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Neural and Cognitive Effects of Hearing Loss on Speech Processing

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Abstract

Understanding speech in the presence of background noise can be difficult and even more so if you suffer from a hearing loss. Although speech understanding depends on hearing acuity, the individual capacity to perform higher-order Working Memory (WM) processing also plays an important role (Lunner, 2003). Despite the impact of cognition on speech processing, it has yet to be determined how hearing loss influences neural signatures of WM processing. By examining the dynamic behaviour of the electroencephalogram (EEG), it is possible to investigate how hearing loss and listening condition affect the neural processing of speech.

The aim of the current thesis was to investigate how hearing loss in elderly listeners influenced speech processing by examining both behavioural and neural measures of the cognitive involvement. In three studies, we tested the hypothesis that hearing loss and adverse listening conditions result in increased cognitive involvement. In the first study (Paper I), worse hearing and lower WM capacity related to poorer performance in a speech-in-noise task where the sound sources were spatially co-located. In a similar speech-in-noise task with spatially separated sounds, the performance was influenced by hearing loss, but not WM capacity. This suggests that the reading span test, used for quantifying the WM capacity, inadequately describes the dynamic nature of the WM involvement under speech processing. In relation to the theoretical Ease of Language Understanding (ELU) model, the results partly confirmed the view that WM abilities are more important during speech processing for listeners suffering from a hearing loss. As suggested by the inconsistent observations in Paper I, there is a need for more objective and dynamic measures in order to understand the relation between WM processing, speech understanding, and hearing loss.

An interesting, cheap, and potentially portable technology for objectively measuring the WM involvement during speech processing is EEG. As a measure of WM involvement, the alpha oscillations (~10 Hz activity in the EEG) was examined during an auditory delayed-match-to-sample task (Paper II). Despite equal task-performance, alpha power was generally higher in listeners with worse hearing. This indicates that worse hearing is linearly related to higher cognitive load during speech processing. In the most difficult experimental condition, an alpha-power breakdown was observed for listeners with the highest degree of hearing loss. This suggests that the generation of alpha power reached an upper ceiling-level, resulting in a breakdown. The internal degradation of the auditory signal brought on by the hearing loss appear to require activation of additional WM resources in order to be overcome.

A potential cause for this increased cognitive load in listeners with worse hearing was investigated in a competing-talker experiment in Paper III. Here, the effect of

hearing loss on the ability to selectively attend to a particular speech stream was examined by cross-correlating the EEG response with the envelope of the presented speech. The results showed that participants with worse hearing encoded both to-be-attended and to-be-ignored speech, but were unable to neurally inhibit the irrelevant speech. Increasing the level of background noise, reduced the neural tracking of the attended speech, indicating that internal and external degradation affected the neural tracking of the two speech streams (attended and ignored) independently.

The observations made in the current thesis provide important insights into the detrimental effects of suffering from a hearing loss on the higher-order processing of speech occurring despite providing hearing-aid amplification.

Acknowledgements

Foremost, thanks to the participants, Swedish and Danish, who voluntarily took part in the experiments that make up the basis of this thesis.

My time as an industrial PhD-student at Eriksholm Research Centre would not have been possible without the crazy idea that my main supervisor Thomas Lunner got around 2008. Suggesting to record EEG from the ear canal for controlling hearing aids was really the starting point of this PhD. Thank you Thomas, for always being ready to offer your support, share your expert knowledge extending far beyond hearing research, and for initiating the construction of two(!) new EEG-labs. Together with the newly formed Cognitive Hearing Science group at Eriksholm, you have truly created an inspiring working environment.

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Of course, my colleagues at Eriksholm Research Centre have played a central role by always engaging in lively discussions and in providing statistical, practical, and methodological help. I would especially like to thank Elisabet Sundewall Thorén for hours of interesting conversation and moral support throughout the years.

Most importantly, I would like to thank my family and friends. A very special thanks to Morten who has always supported me and offered advice no matter how incomprehensible my problems have been. *Tusinde tak, min Morten!* And of course a thanks to little Ida, who has no clue what I'm doing, but nevertheless helps me understand what is really important.

Eline Borch Petersen
Eriksholm Research Centre, January 2017

List of Publications

The current thesis is based on empirical studies published in the peer-reviewed papers referenced in the list below. Throughout the text, the papers will be referred to by their Roman numerals.

Besides the three papers making up the official thesis, scientific results obtained during the PhD has been disseminated through a conference proceeding and several posters and public talks. Furthermore, the research spawned three patent applications, of which one has been granted. Information about the additional dissemination of the thesis is provided on the following pages.

Paper I:

Petersen EB, Lunner T, Vestergaard MD, Thorén ES (2016). Danish reading span data from 283 hearing-aid users, including a sub-group analysis of their relationship to speech-in-noise performance. *International Journal of Audiology* 55(4). doi: 10.3109/14992027.2015.1125533

Paper II:

Petersen EB, Wöstmann M, Obleser J, Stenfelt S, Lunner T (2015). Hearing loss impacts neural alpha oscillations under adverse listening conditions. *Frontiers in Psychology*, 6:177. doi: 10.3389/fpsyg.2015.00177

Paper III:

Petersen EB, Wöstmann M, Obleser J, Lunner T (2017). Neural tracking of attended versus ignored speech differentially affected by hearing loss. *Journal of Neurophysiology*, 117(1), pp. 18–27. doi: 10.1152/jn.00527.2016

Additional scientific dissemination

Conference proceedings

Petersen EB, Lunner T (2015). Cognitive hearing aids? Insights and possibilities. In '*Mechanics of Hearing: Protein to Perception*', proceedings of the 12th International Workshop on the Mechanics of Hearing. *AIP Publishing*, 1703(1), pp. 090001-1–090001-4. doi: 10.1063/1.4939399

A copy of the proceeding can be found in Appendix 1.

Conference posters

Online versions of all posters are available at www.eriksholm.com/publications

Petersen EB, Obleser J, Stenfelt S, Lunner T (2013). Measuring cognitive load during listening: Changes in the EEG with noise level. Poster presented at the *Second International Conference on Cognitive Hearing Science for Communication*, Linköping, Sweden, June 16-19. The content of the poster was orally presented at the pre-conference for PhD students held on June 16.

Petersen EB, Lunner, T (2013). Challenging all aspects of the working memory: An auditory Sternberg study. Poster presented at the *HEAD Graduate School Workshop on Modern Techniques in Auditory and Communication Sciences*, Lidingö, Sweden, October 16-18.

Petersen EB, Wöstmann M, Obleser J, Stenfelt S, Lunner T (2014). Compensated hearing loss predicts generation of auditory evoked potentials. Poster presented at the *Society for Neuroscience (SfN) 44th annual meeting*, Washington DC, USA, November 15-19.

Petersen EB, Wöstmann M, Obleser J, Stenfelt S, Lunner T (2015). Influence of hearing impairment on alpha power during retention of auditory stimuli. Poster presented at the *Speech in Noise (SpiN) workshop*, Copenhagen, Denmark, January 8-9.

Petersen EB, Wöstmann M, Obleser J, Stenfelt S, Lunner T (2015). Tuning in on the target: The influence of hearing impairment on the neural encoding of speech. Poster presented at the *Third International Conference on Cognitive Hearing Science for Communication*, Linköping, Sweden, June 14-17.

Graversen C, **Petersen EB**, Favre-Felix A, Fiedler L, Obleser J, Lunner T (2016). Ear-EEG as a novel technology for wearable brain wave monitoring. Poster presented at the *Society for Neuroscience (SfN) 46th annual meeting*, Washington DC, USA, November 12-16.

Public talks

Cognitive hearing aids? Insights and possibilities (2014). Invited talk given at the *12th International Workshop on the Mechanics of Hearing*, Cape Sounio, Greece, June 27.

The influence of aided hearing loss on neural oscillations (2015). Invited talk given at the *HEAD Seminar Series*, University of Linköping, Sweden, March 11.

Neural speech processing and hearing loss (2016). Invited talk given at the seminar on *Cognitive Decline, Hearing loss, and Hearing Care*, Bolzano, Italy, September 30.

Detecting the neural struggles of hearing loss (2016). Invited talk given at the *Swiss Hearing Day*, Bern, Switzerland, October 27.

Patents and patent applications

Pontoppidan NH, Lunner T, Pedersen MS, Hauschultz LI, Kock P, Naylor G, **Petersen EB**. A hearing assistance device with brain-computer interface. *EP2813175/ US20160119726*, publication date June 2013, granted April 2015.

Frederiksen LP, Bodvarsson TO, Sørensen SH, Pontoppidan NH, Christensen KT, Lunner T, Bramsløw L, **Petersen EB**, et al. Monitoring system for a hearing device. *EP3035710*, publication date June 2016.

Petersen EB, Lunner T, Pontoppidan NH. Method, device, and system for increasing a persons ability to supress non-wanted auditory percepts. *EP3064136/ US20160261962*, publication date September 2016

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Papers I to III	

List of Abbreviations and Key Concepts

CRUNCH	Compensation-Related Utilization of Neural Circuits Hypothesis
DAI	Direct Audio Input
EEG	Electroencephalogram
ELU	Ease of Language Understanding
ERP	Event-Related Potential
fMRI	functional Magnetic Resonance Imaging
HINT	Hearing-In-Noise Test
HL	Hearing Level
ICA	Independent Component Analysis
ITI	Inter-Trial Interval
MEG	Magnetoencephalogram
PTA	Pure-Tone Average across 500, 1k, 2k, and 4kHz
PTA _{8kHz}	Pure-Tone Average also including 8 kHz
rPTA	residualized Pure-Tone Average
RS	Reading Span
SD	Standard Deviation
SNR	Signal-to-Noise Ratio
SRT50 and SRT80	Speech Recognition Threshold at 50% and 80% correct
WM	Working Memory

Attentional modulation	The difference in neural tracking of to-be-attended and to-be-ignored speech signifying selective attention
Cognitive load / WM involvement	The amount of WM resources engaged in solving a given task
EarEEG	EEG recorded from electrodes positioned in the ear canal
External sound degradation	Obstruction of the incoming auditory signal by factors from the external environment
Internal sound degradation	Changes in the neural coding of the auditory signal, e.g. caused by hearing loss
Working memory (WM)	The cognitive system involved in temporarily storing and processing sensory input

Introduction

For most people, understanding speech in the presence of background noise happens automatically and without consciously putting effort into solving the task. We do not often consider the complex processing steps required for successfully understanding sensory auditory inputs. However, for people suffering from a hearing loss, verbal communication in a noisy situation is described as being effortful and cause fatigue (Larsby et al., 2005; Kramer et al., 2006). The concepts of effort and fatigue has been related to the higher-order cognitive processing of speech required to infer meaning to it (Rönnerberg et al., 2008).

This chapter will provide theoretical, behavioural, and neural insights into the involvement of cognition in speech processing, with special emphasis on the impact of hearing loss.

Hearing loss

Hearing loss is a common condition, especially in the older part of the population (> 60 years) where the global prevalence is higher than 20% (Stevens et al., 2013). The hearing threshold is determined by measuring the lowest audible sound level (audiometric threshold) for pure-tone frequencies ranging from 125 Hz to 8 kHz (**Figure 1**). The audiometric thresholds are expressed relative to the quietest hearing level (dB HL) expected for a young normal-hearing listener (ANSI, 1996). Clinically, hearing loss is defined as having audiometric thresholds higher than 25 dB HL across the frequencies 0.5, 1, 2, and 4 kHz, denoted the Pure-Tone Average (PTA; WHO 2014, see **Figure 1**). Increased audiometric thresholds can be caused by blockage of the outer ear or abnormal middle-ear bone connections, resulting in a conductive hearing loss. However, the most common type of hearing loss is sensorineural, typically induced by damage at the level of the cochlea (Moore, 2007). Besides noise exposure and genetic predisposition, age-related changes in the auditory system (presbycusis) also contribute to the development of sensorineural hearing loss (Humes et al., 2012)¹.

Sensorineural hearing loss, hereon denoted only hearing loss, causes several changes in the auditory system (for review, see Moore, 2003). The most prominent changes are (1) reduced audibility resulting from raised audiometric thresholds. As the level at which sounds become uncomfortably loud generally remains unchanged, the raised audiometric thresholds often result in (2) a lower dynamic range (Steinberg & Gardner 1937, see **Figure 1**). The frequency-specificity of the

¹ An older definition of presbycusis includes both age-related and age-acquired, e.g., through prolonged noise exposure, sensorineural damage (CHABA, 1988).

cochlea decreases due to broadening of the auditory filters, reducing the (3) spectral and (4) temporal precision of sound encoding (Moore, 2003). In combination, the lowered spectral and temporal precision cause a reduced sensitivity towards the rapid oscillations within auditory signals, i.e., the temporal-fine structure (Lorenzi et al., 2006; Moore, 2008). Encoding of the temporal-fine structure influence the ability to discriminate between frequencies, which is essential for identification and discrimination of speech signals (Moore, 2008).

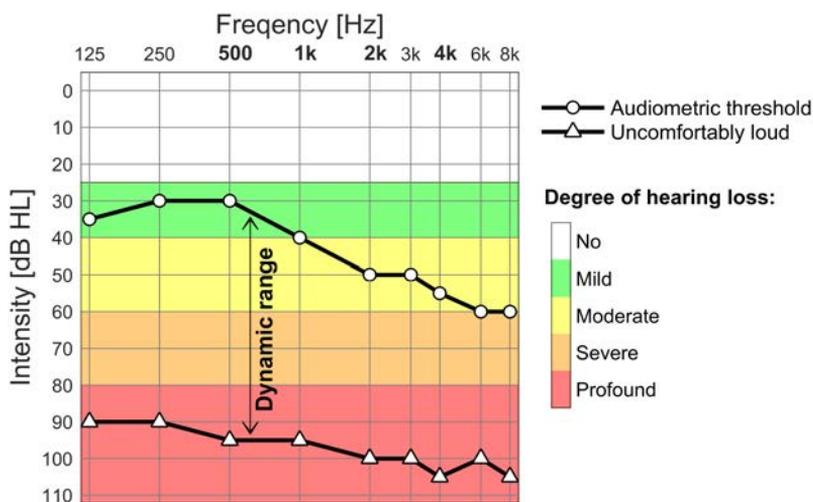


Figure 1: Exemplary audiometric thresholds. The difference between the audiometric thresholds (circle and black line) and the uncomfortable loudness level (triangle and black line) constitutes the dynamic range. The degree of hearing loss is quantified by the Pure-Tone Average (PTA), calculated by averaging the thresholds across the frequencies 0.5, 1, 2, and 4 kHz (highlighted in bold writing). According to the PTA, listeners can be categorized as having no (white area), mild (green area), moderate (yellow area), severe (orange area), or profound (red area) hearing loss. The audiometric thresholds showing in the graph is from a listener with a moderate hearing loss.

Overall, hearing loss is associated with a number of changes, causing distortions in the encoding of sounds. That is, hearing loss causes an *internal degradation* of the auditory signal. In a similar manner, the auditory signal of interest can also be affected by external factors, most prominently background noise, resulting in *external degradation* of the signal. Independently, internal and external degradation cause reduced speech understanding. However, in combination; suffering from a hearing loss and listening to speech presented in background noise, the two have an especially detrimental effect on the speech understanding (Festen and Plomp, 1990; Mattys et al., 2012).

Hearing aid treatment

The partial loss of hearing is commonly treated with hearing aids, which aim at improving audibility by amplifying the incoming sounds. Hearing aids provide gain at different frequencies according to the users' audiometric thresholds, while keeping the stimuli within the dynamic range (Dillon, 2001). Compression schemes ensure that the hearing-aid output is kept within the dynamic range by accounting for variations in the external listening environment. Dynamic compression schemes can be fast- or slow-acting, i.e., have a small or large time constant, referring to the speed of the gain-adjustment following a detection of a change in the external sound input level (Moore, 2008). In practice, hearing aids dynamically change the time constant to follow the sound level input (Simonsen and Behrens, 2009). Hence, fast compression is applied in rapidly changing environments, such as a lively dinner party, whereas slow-acting compression is used under stable listening conditions, such as a one-on-one conversation in quiet surroundings. The slow-acting compression scheme ensures near-linear (quasi-stationary) amplification under stable listening conditions (Simonsen and Behrens, 2009; Le Goff et al., 2016).

Modern hearing aids also incorporate advanced noise-reduction algorithms and directional-microphone control to help improve listening in adverse conditions. The hearing aid continuously estimates the ratio between the signal of interest and the background noise (signal-to-noise ratio, SNR) and adapts its settings accordingly. In situations with a high noise level, i.e., low SNR, the noise-reduction system is activated as to try to attenuate the noise. A popular noise-reduction method assumes speech to be more modulated than noise. Hence, through estimation of the modulation index, frequency bands with a low degree of modulation are classified as containing noise and are thus attenuated (Lunner et al., 2009; Jensen and Pedersen, 2015). At the same time, when the sound of interest is estimated to originate from a frontal position, the directionality of the hearing-aid microphones can be changed to attenuate sounds coming from the back and sides (Dillon, 2001).

Generally, hearing loss does not affect the speech recognition in quiet situations as long as audibility is ensured (Festen and Plomp, 1983; Van Tasell, 1993). However, in situations where the speech of interest is disturbed by background noise, the intelligibility decreases drastically when suffering from a hearing loss, despite providing adequate hearing-loss compensation (Festen and Plomp, 1990). Indeed, as hearing-aid amplification cannot restore normal hearing, hearing-aid users often report being more tired because of their impaired hearing (Kramer et al., 2006).

Speech processing and cognition

Successful speech understanding depends on the ability to extract temporal and spectral cues from the auditory signal (bottom-up processing), as well as on higher-

order (top-down) processing relying on linguistic knowledge and cognitive involvement (Mattys et al., 2012). A cognitive ability that is especially important for speech understanding is the working memory (WM). The WM system is the limited ability of an individual to simultaneously store and process sensory information (Baddeley, 1992). In a model proposed by Baddeley and Hitch, the WM system consists of a central executing function combining the sensory input temporarily stored in the episodic buffer with the information retrieved from the long-term memory (Baddeley and Hitch, 1974; Baddeley, 2000, 2003).

Based on the general WM model from Baddeley and Hitch, Rönnerberg and colleagues developed the Ease of Language Understanding (ELU) model, specifying how WM processing influence speech understanding under adverse listening conditions (Rönnerberg, 2003; Rönnerberg et al., 2008, 2013). According to the ELU-model, a fast, automatic, and implicit match between the speech input contained in the episodic buffer and information stored in the long-term memory is made under optimal listening conditions. In suboptimal listening conditions, where an implicit match cannot be made, an explicit top-down controlled process is initiated. During explicit processing, the WM system is further activated in order to infer meaning to the speech. This happens through syntactic and semantic processing of the speech and through inhibition of irrelevant information. Depending on the quality of the content stored in the episodic buffer and the individuals' WM ability, the outcome of the explicit processing loop can range from full, to partial, or no understanding of the speech input. (Rönnerberg et al., 2008, 2013)

While implicit speech understanding occurs within milliseconds, explicit processing operates on a scale of seconds and is often rated as being subjectively more effortful (Rönnerberg et al., 2013). It should be clarified that there is no threshold at which speech processing change from implicit to explicit, rather the relationship between the two is dynamic and changes depending of the listening situation, as well as on individual differences in cognitive abilities, age, and hearing acuity (Rönnerberg et al., 2013).

Influence of working memory capacity, hearing loss, and age on speech processing

The capacity of the WM to process and store information is limited and can vary considerably between individuals (Daneman and Carpenter, 1980; Just and Carpenter, 1992). Indeed, in relation to speech understanding, hearing-impaired listeners with higher WM capacity are less affected by the presence of background noise (Lunner, 2003; Foo et al., 2007; Lunner and Sundewall-Thorén, 2007; Souza et al., 2010; Arehart et al., 2013; Rönnerberg et al., 2014). At a certain level of background noise, two individuals might require the same amount of WM processing to understand the incoming speech, however leaving fewer resources for storage in

the individual with the lowest WM capacity (Pichora-Fuller, 2007; Lunner et al., 2009). Indeed, even in near-optimal listening conditions (95% intelligibility) hearing-impaired individuals with poorer WM capacity have lower memory-recall performance compared to listeners with higher WM capacity (Ng et al., 2013).

Adverse listening conditions are often brought on by the presence of background noise or reverberation of sounds, but factors such as language of communication and conversation topic can also affect the external listening environment (Rönnerberg et al., 2013). Internal degradation of the auditory signal caused by hearing loss also increases perceptual demands during speech processing. It has been found that while worse hearing had no influence on the memory-recall of visual items, the recall of auditory items presented in quiet significantly decrease with worse hearing (Rabbitt, 1991). This suggests that even in optimal listening conditions, hearing loss in itself requires the allocation of WM resources in order to be overcome (McCoy et al., 2005; Wingfield et al., 2005).

As such, it is generally accepted that hearing-aid amplification releases WM resources by restoring audibility (Edwards, 2007; Lunner et al., 2009). However, some hearing-aid features designed to improve the listening condition, have proven beneficial only for some listeners. Studies have found that, compared to their low-WM peers, hearing-impaired listeners with high WM capacity benefit more from fast-acting compression schemes (Gatehouse et al., 2006; Lunner and Sundewall-Thorén, 2007; Rudner et al., 2011), but experience a reduced benefit of noise reduction in near-optimal listening conditions (Ng et al., 2013). Hence, the benefit of advanced hearing-aid signal processing is a balance between releasing WM resources and increasing the WM involvement by introducing unwanted signal-processing artefacts (Lunner et al., 2009).

Aging poses an additional constraint on the speech understanding, not only through presbycusis, but also by causing a general cognitive decline (Pichora-Fuller and Singh, 2006; Braver and West, 2008; Füllgrabe et al., 2015). Older listeners show a reduced ability to inhibit distractions (Hasher et al., 2008) and generally have lower WM capacity (Salthouse and Babcock, 1991). However, the interaction between age and the influence of WM capacity has recently been questioned. In a meta-analysis of 19 studies, Füllgrabe and Rosen found that WM capacity related to speech understanding in older, but not in younger, normal-hearing listeners (Füllgrabe and Rosen, 2016). Although some observations link WM capacity to speech-in-noise performance for younger normal-hearing listeners (Besser et al., 2013; Gordon-Salant and Cole, 2016), Füllgrabe and Rosen (2016) suggests that WM involvement is more pronounced in older listeners due to age-related changes in the processing of temporal acoustic cues.

While the details are debated, there is no doubt that speech understanding is influenced by a complex interaction between hearing acuity, the consequences of an

aging system, and individual cognitive abilities. However, the behavioural studies investigating the role of WM in speech processing often rely on an observed significant correlation between the outcome measures of two experimental tasks. For most of the studies related in this section, the overall outcome of a WM task correlated with the performance of a speech-in-noise task. Unfortunately, such correlational results constitutes a very static way of examining the influence of WM involvement on speech processing as it offers no insights into potential changes happening across time or between listening conditions.

Speech processing has been linked to changes in physiological measures such as pupil size, skin conductance, and hormone levels (McGarrigle et al., 2014). However, electrophysiological measurements are often preferred as it reacts instantaneously to any changes in the auditory input (McGarrigle et al., 2014). By utilizing electrophysiological measurements, it is possible to obtain a more nuanced picture of how the WM influences speech understanding.

Neural speech processing

Electrophysiological recordings of the synchronous activity of neural populations, as measured by the magneto- or electroencephalogram (M/EEG), can help us understand the mechanisms behind speech processing.

In recent years, the relationship between WM processing and neural oscillatory activity within the alpha frequency range (~10 Hz) has received a lot of attention. According to the *functional inhibition* theory, alpha oscillations reflect inhibition of task-irrelevant neural processes (Klimesch et al., 2007) and brain regions (Jensen and Mazaheri, 2010) as to allocate resources for solving the task at hand. That is, during a difficult listening task, the functional inhibition theory predicts an increase in alpha power because of the increased WM involvement, or *cognitive load*. Indeed, increased alpha power during auditory processing has been observed when (1) increasing the memory load (Leiberg et al., 2006; Kaiser et al., 2007; van Dijk et al., 2010; Obleser et al., 2012), (2) reducing the spectro-temporal detail (temporal-fine structure) of the stimuli (Obleser and Weisz, 2012; Obleser et al., 2012; Becker et al., 2013; Wöstmann et al., 2015), (3) increasing the complexity of the speech material (Meyer et al., 2013), and when reducing the (4) temporal (Wilsch et al., 2014) and (5) contextual (Wöstmann et al., 2015) predictability of the stimuli. In all of the studies mentioned above (with the exception of Wilsch (2014)), alpha power increased over the parietal-occipital regions usually associated with processing of visual information. This suggests that during processing of auditory stimuli, neural activity associated with visual processing is inhibited (Jensen and Mazaheri, 2010).

Alpha power has been shown to co-modulated with oscillation in the theta (~5 Hz) and gamma (>30 Hz) frequency range (for review, see Roux & Uhlhaas, 2014). Whereas theta and gamma activity has been directly linked to WM processing,

inhibitory alpha activity is indirectly associated with WM processing by protecting it from irrelevant information (Roux & Uhlhaas, 2014). Nevertheless, based on findings from the many previous studies related above, the current thesis will focus on alpha power as a measure of cognitive load during speech processing.

Not only inhibition of irrelevant neural processes, but also the inhibition of irrelevant external sounds is vital for speech understanding. In the current thesis, neural WM processing and inhibition of irrelevant stimuli are considered to be interrelated processes. Indeed, during processing of visual stimuli it has been observed that similar neural structures control both processes, suggesting that WM resources can be alleviated through early and effective filtering of relevant information (Gazzaley and Nobre, 2012).

An interesting measure for quantifying the neural encoding and potential inhibition of irrelevant sounds, is the ability of neural activity to phase-lock to the fluctuations in the speech signal(s), also known as *neural speech tracking* (Wöstmann et al., 2016). Although research has mainly focused on neural tracking of the slow temporal variations in the speech envelope, neural activity has been shown to track unintelligible auditory stimuli (Zoefel and VanRullen, 2015), phonetic information used for categorical perception of speech (Di Liberto et al., 2015), and to improve when the talkers face is visible (Crosse et al., 2016).

In a two-talker scenario, it has been shown that when younger normal-hearing listeners selectively attend to one speech stream, it results in stronger neural tracking of the attended stream compared to the ignored (Ding and Simon, 2012a, 2012b; Mesgarani and Chang, 2012; Horton et al., 2013; Hambrook and Tata, 2014; Kong et al., 2014; O'Sullivan et al., 2015). The first response in the M/EEG indicating neural tracking occurs ~50 ms after the speech has been presentation. The first discrepancy between the attended and ignored speech streams (selective attention) is usually observed after ~150 ms. It has been suggested that top-down control of selective attention is possible through the neural formation of individual auditory objects to which attention can be selectively asserted (Shinn-Cunningham, 2008; Simon, 2015). In line with this hypothesis, a majority of the studies investigating the effect of varying the SNR between the two speech streams, observe no effect on the neural tracking of attended speech (Ding and Simon, 2012a; Kong et al., 2014; Presacco et al., 2016)². A stable representation of the speech streams, despite changing SNRs, suggests a neural gain-control mechanisms affecting the tracking of the individual auditory objects (Simon, 2015).

From the results related above, it is evident that cognitive load and selective attention can be quantified during speech processing using M/EEG measurements

² One study observed smaller amplitudes in the early neural tracking response (~50 ms) when lowering the SNR between speech stream (Ding and Simon, 2013).

in normal-hearing listeners. However, it is unknown how hearing loss affects the neural alpha activity and speech-tracking ability.

Hearing loss and neural speech processing

Structurally, hearing loss in elderly listeners has been linked to a decrease in the neural density of the auditory cortex (Peelle et al., 2011; Lin et al., 2014). During the performance of auditory tasks, hearing loss was associated with lower activity in brain regions involved in speech processing (brain-stem, thalamus, and superior temporal gyri; Peelle et al., 2011), while others have observed an increased activity in the pre-frontal cortex, associated with WM processing (Campbell and Sharma, 2013). With hearing loss relating to structural changes in the cochlea and the brain, it is assumed that the neural signatures of speech processing are likewise affected. However, no previous studies have investigated the effect of hearing loss on the dynamics of alpha oscillations or neural speech tracking.

Most studies investigating the effect of hearing loss on speech processing, focus on the evoked Event-Related Potentials (ERPs) generated within the first ~400 ms after the presentation of a sound stimuli. The early part of the ERP-response related to sensory processing, while the later part of the response signifies cognitive processing of the incoming sound (Picton and Hillyard, 1974). Worse (unaided) hearing has been linked to a larger early ERP-response (Tremblay et al., 2003; Harkrider et al., 2006; Alain et al., 2014), suggesting a deficit in the central regulation of sound processing (Alain et al., 2014). Alternatively, it has been speculated that, as the early ERP-response is more sensitive to low-frequency sounds, a high-frequency hearing loss might act as a low-pass filter causing an increase in the early ERP-response (Tremblay et al., 2003).

Increasing the presentation level of the auditory stimuli generally results in a higher ERP-response, but when increasing the presentation level through hearing-aid amplification in younger normal-hearing listeners, studies have found no effect on the ERPs (Tremblay et al., 2006; Billings et al., 2007, 2011). It has been suggested that internal circuit-noise generated by the hearing aid reduce the SNR of the output, counter-acting the effect of increasing the presentation level (Billings et al., 2007). Generally, interpreting the effect of hearing loss on the ERPs is difficult because the response is tightly linked to the properties of the sound stimuli and the sensory encoding of it. Hence, it is practically impossible to disentangle whether changes in the ERP-response are caused by hearing loss, individually prescribed amplification, individualization of the stimuli to ensure equal performance between listeners, or the spectro-temporal nature of the auditory stimuli. For this reason, the current thesis will only focus on induced responses (alpha power and neural speech tracking), reflecting neural activity generated through higher-order processing of the presented auditory stimuli (David et al., 2006).

As no previous studies have investigated the effect of hearing loss on induced neural speech processing, we base our hypotheses on studies of normal-hearing listeners. Knowing that hearing loss reduces the ability to process temporal-fine structure, we look to studies investigating the effect of degrading the spectro-temporal information (temporal-fine structure) of the auditory stimuli presented to normal-hearing listeners.

Studies investigating the effect of temporal-fine structure on the alpha power report reduced inhibitory activity when listening to less degraded speech in younger (Obleser and Weisz, 2012; Obleser et al., 2012; Becker et al., 2013) and older listeners (Wöstmann et al., 2015). Importantly, reducing the spectro-temporal information result in an alpha-power change during processing of intelligible speech, but not when processing unintelligible (spectrally rotated) speech (Becker et al., 2013). Thus, changes in alpha power relate to speech processing and are not induced by alterations in the acoustic detail of the stimuli. Based on these observations, it is expected that worse hearing would result in higher alpha power during speech processing due to the internal degradation caused by the hearing loss.

In studies focusing on neural speech tracking, degrading the spectro-temporal information has been found to cause reduced neural tracking of speech presented in quiet (Ding et al., 2013; Peelle et al., 2013) and when masked by stationary noise (Ding et al., 2013) or competing speech (Kong et al., 2015). In the latter study, degrading the competing speech signals resulted in similar tracking of the two, i.e., no sign of selective attention towards a particular speech stream (Kong et al., 2015). In a similar manner, hearing loss would be expected to cause reduced attentional modulation between the neural tracking of to-be-attended and to-be-ignored speech.

Studies have observed a larger benefit of improving the speech quality (reducing the degradation) in older listeners, compared to younger, both in the alpha power (Wöstmann et al., 2015) and neural speech tracking (Presacco et al., 2016). As age and hearing acuity are often related, this suggests that care should be taken to ensure that any observed effects are indeed caused by worse hearing and not by increased age.

Aims of the Thesis

The overall goal of this thesis was to investigate how hearing loss influenced speech processing. Besides investigating the effect of hearing loss on behavioural (Paper I) and neural (Paper II and III) measures of cognitive speech processing, a secondary aim was to test the effect of altering the listening condition on these measures. Specifically, the listening conditions were altered by varying the spatial separation of sounds (Paper I), the background-noise levels (Paper II and III), and the number of to-be-remembered items (Paper II).

The overall hypothesis was that internal and external degradation of the auditory signal would result in higher WM activation during speech processing.

Utilizing the Reading Span (RS) test-score as a measure of WM capacity (Daneman and Carpenter, 1980), Paper I investigated the relationship between hearing loss, RS score, and speech-in-noise performance for experimental setups with spatially separated and co-located sound sources. We hypothesized that WM capacity, as well as the degree of hearing loss, would influence the speech-in-noise performance for both experimental setups.

In Paper II, the oscillatory activity in the alpha band (6–12 Hz) of the EEG was exploited as a measure of cognitive load during an auditory Sternberg task (Sternberg, 1966; Obleser et al., 2012). It was hypothesized that worse hearing, as well as more to-be-remembered digits and higher background-noise levels, would result in higher cognitive load, evident from an increase in the alpha activity.

In the competing-talker experiment in Paper III, the neural speech tracking of the to-be-ignored and to-be-attended speech was quantified to investigate the effect of hearing loss on the ability to assert selective attention. A weaker neural speech tracking of both attended and ignored speech was expected with worse hearing, whereas increasing the level of background noise was expected to cause weaker tracking of the attended speech, but stronger tracking of the ignored speech.

Participants and Methods

This chapter gives an overview of the different ethical clearances and participant characteristics included in the papers of the thesis. Furthermore, short descriptions of the experimental procedures will be provided in the following.

Ethical approvals

All studies within the thesis were approved by the local ethics committee. The experiments presented in Paper I were conducted at Eriksholm Research Centre and approved by the ethics committee in the Capital Region of Denmark (H-1-2011-033). Data presented in Paper II and III were recorded at Linköping University and approved by the regional ethical review in Linköping, Sweden (DNR 2011/427-31).

Participants

The participants included in the three papers were recruited from two sites: Linköping University Hospital, Linköping, Sweden and Eriksholm Research Centre, Snekkersten, Denmark. Details on the participant demographics and experimental procedures are provided in **Table 1**. All participants were native speakers of the language used in the experiment(s) (Swedish for Paper II–III, Danish for Paper I).

Participation in the studies was on a voluntary basis and no economical compensation was given. All participants received written and oral information regarding the experiments. Informed consent were obtained from all participants before beginning the experiments. At Eriksholm Research Centre, participants were recruited from an existing database of self-enrolled test subjects. Potential participants from Linköping University Hospital were identified from a patient-database of persons having been in contact with the ear, nose, and throat clinic and were contacted via ordinary mail.

Quantifying the degree of hearing loss

To investigate the relationship between hearing loss and cognitive processing of speech, participants suffering from varying degrees of hearing loss were recruited (**Table 1**). This recruitment strategy oppose the often-used extreme-group approach, i.e., testing participants suffering from hearing loss against a normal-hearing (age-matched) group. In all studies, the degree of hearing loss was treated as a continuous predictor, hence avoiding the inflation of statistical power and the assumption of a linear trend between groups innately incorporated into the extreme-group approach (Preacher et al., 2005).

Table 1: Participant demographics and experimental information for each paper. Participants' average age and hearing loss, as measured by the PTA. Parentheses indicate the standard deviation. For the total study population (N), the number of females are noted in parenthesis. The experimental tasks and the outcome measures reported in each paper are denoted in the last two columns. Note that some experiments have multiple outcome measures.

Paper	Participants demographics		Experiments presented in the paper	
	N	Age [years] PTA [dB HL]	Test	Reported outcome
I	283 (140)	65.30 (12.2)	54.2 (11.5)	Reading span test Performance accuracy
				Dantale II test Speech reception threshold of 50%
				Hearing-in-noise test Speech reception threshold of 80%
II	29 (16)	72.24 (5.85)	44.14 (17.9)*	Reading span test** Performance accuracy
				Auditory Sternberg task Performance accuracy Reaction time
				Neural alpha power
III			Competing-talker task Performance accuracy Neural speech tracking	

* A significant relation between PTA_{shiz} and age was found and residualized PTA ($rPTA$) was used to quantify hearing loss

** Data has not been previously presented

Participants recruited from the database at Eriksholm Research Centre (Paper I), all suffered from sensorineural hearing loss, as the presence of a conductive hearing loss was an exclusion criterion.

For the 29 persons recruited from Linköping University Hospital (Paper II and III), bone-conduction audiometric thresholds used for diagnosing conductive hearing loss, were not available for all participants. During an initial clinical visit, air-conduction audiometric threshold were measured for all participants, while the acquisition of bone-conduction thresholds was not done for all:

- No bone-conduction thresholds were obtained for participants (N = 7) showing close-to-normal hearing according to the air-conduction threshold ($PTA \leq 30$ dB HL).
- For participants (N = 4) with newer (< 2 years) air- and bone-conduction audiograms available, bone-conduction thresholds were obtained only for the right ear to confirm the absence of a conductive hearing loss.
- Bone-conduction thresholds were obtained for both ears (N = 18) for participants with older audiograms (> 2 years) or suffering from a moderate to severe hearing loss ($PTA \geq 40$ dB HL).

In **Figure 2**, the air- and bone-conduction thresholds are shown for the participants in Paper II and III with available bone-conduction thresholds (right ear: N = 22, left ear: N = 18). According to international standards, air-conduction thresholds were obtained for the frequency range 0.125–8 kHz, whereas bone-conduction thresholds were measured within the range 0.250–4 kHz (British Society of Audiology, 2012). No participants showed a difference between the air- and bone-conduction audiometric thresholds larger than 20 dB across the PTA. This indicates that all participants in Paper II and III suffered from sensorineural hearing loss.

In Paper I the degree of hearing loss was quantified using the PTA across the audiometric thresholds at 0.5, 1, 2, and 4 kHz for the better-hearing ear (WHO, 2014). For Paper II and III, the PTA-calculation also included the audiometric threshold at 8 kHz (denoted PTA_{8kHz}). As high-frequency hearing loss is associated with age (CHABA, 1988), the threshold at 8 kHz was include to ensure that any effect of age potentially influencing the neural measures, would be captured by the PTA_{8kHz} . Indeed, a significant relation between hearing loss (PTA_{8kHz}) and age was found (Paper II and III, $r = 0.398$, $p = 0.033$, **Figure 3A**).

To obtain a measure of hearing loss independent of age, the residuals of the linear regression between PTA_{8kHz} and age were used to generate the residualized PTA (rPTA; also see **Figure 3**):

$$PTA_{8kHz} = \beta \cdot \text{age} + \varepsilon \quad \text{Eq. 1}$$

$$rPTA = \text{zscore}(\varepsilon) \quad \text{Eq. 2}$$

For statistical reasons, the residuals were normalized (z-scored) to obtain the final measure of rPTA. The rPTA-measure is assumed to constitute the part of the hearing loss not explained by age.

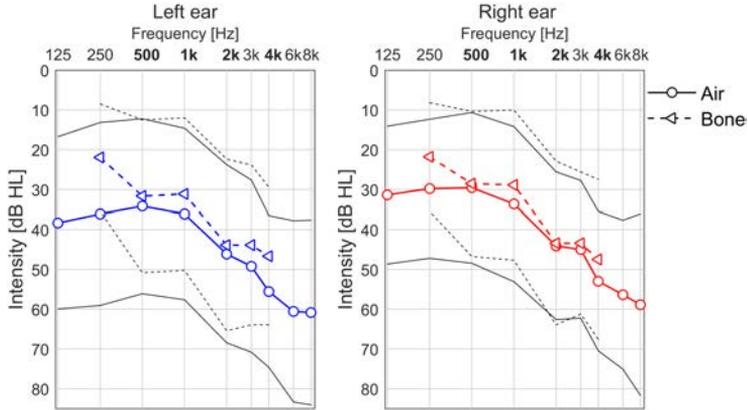


Figure 2: Air- and bone-conduction audiometric thresholds for participants in Paper II and III. Left (blue, N = 18) and right (red, N = 22) ear air- (circle and solid line) and bone-conduction (triangle and dashed line) audiometric thresholds. The black solid and dashed lines indicate ± 1 SD for the air- and bone-conduction thresholds, respectively. PTA-frequencies are highlighted in bold writing.

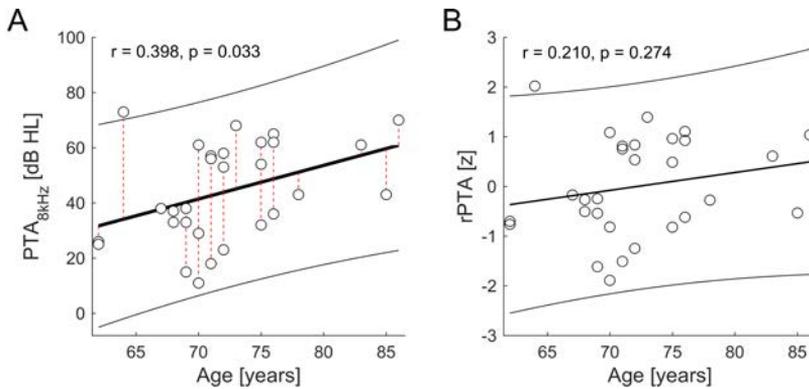


Figure 3: Quantifying the degree of hearing loss independent of age. (A) The significant linear relationship between PTA_{8kHz} and age ($p = 0.033$) indicated with a least-squares regression line in black and the 95% confidence interval in thin black lines. A measure of hearing loss independent of age was obtained by utilizing the residuals of the linear regression between age and PTA_{8kHz} (dotted red lines). (B) The final measure of hearing loss, the z-scored residualized PTA (rPTA), was independent of age ($p = 0.274$).

Experimental procedures

As outlined in **Table 1**, a number of different tests were conducted in each study. In two experiments, EEG was recorded and the tests were therefore designed for, or adapted to, this purpose. The remainder of the experiments are widely used tests, which were conducted in accordance with the standardized implementation, as detailed in the following sections.

Presenting sound stimuli

When investigating speech processing in relation to hearing loss, audibility must be ensured across all listeners to avoid effects caused by the inability to hear the stimuli. In all experiments, audibility was ensured through individually prescribed quasi-linear amplification provided through bilaterally fitted hearing aids. To avoid adverse effects originating from the hearing-aid helping-systems, the noise reduction, volume control, and microphone directionality were turned off during the experiments.

In Paper I, the sound stimuli was presented from loudspeakers at different positions, i.e., free-field presentation. In contrast, all sound stimuli in Paper II and III were presented directly into the hearing aids (Agil Pro, Oticon A/S, Smørum, Denmark) via the Direct Audio Input (DAI), allowing the hearing aids to function as earphones. When presenting stimuli through the DAI-input, the hearing aids were set to attenuate the amplification of the microphone input by 6 dB. As the experiments were conducted in a soundproof booth, no external microphone input was present.

Speech-in-noise tests

All studies include the presentation of speech in background noise. Since hearing loss affects the ability to understand speech in noise, fixed signal-to-noise ratios (SNRs) cannot be applied without creating an unwanted interaction between hearing loss and task performance (Festen and Plomp, 1990). For this reason, individualized background-noise levels were applied in all experiments to ensure equal performance across participants. Two different standardized speech-in-noise tests were applied in the thesis: The Hearing-in-Noise Test (HINT test; Paper II–III) and the Dantale II test (Paper I).

In both the HINT (Nilsson, 1994) and Dantale II test (Wagener et al., 2003), participants were presented with sentences embedded in noise and asked to repeat them back. Using an adaptive tracking procedure (Levitt, 1971), the SNR levels were changed in order to estimate the noise level corresponding to a particular performance level, denoted Speech Reception Threshold (SRT). In

Paper I and II, the SNR at 80% (SRT80) was estimated, while the SNR-values corresponding to 50% intelligibility (SRT50) were used in Paper I.

The main difference between the HINT and the Dantale II test is the presented speech material: While the HINT test incorporates every-day sentences, the Dantale II test consists of five-word sentences with a regular syntactical structure (name, verb, numeral, adjective, and objective).

Reading span test

The Reading Span (RS) test was designed to evaluate the WM capacity (Daneman and Carpenter, 1980; Baddeley et al., 1985). Participants were visually presented with three-word sentences, one word at the time, and asked to verbally indicate whether the sentence was sensible (e.g., *'The captain sailed away'*) or not (e.g., *'The bottle laughed loudly'*). After a list of three to six sentences, the participants were to recall either the first or last word in each sentence. The RS score was calculated as the percentage of correctly recalled words of the 54 presented sentences (possible range 0–100%). The Danish version of the RS test (Paper I) has not been formally validated, but builds on a direct translation of the Swedish version (Hällgren et al., 2001).

Auditory Sternberg task

Inspired by the auditory Sternberg task implemented by Obleser and colleagues (Sternberg, 1966; Obleser et al., 2012), participants were presented with two, four, or six monosyllabic digits (memory load) embedded in stationary speech-shaped noise at three different individualized noise levels (**Figure 4**). The task was to remember the presented digits and later indicate whether a probe-digit was among the previously presented digits. The background-noise levels were individualized based on the SRT80-values obtained from the HINT test (middle condition, denoted 0 dB SRT80). The easier (+4 dB SRT80) and a more difficult (–4 dB SRT80) conditions were generated by adding and subtracting 4 dB from the SRT80-value, respectively. As such, a participant with an SRT80-value of 1 dB SNR would be presented with background-noise levels at –3 dB SNR (–4 dB SRT80), 1 dB SNR (0 dB SRT80), and 5 dB SNR (+4 dB SRT80). During the experiment, participants' answers (correct/incorrect), reaction times, and EEG-activity were recorded.

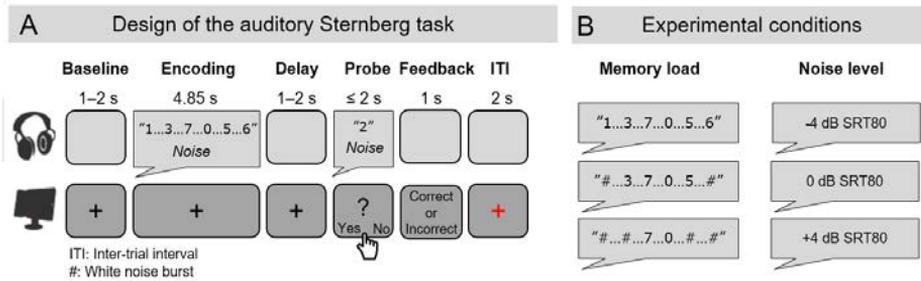


Figure 4: Experimental design of the auditory Sternberg task. (A) After a short quiet baseline-period, the two, four, or six digits were presented in an individualized level of noise. After a 1–2 second delay period, a probe digit was presented in noise and the participants’ were to answer through a button-press whether the probe was among the previously presented digits. After receiving feedback, participants had a two second break (inter-trial interval, ITI) between consecutive trials. (B) The experimental conditions, memory load and noise level, were tested in a 3x3 design. In trials with two or four digits, flanking sounds of white noise (# in the figure) were presented to ensure the presentation of six sounds. Noise levels were adjusted according the individuals SRT80-value (+4 dB SRT80, 0 dB SRT80, and –4 dB SRT80).

Individualization of the background-noise levels

The three levels of background noise (+4, 0, and –4 dB SRT80) were chosen to ensure a variation in the performance between conditions, with the expectation that adding and subtracting 4 dB from the SRT80-values would result in performance levels around 100% and 50% correct in a HINT test, respectively.

Based on the SNR-levels applied in the HINT test and the corresponding ability to repeat the sentence, it was possible to estimate the psychometric function for each of the participants. From the estimated psychometric functions (**Figure 5A**) it is possible to extract the expected performance level for the three background-noise levels (+4, 0, and –4 dB SRT80). As seen in **Figure 5B**, the expected speech recognition for the easier background-noise levels (+4 dB SRT80), was around 100%, as expected. The estimated speech recognition for the most difficult condition (–4 dB SRT80), was lower than expected (mean 26.1%, standard deviation 18.6%). However, it should be noted that the speech recognition performances are rough estimates, as they, especially at –4 dB SRT80, are influenced by the slope of the psychometric function. As the adaptive tracking procedure used in the HINT test is designed to limit the variation in the SNR-levels, an accurate estimation of the slope of the psychometric function is not possible. Importantly however, no linear relation was seen between rPTA and the estimated speech recognition level at +4 dB SRT80 ($p = 0.178$) or –4 dB SRT80 ($p = 0.167$), indicating that the calculation of the individual background noise levels did not introduce a hearing-loss bias.

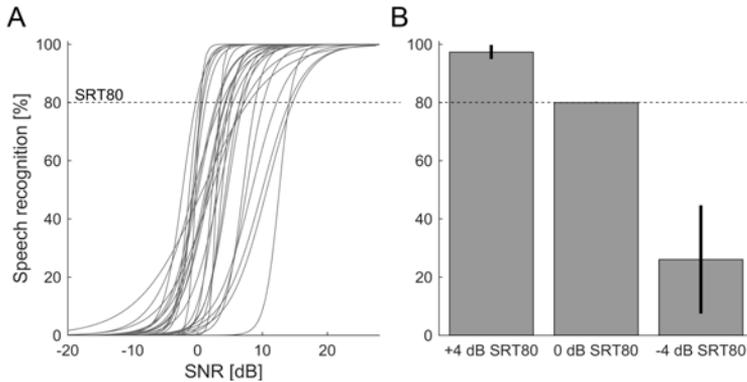


Figure 5: Estimated psychometric functions and expected speech recognition levels based on the HINT test. (A) Individual psychometric functions estimated based on the applied SNR levels and corresponding speech recognition during the HINT test. The intersection between the individuals' psychometric function and the vertical dotted line at 80% speech-recognition level indicates the SRT80-value for that individual. (B) Estimated speech recognition at the three background-noise levels (+4, 0, and -4 dB SRT80) applied in Paper I and II, with the error bars indicating ± 1 SD.

The competing-talker task

In contrast to the highly controlled and trial-based auditory Sternberg task, a more everyday-like competing-talker task was administered in Paper III. Participants were asked to follow the story narrated by a male talker for 12 minutes. In intervals of three minutes, the story was presented in quiet or interrupted by a female talker presented at the same three individualized levels of SNR as applied in the auditory Sternberg task (+4 dB SRT80, 0 dB SRT80, and -4 dB SRT80).

Besides recording EEG during the task, participants' answers to four three-alternative-forced-choice questions presented at the end of the 12 minutes story were recorded.

EEG acquisition and processing

The EEG recordings presented in Paper II-III, were done using the 128-channel EGI HydroCel GSN electrode-net (Electrical Geodesic Inc., Eugene, OR, USA). The EEG was recorded at a sampling rate of 250 Hz using Cz as the reference electrode. The impedance of the Ag/AgCl electrodes were maintained below 50 kOhm (high-impedance system). Eight electrodes were disconnected from the electrode-net and instead connected to electrodes positioned on the earlobes and in the ear canal (see Appendix 1 for an example for EarEEG recordings). The electrode-net had electrodes positioned the cheeks, jaw, and around the eyes, resulting in unwanted contamination of the EEG by muscle and eye movement. To minimize the noise-

contamination, data from eleven additional electrodes were removed before the EEG was analysed.

All data was processed offline using customized MATLAB scripts (R2011b and R2015, MathWorks Inc.) and the Fieldtrip toolbox (Maris and Oostenveld, 2007; Oostenveld et al., 2011). All recordings were pre-processed following the same steps, by: (1) Extracting relevant time-epochs from the continuous recording, (2) removing irrelevant electrodes, (3) band-pass filtering the EEG between 0.5 and 45 Hz using a 6th order Butterworth filter, (4) re-referencing the data to linked mastoids, and finally (5) running Independent Component Analysis (ICA) to remove artefacts (eyeblick, saccadic eye movements, muscle activity, and heart beat) through visual identification and excluding of the contaminated components. After these common pre-processing steps, the neural signatures of interest were extracted.

Results of Empirical Studies

The following chapter will provide short summaries of each of the three studies in the thesis. An overview of the hypotheses and observations of each paper is provided in **Table 3** on page 42.

Paper I

Introduction and aim

Variations in speech-in-noise performance has been linked to individual differences in WM capacity, with larger WM capacity being related to better speech-in-noise performance (Lunner, 2003). The RS test is widely used to quantify the WM capacity and is often the basis for separating participants into high and low WM groups (Lunner, 2003; Foo et al., 2007; Souza et al., 2010; Rudner et al., 2011; Arehart et al., 2013). For this reason, we aimed at providing knowledge regarding the distribution of (Danish) RS scores and its relation to hearing loss, age, and speech-in-noise performance. Specifically, we investigated the relationship between RS score and speech-in-noise performance when presenting spatially separated and co-located sounds.

Results and discussion

The scores resulting from the RS test completed by 283 participants were normally distributed, but with a low mean value of 41.9%, indicating a high test difficulty. With each correctly-recalled word accounting for 1.85% of the total RS score, the score-distribution was sensitive to small changes in recall performance: Compared to the 50th percentile (corresponding to 23 correctly recalled words), only three additional words out of 54 targets, had to be recalled to reach the 75th percentile. This suggests that small variations in the individuals RS scores can have a large impact on the separation of participants into high and low WM groups.

A multiple-regression analysis showed that age ($p < 0.001$), but not hearing loss ($p = 0.290$), significantly affected the RS score. This is in accordance with previous studies promoting cognitive decline with increasing age (Salthouse and Babcock, 1991). From 168 participants having completed a Dantale II test with co-located sounds presented from a single loudspeaker, the SRT50-values decreased with poorer hearing ($p < 0.001$) and lower RS score ($p < 0.001$, **Table 2**). This confirms previous observations linking lower WM capacity to poorer speech recognition (Lunner, 2003; Foo et al., 2007; Ng et al., 2013), however for the first time in a large group of participants with varying degrees of hearing loss. For the 71 participants having completed the Dantale II test with spatially separated speech (from the front) and noise signals (from the sides and back), hearing loss ($p = 0.004$), but not RS

score ($p = 0.484$), influenced the SRT50-values (**Table 2**). This could indicate that the RS score inadequately captures the entirety of the WM capacity, or that processing spatially separated sounds rely on other cognitive factors such as attention (Neher et al., 2011).

Table 2: Effects of age, hearing loss, and WM capacity on speech recognition. Standardized (b^*) and un-standardized (b) regression coefficients showing the effects of PTA, RS score, and age on the SRT50-values from the two experimental setups (co-located and spatially separated sound sources). For each factor the p-values are provided and the significant effects are highlighted in bold writing.

	b^*	b	p
<i>Co-located speech and noise (N = 168)</i>			
PTA [dB]	0.385	0.079	<0.001
RS score [%]	-0.281	-0.103	<0.001
Age [years]	0.063	0.012	0.383
<i>Spatially separated speech and noise (N = 71)</i>			
PTA [dB]	0.381	0.131	0.004
RS score [%]	-0.085	-0.048	0.484
Age [years]	0.081	0.024	0.510

Paper II

Introduction and aim

During adverse listening conditions, higher cognitive load has been linked to an increase in the power of the neural alpha activity (Obleser et al., 2012). The aim of the current study was to investigate how hearing acuity and listening condition affected the alpha-power dynamics.

EEG was recorded during an auditory Sternberg task (**Figure 4**) in order to investigate the effect of memory load (number of digits), background-noise level, and hearing loss on the alpha oscillations. We expected to observe enhanced alpha power with increasing task difficulty, as well as worse hearing. However, it could be suspected that when increasing the task difficulty, the level of alpha power would reach an upper limit (ceiling), resulting in a breakdown in the alpha activity. This is in line with the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) stating that the recruitment of resources can reach a ceiling where activity decreases or stagnates when the task difficulty is increased, without necessarily affecting the task performance (Reuter-Lorenz and Cappell, 2008).

Results and discussion

The performance of the auditory Sternberg task significantly decreased with higher memory loads and noise levels (both $ps < 0.01$), but was generally high (mean 93.1%,

SD 8.0%). As intended, no effect of hearing loss was observed on the task accuracy ($p > 0.185$). To investigate the linear effect, as well as a possible breakdown/ceiling effect in alpha power with worse hearing, both rPTA and rPTA-squared were included as continuous predictors in the ANCOVA test.

Worse hearing was associated with higher alpha power suggesting that internal degradation result in higher WM involvement during speech processing ($p = 0.048$, **Figure 6A**). Significant effects of noise level were seen in interaction with rPTA-squared ($p = 0.004$, **Figure 6B**) and in a three-way interaction with memory load ($p = 0.042$, **Figure 6C**).

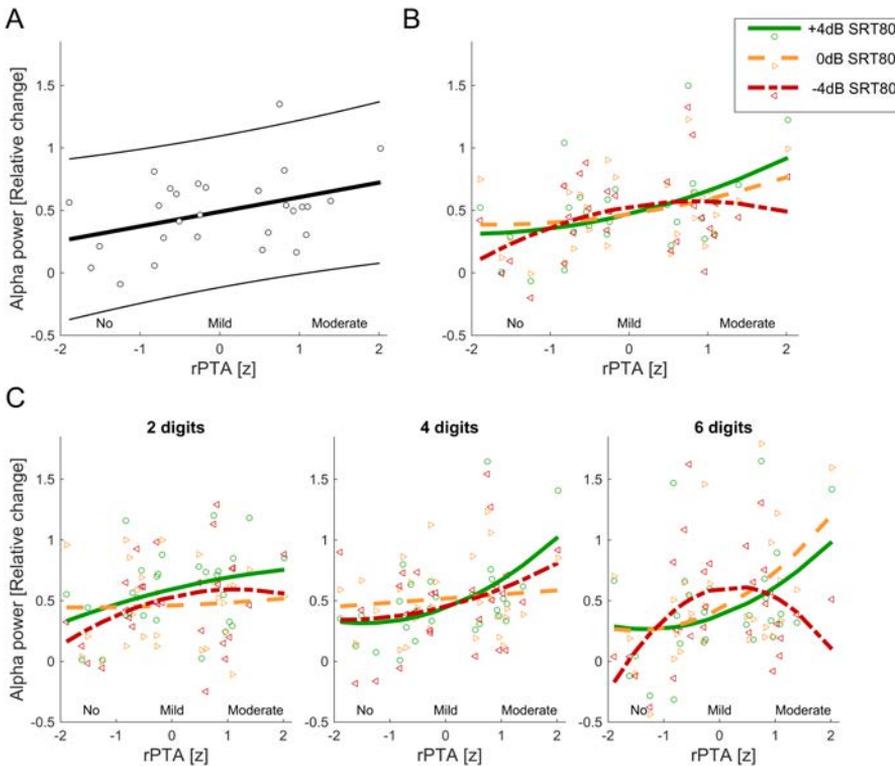


Figure 6: Effects of hearing loss on alpha power. (A) Significant linear effect of hearing loss (rPTA) on alpha power ($p = 0.048$). The least-square regression line (bold black line) and 95% confidence interval of the regression (thin black lines) are shown. Hearing ability (no, mild hearing loss, and moderate hearing loss) is indicated on the x-axis. (B) Two-way interaction between rPTA-squared and noise level (green solid lines and circles: +4dB SRT 80, orange dashed lines and right-pointing triangles: 0 dB SRT80, red dash-dotted lines and left-pointing triangles: -4 dB SRT80). Lines show the least-squares quadratic fits between alpha power and rPTA for each of the three noise levels. (C) Three-way interaction between rPTA-squared, background-noise level, and memory load (2, 4, and 6 digits shown in individual panels).

The three-way interaction showed an increase in alpha power with worse hearing when remembering two and four items for all three noise levels (**Figure 6C**). When having to remember six items, alpha power increased with worse hearing for the more favourable noise levels (+4 and 0 dB SRT80). During the most difficult noise level (-4 dB SRT80), alpha power increased for participants with normal to mildly impaired hearing, whereas a breakdown in alpha power was observed for participants with moderate hearing loss (**Figure 6B–C**). This suggests that in the most difficult condition, participants suffering from worse hearing reach a ceiling where the alpha activity cannot be further enhanced. We suggest that, like aging, the effect of hearing loss complies with the CRUNCH theory as more WM resources are engaged resulting from the loss of hearing (Reuter-Lorenz and Cappell, 2008; Schneider-Garces et al., 2010; Grady, 2012). Under increasing WM demands, the recruitment of resources reaches a ceiling and activity decreases (Reuter-Lorenz and Cappell, 2008).

Paper III

Introduction and aim

Several studies have found that the neural activity in younger normal-hearing listeners track the envelope of attended speech better than that of to-be-ignored speech (Horton et al., 2013; Kong et al., 2014; O’Sullivan et al., 2015). The aim of the current study was to investigate how the degree of hearing loss in elderly listeners affected the neural tracking of to-be-attended and to-be-ignored speech. Furthermore, the effect of manipulating the SNR between the competing talkers on the neural tracking was investigated. We hypothesized that listeners with worse hearing would show reduced neural tracking of both the attended and ignored speech. When improving the SNR-level between the two talkers, a stronger tracking of the attended speech and weaker tracking of the ignored was expected.

Results and discussion

The degree of neural tracking during the competing-talker task was quantified by cross-correlating the pre-processed EEG with the time-aligned speech-onset envelope of the attended and ignored talker. A control condition was generated by cross-correlating the EEG with a non-time aligned segment of the attended speech.

Besides showing significant neural tracking of both attended and ignored speech (significant time-lag interval indicated by blue and red horizontal bars in **Figure 7A**, respectively), the elderly participants generally exhibited attentional modulation, i.e., better tracking of the attended than the ignored speech ($p < 0.001$, black horizontal bar in **Figure 7A**).

The attentional modulation decreased with worse hearing ($r = 0.542$, $p = 0.004$), specifically caused by a change in the tracking of ignored ($r = -0.515$, $p = 0.006$), but not attended speech ($r = 0.096$, $p = 0.633$, **Figure 7B**). Note that the cross-correlation values in **Figure 7B** are averaged across the time-lag and electrodes showing attentional modulation, hence the magnitude of the cross-correlation coefficients does not signify the strength of the neural tracking. A multiple regression analysis revealed that the individualized SNR-levels did not significantly influence the neural tracking of ignored speech (main and interaction effect with rPTA, both $ps > 0.4$). This observation indicates that hearing loss deteriorates the ability to inhibit the ignored talker.

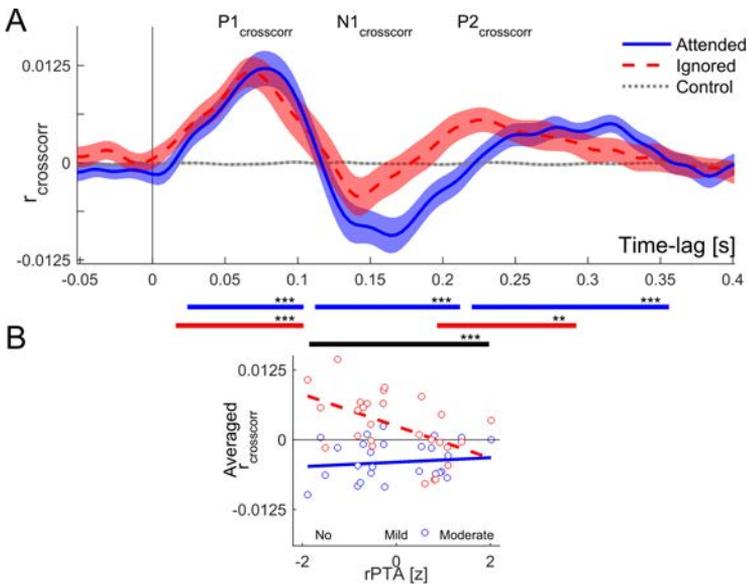


Figure 7: Neural tracking of speech-onset envelope and the effect of hearing loss. (A): Lines and shaded areas respectively show the grand-average and 95% confidence interval of the cross-correlation between the speech-onset envelope and the EEG across averaged across all participants ($N = 27$) for attended speech (blue solid line), ignored speech (red dashed line), and control condition (grey dotted line). The horizontal bars below the responses indicate the time-lags at which the attended (blue, top), ignored (red, middle), and attended-ignored (black, bottom) conditions differed significantly from the control condition. Asterisks indicate the p -value for each cluster ($*** p < 0.001$, $** p < 0.01$). **(B)** The relationship between hearing loss and the neural tracking of attended (blue circles and solid line) and ignored (red circles and dashed line). The degree of hearing loss is indicated on the x-axis. For each of the talkers, the cross-correlation values ($r_{\text{crosscorr}}$) were averaged across the time-lag and electrodes showing significant attentional-modulation (black cluster in (A)). Hearing loss ($r\text{PTA}$) was significantly related to the tracking of ignored ($p = 0.006$), but not attended speech ($p = 0.633$).

Increasing the background-noise level reduced the tracking of attended speech within two time-lag and electrode intervals (both $ps < 0.05$, **Figure 8**), while it did not affect the tracking of ignored speech (all $ps > 0.36$). Looking at the individual differences in neural tracking between the quiet to the most difficult noise condition (-4 dB SRT80), it was observed that participants with worse hearing had a smaller increase in the tracking of attended speech when the listening condition improved ($p = 0.042$).

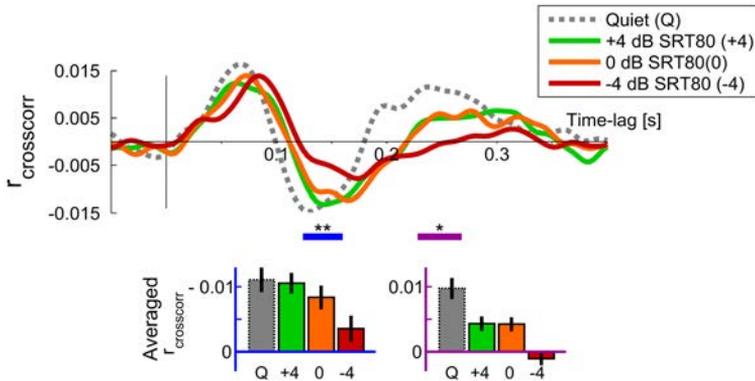


Figure 8: Effect of background-noise level on neural tracking of attended speech. The blue and purple horizontal bars in the upper graph indicated the time-lag interval during which a significant linear increase in neural tracking of attended speech was observed with improved background-noise levels (-4 , 0 , and $+4$ dB SRT80, $** p < 0.01$, $* p < 0.05$). The quiet condition was not included in the statistical analysis, but shown with dotted lines in the figure for comparison. In the two lower graphs, the average cross-correlation coefficients for each noise level (quiet in grey, $+4$ dB SRT80 in green, 0 dB SRT80 in orange, and -4 dB SRT80 in red) with the error bars indicating standard error of the mean (SEM). The color of the lower-plot axis indicates from which of the two clusters (blue and purple horizontal bars in the upper graph) the cross-correlation coefficients have been extracted. Note that the y-axes are reversed.

In summary, the study shows that elderly listeners, similar to younger normal-hearing listeners (Horton et al., 2013; Kong et al., 2014; O’Sullivan et al., 2015), exhibit neural speech-tracking. However, the ability to assert attentional modulation was affected by the degree of hearing loss. Secondly, our observations indicate that internal and external sound degradation affected the tracking of attended and ignored speech independently. This observation supports the theory that attended and ignored speech are processed as separate auditory objects (Shinn-Cunningham, 2008; Simon, 2015).

General Discussion

In three empirical studies, the present thesis investigated the overall hypothesis that more internal and external degradation of the auditory signal would result in increased WM activation. In the following chapter, the main observations of the empirical studies will be discussed. An overview of the hypotheses and results of Paper I–III is provided in **Table 3**. To reinforce and elaborate on some of the observations made in the three studies, results from new analyses will be presented in this discussion. New statistical results will be marked with a superscripted asterisk (*) and a corresponding footnote.

Neural speech processing is affected by hearing loss

The neural measures of speech processing, showed that worse hearing was associated with a general increase in alpha power (Paper II) and a reduction in attentional modulation (Paper III). Although both alpha activity and attentional control relate to inhibition, they serve different purposes: Alpha activity serves to inhibit processes and brain regions not related to speech processing, while attentional modulation relates to inhibition of auditory objects as part of the speech processing.

The current thesis provides some of the first neural evidence that the degree of hearing loss linearly relates to increased cognitive load (alpha power, Paper II) during speech processing. The change in alpha power with worse hearing was observed despite equal task accuracy across listeners, illustrating how neural measures are advantageous in not requiring performance differences to establish condition or group effects. It is interesting to note that the effect of hearing loss on alpha power was observed during the retention period (c.f., **Figure 4**) where listeners had to memorize the presented digits, but where no stimuli was presented. Hence, the effects of hearing loss and listening conditions on the alpha activity were not directly evoked by the properties of the stimuli such as individual differences in noise levels and hearing-aid amplification. The increase in alpha power was found over the centro-parietal region. As WM processing is often related to activity in the pre-frontal lobe (McNab and Klingberg, 2008), the centro-parietal region can be considered task-irrelevant and the observation is thus in accordance with the functional inhibition theory (Jensen and Mazaheri, 2010).

Worse hearing was also associated with poorer attentional modulation, more specifically a reduced ability to inhibit ignored speech (**Figure 7B**, Paper III). Since hearing loss affects the cochlear coding of the speech mixture, we expected to find a decrease in the neural tracking of both speech signals with worse hearing (**Table 3**). Although only partly confirming this hypothesis, the observations are in line with

Table 3: Overview of the hypotheses and corresponding observations made in the three papers. Bold writing indicates that the initial hypothesis was confirmed by the empirical study. All other hypotheses were not, or only partly, confirmed.

Paper	Hypothesis	Observation
I	WM capacity decrease with age, but is not affected by hearing ability	The RS score significantly decreased with age, but was not related to PTA
	Speech recognition decrease with worse hearing and lower WM capacity	Speech recognition of spatially co-located sounds decreased with higher PTA and lower RS score
		Speech recognition of spatially separated sounds decreased with higher PTA, but was not affected by the RS score
II	Listeners with worse hearing have a higher cognitive load during speech processing	Alpha power increased linearly with rPTA
	External degradation (background-noise level and memory load) cause higher cognitive load during speech processing	Alpha power was only affected by background-noise level and memory load in interaction with rPTA-squared
	For the most difficult listening conditions, the alpha power could exhibit a breakdown behaviour	For the conditions -4 dB SRT80 and 6 digits at -4 dB SRT80, listeners with higher rPTA exhibited an alpha-power breakdown
III	Worse hearing is associated with reduced neural tracking of attended and ignored speech	Higher rPTA affected the attentional modulation by reducing the inhibition of ignored speech. Tracking of attended speech was not affected by rPTA
	Less background noise result in improved neural tracking of attended speech and reduced tracking of ignored speech	Tracking of attended speech increased linearly with less background noise. Tracking of ignored speech was not affected by noise level
		Reducing the noise level improved the tracking of attended speech, but this improvement decreased with higher rPTA

the theory that separate speech streams are encoded as independent auditory objects and that hearing loss affects the ability to selectively asserted attention towards a specific object (Shinn-Cunningham and Best, 2008). The observed effect of hearing loss can reasonably be related to behavioural studies showing that increasing age disrupts selective attention, as the ability to inhibit irrelevant information degrades (Hasher and Zacks, 1988; Hasher et al., 2008). With the notion made by Hasher and colleagues, that “*narrowing the focus (of attention) occurs in the face of an individual’s internal and external content*” (Hasher et al. 2008, page 241), we suggest that hearing loss, like aging, alter the internal content/degradation and cause less efficient inhibition of irrelevant speech.

In combination, the observations of Paper II and III could suggest that with worse hearing, the inability to inhibit irrelevant speech cause additional WM activation, inducing an increase in alpha activity during retention of auditory stimuli. Despite being close to significant, a Pearson’s correlation could not confirm a direct relation between alpha power and attentional modulation ($r = 0.345$, $p = 0.084$)*.

Although the neural effects of hearing loss observed in Paper II and III generally complied with our hypotheses (Table 3), it could be argued that the observations were biased by the individualization of the background-noise levels, altering the properties of the auditory stimuli between listeners. The following section will provide a more elaborate discussion on this potential bias.

The confounding relationship between background-noise level and hearing loss

To ensure that neural effects of hearing loss were not induced by differences in task performance, the background-noise levels were individualized. As intended, neither the performance of the auditory Sternberg task (Paper II), nor the competing-talker task (Paper III) were affected by the degree of hearing loss. However, individualization of the noise levels creates an inherent confound between hearing loss and the physical property of the auditory stimuli (SNR-level). In the following section, it will be argued that the individual differences in SNRs, specifically the SRT80-values, were not causing the effects of hearing loss observed in Paper II and III.

The increased alpha power (Paper II) and reduced attentional modulation (Paper III) observed with worse hearing oppose the effects expected from lowering the background-noise levels (higher SNRs). Less external degradation of the auditory signal would be expected to cause a decrease in alpha power and a stronger attentional modulation. Additionally, a multiple regression analysis revealed that

* Results have not previously been presented

rPTA, but not SRT80-values, significantly affected the degree of attentional modulation (Paper III). A multiple regression between alpha power, rPTA, and SRT80-values was not significant ($p = 0.134$)*. A simple Pearson's correlation showed no linear relation between alpha power and the SRT80-values ($r = 0.314$, $p = 0.103$)*. Finally, it is important to note that although hearing loss and speech recognition were highly correlated they are not interchangeable in our studies. Factors such as the WM capacity can influence the SRT80-value independent of hearing loss (Paper I). Indeed, RS scores obtained from the participants in Paper II and III showed significantly poorer speech recognition for listeners with lower WM capacity ($r = -0.377$, $p = 0.048$)*. As such, individualizing the background-noise levels controlled for differences in speech recognition caused by hearing loss, as well as WM capacity.

Specifically for Paper III, it could be argued that at positive SNRs, when a majority of the energy in the speech mixture stems from the attended speech, attentional modulation cannot be claimed. As the SNR-levels applied in the competing-talker experiment were mainly positive, it is possible that the level-difference between attended and ignored speech caused the observed attentional modulation (**Figure 7A**). However, this notion assumes that all participants have the same internal representation of the sound stimuli, i.e., that the SNR of the speech mixture is equivalent to the SNR experienced after the stimuli has entered the auditory pathway. The significantly higher SRT80-values seen for listeners with worse hearing, indicate that the internal representation of SNR changes with the degree of hearing loss. To prove that attentional modulation was also present at negative SNR-values, the difference in neural tracking of attended and ignored speech from 16 listeners were re-analysed. Having SRT80-values below 4 dB SNR, these 16 participants were subjected to listening conditions with negative SNR-values in the competing-talker task. The statistical analysis showed significant attentional modulation in the tracking of speech presented at negative SNRs within the time-lag interval 168–260 ms (70 electrodes, $p < 0.001$)*. This significant cluster overlaps with the temporal and spatial extension of the attentional modulation observed across all listeners and SNR-levels (time-lag 108–232 ms, black bar in **Figure 7A**). Hence, we deem it reasonable to assert that the attentional modulation observed in Paper III was not caused merely by the presentation of sound stimuli at mainly positive SNR-levels.

Neural effects of altering the background-noise levels

Besides the degree of hearing loss, Paper I and II also investigated the neural effects of varying the background-noise level. Different degrees of external degradation

* Results have not previously been presented

was obtained by creating three background-noise levels based on the individual SRT80-values (+4, 0, and -4 dB SRT80). As a change in the level of background noise proved to have very different effects on the alpha power and the neural speech tracking, the observations of Paper II and III will be discussed separately in the following.

Background-noise level and hearing loss influence alpha power

In the auditory Sternberg task (Paper II), the alpha power was affected by the background-noise level only in interaction with the quadratic term of hearing loss (rPTA-squared, two-way interaction), and in a three-way interaction with memory load. As shown in **Figure 6B–C**, alpha power generally increased with worse hearing during easier conditions, reaffirming the hypothesis that listeners with worse hearing require recruitment of additional WM resources during speech processing. Participants with mild to moderate hearing loss exhibited a breakdown/stagnation during the most difficult noise level (-4 dB SRT80). This inverse U-shaped relationship between alpha power and hearing loss suggests that participants with moderate hearing loss reached an upper limit at which no additional neural resources could be released through inhibition, hence a breakdown in alpha power was observed.

A similar breakdown in neural activity has previously been observed in fMRI-studies investigating the effect of aging (Reuter-Lorenz and Cappell, 2008; Schneider-Garces et al., 2010). According to the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH), aging causes increased neural activity at lower task difficulties (Reuter-Lorenz and Cappell, 2008; Grady, 2012). When the task difficulty is raised, the neural activity increase for younger adults, while older adults reach an upper limit (ceiling) in the generation of activity, i.e., a breakdown is observed (Reuter-Lorenz and Cappell, 2008; Grady, 2012). It should be noted that this activity breakdown is not always accompanied by poorer task performance (Reuter-Lorenz and Cappell, 2008). We propose that worse hearing, similar to increasing age, cause a breakdown in the neural activity, due to a higher level of activation at lower task difficulties.

An illustration of how the CRUNCH theory can explain the observed effect of hearing loss on alpha power is shown in **Figure 9** (adapted from Grady (2012)). With increasingly worse hearing, listeners engage their WM resources at lower task difficulties, causing a shift in the relationship between task difficulty and alpha activity. At a low task difficulty (green dashed line in **Figure 9**, illustrative of the +4 and 0 dB SRT80 conditions), this results in a linear increase in alpha activity with worse hearing (right bottom graph in **Figure 9**). Listeners with worse hearing reach the upper limit (ceiling) of how much alpha power can be generated at a lower task difficulty (magenta dash-dotted line in **Figure 9**, illustrative of the -4 dB SRT80

condition) compared to better hearing listeners, resulting in an alpha-power breakdown (right top graph in **Figure 9**).

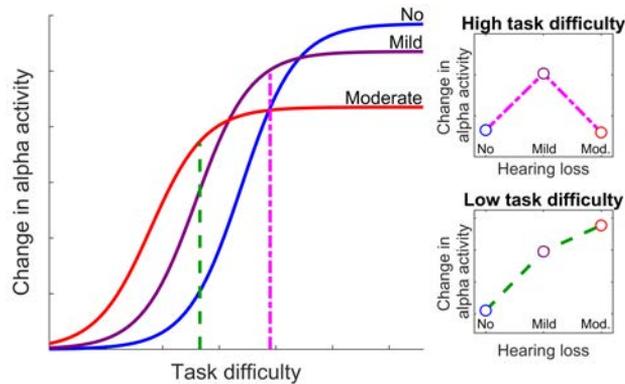


Figure 9: Illustration of the theoretical relation between alpha activity and hearing loss according to CRUNCH. The figure is adapted from Grady (2012). **Right:** The change in alpha activity with increasing task difficulty for listeners with no (blue), mild (purple), or moderate/mod. (red) hearing loss. The green dashed and magenta dash-dotted lines indicate points of low and high task difficulty, respectively. **Left:** The relationship between hearing loss and alpha activity during high (top, magenta) and low (bottom, green) task difficulty.

The fact that the alpha-power breakdown was not accompanied by a reduced task accuracy for listeners with worse hearing could be explained by these listeners adopting a different task-solving strategy. Moreover, the task accuracy might have been on the verge of breaking down for participants with worse hearing. As illustrated with the magenta dash-dotted line in **Figure 9**, if participants were tested just as they reach their upper alpha-power threshold, it might not have been accompanied with a decline in task performance. Had the task difficulty been higher, it is possible that the breakdown in alpha power would have been accompanied by a decrease in task accuracy.

Neural speech tracking of attended speech affected by background-noise level

In Paper III, it was observed that hearing loss and background-noise level affected the neural tracking of ignored and attended speech, respectively. Although this complies with the view that attended and ignored speech are neurally processed as separate auditory objects, it is interesting that hearing loss and background noise affected the two objects so independently. Re-analysing the cross-correlation coefficients from the time-lag and electrodes showing an effect of hearing loss (**Figure 7A**) showed no significant effect of noise level for either of the speech

streams (ANOVA, all $ps > 0.19$)*. Likewise, no influence of hearing loss was found within the two clusters showing effects of the background noise (**Figure 8**, Pearson's correlation, both $ps > 0.15$)*. These results indicate that hearing loss and background-noise levels are indeed affecting the two auditory objects (attended and ignored speech) independently.

Most previous studies have reported no effect of altering the background-noise level on the neural speech tracking of attended speech in younger (Ding and Simon, 2012a; Kong et al., 2014), as well as older (Presacco et al., 2016) listeners. However, the gain-control mechanism argued to cause this robust neural tracking of attended speech (Simon, 2015), could potentially be compromised by the presence of a hearing loss or the individualization of background-noise levels.

It should be noted that changes in the background-noise levels only affected neural tracking in two short time-lag intervals (**Figure 8**). In comparison, the significant effect of hearing loss was observed within the larger time-lag interval showing attentional modulation (**Figure 7A**). This suggests that external degradation of the speech signal had a smaller impact on the neural tracking than the internal degradation caused by the loss of hearing. Furthermore, the applied exhaustive-search cluster-based statistical approach is potentially more sensitive to changes in the level of background noise than analysis of the neural-tracking response peaks (Ding and Simon, 2012a; Kong et al., 2014) and the cross-correlation between the reconstructed and presented speech stimuli (Presacco et al., 2016).

The interaction between hearing loss and background-noise level on the tracking of attended speech was investigated by looking at the change in neural speech tracking between the quiet and most difficult noise condition (-4 dB SRT80). When improving the listening condition, participants with worse hearing exhibited a smaller increase in the tracking of attended speech than better-hearing listeners. This indicates a reduced sensitivity to changes in the SNR with worse hearing. Considering that the neural tracking of attended speech in older listeners improved more than that of younger when reducing the spectro-temporal degradation of the auditory signal (Presacco et al., 2016), it might have been expected that listeners with worse hearing would experience a larger benefit from reducing the external degradation. However, a previous study has observed a similar reduced sensitivity towards improvements in the speech intelligibility in the pupil-data of elderly hearing-impaired listeners compared to younger and age-matched normal-hearing listeners (Zekveld et al., 2011). Zekveld and colleagues suggested that the observation could result from speech processing being more superficial for the listeners with worse hearing (Zekveld et al., 2011). Whether poorer semantic processing caused the reduced benefit of improving the noise level with worse

* Results have not previously been presented

hearing observed in Paper III, could potentially be investigated in the neural tracking of phonemes and phonetic information. Indeed, a recent study has shown that the neural activity during speech processing is best described when including both low-level spectro-temporal information and high-level categorical phonetic features of the auditory input (Di Liberto et al., 2015).

Taken together, both alpha power and attended speech tracking were affected by an interaction between hearing loss and background-noise level. This indicates that hearing loss not only affects neural speech processing on its own, but also poses additional detriments in relation to external degradation. Indeed, despite providing adequate hearing-aid compensation, the internal degradation caused by the loss of hearing is still present, resulting in increased WM involvement during speech processing.

Behavioural and neural findings support the ELU-model

In a larger scope, the observations made in the current thesis generally complied with the existing theoretical framework of the ELU-model (Rönnberg et al., 2008, 2013). The ELU-model describes how worse hearing ability (internal degradation) and lower WM capacity have a negative effect on speech processing and recognition (external degradation).

In line with this, it was observed that worse hearing and lower WM capacity was associated with poorer speech recognition when sound sources were spatially co-located (Paper I). This confirms the findings of multiple previous studies (Lunner, 2003; Foo et al., 2007; Lunner and Sundewall-Thorén, 2007; Neher et al., 2009; Souza et al., 2010; Rudner et al., 2011; Ng et al., 2013). Although hearing loss (PTA) and WM capacity (RS score) were statistically unrelated, the two factors explained 22.6% of the variance in the speech-recognition performance. As Paper I included a large group (N = 168) of listeners with a wide range of hearing acuity and age, originating from multiple studies testing different hearing-aid types, it is expected that the observed percentage of explained variance was lower than that reported in otherwise comparable studies (Lunner, 2003; Foo et al., 2007, both with adjusted R-squared > 37%).

Interestingly, our neural observations also complied with the ELU-model in that the degree of hearing loss was linearly related to increased cognitive load (alpha power) during speech processing (**Figure 6A**, Paper II). This observation is in line with the theoretical view that with worse internal degradation, speech processing gradually becomes more WM-driven. Also the observation that hearing loss is associated with poorer attentional modulation (Paper III) supports the ELU-model

in that explicit processing rely on the ability to inhibit irrelevant information (Rönnberg et al., 2013). Opposed to the traditional approach of examining the correlations between behavioural results for establishing effects of hearing loss, neural responses allow for more complex statistical testing of group and condition effects. Indeed, the breakdown in alpha activity with worse hearing under the most difficult listening conditions indicates that a finite WM-processing capacity was reached (**Figure 6B–C**, Paper II).

Not all observations in the current thesis complied with the ELU-model: No significant effect of WM capacity was found on the speech recognition when sounds were spatially separated (**Table 2**, Paper I). Two (Neher et al., 2011; Zekveld et al., 2014) out of three studies (Neher et al., 2009) investigating the relationship between the RS score and speech understanding of spatially separated sounds, similarly observed no relation between the two. In one of the studies, a significant effect of attention was found on the speech recognition (Neher et al., 2011). If attention and WM processing are independent functions, or if the RS test inaccurately captures the WM capacity, this could explain the non-significant effect of RS score observed in Paper I.

The WM was initially believed to automatically allocate resources for storage when less processing was performed (Daneman and Carpenter, 1980). In a more recent theory, WM is regarded as being controlled by attention, such that better WM capacity results in better protection of the stored information from distractors (Kane and Engle, 2000; Kane et al., 2001; Hasher et al., 2008). Specifically regarding the RS test, it has been argued that the performance score only partly reflects attention control, activated during the retrieval of the to-be-remembered target words, but not during the visual presentation of the sentences (Cowan et al., 2005). This suggests that the RS score does not capture the entirety of the WM capacity which could result in inconsistent observations in the relationship between RS score and speech recognition (Paper I; Zekveld et al. 2014; Neher et al. 2011; Neher et al. 2014; Koelewijn et al. 2014).

Within the field of psychoacoustics, the influence of WM processing has traditionally been investigated by examining the overall correlation between (reading) span scores³ and speech recognition. However, as outlined above, this relationship might not be as well understood as previously assumed. Interestingly, both the effects of hearing loss on alpha power (Paper II) and neural speech tracking (Paper III) complied with the framework of the ELU-model, encouraging the usage of neural markers to investigate the effects of hearing loss on speech processing.

³ A variety of ‘span’ tests exist (reading span, digit span, listening span, size comparison span), all aiming at quantifying the WM capacity

Methodological considerations

In the current thesis, participants with different degrees of hearing loss were included and the PTA/rPTA-values used a regressor in the statistical analyses. This method oppose the more traditional approach of testing hearing-impaired listeners against a group of normal-hearing (age-matched) participants. Unfortunately, we did not manage to adequately control for the effect of age on hearing loss in the recruitment of participants for Paper II and III. The significant relationship between age and PTA_{skHz} was accounted for by quantifying hearing loss as the residualized PTA (rPTA, **Figure 3**). However, from a clinical perspective it could be argued that it does not make sense to separate hearing loss from its common predictor, namely age. Considering that our aim was to investigate the effect of hearing loss and knowing that aging affects neural processing, we deemed it reasonable to generate a measure of hearing loss independent of age.

Estimating the individual noise levels based on the SRT80-values of a HINT test pose a limitation. As the HINT test incorporates a different speech material and noise masker than those applied in the EEG-experiments, speech-recognition performance could be significantly different between tasks, potentially affecting the neural measures. Furthermore, as indicated in **Figure 5**, the calculation of the flanking noise conditions (+4 and -4 dB SRT80) by adding and subtracting 4 dB from the SRT80-value introduced an inaccuracy by not accounting for the slope of the individuals' psychometric function. During the auditory Sternberg experiment, the task accuracy was higher than expected (mean 93.1%, SD 8.0%) and importantly showed no effect of hearing loss (Paper II). The accuracy was likely improved by limiting the stimuli to a closed set of single-syllable digits. In Paper III, the noise masker (HINT test) was changed to a competing opposing-gender talker. Such a change has been shown to improve speech recognition at SRT50 for younger normal-hearing listeners, while not influencing the speech recognition for elderly hearing-impaired listeners (Festen and Plomp, 1990). Hence, it is possible that the speech recognition was unintentionally improved for the better-hearing listeners by introducing a female competing talker. Although the performance metric in Paper III was sparse, we observed an above-change performance, which was not influenced by rPTA. This indicates that hearing loss did not affect the speech understanding during the two EEG-experiments.

All participants were wearing hearing aids during the experiments, independent of their degree of hearing loss and hearing-aid experience. It has been suggested that hearing-aid experience affects behavioural (Tremblay and Moore, 2012) and neural measures (Bertoli et al., 2011) of speech processing, although inconsistent neural effects of acclimatization have been reported (Dawes et al., 2014). Most listeners in Paper I were hearing-aid users, although with unknown hearing-aid experience. In Paper II and III, participants with worse hearing were generally

wearing hearing aids, whereas listeners with no to mild hearing loss were less likely be hearing-aid users. As none of the participants were daily users of the particular hearing aid used in the studies, it is not suspect that auditory acclimatization affected our results.

Similarly, it could be speculated whether the hearing-aid processing affected the neural outcome measures. The applied quasi-stationary amplification scheme ensured a near-linear gain for all participants to circumvent interaction-effects between amplification and hearing loss to influence the neural and behavioural measures. However, the amplification scheme itself could also affect the results. For example, Humes (2007) used a strategy not implemented in current hearing aids to carefully amplify sounds up to 4 kHz, reducing the effect of hearing loss on speech recognition, while the impact of cognition increased. In the current thesis, it could be speculated whether such an amplification approach could have caused a reduction in external degradation, e.g., such that a breakdown in alpha power with worse hearing would not have occurred (Paper II). In the current thesis, we were interested in establishing how hearing loss affected speech processing in an 'every-day'-like listening scenario. As hearing aids are the best way of ensuring audibility outside the laboratory, it was chosen to provide hearing-loss compensation using state-of-the-art hearing aids.

Concluding Remarks and Future Directions

This thesis set to investigate how hearing loss (internal degradation) and listening condition (external degradation) influenced speech processing by examining behavioural (Paper I) and neural measures (Paper II and III) thereof. Across three studies, we found evidence for our hypothesis: That internal and external degradation of the auditory signal result in higher WM activation during speech processing.

For many years, psychoacoustic experiments (Paper I) have been the golden standard for establishing the influence of hearing loss and hearing-loss compensation on speech understanding. Although the findings in Paper I are not consistent between experimental conditions (spatially separated and co-located sounds), the results indicate that WM capacity and hearing loss influence speech recognition. Within recent years, more studies have focused on neural measures of speech processing as a tool for understanding the cognitive mechanisms behind the behavioural observations. Indeed, neural measures can be successfully applied to investigate group and condition effects on speech processing, even when no differences in behavioural task-performance is observed (Paper II and III).

The current thesis expands the knowledge regarding the impact of hearing loss on induced neural activity during speech processing. The novel observations that listeners with worse hearing generally experience a higher cognitive load (Paper II) and reduced inhibition of ignored speech (Paper III), provide the first evidence of a linear relationship between the degree of hearing loss and neural speech processing. Our observations are in line with previous behavioural evidence indicating that listeners with worse hearing have a higher degree of WM involvement during speech processing. This highlights the well-known fact that state-of-the-art hearing-aid amplification cannot restore normal hearing.

Worse hearing was associated with an alpha-power breakdown under the most difficult listening conditions (Paper II), suggested by the CRUNCH theory to arise from a generally higher cognitive load during lower task difficulties. To study the nature of the activity breakdown, it would be interesting to examine the alpha-power behaviour across a larger span of task difficulties, speech materials, and listening tasks. Indeed, by implementing a competing-talker experiment, it would be possible to relate change in alpha power (Paper II) to the degree of attentional modulation (Paper III) and hearing loss to establish how the three measures interact.

In the competing-talker experiment in Paper III, worse external and internal degradation affected the neural tracking of attended and ignored speech, respectively. These results indicate that the auditory objects were independently processed, thus making internal and external degradation able to affect them

separately. Interestingly, interactions between the degree of hearing loss and the level of background noise influenced both the alpha activity (Paper II) and the neural speech tracking (Paper III), underpinning how noisy listening situations are especially detrimental for listeners with poorer hearing.

The neural measures investigated in the current thesis could also act as guidelines in the development and testing of new hearing-aid algorithms. For example, as hearing loss was observed to reduce the inhibition of ignored speech (Paper III), listeners with worse hearing might benefit more from noise-reduction algorithms removing irrelevant sounds, than algorithms enhancing the relevant speech. In addition, changes in the alpha activity could potentially serve to quantify whether a hearing-aid feature improves speech processing by causing a decrease in alpha power.

An even more futuristic direction is the potential application of neural measures for real-time adjustments of hearing-aid settings. For such a scenario to be feasible, we have showed that reliable EEG could be recorded from electrodes positioned on the in-the-ear part of a hearing aid (EarEEG, see Appendix 1). Upon detecting changes in the degree, timing, or hemispheric distribution of neural activity, hearing-aid processing could be adapted accordingly. This has been suggested in the three patent applications arising from the current work, see Patents and patent applications. However, before such real-time application of EarEEG is possible, the effect of hearing loss on relevant neural measures must be understood (Paper II and III). For this purpose, the current thesis provides valuable insights by showing that hearing loss affects neural speech processing both on its own and in interaction with the external sound environment.

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Papers

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