onto their corresponding phonological and/or orthographic representations. Activation spreads to matching lexical and semantic representations, resulting in access to word meaning. Language production proceeds in the opposite direction and is initiated by activation of a concept to be expressed spreading in a top-down manner to corresponding lexical, phonological and articulatory representations (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Grainger & Holcomb, 2009; Levelt, 1999; McClelland & Elman, 1986). There is as yet no consensus as to whether there is one single, two wholly separate, or two separate but interconnected, system/s for the input, or receptive, phonology used in comprehension and the output, or expressive, phonology used in production (Hickok, 2009; Jacquemot, Dupoux, & Bachoud-Levi, 2007; Martin & Saffran, 2002; Shelton & Caramazza, 1999). Language models further differ in how they view the exact directionality and timing of activations, whether units are organized in a localized or distributed fashion, the exact size and type of information held by representations and the number of levels (subsystems) involved, but they are basically compatible with the framework above.

Phonological representations

Oral language phonological representations are abstract mental representations of the speech sounds and combinations of speech sounds that form words in a language. Phonological representations are closely linked to the acoustic/phonetic and articulatory representations that contain information about distinctive features of words, such as place and manner of articulation and voicing (Anthony et al., 2010; Harm & Seidenberg, 1999; Hickok & Poeppel, 2007) and they are encoded by articulatory, acoustic or orthographic forms in speaking, listening and reading, respectively (Cutler, 2008).

Development of phonological representations

Phonological representations are formed early in infancy. Word recognition in children as young as 18 months is affected by slight mispronunciations, which suggests they have representations that are phonetically detailed (Swingley & Aslin, 2000). However the awareness and organization of phonological representations develop during childhood with sensitivity to progressively more fine-grained phonological information, a process that may be related to the need to differentiate between a growing number of similar sounding words in the mental lexicon (Garlock, Walley, & Metsala, 2001; Gathercole, 2006; Snowling & Hulme, 1994). This development is related to auditory processing abilities (Corriveau, Goswami, & Thomson, 2010) and oral language experience (Anthony & Francis, 2005). In reading acquisition, phonology and orthography enter a reciprocal relationship in which orthographic information starts to influence phonological awareness and over time the specificity and redundancy of word representations successively increase (Anthony et al., 2010; Ziegler & Goswami, 2005). The specificity of a representation refers to the amount of distinctive feature information it holds (Elbro & Jensen, 2005) and poorly specified representations lack part/s of the phonetic details of the units they represent (Elbro & Jensen, 2005). Representational units with fewer features need not necessarily interfere with word production or perception in everyday situations. The information available may be sufficient for lexical access and retrieval on the whole-word level. However, underspecified representations will have a negative effect on phonological awareness (Elbro & Jensen, 2005), a skill typically assessed by tasks requiring phonological segmentation and comparison such as rhyme judgment or phoneme deletion (e.g. Anthony & Francis, 2005; Yopp, 1988).

Phonological representations in reading

Phonological awareness is important for reading acquisition (e.g. Anthony & Francis, 2005, Savage, Lavers, & Pillay, 2007; Wagner & Torgesen, 1987; Ziegler & Goswami, 2005). While difficulties detecting and manipulating the sounds in words make learning to read more challenging, well-specified phonological representations facilitate the learning of mapping from orthography to phonology (Snowling & Hulme, 1994; Snowling, Nation, Moxham, Gallagher, & Frith, 1997). After reading acquisition, orthographic knowledge contributes to performance in phonological tasks. Word spelling starts to exert an influence on processes such as making phonological similarity judgments, also exerting an influence when the judgment is to be conducted on aurally presented words (Castles & Coltheart, 2004; Seidenberg & Tanenhaus, 1979). Indeed, there is an ongoing debate as to whether

experienced readers necessarily need to involve phonological decoding of written words to access word meaning. Theoretically, word meaning in reading could be accessed either directly from its orthographic form, indirectly via phonological recoding of the orthographic form, or both. Computational models of reading (Grainger & Holcomb, 2009; Harm & Seidenberg, 2004) suggest that both pathways operate in parallel. Whether lexical access is achieved directly from the orthographic form, or mediated by phonology, is suggested to depend on task and stimulus specific factors, for example word frequency, the relative speed with which the semantics of specific words are accessed by the two pathways, and the depth of the orthography. Activation of semantics directly from orthography is suggested to take longer to learn, but to be faster once it is learned (Harm & Seidenberg, 2004). Similarly, the dual route model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) which focuses on how word phonology is accessed in reading, that is, the mechanisms behind reading aloud, also proposes two pathways. In the *indirect route*, word phonology is reached by sub-lexical grapheme-to-phoneme conversion and phonological assembly. In the *direct route*, the visual word form leads directly to its semantics and from its semantics to its pronunciation (addressed phonology). Thus, different models indicate that word meaning and whole-word phonology may, under certain circumstances (for example familiar, high frequency or regularly spelled words), be accessed in reading without necessarily involving activation of sublexical phonological representations. Rather, different strategies may be implicitly or explicitly used depending on task and skills.

Phonological representations in speech recognition

Speech recognition is the end result of both the acoustic and phonetic analyses applied to a speech signal and the mapping of the outcome of these analyses to phonological representations, followed by lexical selection and semantic access (Hickok & Poeppel, 2007; Luce & Pisoni, 1998; Marslen-Wilson & Warren, 1994; McClelland & Elman, 1986). If the input signal is degraded, for example by noise or HI, a lexical decision will have to be made based on insufficient information. Under such circumstances, speech recognition is facilitated for words that are highly practiced and easy to discriminate from the set of potential candidates, that is, words that are frequently used in the language, have few phonological neighbours or were acquired early in life (Luce & Pisoni, 1998). Phonological representations of such words are likely to be better specified while representations of poorer “resolution” supply less information for correct discrimination between competing candidates (Garlock et al., 2001). In the ELU model (Rönnberg, 2003; Rönnberg et al., 2013), mapping is the function of the RAMBPHO buffer in which multimodal phonological information is bound together in syllable level units and matched to their corresponding phonological representations. If these contain insufficient information, implicit matching is impeded and activation of representations at the lexical level will be less accurate or fail. Availability of other information, such as word spelling or semantic context, will then determine which word will be retrieved (Rönnberg et al., 2013).

Phonological representations in verbal retrieval and generation

In verbal retrieval, the first stage is selection of a lexical item to be expressed; the second stage is activation of its phonology for articulation (Dell et al., 1997; Levelt, 1999). However,

the spreading of activation from a selected lexical item to its phonological form is vulnerable: as evidenced by tip-of-the-tongue states, the complete phonology of a word can be temporarily inaccessible even when part of it, for example the initial phoneme, is retrieved (Burke & Shafto, 2004). Word finding difficulties in the form of increased occurrence of tip-of-the-tongue states have been coupled to difficulties specifically in the retrieval of phonological representations in children and adolescents with dyslexia (Faust, Dimitrovsky, & Shacht, 2003; Faust & Sharfstein-Friedman, 2003; Hanly & Vandenberg, 2010), an impairment known to include deficits in phonological awareness (e.g. Savage et al., 2007). It has further been suggested that fine-grained phonological representations support the ability to produce words in which the initial phoneme is segmented from the rest of the word (Nash & Snowling, 2008), an ability taxed by the letter fluency task (further described in the *Assessing phonological abilities* section). In word production, articulation may also be impacted by the specificity of representations. Pronouncing words become more difficult when there is a lack of information about the phonemic segments of words, and/or the articulatory gestures needed to produce these segments, that are normally contained in stored representations. Such lack of information may lead to articulation errors (Fowler & Swainson, 2004). Continuous auditory feedback plays an important role throughout adulthood in maintaining the quality of internal representations, and thereby the distinctness of pronunciation (Waldstein, 1990).

Neural representation of phonological processing

The neural representation of phonological processing is task-dependent but the brain networks engaged in speech comprehension and speech production tasks also partly overlap (Hickok, 2009). The superior temporal gyrus (STG) has been identified as an important site for the representation and processing of phonological information. The STG is activated in tasks that require access and maintenance of phonological information in both language comprehension and production tasks (Bitan et al., 2007; Hickok, 2009; Hickok & Poeppel, 2004; Jobard, Crivello, & Tzourio-Mazoyer, 2003). The left posterior inferior frontal gyrus (IFG, Broca's area) is also reliably activated in phonological tasks such as rhyme judgments in both the visual and auditory modalities (Bitan et al., 2007; Burton, LoCasto, Krebs-Noble, & Gullapalli, 2005; Hickok, 2009). This area is implicated in covert articulation and phonological decoding and has been suggested to play an important part in sensory-motor integration, sublexical processing and verbal short-term memory (Hickok, 2009; Hickok & Poeppel, 2004). Studies that have compared left IFG (Broca's area) activation during phonological and semantic tasks suggest it is its more posterior, opercular, part that is involved in phonological decoding and covert articulation, while its anterior, triangular, part may be more specialized in semantic access and processing (Jobard et al., 2003; Poldrack et al., 1999; Vigneau et al., 2006). The left angular gyrus is an additional area that has been implicated in for example rhyme judgment tasks and has been suggested to play an important role in mapping between phonological and orthographic representations (Booth et al., 2004) as well as in perceptual learning of degraded speech (Eisner, McGettigan, Faulkner, Rosen, & Scott, 2010).

Knowledge about the role of cortical regions in phonological processing typically comes from studies using functional Magnetic Resonance Imaging (fMRI), a method with high topographic, but poor temporal, resolution. By contrast, the event-related potentials (ERP) technique utilizes the excellent timing data afforded by the electroencephalogram (EEG) and measures the electrical activity of the brain in response to specific stimuli with millisecond resolution (Luck, 2005). ERP studies often take advantage of the facilitation, or priming, by contextual cues that modulate access to linguistic representations. Facilitation may be the result of fast, implicit spreading of excitation through neuronal network and/or relatively slower explicit, predictive, processes (Lau, Phillips, & Poeppel, 2008; Neely, 1977). In rhyme judgments for example, presentation of the first word in a rhyme pair leads to increased implicit activation of representations phonologically related to the presented word. Very short time-intervals between presentations of two words in a pair limit the opportunity to involve explicit strategies, but with longer time-intervals, generation of predictions and expectancies evolve (Dufour, 2008; McQueen & Sereno, 2005; Radeau, Morais, & Segui, 1995). In the ERP waveforms, non-primed stimuli elicit larger negative amplitudes than do primed stimuli in components (that is, reliably elicited brain wave deflections) that are sensitive to mismatch between a presented stimulus and the context. Results of ERP studies indicate that access to phonological representations and initiation of the processing mechanisms leading to the detection of phonological mismatch is achieved within around 250 ms after presentation of a written or spoken word (Barber & Kutas, 2007; Connolly & Phillips, 1994; Connolly, Service, D'Arcy, Kujala, & Alho, 2001; Diaz & Swaab, 2007; Grainger & Holcomb, 2009).

Assessing phonological processing abilities

There is a plethora of tests, designed to assess more or less specific phonological processes or subprocesses, described in the literature (e.g. Alloway et al., 2004; Anthony et al., 2010). For example, tests of input phonological awareness include rhyme judgment, blending of phonological elements, phoneme or syllable counting and phoneme deletion. The tests differ in the size of the units to be manipulated, the degree of metalinguistic awareness required, memory demands and involvement of orthographic processing (Alloway et al., 2004; Yopp, 1988). The smaller the size of the unit to be manipulated and the higher the memory demands, the more difficult the test. Further, orthographic information (use of written words) may either support or impede performance on tasks such as those assessing phonological awareness, depending on whether the cues provided by the orthography are congruent or incongruent with the cues provided by word phonology. For example, text-based rhyme judgment tests can use word pairs that rhyme (R+) or not (R-) and are orthographically similar (O+) or dissimilar (O-). Thus, four conditions can be created, two in which phonology and orthography match (R+O+, *rung-sung*; R-O-, *gift-road*) and two in which they mismatch (R+O-, *moose-juice*; R-O+, *bead-dead*) with respect to the judgment task (e.g. Rugg & Barrett, 1987). The mismatching conditions are considerably more difficult, even for experienced adult readers (Johnston & McDermott, 1986; Kramer & Donchin, 1987; Rugg & Barrett, 1987). These conditions require heavy reliance on phonological representation, together with inhibition of the orthographic information.

In tasks of output phonology, distinctness of pronunciation is often used to infer the quality of stored representations (Martin & Saffran, 2002). An example is non-word repetition in which the test-taker needs to store a phonological pattern in verbal short-term memory in order to reproduce it. Verbal retrieval, the ability to access words from semantic long-term memory, is often assessed by verbal fluency tasks (Benton, 1968; Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998). In these, the task is to generate as many words as possible that belong to a certain category, for example words that are animals (category fluency), or words beginning with a certain letter, typically F, A and S (letter fluency). In letter fluency, words need to be retrieved according to a phonemic search strategy which involves temporary storage and manipulation of phonological sub-lexical information (Rende, Ramsberger, & Miyake, 2002). Consequently, phonological difficulties are associated with impaired letter fluency (Löfkvist, Almkvist, Lyxell, & Tallberg, 2012; Marczinski & Kertesz, 2006; Snowling et al., 1997). An interesting aspect of letter fluency is that performance can be analyzed in terms of the strategies underlying retrieval, clustering and switching (Troyer, Moscovitch, & Winocur, 1997). Clustering refers to the relatively automatic retrieval of words from a phonologically associated subcategory, such as words beginning with the same two initial phonemes (e.g. farm, far, father). Switching reflects the strategic search for new phonological subcategories to retrieve from (Gruenewald & Lockhead, 1980; Troyer et al., 1997; Unsworth, Spillers, & Brewer, 2011).

Postlingually acquired hearing impairment and phonological processing

The relatively few studies that have examined phonological processing in individuals with postlingually acquired severe HI have found a negative effect of severe HI on phonological awareness. Performance is lower when compared with that of normally hearing individuals in text-based rhyme judgments on rhymes that are orthographically dissimilar or non-rhymes that are orthographically similar (Andersson, 2002; Andersson & Lyxell, 1998, 1999) and in rhyme generation (Andersson, 2002). Similar results have been found for postlingually deafened adults (Lyxell et al., 1998; Lyxell et al., 1994). Further, text-based rhyme judgment performance has been found to correlate negatively with duration of hearing loss (Andersson & Lyxell, 1998; Lyxell et al., 1994) during the first 10-15 years after hearing loss onset (Andersson, 2002). When phonological processing plays a less important role in task performance, for example in semantic and lexical decision making or antonym generation, individuals with severe acquired HI perform on a par with normally hearing individuals (Andersson, 2002; Andersson & Lyxell, 1998, 1999).

Presumably, when incoming speech signals continually lack part of the information available to normally hearing individuals, activation of those features of the phonological representations that correspond to the missing information progressively decrease. Over time the information in the representations will most likely be impoverished to a level where it more closely matches the degraded information in the incoming speech signal. Additional, but relatively stable changes in the speech signal, for example by habitual use of hearing aids or CIs, are then likely to lead to a corresponding adjustment in the featural composition of the phonological representations (see Rudner, Foo, Rönnerberg, et al., 2009). As the information in both the incoming signal and the stored representations become increasingly impoverished,

matching between them will, however, fail more often (Rönnberg et al., 2013). Rhyme awareness has been found to support speech recognition in noise in HI (Lunner, 2003; paper III of this thesis) so that there may be a negative cycle where degradation of the incoming speech signal over time due to HI leads to impoverished representations in semantic long-term memory, which in turn may impede the recognition of spoken words.

Acquired deafness affects not only receptive phonology but also has an impact on the expressive side such that with time, phonetic precision in speech production gradually declines (Waldstein, 1990). Apart from studies examining articulatory precision, little is known about the impact of HI on word generation and production.

Neural correlates of phonological processing in individuals with hearing impairment

Postlingual HI is further associated with changes in the neural processing of sound. For example, Lee et al. (2007) found evidence of cross-modal plasticity in the form of an enhanced receptiveness to visual linguistic input in the auditory speech regions of the brain in deafened adults. It has been suggested that if the left lateralized temporal regions that are normally devoted to phonological processing become more responsive to visual linguistic information, the right lateralized auditory areas that are otherwise involved in processing of environmental sounds may in turn be recruited for the processing of phonology (Lazard, Lee, Truy, & Giraud, 2012). Recruitment of auditory areas for visual processing following hearing loss may even interfere with auditory speech recognition by affecting the ability to segregate conflicting auditory and visual information (Champoux, Lepore, Gagne, & Theoret, 2009). Indeed, audiovisual presentation of stimuli may increase processing load when compared to auditory only presentation. This is also true in normally hearing individuals when the visual cues do not add task-relevant information (Mishra, Lunner, Stenfelt, Rönnberg, & Rudner, 2013). However, even in prelingually deafened individuals, cross-modal reorganization does not seem to affect primary auditory areas, but the multimodal secondary auditory areas (Bavelier, Dye, & Hauser, 2006; Giraud & Lee, 2007). The cross-modal plasticity may therefore be conceptualized as a tuning of language processing regions, including those responsive to heard speech, to relevant visual inputs mediated for example via speechreading or sign language following HI.

The results of a recent fMRI study (Lazard et al., 2010) indicates that auditory deprivation may also affect reading strategy such that accessing word phonology via grapheme to phoneme conversion, that is, the indirect route (Coltheart et al., 2001) may be gradually replaced by phonological access via whole word semantics, that is, the direct route, in a subgroup of individuals with severe HI. In the study by Lazard et al. (2010), with postlingually deafened adult CI candidates, neural activation indicating a direct route to reading during performance of a text-based rhyme judgment task correlated with hearing loss duration but was also predictive of poorer speech perception after cochlear implantation.

There is an extensive body of literature on speech sound discrimination in individuals with HI and CI users that has utilized ERP-markers of auditory perception, discrimination and sound classification (for reviews see Alain & Tremblay, 2007; Johnson, 2009). However, the

possibilities to investigate changes in semantic long-term memory representations associated with acquired hearing loss with electrophysiological measures have so far not been taken advantage of. Interestingly, a recent ERP-study compared the performance of adult native signers with prelingual deafness to that of individuals with normal hearing in a text-based rhyme judgment task. The results showed similar rhyme processing in both groups, as indicated by neural responses (MacSweeney, Goswami, & Neville, 2013).

Relation between working memory capacity and phonological processing

Phonological processing and working memory represent separate but interrelated cognitive domains that may be conceptualized as cooperating in language processing. For example, WMC and phonological awareness are associated in children (Alloway et al., 2004; Leather & Henry, 1994; Oakhill & Kyle, 2000; Savage et al., 2007), and both predict reading proficiency (Leather & Henry, 1994; Savage et al., 2007). However, they also tap separate functions; working memory and phonological processing load on different factors in factor analyses (Alloway et al., 2004) and they make unique contributions to reading development (Savage et al., 2007).

In Baddeley's multicomponent model (Baddeley, 2012) phonological functions are incorporated into the working memory model in the form of a phonological loop. This module is responsible for the brief storage of phonological information and maintenance by vocal or subvocal rehearsal, that is, verbal short-term memory. The phonological loop is bi-directionally linked to semantic long-term memory and is critical for vocabulary learning. It also plays an important role in the control of action via self-instruction. Phonological awareness is closely related to verbal short-term memory (Alloway et al., 2004; Gathercole, 2006; Johnston & McDermott, 1986). It may be that they share the same phonological processes or that both tap the specificity of phonological representations (Alloway et al., 2004; Snowling & Hulme, 1994). Further, awareness tasks typically load on verbal short-term memory, contributing to the difficulty of separating phonological awareness from short-term memory function (Yopp, 1988). There is, however, evidence that phonological short-term memory and phonological awareness form partly separable abilities (Alloway et al., 2004; Savage et al., 2007). One way to conceptualize the difference is to distinguish between the relatively implicit phonological processing involved in verbal short-term memory, for example in speeded naming tasks, and the explicit, metalinguistic ability required for phonological awareness where there is a need to reflect upon and manipulate phonological subcomponents of words (Alloway et al., 2004; Clarke, Hulme, & Snowling, 2005; Snowling & Hulme, 1994; Wagner & Torgesen, 1987).

In the ELU model (Rönnberg, 2003; Rönnberg et al., 2013) working memory processing resources are invoked to repair (for example by reconstruction, elaboration and inference-making) when implicit phonological level matching of linguistic information to stored phonological representations fails and mismatch occurs. Resolution of the mismatch will then partly depend on the capacity of the working memory system, and individual differences in WMC will further influence the amount of cognitive load experienced (Rönnberg, Rudner, Lunner, & Zekveld, 2010). This assumption has been tested by inducing phonological

mismatch in a speech recognition task in participants with HI that were habitual hearing aid users (Rudner, Foo, Rönnberg, et al., 2009). Involvement of WMC in the speech recognition task in a condition in which the participants listened through hearing aid settings they had become familiarized with (phonological match), and a condition where the hearing aid settings were manipulated to process the speech signal in a slightly unfamiliar way (mismatch), were compared. WMC was found to predict performance specifically in the mismatch condition. Thus, in speech recognition, better WMC supports recognition when signal distortion disrupts the habitual mode of phonological processing.

Similarly to speech recognition under more or less taxing conditions, phonological awareness tasks can be divided into two groups: tasks that require only single operations, such as segmenting a spoken word into its phonemes, and tasks with higher memory demands (Yopp, 1988). Phonological tasks such as those assessing phonological awareness, for example phoneme deletion tasks or rhyme judgments, require the extraction, storage *and* manipulation of phonemes or syllables and load on WMC as measured by complex span tasks (e.g. Leather & Henry, 1994; Oakhill & Kyle, 2000). Thus, in terms of capacity theory, they tax the ability to simultaneously store and process phonological information.

Working memory capacity and phonological processing in rhyme judgment

Text-based rhyme judgment requires the maintenance of phonological codes in working memory while performing operations such as sublexical segmentation of the rhyme and making phonological comparisons. Further, the orthographic cues may be misleading and need to be inhibited. Such discrimination between relevant and irrelevant information with regard to task goals is a precursor of working memory engagement (Unsworth & Engle, 2007). In terms of the multicomponent model (Baddeley, 2012), both phonological loop functions like articulatory recoding and executive/attentive control via the central executive need to be involved in the successful resolution of the conflict. As discussed (section *Assessing phonological processing*), the mismatching rhyme task conditions (R+O-, R-O+) are more difficult than the matching (R+O+, R-O-) because they require heavier reliance on phonological representations and inhibition of the orthographic information (Johnston & McDermott, 1986; Kramer & Donchin, 1987; Rugg & Barrett, 1987).

Several studies have found that the effect of mismatching orthographic cues is most pronounced in the R-O+ condition (Johnston & McDermott, 1986; Kramer & Donchin, 1987; Polich, McCarthy, Wang, & Donchin, 1983; Rugg & Barrett, 1987). This has been suggested to reflect an encoding bias, such that the second word is initially assigned the phonology of the first word (Meyer, Schvaneveldt, & Ruddy, 1974). An alternative explanation refers to the effect of orthographic priming and suggests that an initial rhyme judgment is made based on whether the final letters of the second word are consistent with letter sequences that are phonologically similar to the final letters of the first word or not. Both encoding bias and orthographic priming will lead to more errors in rhyme judgment of word pairs like bead-dead than in pairs like moose-juice. Phonological priming, whereby presentation of the first word in a pair leads both to activation of lexical representations that are phonologically related to it, and to generation of expectancy sets involving rhyming candidates, are other

mechanisms that make R-O+ judgments more difficult than R+O- judgments. In R+O-, phonological priming facilitates the decision, but in R-O+ primed candidates need to be inhibited and rapid access has to be made to the phonology of the second word while simultaneously maintaining a representation of the first word (Johnston & McDermott, 1986).

There are a few differences between English and Swedish rhyme judgment stimuli. Swedish R+O- word pairs are equivalent to their English counterparts, for example *helg-välj*, [hel:j]-[vel:j], but because Swedish is more consistent in its grapheme-to-phoneme correspondence than English (Seymour et al., 2003), Swedish R-O+ word pairs used in rhyme judgment tasks have orthographically similar, but not identical, endings, for example *sant-saft*, [san:t]-[saf:t] (Andersson, 2002; Andersson & Lyxell, 1998; Lyxell et al., 1998). Due to the fine-grained phonological difference between the words, they are difficult to separate phonologically. While Swedish words in R+O- pairs are irregularly spelled, Swedish words in R-O+ pairs may be regularly or irregularly spelled. The phonology of irregularly spelled words is not accessible via spelling-to-sound conversion and hence, R+O- rhyme judgments need to be based more exclusively on phonological representations. R-O+ word phonology can to a larger degree than R+O- word phonology be accessed by spelling-to-sound conversion in working memory. Swedish R+O- judgments have therefore been suggested to primarily tap the specificity of phonological representations while R-O+ rhyme judgment to a larger extent than R+O- judgments also capture the ability to perform phonological operations (Andersson, 2002). Taken together, the non-rhyme status, the regular or irregular spelling, and the fine-grained phonological and orthographic similarity between words in Swedish R-O+ judgments are likely to make this condition relatively more working memory demanding than R+O-, but also relatively more amenable to compensatory working memory engagement when phonological representations are underspecified.

Working memory capacity and phonological processing in verbal fluency

Verbal fluency requires the strategic retrieval of unique words based on a specific search cue, monitoring of the output in order to avoid repetitions, and generation of subcategory cues (for example farm animals, or words beginning with the same two first letters) to semantically or phonologically related clusters of words to retrieve from. Several studies have found that WMC supports fluency performance (Azuma, 2004; Rende et al., 2002; Rosen & Engle, 1997; Unsworth, Spillers, et al., 2011). As is the case with the visual rhyme judgment task, temporary storage and manipulation of phonological information in the phonological loop, and also central executive functions, perhaps particularly switching, are involved when the task is to generate words based on a phonological cue (Rende et al., 2002). Unsworth et al. (2011) used latent variable analysis to investigate how WMC, inhibition, vocabulary size and processing speed were related to verbal fluency performance and found that WMC was the variable with the strongest relation to the number of words generated. WMC also predicted unique variance in two measures of verbal fluency strategy use, clustering and switching (Troyer et al., 1997; Unsworth, Spillers, et al., 2011). It is therefore likely that a more capacious working memory allows for quicker and more efficient strategic search and generation of retrieval cues (Unsworth, Spillers, et al., 2011).

Summary

HI is associated with changes in the neural processing and representation of sound and an increased risk of cognitive impairment in aging. Hearing-related difficulties with spoken communication may have a substantial impact in daily life and the extra processing required for successful speech recognition may interfere with memory encoding. However, the consequences of hearing loss are, in part, determined by the interaction between bottom-up auditory and top-down cognitive functions. For example, prior knowledge and contextual cues can be utilized to fill in the gaps when spoken words are not clearly perceived, and the dual storage and processing capacity of working memory supports speech recognition in adverse conditions. Long-term severe acquired HI is associated with changes in the semantic long-term memory representation of sound and impaired phonological awareness skills. While individual differences in WMC have been found to modulate speech recognition in noise (an ability, in part, supported by phonological awareness), it is not known whether WMC may also help compensate for the phonological processing declines resulting from degraded representations. However, the ELU model (Rönnberg, 2003; Rönnberg et al., 2013) suggests that this may be the case.

The empirical studies

General aims

The two primary aims of this thesis were to examine phonological processing in adults with postlingually acquired moderate-to-profound HI and to determine whether explicit working memory processing of phonology and WMC can compensate for phonological declines in this group (paper I- III). Paper I examined the neural correlates of phonological processing under conditions that, to a greater or lesser extent, restricted the possibilities to engage explicit working memory processes in a text-based, rhyme judgment task. This task was chosen because it is known to be sensitive to phonological decline in this group (e.g. Andersson, 2002). Further, the text-based format minimizes confounding effects related to hearing acuity. Finally, because this task is the one most frequently used in examining phonology in the present population, it was also chosen to be able to relate the results to those of previous studies. Paper II examined how individual differences in WMC impacted upon hearing-related phonological processing as measured by (1) performance in the text-based rhyme judgment task and (2) subsequent incidental episodic memory recognition of words from this task. In paper III, the effect of postlingually acquired HI on an index of output phonology in verbal retrieval, the letter fluency task, was examined. Like text-based rhyme judgments, this task is sensitive to phonological processing ability and does not involve on-line audition. Further, the two measures of clustering and switching were assessed and this allowed for a more fine-grained analysis of strategy use. Both total performance, that is, number of words generated, and the strategy measures were related to WMC. Together, papers I-II investigated the relation between input phonology, explicit working memory processing of phonology and WMC on behavioral performance and neural function, and paper III, the relation between WMC and output phonology and strategies employed in phonologically based word generation. In all three papers, the results of the participants with

HI were compared to the results of a matched reference group of participants with best ear pure tone hearing thresholds of 26 dB HL or better.

The measure used to assess WMC was the RST, the Swedish version of the reading span test (Rönnberg et al., 1989), which has been used in a number of studies in cognitive hearing science. There are however no published reference data on RST performance. A secondary aim of this thesis was therefore to provide such data on performance in both the original RST version, and a shortened version, in a larger sample of individuals with HI in different age cohorts. RST performance in the two versions of the test, and in two age groups, was also related to age, gender and speech recognition in noise (paper IV).

Method

Participants

Papers I-III

Participants with moderate-to-profound HI, defined as mean best ear PTA measured across 500, 1000, 2000 and 4000 Hz (BestEarPTA) exceeding 40 dB HL, were recruited from the audiological clinic, Linköping University Hospital, Sweden. A normally hearing reference group was recruited from the general population. Normal hearing (NH) is here defined as a BestEarPTA < 26 dB HL. Included were native Swedish speakers with normal or corrected-to-normal vision and no self-reported history of neurological disease, traumatic brain injury or dyslexia. Additional inclusion criteria for the participants with HI were a postlingually acquired binaural, moderate-to-profound sensorineural hearing loss which had lasted for at least 5 years and habitual use of bilateral hearing aids.

A total of 71 adults, 37 with HI and 34 with NH, were recruited. Of these, 5 individuals with HI and 4 with NH were excluded either because their hearing profile was discovered not to meet the criteria or because they did not complete the testing. The participants who were excluded due to their hearing profiles were participants discovered to have a hearing loss exceeding 26 dB HL in the group with NH and in the group with HI, participants in whom self-reported HI onset was earlier than the age of 6. Of the 32 remaining participants with HI, two had a HI in the moderate range, 22 in the severe range, and 8 in the profound range. Mean BestEarPTA was 75.2 dB HL ($SD = 12.6$) and mean age 63 years ($SD = 7.1$). In the group with NH, mean BestEarPTA was 14.0 dB HL ($SD = 6.3$) and they were on average 62 years old ($SD = 8.1$). The project was approved by the regional ethics committee in Linköping (Dnr 77-09) and all participants provided written informed consent before testing started.

Paper II included the first 21 participants with HI and NH that were tested. Paper I included the 26 participants with HI and 27 with NH for whom there was a sufficient number of artifact-free ERP trials in the conditions analyzed. Paper III included all participants tested except one who did not have time to finish the verbal fluency test. In neither of these papers were there any differences between the groups in mean age, WMC or receptive vocabulary.

Paper IV

For paper IV, data from several published and unpublished projects from our laboratory and its collaborators were collated into a single database ($n = 553$). Participants were selected from this database based on the inclusion criteria that they had performed the RST in its original (LongRST) or shortened (ShortRST) version, had a mild-to-severe sensorineural HI with BestEarPTAs ranging from 26 to 81 dB HL, and were aged 50 or above. This selection resulted in a total of 339 (153 female) participants from 9 different projects whose data were reanalyzed. Mean BestEarPTA was 44.1 dB HL ($SD = 11.2$) and mean age was 67 years ($SD = 7.97$). The selected participants represented 3 groups; participants who had performed the ShortRST who were all 50-69 years old ($n = 116$), 50-69 year olds who had performed the LongRST ($n = 106$), and 70-89 year olds who had also performed the LongRST ($n = 117$).

General procedure

Papers I-III

Participants were tested in two separate sessions. The first included the collection of background data, followed by a text-based visual rhyme judgment task during which ERPs were registered. An incidental episodic recognition memory task, using stimuli from the rhyme judgment task, was then administered off-line. After a break, participants completed a cognitive test battery including the RST (see Table 1). In a second session, audiograms and speech recognition thresholds using the Hagerman sentences test (Hagerman, 1982) were collected by an experienced audiologist.

Paper IV

Different protocols had been used in the different projects but in addition to RST performance, aided speech recognition in noise as assessed by the Hagerman sentences test was available for a majority of the participants ($n = 213$). Further, speed of lexical access, assessed by a lexical decision making test (Rönnberg, 1990; Rönnberg et al., 1989), was available for 211 participants. The data was analyzed in 4 steps: (1) RST performance was converted to percentage correct and the frequency distributions of scores and their corresponding percentiles were examined in the three groups, (2) performances in the ShortRST and the LongRST were compared, (3) LongRST performance and its relation to other variables were compared across the two age groups and, finally, (4) an exploration of predictors of LongRST performance was conducted.

Tests

A list of tests used in the present thesis is provided in Table 1. Below, only those tests that are the primary focus of papers I-IV are described in detail. Full descriptions of other tests are found in the papers.

The RST

The RST (Rönnberg et al., 1989) is a complex span test designed to assess the dual storage and processing that defines WMC. The original version, the LongRST, was used in papers I-IV. The LongRST begins with 2 practice trials. Fifty-four sentences are then presented in sets of 3 to 6 with successively increasing set sizes and 3 trials per set size. Each sentence consists

of 3 words, shown one at a time at the center of a computer screen. The first and the last words are always content words. Half of the sentences are absurd (e.g. *Gaffeln grät ofta*, the fork often cried) and half are not (e.g. *Bilen gick fort*, the car went fast). After each sentence, participants are to report orally whether the sentence was absurd or not and after each set of sentences s/he is required to report orally either the first or the last words of each sentence in the set. Participants do not know which words (first or last) they will be asked to report until after they have read all the sentences in the set. In paper IV, the shortened, ShortRST, version was also used. The ShortRST consists of a subset of 24 sentences from the LongRST, the maximum set size is reduced to 5 and the number of trials per set size to 2. The semantic judgments are made by button press instead of oral report. Apart from these adjustments, the two versions are identical. Total number of correctly recalled words, irrespective of order of recall, has been found to optimize individual variation in performance (Lunner, 2003; Rönnberg, 2003; Rönnberg et al., 1989) and in the present work the percentage correctly recalled words was used as dependent measure.

Rhyme judgment

A Swedish text-based rhyme judgment test with four conditions, two matching (R+O+, R-O-) and two mismatching (R+O-, R-O+) was developed for the present project. Existing tests had 12 or 13 trials per condition (e.g. Andersson, 2002) which was not sufficient for collection of reliable ERPs. As described in the *Background* (section *Working memory capacity and phonological processing in rhyme judgment*), Swedish rhyme judgment tests differ from English versions because Swedish is more consistent in its grapheme-to-phoneme correspondence than English. Swedish equivalents of English R-O+ word pairs in which the rhyme is orthographically identical but phonologically dissimilar (e.g. bead-dead), are therefore rare and Swedish R-O+ word pairs instead have orthographically similar, but not identical, endings. Swedish is, however, less consistent in its phoneme-to-grapheme mapping and it is possible to construct Swedish R+O- word pairs that are equivalent to such pairs in English (e.g. moose-juice) even if these too are rare. In constructing the rhyme test for the present project, word pairs in the R+O- condition therefore included words of low frequency and words from different open word classes (nouns, verbs, adjectives and adverbs). Words for the other conditions were selected to match the R+O- words in word frequency, word length, word class, number of syllables and stress pattern to ensure the four conditions did not differ in any of these variables. In selecting word pairs for the R-O+ condition, a number of different strategies were adopted to create similar word-end gestalts. In most cases word-endings differed by one letter (e.g. *sant-saft*, [san:t]-[saf:t]). In other cases letters were rearranged (e.g. *rost-fots*, [rås:t]-[fø:ts]) or added (e.g. *besked-beskydd*, [bef̥e:d] [bef̥yd:]). This variety of solutions reduced the predictability of the orthographic form of the second word in each pair which ensured the saliency of the mismatch.

The rhyme task material consisted of 192 word pairs with 48 pairs in each of the four conditions, R+O+ (e.g. *korp-torp*, [kår:p]-[tår:p]), R+O- (e.g. *helg-välj*, [hel:j]-[vel:j]), R-O+ (e.g. *sant-saft*, [san:t]-[saf:t]) and R-O- (e.g. *bröd-spik*, [brö:d]-[spi:k]). All words were three to nine letters long, mono- or disyllabic and selected from the Swedish text corpus PAROLE (Språkbanken, University of Gothenburg). The distribution of mono- and disyllabic words,

word classes and stress patterns was even over conditions and positions in word pairs. ANOVAs with word length and word frequency as dependent variables, and condition (4 levels: R+O+, R+O-, R-O+ and R-O-) and position (2 levels: first word, second word), as independent variables, showed that there were no differences in either word frequency or word length over conditions or positions. The word pairs were pseudo-randomized into a single list in which no more than 5 “yes” or “no” answers, and no more than 3 consecutive trials from the same condition was allowed.

Table 1. Test used in papers I-IV

Domain	Test	Specifics	Dependent variable
Cognitive function			
Non-verbal ability	Ravens matrices	Non-verbal logical reasoning	No. correct
Memory	the RST	Verbal WMC	% correct
	Digit span	Phonological short-term memory	No. correctly recalled in the right position
	Episodic recognition	Incidental episodic recognition memory	% correct
Verbal ability	"Word comprehension"	Receptive vocabulary, word comprehension	No. correct
	Verbal fluency	Lexical access and retrieval, word generation	
	Letter fluency	Phonologically mediated lexical access and retrieval	No. correct generated No. of clusters
	Category fluency	Semantically mediated lexical access and retrieval	No. of switches Mean size of clusters
Lexical access	Lexical decision making	Speed of lexical access	Reaction time, ms
Phonological skills	Rhyme judgment	Phonological awareness	% correct
	"The sounds give the word"	Pseudohomophone detection , phonological decoding	No. correct
Orthographic skills	"The letters give the word"	Orthographic decoding	No. correct
Auditory function			
Auditory thresholds	Audiogram	Pure tone hearing thresholds	dB HL
Speech recognition in noise	Hagerman sentences	Speech recognition in unmodulated background noise	SNR

The words in each pair were presented consecutively on a computer screen. Each trial began with a fixation cross displayed for 1000 ms. The fixation cross was followed by a 200 ms presentation of the first word. An interstimulus interval (ISI) of either 50 ms or 800 ms preceded presentation of the second word. In the longer ISIs there was time for engagement of explicit top-down processes while the short ISIs limited involvement of such mechanisms. The second word remained on screen for 200 ms and a response probe appeared 1000 ms after second word offset. The task was to decide with a button press whether the words in each pair rhymed or not. From probe onset participants had five seconds to respond. In order to encourage a phonological strategy, participants were instructed not to pay attention to how the words were spelled, but to decide solely on basis of word pronunciation. The rhyme judgment list was presented twice to all participants, once with short ISIs and once with long ISIs, in counterbalanced order.

Incidental episodic recognition

Two lists of words were created for the episodic recognition task. Each contained half of all the words that occurred as the second word in the rhyme judgment word pairs. To these 96 old words (24 from each rhyme condition), an equal number of new words were added, selected from the same text corpus as the rhyme words. The new words were matched to the rhyme words on frequency, word length, word class and proportion of mono- and disyllabic words. The same new words were used in both lists and presentation of the two lists was counterbalanced across the participants. This episodic recognition task was presented without forewarning after the rhyme judgment task. Participants were required to judge, using button presses and without a time-limit, whether the words had been presented in the rhyme judgment task or not. The dependent variable was the proportion of correctly recognized old words. For each participant, only words belonging to rhyme task word pairs that had been correctly judged were included.

Verbal fluency

Phonologically and semantically based verbal retrieval were measured by performance on the letter fluency and category fluency tests (Benton, 1968). In the letter fluency test, the task was to orally generate as many words as possible starting with the letters F and A during 60 s time-intervals. In the category fluency test, participants were asked to generate as many words as possible that are animals. Proper names, numbers, and variants of the same root word were not allowed. All participants were given the tasks in the same order (F, A, animals). Instructions were given orally and care was taken to ensure that all participants correctly understood the test procedures. Responses were recorded on a digital voice recorder. Clustering and switching scores were computed for each of the two tasks following an established scoring procedure (Tallberg, Carlsson, & Lieberman, 2011). The dependent measures were (1) the total number of words generated in each task (letter fluency, category fluency) and (2) the number of switches, the number of clusters and the mean cluster sizes in each task.

Hagerman sentences

The Hagerman sentences test (Hagerman, 1982) was used to assess speech recognition in noise. This is a test in which sets of pre-recorded five-word sentences (e.g. *Peter kept seven*

old buttons, Karin has four black baskets) are presented in unmodulated noise (Hagerman, 1982). The task is to repeat as many of the words as possible after each sentence. All sentences have the same proper noun– verb– numeral–adjective– noun syntactic structure and therefore low redundancy. Hence, contextual cues cannot be used to aid speech recognition. An adaptive procedure was applied to determine the signal-to-noise (SNR) ratio required for a performance level of 50% correctly repeated words (Hagerman & Kinnefors, 1995). In paper IV, 92 participants had been tested at the level of 40% correct. The slope of the psychometric function for the Hagerman sentences test at around the level of 50% correct is 10%/dB, hence the SNRs required for 50% correct are about 1dB better than those required for 40% correct (Hagerman & Kinnefors, 1995). The SNRs for the participants tested at the 40% level were therefore adjusted by 1 dB. For example, an individual SNR of -3dB was adjusted to -2 dB (Hagerman & Kinnefors, 1995). Lower SNRs represent better performance and the SNR constitutes the dependent measure.

ERP acquisition and preprocessing

EEG data were acquired and analyzed using the EGI (Electrical Geodesics Inc., Eugene, OR) Geodesics Net Amps system with 128-channel HydroCel Geodesic Sensor Nets, a Net Amps 300 Amplifier and NetStation software version 4.4.2. The EEG was recorded at a 250 Hz sampling rate with electrode impedances kept below 50 k Ω using a vertex reference. After acquisition, the EEG was 0.30-30 Hz bandpass filtered and segmented into epochs from 200 ms before either target onset (long ISIs), or prime onset (short ISIs), to 1000 ms post target onset. Longer epochs were extracted in the short ISIs to ensure a time-window for baseline correction that was free from ERPs elicited by the prime. Only trials with correct answers were retained for statistical analyses. Artifacts were identified using the NetStation Artifact Detection tool with thresholds set to ± 100 μ V for eye blinks and ± 45 μ V for horizontal eye movements. Channel thresholds were set to detect voltage changes larger than ± 70 μ V within 150 ms intervals, or less than 1 μ V within an epoch. A channel was marked as bad for the entire session if it was deemed bad in more than 20% of the trials. Epochs containing more than 10 bad channels, eye-movements or eye blinks were rejected. The Bad Channel replacement tool was applied to interpolate bad channels in good epochs using spherical splines, a procedure applied to about 1.5% of the data. All data were also visually inspected. In total, 15% of the epochs, evenly distributed over the conditions, from correctly answered trials were excluded. Accepted epochs were averaged in each condition, re-referenced to the average reference, and baseline corrected either over the 100 ms before target onset (long ISIs), or over the 100 ms before prime onset (short ISIs). Six groups of electrodes representing frontal, centroparietal and occipital areas in both hemispheres were chosen for statistical analyses.

Summary of the papers

Paper I

Purpose

Severe acquired HI has been associated with a reduced specificity of phonological representations and a functional reorganization of both the left and right temporal cortices.

The reorganization likely reflects an increased responsiveness to visual stimuli in the left temporal cortex together with recruitment of the right temporal cortex for phonological processing (Lazard et al., 2011; Lazard et al., 2010; Lazard et al., 2012). While fMRI studies have indicated topographical changes in phonological processing following acquired HI, the time-course of these changes has not been examined previously. Further, the contribution of explicit working memory processing of phonology to text-based rhyme judgment performance in individuals with HI has not been examined. This paper aimed to investigate the time-course of phonological processing in individuals with moderate-to-profound postlingually acquired HI compared to a normally hearing reference group under conditions that (1) were to a greater or lesser extent conducive to the engagement of explicit working memory processing of phonology and (2) phonologically demanding to a greater or lesser degree. The ERP components of primary interest were the N2 and the N400. Both are considered markers of violations of phonological/orthographic expectancies at the sublexical and lexical levels, respectively. In addition, a later component, related to continued analysis or reanalysis of stimuli that are challenging to integrate or categorize, the P600, was examined.

Figure 1. (A) Grand average ERP waveforms at electrode Cp6 and (B) mean amplitudes in the right hemisphere elicited by R+O+, R+O-, R-O+ and R-O- target words in the 100-300 ms latency window, long ISI, divided by group. Error bars represent 95% confidence interval.

Method

ERPs were registered during the text-based rhyme judgment task with matching (R+O+, R-O-) or mismatching (R+O-, R-O+) orthography. Mismatching orthography makes the task more phonologically demanding because the visual cues do not aid the rhyme judgment,

which instead has to be made based on phonology alone. The interstimulus interval (ISI) between the words in each rhyme pair was manipulated to be either short (50 ms) or long (800 ms). The long ISIs allows for the engagement of top-down, explicit processes to a larger extent than the short ISIs. Behavioral performance was assessed in terms of percentage of correct judgments. A delayed response paradigm was used to ensure the ERP waveforms were not influenced by neural activity related to response preparation, but this precaution also precluded use of reaction time as a meaningful variable. Only correctly judged trials were analyzed to make sure the analyzed data reflected processes related to the task rather than for example attentional distraction. Mean amplitudes were analyzed separately for each ISI condition in three consecutive time-windows: 100-300, 300-500 and 500-700 ms post onset of the second word in word pairs. The first time-window captured the N2, the second the N400, and the last the P600. Mixed ANOVAs with rhyme (R+, R-), orthography (O+, O-) site (frontal, centroparietal, occipital) and hemisphere (left, right) as within-participants variables and group (HI, NH) as between-participants variable were used. Further, peak latencies were analyzed for the N2 and N400 components in the topographic regions where they were most pronounced using mixed ANOVAs with the factors rhyme, orthography and group.

Results and discussion

The results showed that behavioral performance in the mismatch conditions was lower in the participants with HI than in the participants with NH in short ISIs, but there were no group differences in ERP amplitudes or peak latencies. Thus, when there was minimal time to engage explicit working memory processing of phonology before presentation of the second word, and word phonology was not supported by visual (orthographic) cues, participants with HI made more rhyme judgment errors than did participants with NH. However, when their judgment was correct, their ERPs did not differ from those elicited by the participants with NH during correct judgments. This implies that when their phonological representations were sufficiently specified to detect phonological match/mismatch under these taxing conditions, their processing did not differ from that of the normal hearers.

By contrast, in long ISIs, where time allowed for engagement of explicit working memory processing of phonology between words in rhyme pairs, the participants with HI performed on a par with the participants with NH. In both groups, the benefit of explicit processing, as evidenced by better performance, was largest for R-O+ judgments. Further, in participants with HI only, ERPs differed between rhyme task conditions in long ISIs, showing an amplified N2-like negativity in the R-O+ condition. The N400 and later ERP waveforms were however not sensitive to hearing status, indicating that processing at the subsequent, whole-word level, was not affected by HI. The enhanced N2-like negativity was elicited only when there was time to recruit explicit processes and R-O+ performance of the participants with HI was on a par with that of the normally hearing participants. This suggests it was related to top-down processing that helped to compensate for difficulties making the non-rhyme judgment. For example, increased elaboration, phonological and/or orthographic, of the first word in a pair, enriching the representation held in working memory, and the generation of expectancy sets allowed by the longer ISIs, are mechanisms likely to facilitate

early detection of phonological mismatch at presentation of the second word, and hence trigger allocation of resources as indicated by the enhanced N2-like response.

These findings thus indicate that explicit working memory processing of phonology and/or orthography can be employed to support performance in a text-based phonologically challenging task in participants with HI. They also show that HI had an effect at the sublexical level but not at the whole word, lexical level.

- The novel findings in this paper are (1) the identification of an ERP marker of phonological processing in individuals with postlingually acquired HI and (2) the discovery that in this group, explicit resources can help compensate for poorer phonology in text-based phonological tasks.

Paper II

Purpose

The ELU model (Rönnberg, 2003; Rönnberg et al., 2013) assumes that WMC may help to compensate for poorly specified phonological representations, whether they are derived from spoken, signed or textual tokens (cf. RAMBPHO). While low-specificity representations will lead to an increased occurrence of mismatch in phonological tasks, and thus lower performance, access to WMC resources is proposed to mitigate this effect because WMC can be engaged to resolve mismatch. The purpose of this paper was to test that prediction by exploring if individual WMC modulated performance in a text-based rhyme judgment task in individuals with acquired severe-to-profound HI. In addition, because increased occurrence of mismatch is assumed to occupy more processing resources and thereby interfere with episodic memory encoding, a delayed incidental episodic recognition memory task, using words from the rhyme judgment test, was used. This allowed for an examination of whether hearing-related mismatch affected episodic memory encoding, and if any effect on memory encoding interacted with WMC.

Method

A median split of RST scores was used to divide the participants into 4 subgroups: normally hearing participants with high ($n = 8$) or low ($n = 9$) WMC and participants with HI and high ($n = 8$) or low ($n = 9$) WMC. Interactions between hearing status and WMC were examined using ANCOVAs with performance in the text-based visual rhyme judgment task and the incidental episodic recognition memory task as dependent variables.

Results and discussion

Participants with HI made significantly fewer correct rhyme judgments than participants with NH in the mismatching rhyme task conditions (R+O-, R-O+). WMC did not impact upon rhyme performance in participants with NH but in participants with HI, individuals with high WMC performed significantly better than those with low WMC in the R-O+ condition. In the episodic recognition task, high WMC was associated with better recognition in the participants with NH. In the participants with HI, WMC influenced recognition of words from the R-O+ condition: individuals with high WMC recognized significantly fewer R-O+

words than did individuals with low WMC. WMC thus modulated both rhyme judgment performance and episodic recognition memory in the R-O+ condition in participants with HI; those with high WMC performed exceptionally well in the judgment task, but later recognized few of the words. In contrast, those with low WMC showed a reversal of this pattern and performed poorly in the judgment task but later recognized a surprisingly large proportion of the words.

Figure 2. Mean percent correct rhyme judgments (chart to the left) and mean proportion correctly recognized words from correctly judged rhyme task word pairs (chart to the right) as a function of hearing status, WMC and condition after controlling for age. Error bars represent 95% confidence intervals.

The R-O+ rhyme condition puts relatively higher demands on the ability to perform phonological operations and analyses in working memory than the other rhyme conditions (Andersson, 2002; Johnston & McDermott, 1986; Rugg & Barrett, 1987). The possibility to compensate for underspecified phonological representations by recruitment of working memory resources for elaborate sublexical phonological processing is therefore likely to be larger in this condition. Such elaborate processing will however occupy WMC resources and leave fewer available for storage processes, in line with the good R-O+ rhyme performance and low recognition rate of the high WMC participants with HI. With lower WMC, the option to engage working memory processing to compensate for phonological decline is likely to be relatively reduced as fewer resources are available for careful phonological analyses. Resorting to a whole word, lexico-semantic based route to word phonology may then be an alternative way to compensate for degraded representations (Lazard et al., 2010; Lazard et al., 2012). Such a strategy is likely to interfere with rhyme judgment but enhance recall via increased attendance to semantic rather than phonological features (Craig & Tulving, 1975; Morris, Bransford, & Franks, 1977; Unsworth, Brewer, & Spillers, 2011).

Supporting the ELU prediction, these results indicate that good WMC can compensate for the negative impact of auditory deprivation on phonological processing abilities by allowing for the efficient use of phonological processing skills. They also suggest that individuals with HI

and low WMC may use a more semantic strategy in phonological tasks, which can have the beneficial side effect of improving memory encoding.

- The novel findings in this paper are (1) that phonological processing abilities are related to WMC in individuals with acquired long-term severe HI and (2) that working memory dependent strategy-use in the rhyme task is evidenced by differences in episodic recognition memory performance.

Paper III

Purpose

There is little knowledge about output phonology and word generation in individuals with postlingually acquired HI. The purpose of this paper was to examine if HI affected output phonology as indexed by phonologically mediated lexical access, retrieval and generation in the letter fluency task. By breaking down letter fluency performance into the strategy measures of clustering and switching (Troyer et al., 1997), the balance between retrieval of words from within phonologically related clusters and switching to new phonological retrieval cues could also be examined. WMC has been implicated in fluency performance (Azuma, 2004; Rende et al., 2002; Rosen & Engle, 1997; Unsworth, Spillers, et al., 2011). A second purpose was to explore whether individual WMC could serve as a compensatory function for phonological decline by supporting overall performance and/or strategy use in the participants with HI.

Method

Participants with NH and participants with postlingually acquired moderate-to-profound HI performed two verbal fluency tasks, letter fluency (letters F, A) and category fluency (animals). The latter requires a predominantly semantic search strategy and the former a more phonologically based search. Four dependent measures were computed in each task: number of words generated, number of clusters, number of switches and mean cluster size. Measures of hearing acuity, WMC, receptive vocabulary and phonological skills (as assessed by a text-based pseudohomophone detection task and rhyme judgment performance) were also analyzed and related to letter fluency performance in regression analyses.

Results and discussion

There was no significant difference between the groups in category fluency performance in either of the measures. In letter fluency, however, the participants with HI produced significantly fewer words than the participants with NH and their production was characterized by fewer switches. There was however no difference between groups in number or size of clusters. Regression analyses showed that hearing acuity and a measure of phonological skills (text-based pseudohomophone detection) directly predicted letter fluency performance in participants with HI, while no predictors reached significance in the group with NH. Pseudohomophone detection was also the only variable that predicted letter fluency switching. This was the case in both groups, showing the importance of phonological abilities to switching in this task. There was a unique contribution of WMC to strategy use in the

participants with HI only; better WMC predicted making more switches and smaller clusters in this group.

Figure 3. Mean number of words generated in the letter fluency and category fluency tasks (chart to the left) and mean performance in the strategy measures (chart to the right), divided by group. Error bars represent 95% CI intervals.

The specific effect of HI in phonologically, but not semantically mediated lexical access and retrieval is in line with previous research showing intact semantic processing in individuals with HI (Andersson, 2002; Andersson & Lyxell, 1998; Lyxell et al., 2003). The equivalence between groups in number and size of clusters indicate that the relatively automatic retrieval of phonologically related items from semantic long-term memory required for clustering also remains intact. HI was specifically related to impaired retrieval and generation of phonologically unrelated words (that is, words sharing more phonological similarity than beginning with the same initial phoneme). This suggests difficulties in generating new phonologically based retrieval cues and a reluctance to venture outside clusters. Switching was supported by phonological skills irrespective of hearing status and in the participants with HI, WMC also supported switching. Generation of phonological codes and matching them to long-term memory representations is thus likely to be more working memory demanding in this group. Less well specified phonological representations can be expected to influence many facets of processing and maintenance of phonological information in letter fluency, that is, the facility with which specific, but similar (e.g. [fa], [fo]) phonological codes are generated, identified as separate, matched to long-term memory representations and identified as real words, while concurrently maintaining and keeping track of previously reported, also phonologically similar, words, in order to avoid repeating items.

- The novel findings in this paper are (1) that postlingually acquired, moderate-to-profound HI is associated with reduced letter fluency performance, and (2) that WMC supports the efficient strategy of switching in this group.

Paper IV

Purpose

The purpose of this paper was to examine RST performance in a larger population of individuals with HI. The primary aim was to provide reference data for the long (LongRST) and short (ShortRST) version of the test, and for two age groups in the LongRST (Rönnberg et al., 1989). The RST is a test frequently used in cognitive hearing science research that has proven to be a good predictor of speech recognition in noise in adverse conditions in several experimental studies (see reviews by Akeroyd, 2008; Besser et al., 2013). A second aim was to examine the relation between the RST and speech recognition in noise in this large sample of individuals, representative of patients seeking rehabilitation at Swedish audiological clinics. The RST is theoretically anchored to the ELU model (Rönnberg, 2003; Rönnberg et al., 2013) and is a candidate for inclusion in clinical assessment as a measure of cognitive capacity.

Method

Data from 339 participants, tested in 9 different ongoing and finished projects, were collated and re-analyzed. Participants were selected from a larger database based on the inclusion criteria that they had performed either version of RST, were 50-89 years old and had a HI as defined by a BestEarPTA > 25 dB HL. In addition, all had performed the Hagerman sentences test (Hagerman, 1982), a test of speech recognition in noise frequently used in Swedish audiology clinics. Scores in lexical matching, a test assessing speed of lexical access, were available for a subset of the participants. The resulting dataset allowed for an examination of RST performance and the relation between RST performance and speech recognition in noise in (1) participants who had performed ShortRST who were all 50-69 years old, (2) 50-69 year olds who had performed LongRST, and (3) 70-89 year olds who had performed LongRST. RST performance and the frequency distributions of scores and their corresponding percentiles were examined in the three groups. An analysis of predictors of LongRST performance was conducted, performances in ShortRST and LongRST were compared and, finally, LongRST performance was examined across age groups.

Results and discussion

Results showed that age, but not sex, was related to RST performance, with lower scores in older participants. BestEarPTA accounted for a small but significant amount of the variance in RST performance, such that better hearing was related to higher scores. Both the means and frequency distributions of scores were equivalent across the two RST versions, and performance in both versions was significantly correlated with speech recognition in noise. The older participants performed worse than the younger participants in both RST and speech recognition in noise. Further, although RST performance was related to speech recognition in noise in both age groups as indicated by the correlation analyses, the effect size was small in the 70-89 year olds. In the 50-69 year old participants, the corresponding effect size was moderate-to-large. Regression analyses showed that in the 50-69 year olds, RST explained 10% of the variance in speech recognition in noise after accounting for the effect of age, BestEarPTA and variance due to participation in different projects. By contrast, in the 70-89 year olds, RST did not reach significance as a predictor of speech recognition in noise. It

might have been expected that the older group would have needed a larger recruitment of cognitive resources for speech recognition in noise. However, the older group also had fewer WMC resources to engage in the speech task. Possibly, age-related cognitive decline may impede recruitment of WMC to compensate for speech recognition in noise difficulties.

- The novel finding in this paper is the indication of an age-related difference in the recruitment of WMC in speech recognition in noise in individuals with HI. Further, this is the first paper that examines RST performance in a larger sample of adults with HI and offers reference data on performance in different age groups and two versions of the test.

Methodological considerations

The present work is based on a quasi-experimental design and quantitative analyses of data collected in a laboratory setting. While the control allowed by a laboratory setting may be required for the focused study of specific variables, the ecological validity of the collected data may be restricted (Clark-Carter, 1997). For example, speech recognition in noise in natural settings may be better, or worse, than indicated by the audiological testing. The low-redundancy speech material of the Hagerman sentences (Hagerman, 1982) test leaves little room for guessing or making inferences based on the semantic context while everyday conversational situations often allow for the use of contextual cues to support recognition. Speech recognition in noise has been shown to differ less between listeners with NH and HI when they are tested with sentences that are semantically and syntactically rich than when low-redundancy material is used (Wilson, McArdle, & Smith, 2007). Supportive context is particularly beneficial to older listeners (Pichora-Fuller, 2008; Tye-Murray et al., 2008). There are also studies showing that WMC is less predictive of speech in noise recognition when sentence material with high semantic redundancy is used (Rudner, Foo, Rönnberg, et al., 2009; Rudner et al., 2011), indicating that the availability of contextual cues reduces mismatch. While conversational content might facilitate speech recognition in everyday life as compared to during audiological testing, acoustic factors such as reverberation (Nabelek, 1988) may in contrast make it more challenging.

In studies comparing individuals with HI and NH, quasi-experimental designs can hardly be avoided. Therefore, there may be differences between the groups in other than the independent variable which may have an impact on the dependent variable/s (Clark-Carter, 1997). For example, HI has been found to have a negative effect on educational outcome and unemployment is more common in individuals with HI than NH (Järvelin, Mäki-Torkko, Sorri, & Rantakallio, 1997). Careful assessment of the factors known to influence performance on the tests used in a study is one way to handle this issue, hence the collection of data concerning for example verbal and non-verbal abilities in the present work (papers I-III). However, use of a structured interview or self-report questionnaire would have added information, for example, as to whether the perceived impact of HI in daily life is related to cognitive function (Ng, Rudner, Lunner, & Rönnberg, 2013). This question has so far received relatively little attention but is motivated in view of the connection between speech recognition in adverse conditions, cognitive capacity and listening effort (Desjardins &

Doherty, 2013; Rudner et al., 2012). Effort in hearing has in turn been identified as a risk factor for stress-related sick-leave in individuals with HI (Kramer et al., 2006). Self-report questionnaires such as the International Outcome Inventory-Hearing Aids (IOI-HA; Cox & Alexander, 2002) or the Speech, Spatial and Quality of Hearing Scale (SSQ; Gatehouse & Noble, 2004) may be used to assess factors such as benefit of hearing aids and hearing-related disability across different situations. Linking research results more closely to the everyday life experiences of the participants would both increase the relevance of the results to individuals with HI themselves and extend the knowledge about how hearing and cognition interact.

General discussion and future directions

Main findings and conclusions

The main finding of the present thesis was that explicit working memory processing of phonology and WMC support performance on phonologically demanding tasks in individuals with HI (paper I-II). While the data indicate a direct link between working memory and input phonology (text-based rhyme judgments, paper II), the impact of WMC in output phonology (letter fluency, paper III) was indirect. In papers I-II, the opportunity to engage explicit processing of phonology (long ISIs, paper I) and high WMC (paper II) were related to better rhyme judgment performance in the participants with HI and hence helped to compensate for phonological decline. An ERP marker of this hearing-related top-down compensation for phonological difficulties in rhyme judgments was also found (paper I). Paper II further showed that in the participants with HI only, differences in WMC were related to use of different strategies in the rhyme judgment task and that these strategies in turn had differential effects on episodic memory encoding. In paper III, participants with HI were found to perform below participants with NH in the letter fluency task. Thus, moderate-to-severe HI may also affect output lexical access and retrieval. WMC was a significant predictor of letter fluency switching in participants with HI only, and in this group, the number of switches was highly related to the number of words generated. In speech recognition in noise, explicit resources are known to play an important role in overcoming hearing-related mismatch. This was replicated in paper IV and extended to include situations with optimal, that is, visual, linguistic input (papers I-II). However, the results of paper IV also indicate that there may be age-related differences in the ability to recruit cognitive resources to aid speech communication. RST performance in the original and a shortened version of the test was examined and found to be equivalent in terms of mean performance and frequency distributions (paper IV). Further, performance in both versions of the test was significantly correlated with speech recognition in noise. The short version may therefore be a suitable test for clinical assessment of WMC. Reference data for both versions of the test, and for two age groups in the original version, were also provided (paper IV).

Phonological processing and hearing impairment

Previous findings showing impaired phonological awareness in adults with postlingually acquired HI in the severe-to-profound ranges (Andersson, 2002; Andersson & Lyxell, 1998, 1999) were replicated here. Hearing-related declines were found in the mismatching rhyme

judgment conditions (papers I-II) but also in letter fluency (paper III). These tasks require sublexical segmentation under conditions with conflicting (rhyme judgment) or no (letter fluency) visual support. Phonological awareness, as measured by the rhyme judgment task, accounted for a significant amount of variance in speech recognition in noise in the participants with HI (paper III), which is in line with the findings reported by Lunner (2003). Finally, performance on tasks in which there is less need to rely exclusively on phonological processing, such as RST and category fluency, was not depressed by HI in the present or earlier studies (Andersson, 2002; Andersson & Lyxell, 1998, 1999; Lyxell et al., 1998). With the ongoing technical development of hearing aids it will be interesting to see whether phonological representations will be less affected by severe HI in the future (cf. Lunner, Rudner, & Rönnerberg, 2009).

Rhyme judgment – the input side

This thesis found a differential involvement of explicit processing in rhyme judgments in participants with HI when compared to participants with NH. To recapitulate, participants with HI showed an N2-like sensitivity in the R-O+ when compared to the R-O- rhyme condition and better behavioral R-O+ performance when the longer ISIs allowed for explicit processing to be engaged. Behaviorally, participants with NH also benefitted from the longer ISIs in R-O+ judgments, but there was no effect on ERPs in the N2 time window (paper I). Further, paper II showed that verbal WMC had a significant impact on R-O+ performance in participants with HI, but not in the group with NH. In addition, WMC impacted upon subsequent recognition of the R-O+ rhyme task words in the group with HI.

Rhyme judgment and explicit processing

As noted in the *Background*, R-O+ words do not rhyme and hence, phonological priming will impede rather than facilitate the rhyme judgment. Predictions need to be abandoned and rapid access made to the phonology of the second word in the pair while maintaining the representation of the first word in working memory (Johnston & McDermott, 1986). Due to the regular spelling of many of the R-O+ words, participants could also use spelling-to-sound conversion strategies if the rhyme status decision was difficult. Further, if the participants with HI relied more on visual cues (Champoux et al., 2009; Park et al., 2013; Rouger et al., 2007) they would be more vulnerable to orthographic interference in both mismatching conditions (cf. Mishra et al., 2013), but particularly in R-O+, where there is no facilitating effect of phonological priming. Indeed, phonological priming at the lexical level, as measured by N400 amplitude, did not differ between participants with HI and NH (paper I). These characteristics of the R-O+ word pairs help to explain why there were effects of both opportunity to engage explicit top-down processing (paper I) and individual differences in WMC (paper II) in this condition. Indeed, the benefit of a longer ISI was largest for R-O+ word pairs in both participants with HI and those with NH. That is, irrespective of HI, the engagement of top-down processing is particularly helpful in R-O+ judgments.

Because the word-final spellings in the R-O+ word pairs were similar, but not identical, it could be argued that participants used an orthographic strategy. That is, that rhyme decisions were made by comparing the word-final spellings in the R-O+ condition. However, task

demands, explicit instructions to base judgments on word phonology, consecutive (as opposed to simultaneous) presentation of words in the pairs, and randomized presentations of word pairs from the four conditions, worked to minimize reliance on a proactive orthographic strategy. That is, as R-O+ word pairs were randomly mixed with pairs from the other conditions and words in each pair were presented consecutively, participants could never, on seeing the first word, predict whether an orthographic strategy would be successful or not. Therefore, phonological decoding of the first word in all pairs was necessary in order to make correct judgments, hence all judgment conditions involved phonological processing.

The results of paper I showed that ERPs were sensitive to early, sublexical-level processing in participants with HI only, with an enhanced N2-like negativity in the R-O+, when compared to the R-O- condition with long ISIs. As behavioral performance in this condition was also better in the long ISIs this implies that with more time, participants with HI were better able to detect the mismatch and allocate resources to resolve it. That such an early sublexical effect was evident in long, but not short, ISIs indicates that it was contingent upon the deeper processing of the first word in the pairs, perhaps including spelling-to-sound conversion strategies, allowed by the longer time-interval between presentations of the words. In turn, this facilitated early detection of phonological mismatch at presentation of the second word.

The overall pattern of the ERP results (paper I) shows that there are more similarities than differences between participants with HI and NH in terms of the neural processing of correct rhyme judgments. Interestingly, a recent publication examined phonological processing using behavioral and ERP measures of text-based rhyme judgments in prelingually deafened adults who were native sign language users (MacSweeney et al., 2013). MacSweeney et al. (2013) found similar N400 (referred to as N450) distribution, amplitude modulation and onset latencies in the deaf and the normally hearing participants, when only individuals who had performed above chance level behaviorally ($n = 9$) were included. This was in spite of a significantly lower performance when measured by rhyme judgment accuracy in the deaf participants. The authors suggested that oral language rhyme sensitivity, presumably developed via speechreading and articulatory information in the deaf participants, is supported by the same neural systems in both deaf and hearing individuals. Results from fMRI studies using pictures (MacSweeney, Brammer, Waters, & Goswami, 2009) or written words (Aparicio, Gounot, Demont, & Metz-Lutz, 2007) as stimuli also suggest that similar neuronal networks are engaged in rhyme judgment processing in deaf as in normally hearing individuals. Deaf participants however show larger activations in the left IFG, suggesting enhanced use of articulatory recoding and spelling-to-sound conversion strategies (Aparicio et al., 2007; MacSweeney et al., 2009). The present results show that the R-O+ condition may be important to include when examining rhyme judgments in individuals with HI. The study by MacSweeney et al. (2013) described above did not use this condition but it would be interesting to investigate if an N2-like response would also be elicited in deaf participants.

Rhyme judgment and working memory capacity

Paper II showed that when individual differences in WMC were not considered, HI was associated with significantly lower rhyme judgment performance when compared to scores obtained by participants with NH in the mismatching conditions, that is, the conditions in which there was a need to rely heavily on phonological representations without support from visual cues. However, when individual differences in WMC were used to divide participants into high and low WMC subgroups, results showed that participants with HI and high WMC performed even better than participants with NH and high WMC in R-O+ rhyme judgments. In contrast, participants with HI and low WMC performed worse than participants with NH and low WMC in this condition. These results were found even though there were no differences between the high and low WMC participants with HI in either BestEarPTA or hearing loss duration, and there were no differences between participants with HI and NH in either the high or the low WMC subgroups in non-verbal reasoning ability, receptive vocabulary, WMC or phonological short-term memory. Paper II thus clearly indicates that WMC can modulate performance in phonologically challenging tasks in individuals with HI. This result confirmed the prediction made by the ELU model (Rönnberg, 2003; Rönnberg et al., 2013) that participants with HI and high WMC can compensate for poor phonological representations in semantic long-term memory.

The fact that WMC did not impact R+O- rhyme judgments in the participants with HI, that is, the condition which is likely to more directly tap into the quality of phonological representations (Andersson, 2002), indicates that high WMC does not prevent degradation of semantic long-term memory knowledge representations, *per se*. Rather, WMC can be employed to compensate for degraded phonological representations when the task is such that explicit processing of phonology can support performance.

That participants with high WMC and HI performed exceptionally well in R-O+ rhyme judgments but later recognized few of the words was interpreted in terms of successful engagement of strategies such as repeated double-checking of spelling and sound and articulatory recoding in the judgment task. Strategies like these will enhance rhyme judgment performance, but occupy working memory resources that could otherwise be employed for memory encoding. They will also retain word processing at a relatively shallow, predominantly phonological/orthographic level which is associated with less durable memory encoding than semantic word processing (Craig, 2002; Craig & Tulving, 1975; Unsworth, Brewer, et al., 2011). The low rhyme judgment but high recognition performance of the participants with low WMC and HI instead point to a more semantic, whole-word based route to word phonology. Several studies have shown that the extra processing required by a listener with HI to correctly perceive spoken words disrupts memory encoding (McCoy et al., 2005; Piquado, Cousins, Wingfield, & Miller, 2010; Surprenant, 2007; Tun et al., 2009). Paper II shows that hearing-related processing load may interfere with long-term episodic memory encoding also in visually presented phonologically challenging tasks.

Taken together these results imply that individual differences in WMC are associated with different ways to compensate for phonological decline in individuals with HI that have

different effects on episodic memory encoding. While low WMC may be associated with a more semantic approach irrespective of task demands, high WMC may allow for a more flexible adoption of diverse strategies depending on task demands (Rönnberg et al., 2013). Future studies may explore whether this is so by manipulating processing level at both encoding and recall. For example, Unsworth et al. (2011) used cue-target word pairs in which the cue words either rhymed with or were semantically related to the target word. The task in the encoding phase was to make phonological and semantic relatedness judgments. In the recall phase, the cue words were presented together with a statement indicating that the to-be-recalled target rhymed or was semantically related to the cue (for example “Rhymes with *dog*” or “Associated with *dog*”). Results showed that high WMC participants had better recall than low WMC participants when encoding and cued recall were both at the same processing level, but performed as poorly as the low WMC participants when they mismatched (that is, cues words presented in rhyme judgment trials at encoding but with a semantic recall cue, and vice versa) (Unsworth, Brewer, et al., 2011). If participants with severe HI and low WMC predominantly process words at a semantic rather than a phonological level irrespective of task, but participants with HI and high WMC efficiently switch between phonological and semantic processing depending on task demands, then low WMC participants should outperform the high WMC participants at both mismatching recall conditions following the logic presented in the previous paragraph.

One of the research questions posed in this thesis was whether rhyme judgment performance would differ as a function of the degree to which explicit working memory processing of phonology could be engaged (short and long ISIs). As the number of mismatching word pairs was necessarily limited, the participants were presented with them twice, once in each ISI condition. Therefore, ERPs at the encoding phase could not be directly linked to ERPs at the recognition phase and hence, ERPs were not recorded during the recognition task. Future studies should register ERPs during both the rhyme judgment and the recognition tasks in high and low WMC participants with HI and NH. This design would allow for the examination of neural processes at the encoding phase that are predictive of subsequent recognition versus forgetting, as well as for examination of the neural signatures of recognized versus forgotten words at recognition. There are studies indicating that ERPs may be sensitive to level of processing (deep versus shallow) at encoding (Donaldson & Rugg, 1998; Guo, Zhu, Ding, Fan, & Paller, 2004; Marzi & Viggiano, 2010) and ERP markers have been identified for encoding processes predicting recognition as well as for successful recognition versus forgetting (Rugg & Curran, 2007; Voss & Paller, 2009). The investigation of ERPs could be complemented by time-frequency analyses, exploring for example the high-frequency gamma-activity that has been linked to working memory processing (Fell & Axmacher, 2011) and has been found to predict subsequent recognition (Gruber, Tsivilis, Montaldi, & Muller, 2004). It may be that larger processing load in the participants with HI during rhyme judgments is reflected by increased gamma activity when compared to the normally hearing individuals.

Letter fluency – the output side

Rhyme judgment concerns receptive, or input, phonology, and letter fluency involves expressive, or output, phonology. While it is unclear whether input and output phonology are served by the same or different networks, there is at least a close link between phonological processing for perception and production (Hickok, 2009; Jacquemot et al., 2007; Martin & Saffran, 2002). This suggests that any degradation of phonological representations due to impoverished auditory input may also affect output phonology (Martin & Saffran, 2002). Surprisingly few studies have examined output phonology in adults with acquired HI. The study by Lin et al. (2011) is one exception, but they found no association between hearing loss and letter fluency in their 347 participants. However, only 40 of the participants had a hearing loss exceeding 40 dB HL, and as few as 3 had 70 dB HL hearing loss or worse. In the present thesis, the independent variable (HI) was optimized for the detection of phonological difficulties and results of paper III showed that letter fluency, but not category fluency, was impaired in individuals with moderate-to-profound HI. Indeed, after accounting for the effect of age and education level, BestEarPTA remained a significant predictor of letter fluency performance in the group with HI and, together with an index of phonological skills, accounted for an additional 21% of letter fluency variance. Letter fluency involves generation of similar-sounding phonological codes and matching of these codes to long-term memory representations in search for lexical matches, while concurrently keeping track of previously reported, also phonologically similar, words. With poorly specified phonological representations this will be a challenging task (Snowling et al., 1997).

The participants with HI made significantly fewer switches than the participants with NH. The same result has been found in children with CIs (Löfkvist et al., 2012). Fewer switches indicate difficulties in generating phonologically based retrieval cues, and in the participants with HI only, WMC accounted for significant variance in switching over and above the effect of age and education level. Further, switching was highly correlated with total output in the group with HI. Thus, WMC indirectly supported letter fluency in participants with HI while phonological skills and hearing acuity were direct predictors.

That moderate-to-severe HI negatively impacts phonologically mediated lexical access and retrieval in word production suggest HI may affect verbal communication on the production side by mechanisms other than reduced distinctness of pronunciation (Waldstein, 1990). Indeed, word finding difficulties have been found in children with milder HI (Borg, Edquist, Reinholdson, Risberg, & McAllister, 2007) and a relation between phonological processing difficulties and word finding problems, as evidenced by an increased rate of tip-of-the-tongue states, has been demonstrated in children and adolescents with dyslexia (Faust et al., 2003; Faust & Sharfstein-Friedman, 2003; Hanly & Vandenberg, 2010). Tip-of-the-tongue states are typically marked by access to the semantic features of a word and parts of its phonology, but a temporary inability to access complete word phonology (Levelt, 2001; Levelt, Roelofs, & Meyer, 1999) and tend to become more common with increasing age (Brown, 1991; Burke & Shafto, 2004; James & Burke, 2000). These retrieval failures have been suggested to arise from incomplete activation of phonological representations due to weakened connections between phonological nodes in semantic long-term memory (Burke, Mackay, Worthley, &

Wade, 1991). In future studies, it would be interesting to investigate whether hearing loss is associated with more tip-of-the-tongue-states in older individuals.

An interesting effect found in the letter fluency task, but not reported in the manuscript, was that the words generated by the participants with HI in the F-task, but not in the A-task, were words more common in the language than those generated by the normally hearing participants. These analyses were conducted because common words are generally more accessible phonologically than infrequent words (Garlock et al., 2001; Luce & Pisoni, 1998). Phonologically mediated retrieval difficulties may thus be manifested in the generation of more common words. In spoken Swedish, the phoneme [a:] consists mainly of sound information at frequencies around 1000 Hz, while the phoneme [e:] consists of frequencies around 4000 Hz. Hearing loss in the group with HI was significantly larger at 4000 Hz than at 1000 Hz ($M_{1000} = 72$ dB HL, $M_{4000} = 88$ dB HL). The participants with HI thus generated words that are more frequently used in the language, and thereby more phonologically accessible, specifically when the task required them to search for, and access, words beginning with a phoneme whose frequency information in spoken language lies in the range where their hearing loss was more severe. The difference in hearing between the two frequencies was relatively small, and the mean hearing loss was severe in both (cf. Dunn & White, 1940). However, speculatively, verbal retrieval and generation in individuals with HI may be more disrupted for words beginning with phonemes containing sound frequency information corresponding to the frequency range where hearing is most impaired (cf. Stenfelt & Rönnberg, 2009). Another suggestion for future research is to examine this hypothesis. For example, in a very simple exploratory study, individuals NH and severe HI specifically in the high frequency ranges (e.g. 4000 Hz), but preserved auditory function in lower frequencies (e.g. 500-1000 Hz), could be given the letter fluency test with the low frequency letter cues B and R and the high frequency letter cues F and S.

The RST, speech recognition in noise and aging

The RST (Rönnberg et al., 1989) has been used since 1989 to examine the relation between speech recognition in noise and WMC in both Swedish (e.g. Foo, Rudner, Rönnberg, & Lunner, 2007; Hällgren, Larsby, Lyxell, & Arlinger, 2001; Lunner, 2003; Rudner, Foo, Rönnberg, et al., 2009; Rudner et al., 2008) and other languages (Arehart et al., 2013; Besser, Zekveld, Kramer, Rönnberg, & Festen, 2012; Desjardins & Doherty, 2013; Rudner et al., 2008). Paper IV provides reference data for Swedish RST performance in the original and a shortened version of the test. The results showed that the two versions were comparable in terms of mean performances and frequency distributions of scores in two larger samples of 50-69 year olds with HI. Further, performance in both test versions was significantly correlated with speech recognition in noise. Thus, the shortened version can be used instead of the longer version. In addition, mean performances were found to be equivalent in the English translation and the Swedish original, indicating that performance is not sensitive to language when Swedish and English are compared.

RST performance across two age groups of individuals with HI was also examined. The decline in working memory capacity often found in aging was indicated by the lower RST

performance in 70-89 year old when compared to 50-69 year old participants. A perhaps less expected finding was that WMC was a significant predictor of speech recognition in noise only in the 50-69 year olds. This result was not related to group differences in mean BestEarPTA. The older participants could have been assumed to need larger recruitment of cognitive resources for speech recognition in noise than the younger group (Davis et al., 2008; Pichora-Fuller et al., 1995; Wong et al., 2010; Wong et al., 2009). At the level of zero-order correlations better WMC was significantly related to better speech recognition in noise in the older participants, showing that cognitive resources were also implicated in task performance in the 70-89 year olds.

There has been much interest in the recruitment of cognitive resources and the relation between brain activation and behavioral performance in older adults over the last decade. The relation is complex because over-recruitment in older adults may lead to better, equivalent or worse performance when compared to younger adults (Grady, 2012). According to the compensation-related utilization of neural circuits hypothesis (CRUNCH; Grady, 2012; Reuter-Lorenz & Cappell, 2008) of aging, older adults need to recruit more neural resources even at levels of relatively low cognitive load, that is, lower task demands, than younger adults need to. When task demands increase, older adults may therefore not have any additional resources available to engage in the task. In other words, cognitive recruitment may plateau earlier in older, when compared to younger adults (Reuter-Lorenz & Cappell, 2008). Such an effect would help to explain the fact that WMC did not reach significance as a predictor of speech recognition in noise in the older participants.

A second interesting finding in paper IV was the relation between BestEarPTA and WMC as measured by RST. In the *Background* it is noted that epidemiological studies have shown an increased risk of cognitive impairment in individuals with hearing loss and that rate of cognitive decline as well as risk of cognitive impairment are associated with severity of hearing loss (Lin et al., 2013). The negative effect of HI on executive functions in aging (Lin, Ferrucci, et al., 2011; Lin et al., 2013) may well have an impact on RST performance. Alternatively, individual difference in attentional capacity may influence performance in both RST and pure tone audiometry (Näätänen, Paavilainen, Titinen, Jiang, & Alho, 1993).

Hearing impairment and compensation

This thesis has touched upon several mechanisms that may act to compensate for HI in language processing, including reliance on visual cues and addressed rather than assembled phonology, use of context, and individual differences in WMC. These may support language understanding, but also have costs in specific situations. For example, cross-modal reorganization may be detrimental to speech recognition following cochlear implantation (Buckley & Tobey, 2011; Doucet, Bergeron, Lassonde, Ferron, & Lepore, 2006; Giraud & Lee, 2007; Lee et al., 2001) and lead to greater interference from unrelated visual information during speech recognition (Champoux et al., 2009). In executively demanding tasks, audiovisual presentation may lead to worse performance than auditory only presentation also in individuals with NH, indicating that audiovisual integration may under some circumstances be associated with increased processing load (Mishra et al., 2013). However,

attending to visual information may also be compensatory and lead to better performance. For example, better lip-reading skills before cochlear implantation has been associated with better postoperative speech recognition at a 6 month follow-up appointment (Heydebrand, Hale, Potts, Gotter, & Skinner, 2007; Rouger et al., 2007) and lip reading proficiency has been shown to continue to support speech recognition after implantation (Rouger et al., 2007). Children and adults with HI may compensate for weak phonological awareness by relying on a more whole word, semantic, strategy in reading (Lazard et al., 2010; Lazard et al., 2012; Park et al., 2013).

As shown by papers I-II, WMC and explicit working memory processing of phonology also help to compensate for phonological decline and may represent a variable that influences which reading strategies, that is, working memory demanding phonological, or less working memory demanding lexico-semantic, will be developed in response to perceptual decline. Similarly, in letter fluency, lower WMC was associated with making fewer switches, which in turn was associated with generation of fewer words. For individuals whose phonology is not so versatile, such strategies are likely to be less cognitively taxing. Working memory has also been implicated in CI outcome. For example, in congenitally deaf children, increased preoperative resting metabolism in Broca's area, the left dorsolateral prefrontal cortex and the angular gyrus, areas implicated in working memory and executive functions, have been associated with better speech perception following cochlear implantation (Giraud & Lee, 2007) as has working memory when measured by digit span, verbal rehearsal speed (Geers & Sedey, 2010) or letter span (Heydebrand et al., 2007). Taken together, different compensatory strategies may thus have different consequences for episodic memory encoding as in paper II or for word generation and retrieval as in paper III as well as for benefit from CIs (Lazard et al., 2010). Perhaps the increased processing load in phonologically challenging tasks by high WMC individuals with HI is one out of several mechanisms by which HI can have a negative effect on episodic memory (Rönneberg et al., 2011). Speech recognition in everyday life is phonologically taxing when lexical access need to be achieved based on a fragmented or distorted speech signal. Perhaps, counterintuitively, an individual with high WMC and a listening strategy focused on maximum speech recognition may expend more effort and encode less of the speech content into episodic memory than an individual with relatively lower WMC who rather settles for catching the gist of a conversation. For example, a recent study (Ng et al., 2013) found that participants with HI who performed better in a rhyme judgment test, and better in a test assessing delayed recall of spoken words heard in noise, indicating more remaining cognitive resources after identification of degraded speech (Mishra et al., 2013), reported greater remaining difficulties with their hearing aids in the real life situation in which they most wanted to hear better. The authors suggested this result may reflect a larger engagement of explicit processing, and thus a larger effort, in adverse listening situations in individuals with better working memory (Ng et al., 2013).

Lövdén et al. (2010) propose a framework for cognitive plasticity in adults. They focus on the relationship between individuals' functional capacity in terms of knowledge representations and processing efficiency on the one hand (for example WMC and hearing acuity) and experienced environmental demands (for example training) on the other. Lövdén et al. (2010)

propose that mismatches between individual functional capacity and experienced demands occur either when demands exceed capacity (negative mismatch) or when capacity exceeds demands (positive mismatch). A stable functional capacity is an indicator of a state of dynamic equilibrium between capacity and demands. If encountered with prolonged periods of negative mismatch, whether due to reduced capacity as in age-related cognitive decline, or to increased demands, structural changes at the neural level are triggered. These changes may take the form of plastic reorganization or recruitment of alternative/complementary brain networks. The result is a change in capacity which will progress until a new state of dynamic equilibrium is reached. The process is initiated only in response to situations where the demands are at near-ceiling level of the capacity and there is a potential for plasticity to occur. That is, if the demands are too high, too low, or the potential for plastic change is limited by for example traumatic brain damage or neurodegenerative processes, there is no impetus or no possibility for the system to respond. Changes in capacity, either in the form of restoration of lost function following injury, or of learning-induced increases following growing demands, is thus seen as a function of individual differences in capacity, experienced demands and potential for plasticity.

Such a framework is interesting in relation to the present findings and may also provide a larger context to which the more specific ELU-model (Rönnerberg, 2003; Rönnerberg et al., 2013) can be related. The disuse hypothesis (Rönnerberg et al., 2011; Rönnerberg et al., 2013) proposes that short-term memory and working memory will be relatively less affected by HI than episodic memory because the frequent mismatches between speech signal input and stored phonological representations associated with HI will ensure an increased overall level of working memory engagement to resolve ambiguities. This is suggested to result in training effects and thus a relative resiliency of working memory function to decline (Rönnerberg et al., 2013). A suggestion based on these two models is that HI may be associated with better working memory due to training effects up to the point where age-related changes in plasticity impede further resilience (see Rönnerberg et al., 2011).

Conclusions

Moderate-to-severe acquired HI affects semantic long-term memory by leading to progressively impoverished phonological representations. This phonological decline may in turn affect both language comprehension and production when sublexical segmentation and phonological operations are required. Degraded representations further lead to mismatches in speech perception in adverse conditions. Working memory resources can compensate for the negative effects of phonological decline in both comprehension and production of language and allow for a continued versatile use of phonological operations when required. With fewer working memory resources, either reflecting individual differences or age-related changes, the ability to compensate for phonological decline is relatively lower. This may impede flexible switching between phonological and semantic level processing of language. Older individuals with HI and high WMC who maintain reliance on phonological and other working memory demanding strategies to support language comprehension may retain or even improve their working memory function.

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