The Facilitation of Perceptual Processing by Auditory-Visual Speech and the Subsequent Effect on Working Memory in Older Adults with Hearing Loss or Cognitive Impairment

Jana Baranyaiova Frtusova

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By: Jana Baranyaiova Frtusova

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Chair
Dr. C. DeWolf

External Examiner
Dr. M. Rudner

External to Program
Dr. B. Grohmann

Examiner
Dr. A. Johnson

Examiner
Dr. K. Li

Thesis Supervisor
Dr. N. Phillips

Approved by:
Dr. A. Arvanitogiannis, Graduate Program Director

November 20, 2014 Dr. A. Roy, Dean, Faculty of Arts & Science

ABSTRACT

The facilitation of perceptual processing by auditory-visual speech and the subsequent effect on working memory in older adults with hearing loss or cognitive impairment

Jana Baranyaiova Frtusova, Ph.D.

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It has been proposed in the literature that if too many processing resources need to be devoted to perception then higher-order cognitive functions, such as working memory (WM), may suffer. This effect may be particularly evident in individuals who have restricted processing resources, such as older adults (OA) suffering from hearing loss or cognitive impairment. One possibility to facilitate perception during speech processing is through the auditory-visual (AV) modality. The current research examined whether AV speech perception helps to facilitate perceptual and WM processing in OAs with restricted processing resources. In both studies, participants completed a WM *n*-back task under different speech modalities: AV, auditory-only, or visual-only (Study 1). Both behavioural and event-related potentials (ERPs) measures were collected during the task.

Study 1 examined the effect of AV speech on WM in OAs with hearing impairment compared to normal-hearing OAs. The results showed that AV speech in comparison to auditory-only speech led to facilitated perceptual processing in OAs with hearing impairment, as indicated by ERP responses. The AV modality also led to facilitated WM functioning in both groups, as suggested by ERP responses and behavioural reaction time.

A few measures indicated that visual speech cues may have helped OAs with hearing impairment to counteract the demanding auditory processing.

Study 2 examined the effect of AV speech on WM in OAs suffering from mild cognitive impairment (MCI) or Alzheimer disease (AD) compared to cognitively healthy OAs. The ERP responses showed that the AV modality compared to the auditory-only modality led to facilitated perceptual and WM processing in both groups. In addition, the behavioural results showed improved accuracy during the WM task for the patient group, and faster reaction time for both the patient group and the cognitively healthy control group.

Overall, the results showed that OAs with hearing or cognitive impairment benefit from AV speech in terms of improved WM performance. In fact, there were a few indications that the AV benefit may be even more robust in these groups than in cognitively healthy OAs. The theoretical and practical implications of these findings and directions for future research are discussed.

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CONTRIBUTIONS OF AUTHORS

The two studies that comprise this thesis were conceptualized by Jana Baranyaiova Frtusova with guidance from Dr. Natalie Phillips. The ideas for the studies were an expansion of our previous research examining the effect of auditory-visual speech in healthy younger and older adults (Frtusova, Winneke, & Phillips, 2013), the research idea that was originally conceptualized by Dr. Natalie Phillips with contributions from Jana Baranyaiova Frtusova and Dr. Axel Winneke. For the current projects, Jana Baranyaiova Frtusova edited the stimuli, recruited the participants, designed and conducted the experiments, and processed and analyzed the data. This was done under the supervision of Dr. Natalie Phillips. Other members of the Cognition, Aging, and Psychophysiology Lab contributed to participant recruitment, testing, and data processing. Jana Baranyaiova Frtusova and Dr. Natalie Phillips interpreted the results collaboratively. Jana Baranyaiova Frtusova wrote the first draft of both manuscripts, with a subsequent revision by Dr. Natalie Phillips. Throughout this thesis, the pronoun "I" refers to reflections by the author of the thesis, Jana Baranyaova Frtusova, whereas pronoun "we" refers to findings and interpretations of the results from the two studies co-authored by Jana Baranyaiova Frtusova and Dr. Natalie Phillips.

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LIST OF ABBREVIATIONS

AD	Alzheimer disease
A-only	Auditory-only
AV	Auditory-visual
A+V	Auditory + Visual
EEG	Electroencephalography
ELU	Ease of language understanding
EOG	Electro-occulogram
ERP	Event related potentials
fMRI	Functional magnetic resonance imaging
HIP	Hearing Impaired Participants
IVR	Interactive voice response
LNS	Letter-number sequencing
MCI	Mild cognitive impairment
MEG	Magnetoencephalography
MMSE	Mini-mental state examination
MSE	Mean square error
MoCA	Montreal Cognitive Assessment
NEC	Normal elderly controls
PET	Positron emission tomography
PiB	Pittsburg Compound-B
PolyRex	Polygraphic Recording Data Exchange
PTA	Pure tone average

RT	Reaction time
S/N	Signal-to-noise ratio
STS	Superior temporal sulcus
TTL	Transitor-transitor logic
V-only	Visual-only
WAIS-IV	Wechsler Intelligence Scale Fourth Edition
WM	Working memory

Chapter 1: General Introduction

Even during the most mundane tasks, our brain is exposed to multiple sources of information that need to be processed simultaneously. For example, during a simple task such as grocery shopping, we scan the aisles, search for needed items, track what we already have in our basket and what is still missing from our shopping list, and we listen to announcements about what is on sale that day. Despite the fact that our brain has an amazing cognitive capacity and that we are able to complete most of our daily activities without any difficulty, it has long been recognized that there is, nevertheless, a limit to our processing abilities (Baddeley & Hitch, 1974). In fact, this limit becomes increasingly restricted with age, and can be further reduced by neurodegenerative disorders and/or sensory decline. Although we may not be able to prevent these adverse events, we may be able to identify methods or conditions that facilitate our brain's functioning, so that the available resources are used more efficiently.

Speech is an important method of communication and social interaction. While we may take speech perception for granted, it actually represents a complex process that requires not only perceptual abilities but also several higher-order cognitive processes, including memory (Grant, Walden, & Seitz, 1998). Furthermore, in many social situations, speech perception occurs in less than ideal conditions due to distractions from background noise, which takes even more resources from our limited pool. In contrast, the presence of visual speech cues, such as face, lips, teeth and tongue movements, facilitate auditory speech perception and enhances working memory (WM) processing in both younger and older adults (e.g., Frtusova, Winneke, & Phillips, 2013; Pichora-Fuller, 1996). Thus, auditory-visual (AV) speech modality represents one possibility, which could make speech processing more efficient.

1.1 Organization of the Dissertation

The following dissertation examines the relationship between AV speech perception and higher-order processing, more specifically WM, in older adults who are at extra risk of exceeding their limited processing resources due to cognitive or hearing impairment. Chapter One explains the theoretical framework and introduces the background information on AV speech perception and its effects on WM. This is followed by a discussion of age-related changes in these functions. Further in the chapter, the background information on two populations investigated in this thesis, namely older adults with hearing impairment and older adults suffering from Alzheimer disease (AD) or mild cognitive impairment (MCI), is presented. The chapter concludes with a discussion of the event-related potentials (ERPs) methodology and its contributions to our understanding of multisensory processing as well as the overall summary and rational for the current research.

In Chapter Two, a manuscript describing a study that investigated the AV speech benefit in older adults with hearing impairment is presented. In Chapter Three, a manuscript describing a study that investigated the AV speech benefit in older adults with MCI and AD is presented. Finally, the last chapter discusses the overall results, limitations and implications of the findings from the two studies and presents suggestions for future research.

1.2 Theoretical Framework: An Integrated Perceptual-Cognitive System

The ideas in the current thesis are conceptualized under the theoretical framework that perceptual and cognitive functioning are parts of an integrated information-processing system, proposed by Schneider and Pichora-Fuller (2000). According to this framework, perception and cognition share a certain number of processing resources that can be flexibly reallocated during a task. This suggests that there is a strong reciprocal relationship between perceptual and cognitive processing and that putting a higher load on one part of the system can negatively impact the other parts. For example, the degradation of a sensory stimulus puts more demands on the perceptual system and consumes resources that could otherwise be available for higher-order cognitive tasks, such as memory. To illustrate this process, let's consider a conversation happening on a busy street; our brain needs to devote more resources to perceptual processing in order to distinguish speech signal from background noise and, thus, has less resources available for encoding the actual content of the conversation in our memory. In many situations, the brain has enough processing resources available to adequately complete both perceptual and higher-order functions. However, age-related and/or disease-related processes can negatively affect perception, cognition, or both and the reallocation of processing resources becomes especially important. As Schneider and Pichora-Fuller (2000) pointed out, the availability of a shared pool of processing resources allows for compensation of either perceptual or higher-order cognitive deficits. However, the re-allocation of resources to an earlier stage of processing may happen at the expense of subsequent processing stages. For example, age-related decline in vision or hearing may require an older adult to recruit a broader range of neural resources for perceptual processing. This may render the subsequent processing stages, such as storage of information in memory, less effective due to insufficient processing supplies. Thus, sensory/perceptual difficulties can contribute to the secondary effect on memory or other cognitive function. To take an example from the other end of processing stage, for older adults with neurodegenerative disorders affecting memory systems, such as AD, the need to recruit extra resources for perceptual processing may take away from their already restricted processing capacity and exacerbate their memory difficulty.

Results of multiple studies provide revealing evidence about the strength of the relationship between perceptual and higher-order abilities (for a comprehensive review see Schneider & Pichora-Fuller, 2000), and highlight the importance of considering sensory/perceptual abilities in cognitive research especially when studying older adults (K. Z. Li & Lindenberger, 2002). For example, Baltes and Linderberger (1997) reported that in a cross-sectional sample of individuals between 25 and 101 years old, the difference in vision, hearing, or both accounted for 67.7% of total and 94.7% of age-related differences in cognitive functioning. Furthermore, they found that controlling for sensory functioning reduced age-related differences in cognition to a similar extent as controlling for processing speed, which is known to be a strong contributor to age-related variability in cognitive functioning (e.g., Salthouse, 1993; Verhaeghen, 2011). Other correlational studies also report strong associations between differences in sensory/perceptual functioning and age-related differences in cognition (e.g., Lindenberger & Baltes, 1994; Salthouse, Hancock, Meinz, & Hambrick, 1996).

More recently published studies continue to support the notion that sensory/perceptual impairment may have an important role in cognitive performance. For example, a large-scale database study found that better visual acuity is associated with higher global cognitive scores and that this relationship is independent of factors such as age, education, and gender (Elyashiv, Shabtai, & Belkin, 2014). In the auditory domain, recent research has found that in a large-scale community sample of older adults, hearing loss was associated with lower performance and greater decline over time on cognitive tasks, even after they made adjustments for demographic (e.g., age, sex, education) and cardiovascular factors (e.g., Lin, 2011; Lin et al., 2013). Interestingly, in these studies, hearing decline was found to be associated with poorer performance on visual cognitive tasks. Lin and colleagues (2013) proposed that hearing impairment may have a secondary effect on cognition, mediated through feelings of social isolation that are related to cognitive decline. In this case, the modality of testing would be irrelevant. Alternatively, they suggested that cognitive load caused by hearing impairment requires compensatory mechanism from other neural networks, which, subsequently, affects a variety of cognitive abilities. However, visual abilities were not controlled for in these studies and, thus, concurrent visual decline may have been a contributing factor to the observed cognitive changes.

Furthermore, there is support for a significant effect of perception on higher-order cognition from experimental research. For example, one research study that used varying degrees of simulated blurred vision in young adults found that even a ‘minimal’ distortion of visual acuity (defined as 20/40 vision in the study) had a negative impact on certain non-verbal neuropsychological tests that used small size, high spatial frequency items, and/or required visual scanning (Bertone, Bettinelli, & Faubert, 2007). Another study showed that age-related differences in cognition can be reduced or even eliminated by manipulating perceptual load (Pichora-Fuller, Schneider, & Daneman, 1995). More specifically, this study found that while older adults had lower WM ability than younger adults for spoken material, the two groups performed similarly on read material, suggesting that age-related decline in auditory perception rather than WM per se may have been a contributing factor to observed difficulties of older adults on the WM task. Overall, there is quite convincing support for the an integrated perceptual-cognitive system, with research finding showing that sensory/perceptual abilities can significantly affect higher-order functioning and may contribute to age-related differences in cognition.

1.3 Auditory-Visual Speech Perception

The results summarized in the previous section suggest that facilitation of perceptual processing should be associated with better cognitive performance. This thesis tests this hypothesis by examining the perceptual facilitation associated with AV speech. While we often think of speech as primarily auditory-based communication, research indicates that visual speech cues also play an important role and can significantly affect auditory perception. This is clearly demonstrated by the McGurk illusion, described by McGurk and McDonald (1976) . In this paradigm, one spoken syllable, such as /ba/ is presented over visual speech cues of another syllable, such as /ga/, which for many people results in an illusionary perception of a completely different syllable, in this case /da/. This phenomenon demonstrates that two modalities, auditory and visual, interact with each other during speech perception. However, it does not necessarily help us to understand the role of visual speech cues during day-to-day interactions, where auditory and visual speech cues are typically complementary to each other rather than conflicting.

In our daily life, we often have conversations on busy streets and restaurants, or while televisions or radios are producing noise in the background. In a seminal study, Sumby and Pollack (1954) demonstrated that adding visual speech cues significantly improves speech perception in noise, in certain cases by as much as 40 to 80 percent. The AV effect of improved speech perception in noise has since been replicated by many others (e.g., Bernstein & Grant, 2009; Callan, Callan, Kroos, & Vatikiotis-Bateson, 2001; Fraser, Gagne, Alepins, & Dubois, 2010; Ma, Zhou, Ross, Foxe, & Parra, 2009; Ross, Saint-Amour, Leavitt, Javitt, & Foxe, 2007; Tanaka, Sakamoto, Tsumura, & Suzuki, 2009; Winneke & Phillips, 2011). Importantly, it has also been shown that visual speech cues can enhance speech perception even when the speech signal is not degraded by the background noise (e.g., Klucharev, Möttönen, & Sams, 2003).

What remains uncertain is how exactly the auditory and visual modalities interact with each other during speech perception and at what level of information processing the interaction begins. One explanation for the enhancement effect of auditory processing by visual speech was proposed by Schroeder, Lakatos, Kajikawa, Partran and Puce (2008). They suggested that visual speech cues reset the neural oscillation in the auditory cortex, such that the sound arrives during a high excitatory state, resulting in an amplified auditory input. An integral part of this theory is that the enhancement effect occurs in every early stages of cognitive processing, at the level of auditory cortex. The support for this theory comes from a magnetoencephalography (MEG) study by Luo, Liu, and Poeppel (2010) who demonstrated that low frequency activity (i.e., theta and delta) in the auditory cortex tracks both the auditory and visual stimulus dynamics. Furthermore, their results suggested that the visual information modulated the low frequency auditory activity such that the subsequent auditory input would arrive during an excitatory state. A similar effect of auditory information on visual processing was also found.

Brain imaging studies using functional magnetic resonance imaging (fMRI) and/or positron emission tomography (PET), found that AV speech perception is associated with modulation of activity in different brain regions, including auditory and visual cortices (e.g., Calvert et al., 1999; L. M. Miller & D'Esposito, 2005), superior temporal sulcus (STS; Calvert, Campbell, & Brammer, 2000; L. M. Miller & D'Esposito, 2005; Sekiyama, Kanno, Miura, & Sugita, 2003), superior temporal gyrus (Callan et al., 2003; Wright, Pelphrey, Allison, McKeown, & McCarthy, 2003), intraparietal sulcus and inferior frontal gyrus (L. M. Miller & D'Esposito, 2005). Furthermore, an fMRI study has identified activation in the claustrum/putamen during temporally synchronized AV speech, suggesting that subcortical regions may be involved in AV speech processing (Olson, Gatenby, & Gore, 2002). However, the exact neuroanatomical explanation and timing continues to be debated.

What becomes more and more obvious is that the AV interaction occurs in a very early stage of auditory processing. The ERP studies using scalp recordings provide evidence for an early multisensory effect in the auditory processing stream, sometimes as early or even earlier than 100 ms after the stimulus onset (Frtusova et al., 2013; Winneke & Phillips, 2011). Similarly, observations from intracranial ERP indicated that modulation of auditory processing during AV speech perception was as early as 40-50 ms after the onset of the sound (Besle et al., 2008). Furthermore, AV speech perception was found to be associated with increased long-distance electroencephalography (EEG) phase synchronization 40-70 ms after the onset of the auditory stimulus (Doesburg, Emberson, Rahi, Cameron, & Ward, 2008) and MEG research found evidence of multisensory interaction in the auditory cortex happening prior to AV modulation of processing in higher-order multisensory regions, such as the superior temporal sulcus (Möttönen, Schürmann, & Sams, 2004).

There seems to be a consensus in the literature on AV speech perception that in order for multisensory interaction to occur, the visual information must arrive before the auditory information. This suggests that visual information needs to be transferred from the visual processing areas to auditory processing areas, specifically to the auditory cortex. Schroeder and colleagues (2008) described three neuroanatomical pathways that could accomplish the transfer of information from the visual regions to the auditory cortex. The first pathway involves direct lateral projections from the visual cortex. The second option is a direct ascending thalamic pathway. Schroeder and colleagues (2008) suspected that there is an implication of this pathway in the phase resetting of auditory processing by the visual input. They have described that this pathway carries non-specific information, as these neurons are not very sensitive to the specific features of the stimulus. If this pathway is indeed involved in AV speech interaction, at least in the very early stages of the processing, it may explain why it is important that the visual information precedes the auditory information while the exact identity (i.e., specific features) of the information seems less relevant (Stekelenburg & Vroomen, 2007). Further support for an involvement of the direct pathway in early AV multisensory effect comes from the finding that the auditory cortex becomes activated by visual speech cues within approximately 10 ms after the activation of visual regions (Besle et al., 2008).

The third pathway is indirect and passes through the higher-order cortical areas, such as the superior temporal sulcus (Schroeder et al., 2008). The superior temporal sulcus was found to play an important role in multi-sensory processing during AV speech perception. For example, Beauchamp, Nath, and Pasalar (2010) found that the temporary stimulation of the superior temporal sulcus resulted in decreased likelihood of the McGurk fusion. In contrast to the direct thalamic pathway described in the previous paragraph, which carries non-specific information, the superior temporal sulcus seems to be implicated in more specific processing, For example, it was found to be involved in phonetic categorization (Desai, Liebenthal, Waldron, & Binder, 2008). Thus, it could be speculated that by narrowing the focus on relevant frequencies (van Wassenhove, Grant, & Poeppel, 2005), visual speech cues could help to facilitate this categorization processes. Multisensory perception is a complex process and, consequently, different brain regions and networks may play contributing roles at different stages of the information processing. Overall, visual speech cues were found to improve speech perception. While the exact mechanisms of this effect are still being debated, it is evident that multisensory interaction during AV speech occurs in very early stages of auditory processing.

1.4 Auditory-Visual Speech Perception and Working Memory

During verbal interactions, we not only need to correctly perceive the spoken words but also temporarily store them in order to understand the meaning of the sentences. In other words, we utilize WM in order to comprehend speech (Just & Carpenter, 1992; Rönnberg et al., 2013; Rönnberg, Rudner, Foo, & Lunner, 2008). According to the model by Baddeley and Hitch (1974), WM can be considered to represent a work-space, which allows us to temporarily store verbal information in a phonemic buffer as well as process the stored information via a central executive component. However, there is a limited storage and processing capacity for the overall system and, thus, if considerable resources need to be devoted to holding on to information in the phonemic buffer, there will be fewer remaining resources for subsequent processing of the information. Thus, Baddeley and Hitch's WM theory (1974) can be directly linked to Schneider and Pichora-Fuller's (2000) theory of shared processing resources. More specifically, demanding perceptual conditions make it more difficult for the phonemic buffer to temporarily store information and drive the resources away from the central executive. This may result in exceeding the limited WM capacity, and lead to the inability to successfully process the information in such a way that it could be remembered. On the other hand, perceptual facilitation provided through means such as AV speech, may reduce demands on the phonemic buffer and, consequently affords more resources to the central executive to process the information.

An early demonstration of how perceptual overload affects WM came from a series of studies by Rabbitt (1968). In the first experiment, lists of spoken digits were presented either with or without background noise and participants were asked to either transcribe or remember and reproduce the lists. The results showed that participants were more likely to correctly remember the lists of digits if they were presented without the background noise. In the second experiment, either the first part or the second part of the list was presented in noise. The results showed that presenting the second half of the list in noise interfered with the memory for the first part of the list but presenting the first part of the list in noise did not affect memory performance for the second part of the list. The third experiment showed similar results using prose passages as stimuli and asking comprehension questions. That is, results showed that participants recalled fewer details from the first part of the story if the second part was presented in noise in comparison to the entire story being presented without noise. Overall, Rabbitt (1968) interpreted these results as support for the idea that if the information processing system needs to devote too much of its limited resources to the recognition of words through noise, it would not have enough remaining resources for subsequent processing steps, such as the encoding of information in memory.

These effects were replicated by Pichora-Fuller and her colleagues (1995). They presented groups of younger and older adults with spoken sentences at different signal to noise ratios. Participants had to report the last word of each sentence and, after a set of 2, 4, 6, or 8 sentences was presented, they needed to recall all of the last words from the set size. The last words were either predictable (high context) or non-predictable (low context) from the context of the sentence. They found that older adults recalled fewer words than younger adults, but both age groups recalled more final words for high context than low context sentences and more words in higher than lower signal to noise ratio. These effects were evident despite the fact that credit was given for recalling misperceived words. Furthermore, the effect of age, context, and signal to noise ratio depended on WM load, being evident in more demanding conditions. As suggested by Pichora-Fuller and colleagues (1995) these results indicate that when word recognition is made more demanding, fewer resources are available for remembering the words. Others have also shown that presenting speech in noise can interfere with memory performance (e.g., (Murphy, Craik, Li, & Schneider, 2000; Tun, O'Kane, & Wingfield, 2002).

In contrast to the negative effect of auditory perceptual load (i.e. degraded auditory stimuli), AV speech was found to be associated with improved WM performance. Pichora-

Fuller (1996) again presented participants with lists of sentences under two different noise levels, but this time the sentences were presented in either the auditory-only (A-only) or the AV modality. Participants were asked to recognize the final words of the sentences and after a set of sentences was presented they needed to recall all of the final words from the set. In order to account for perceptual errors, the memory performance was based on words that participants reported during recognition not based on the actual words from the sentences. In a more favorable listening condition (i.e., less noise), there was no difference in memory performance across both modalities. However, in the less favorable listening condition (i.e., more noise) participants' memory performance decreased in the A-only but not in the AV condition, suggesting that visual speech cues may have helped to offset the negative effect of noise on WM.

Another study that examined the effect of AV speech on WM was conducted by Brault, Gilbert, Lansing, McCarley and Kramer (2010). They presented older adults with or without hearing loss with word lists of unpredictable length and upon a signal, participants had to recall last three words from the list. In the first experiment they found that some participants, specifically those with hearing loss who were also good lip-readers, performed better under the AV condition than under the A-only condition. In the second experiment, which had a similar paradigm but also used a background noise as a factor, they found that visual speech cues improved performance independently of hearing loss status or lip-reading proficiency. Furthermore, AV speech information also decreased the participants' subjective ratings of cognitive workload during the task.

Interestingly, Brault and colleagues (2010) argued that according to their results, AV speech improves speech perception but not WM performance. This argument was based on observation that the presentation modality did not interact with the lag (i.e., the position of the word in the list). That is, participants benefited from the AV modality in comparison to the A-only modality to the same extent for the last word, second to last word, and third to last word on the list. The last word was considered to reflect speech perception, whereas the second and the third to last words were considered to reflect WM ability. However, an alternative explanation could be that the design of the study was not sensitive enough to make the distinction between the improvement in perception and the improvement in WM. For example, there was no constraint put on the order in which the words were to be recalled. Thus, participants may have recalled the last three words in order they were presented, in which case the recall of the last word may have required a similar number of retention resources as the recall of the second to last or first to last word. Furthermore, with the sample size of 31 in the first experiment and 28 in the second experiment, the study might have been lacking statistical power to detect a significant interaction between the lag and presentation modality.

In a previous study conducted in our laboratory (Frtusova et al., 2013), we assessed WM in younger and older participants with normal hearing by using an *n*-back task, in which participants had to decide whether the currently presented digit matched the one presented in the previous trial (1-back), two trials before (2-back), three trials before (3-back) or whether the currently presented digits matched the one assigned at the beginning of the block (0-back). Hence, the task required constant updating of WM and matching of the current stimulus with the target digit presented *n*-trial before (Watter, Geffen, & Geffen, 2001). We found an improvement in the reaction times across all memory loads (0-, 1-, 2-, and 3-back) and better accuracy in the most demanding WM conditions (2- and 3-back) when the speech stimuli were presented in the AV condition in comparison to the A-only condition for both age groups. The fact that the accuracy scores were improved during AV speech for the most demanding WM conditions suggest that the effects cannot be attributable solely to improved perceptual processing. Therefore, this study supported the notion that AV speech presentation can enhance WM processing.

The study by Pichora-Fuller and colleagues (1995) suggested that the reallocation of processing resources between perception and higher-order functioning is particularly important when either the memory task is more demanding or when the auditory signal is degraded. This was supported by the results of our previous research, which suggested that AV speech is particularly beneficial in the most demanding WM conditions (Frtusova et al., 2013). Based on these observations, we wondered whether AV speech can also help to offset the negative effect of perceptual load in those who are particularly vulnerable to exceed their available pool of processing resources, specifically older adults with hearing impairment or older adults with memory difficulties, such as those with AD or MCI. Before presenting the results of the two studies that examined these issues (in Chapter Two and Chapter Three), the background information describing the effect of age on sensory/perceptual functioning and WM processing is presented, followed by information relevant to AV speech perception and WM in older adults with hearing impairment and those with AD or MCI.

1.5 The Effect of Aging on Auditory-Visual Speech Perception and Working Memory

There are many physical, sensory and cognitive changes associated with aging. Given that this thesis examines the relationship between AV speech perception and WM functioning in older adults, a brief description of age-related changes in hearing, vision, AV speech processing and WM is provided.

In regards to hearing, multiple factors are considered to play a role in the development of presbycusis (i.e., age-related hearing loss), including external factors, such as noise exposure, and internal factors, such as genetics (X. Z. Liu & Yan, 2007). The primary characteristic of presbycusis is a clinically significant loss of acuity for high-frequency sounds, resulting mostly from a loss of inner hair cells within the basal region of the basilar membrane (i.e., sensorineural hearing loss; Schneider & Pichora-Fuller, 2000; Wingfield, Tun, & McCoy, 2005). However, other age-related changes in cochlea, such as loss of outer hair cells, vascular changes and reduction in endocochlear potential, may also play an important role and contribute to the decline of spectral and temporal processing (Schneider, 1997; Wingfield et al., 2005). In addition, aging was suggested to be associated with the loss of synchrony in neural firing, which affects various auditory functions, including temporal processing (Schneider & Pichora-Fuller, 2000, 2001). Subsequently, age-related changes in the auditory system affect speech perception, which is dependent not only hearing threshold but also on the ability to process spectral and temporal cues (e.g., Baer & Moore, 1994; Pichora-Fuller, Schneider, Macdonald, Pass, & Brown, 2007; Schneider, 1997; Schneider & Pichora-Fuller, 2001; Wingfield et al., 2005).

In many cases, presbycusis becomes recognized only once there is a clinically significant elevation in the hearing threshold sensitivity that can be detected on an audiogram (Schneider & Pichora-Fuller, 2000). However, the above-presented information signifies that even in individuals with normal hearing thresholds, intact auditory processing cannot be assumed (Schneider & Pichora-Fuller, 2000). For many older adults, the effects of presbycusis may only become evident when auditory processing is challenged by perceptually taxing situations, such as speech perception, especially under the condition of background noise (Kim, Frisina, Mapes, Hickman, & Frisina, 2006; Schneider & Pichora-Fuller, 2000).

In addition to the decline in hearing, many older adults also experience a decline in vision. As reviewed by Schneider and Pichora-Fuller (2000), aging is associated with various changes in the structure of the eye. These changes include a decrease in the elasticity of the crystalline lens, resulting in presbyopia or a diminished ability to focus on objects at different distances. In addition, there is a decrease in motility of the iris, resulting in a smaller pupil size, as well as an increase in the optical density of the lens. These effects result in a less illuminated retina and subsequently lead to a decreased sensitivity of rod and cone vision. Further age-related changes in vision include loss of rods in central vision, loss of retinal ganglion cells, and thinning of the choroid (i.e., of the layers of the retina), possibly resulting in reduced blood flow to the retina.

Unfortunately, correction with optic lenses does not seem to completely resolve age-related decline in vision. One study compared the retinal image quality in the fovea between younger and older adults (Artal, Ferro, Miranda, & Navarro, 1993) and results showed that despite controlling for important optic variables (e.g., all participants had 20/20 vision or better, normal visual fields, normal color vision and normal intraocular pressure), older adults had more blurred retinal image. Artal and colleagues (1993) suspected that this decline in retinal image quality likely accounted for a substantial proportion of age-related decline in contrast sensitivity.

Decline in both visual acuity and contrast sensitivity in older adults were found to interfere with the ability to perform activities of daily living, such as reading medicine bottles, threading a needle or using a screwdriver (Owsley, McGwin, Sloane, Stalvey, & Wells, 2001). However, in certain situations, contrast sensitivity may predict daily functioning more than visual acuity (Schneider & Pichora-Fuller, 2000). Age-related decline in contrast sensitivity is greatest for higher spatial frequencies (Schneider & Pichora-Fuller, 2000), which could potentially interfere with older adults' ability to benefit from visual speech cues. This statement is supported by the observation that older adults do not perform as well on lip-reading tasks as younger adults (Cienkowski & Carney, 2002; Sommers, Tye-Murray, & Spehar, 2005; Winneke & Phillips, 2011).

Despite a decline in vision and poorer performance on lip-reading, older adults were found to rely on visual speech cues more than younger adults (Cienkowski & Carney, 2002; L. A. Thompson & Malloy, 2004). Further, it has been suggested that a greater reliance on visual speech cues in older adults may be a compensatory mechanism for a decline in hearing (Cienkowski & Carney, 2002). Most importantly for the topic of this thesis, older adults were found to be able to successfully integrate auditory and visual speech cues (Cienkowski & Carney, 2002) and benefit from AV speech perception. Summers and colleagues (2005) demonstrated that after controlling for lower performance in the visual-only (V-only) condition, older adults benefited from AV speech to a similar extent as younger adults. Moreover, previous research from our laboratory also confirmed that older adults show a similar behavioural AV speech benefit as younger adults during an object categorization task (Winneke & Phillips, 2011). Furthermore, electrophysiological responses indicated a greater AV speech benefit in older adults in comparison to younger adults (Frtusova et al., 2013; Winneke & Phillips, 2011).

In addition to sensory decline, aging is also associated with a decline in cognitive functioning, including WM (e.g., Bopp & Verhaeghen, 2009; McCabe & Hartman, 2008; Salthouse, 1994). However, a greater decline appears to be observed on more demanding tasks of WM, such as those requiring manipulation of information, compared to simpler tasks, such as those that only require short-term retention (Babcock & Salthouse, 1990; Bopp & Verhaeghen, 2009). Thus, a well-validated task is needed when examining age differences on WM.

In this current research, we assessed WM by using an *n*-back task, which has been well validated in regards to effects of aging. More specifically, older adults were found to be slower and less accurate, especially during higher n-back loads (e.g., Van Gerven, Meijer, & Jolles, 2007; Van Gerven, Meijer, Prickaerts, & Van der Veen, 2008; Vaughan, Basak, Hartman, & Verhaeghen, 2008; Verhaeghen & Basak, 2005; Vermeij, van Beek, Olde Rikkert, Claassen, & Kessels, 2012). Van Gerven and colleagues (2008) assessed whether the disproportionate difficulties of older adults on higher WM loads (e.g., 2-back) of n-back task were due to reduced WM capacity or due to difficulties with focus switching. To examine this question, they asked younger and older adults to perform traditional 1-back and 2-back conditions with printed digits as well as a non-traditional two-digit 1-back condition, in which pairs of digits rather than a single digit were presented during a trial. The assumption was that this condition would match the 2-back condition in terms of WM load and the 1-back condition in terms of the focus switching requirements. The results showed that in comparison to younger adults, older adults showed a disproportionally greater drop in accuracy in the 2-back condition relative to both the single digits and the two-digit 1-back conditions. Thus, the results suggested that difficulties on the n-back task in older adults may be related to an age-related decline in the focus switching ability rather than a decrease in their WM load capacity. However, other variables, such as age-related decline in WM for temporal context information, were also proposed to affect performance on the n-back task (McCabe & Hartman, 2008).

In a previous study from our laboratory (Frtusova et al., 2013), in which we used speech stimuli during the *n*-back task, older adults were generally slower than younger adults (i.e., independently from WM load). However, similarly to findings of other studies, they were less accurate only during the 2-back and 3-back conditions. The most relevant information for the topic of this thesis is that WM performance of the older adults during the AV modality did not differ from that of the younger adults in the A-only condition. This suggests that AV speech information may have helped to counteract some of the age-related WM deterioration. Thus, this study supported the suggestion that some of the age-related decline in higher-order functions may be secondary to the perceptual difficulties (Schneider & Pichora-Fuller, 2000). Overall, despite age-related decline in both hearing and vision, older adults seem to be able to integrate auditory and visual speech cues and they show AV speech benefit on WM performance.

1.6 Hearing Impairment

Recall that according to the Pichora-Fuller and Schneider theory (2000), the reallocation of processing resources between perception and cognition is especially important when the overall processing capacity is reduced, for example due age-related or disease related processes. Hearing impairment is one of the age-related processes that affect processing capacity. A partial goal of this thesis was to examine the resource reallocation and AV speech benefit in older adults with hearing impairment. The following section reviews background literature relevant to this research question.

1.6.1 Prevalence and Impact on Quality of Life

Examining the effects of hearing impairment on cognition is extremely pertinent as aging of the population results in a greater number of people living with hearing loss. According to the Canadian Association of the Deaf, approximately 3.15 million of Canadians are hard of hearing, and about 350,000 are profoundly deaf or deafened (http://www.cad.ca/statistics_on_deaf_canadians.php). The prevalence of hearing impairment and the likelihood that hearing impairment affects activities of daily living increases with age (Statistics Canada, 2006; Strawbridge, Wallhagen, Shema, & Kaplan, 2000; Zhang, Gomaa, & Ho, 2013). Also, hearing impairment is the third most common chronic condition in older adults, ranking just after arthritis and hypertension (Zhang et al., 2013).

Hearing loss has a significant impact on an individual's quality of life. This makes research, such as this present thesis, concerning possible methods that could offset some of the challenges that accompany hearing loss, imperative. In the survey on participation and activity limitation conducted by Statistics Canada (2006), among the participants who reported that hearing impairment had an effect on their everyday functioning, many reported other limitations such as mobility, pain and agility. Also, about 15% reported difficulty with learning, memory and communication. Given that the survey was conducted across different age groups, the prevalence of latter mentioned difficulties can be expected to be much higher in older adults. To illustrate this, in one study using participants between 53-97 years old, 59% of those with mild hearing loss and 80% of those with moderate to severe hearing loss reported that they had communication difficulties (Dalton et al., 2003). Furthermore, the severity of hearing loss was associated with other factors including lower scores on vitality, social functioning, mental health, and physical functioning (Dalton et al., 2003).

A longitudinal study that used self-report measures of hearing impairment and other variables also confirmed the negative impact of hearing loss on physical and mental health (Strawbridge et al., 2000). Strikingly, it was found that people with moderate or severe hearing impairment at the baseline assessment were twice as likely than participants without a hearing impairment to report depression one year later. These results were presented after adjusting for age, gender, chronic condition, education and baseline level of depression. Participants with both mild hearing impairment and moderate or severe hearing impairment were also more likely to report feeling lonely and left out in group settings (Strawbridge et al., 2000). Overall, these findings suggest that hearing impairment has important consequences on several fundamental areas of individuals' lives.

1.6.2 The Effect of Hearing Loss on Working Memory

As you may recall, this thesis focuses on examining the effects of hearing loss on WM. While it is expected that hearing impairment affects speech perception (Rabbitt, 1991), several studies confirmed the adverse effects of hearing impairment on various higher-order cognitive abilities, including WM. For example, one study (Cervera, Soler, Dasi, & Ruiz,

2009) compared young individuals with normal hearing to young elderly participants (age 55-65) whose hearing ranged from normal to mildly/moderately impaired. In this study, older participants did not perform as well as younger participants on tasks of speech recognition (i.e., consonant and sentence recognition) and WM (serial word-list recall and digit reordering recall), but the age difference was not evident once the hearing thresholds were taken into account.

Another study compared older adults with normal hearing to those with mild/moderate hearing loss on a speech comprehension task using sentences that varied in syntactic complexity, and thus WM demands (Stewart & Wingfield, 2009). The results showed that in comparison to participants with normal hearing, those with hearing impairment had greater difficulty with syntactically complex sentences compared to syntactically less complex sentences. The results were interpreted as an indication that effortful listening in older adults with hearing impairment created greater demands on their processing resources which, in the context of age-limited WM capacity, negatively affected their performance (Stewart & Wingfield, 2009).

The question may be raised as to what extent the difficulties observed on memory tasks are caused by speech perception difficulties. This issue was addressed in a series of experiments by Rabbitt (1991) who tested word list recall of older participants that varied in age between 53 and 79 years and had various levels of hearing impairment. Importantly, the memory scores only included words that participants correctly repeated immediately after the presentation and thus the memory performance was not affected by the perception errors. He found that the level of hearing impairment interacted with age in affecting memory recall, suggesting that as people age they may have less capacity to compensate for reallocation of extra resources to word identification (Rabbitt, 1991). In the same series of studies, Rabbitt (1991) also reported that higher IQ can help to counteract the effect of age and hearing impairment on memory.

In a WM paradigm, McCoy and colleagues (2005) asked older adults with mild/moderate hearing impairment and those without hearing loss to recall the last three words from the word list of unpredictable length and varying in the degree of contextual constraint. While no group differences were seen for the word-list with high contextual constraints, older adults with hearing impairment performed worse than older adults with normal hearing on low contextual constraint lists. Furthermore, groups did not differ in the recall of the final word of the list, but differed in the recall of the second to last and third to last word in the list. Thus, the group differences cannot be completely attributed to word-recognition differences. Rather, the results suggest that participants with hearing impairment had to allocate more resources to speech recognition and thus had fewer processing resources available for successful encoding of the information in memory (McCoy et al., 2005). Overall, this research and other studies presented above support Rabbitt's (1968) original hypothesis of a detrimental effect of effortful listening on memory. Interestingly, WM capacity was also found to influence the subjectively perceived effort during speech recognition in noise for individuals with hearing loss (Rudner, Lunner, Behrens, Thorén, & Rönnberg, 2012). Furthermore, greater WM capacity was found to be associated with better speech perception performance in noise by hearing impaired individuals (Rudner, Rönnberg, & Lunner, 2011). For a more comprehensive review on the interaction effect between WM capacity and the effect of hearing impairment on memory see Rönnberg and colleagues (2013).

Tun, McCoy and Wingfield (2009) examined the interactive effect of aging and hearing impairment on higher-order functioning by using a dual task paradigm. They asked younger and older adults with and without hearing loss to recall a list of words while they were doing a visual tracking task. They found that hearing impairment affected memory recall. However, older adults with hearing impairment, in comparison to older adults with good hearing, and younger adults with good and poor hearing, had the highest cost on the secondary tracking task caused by word recall. Overall, these results suggest that while the effortful listening affects memory of both age groups, older adults with hearing impairment have less residual resources for other tasks due to age-related constraints in the overall processing capacity. In more general terms, it seems that effortful perceptual processing has particular detrimental effects on higher-order functions in older adults, and likely other populations with restricted processing resources.

1.6.3 Auditory-Visual Speech and Hearing Impairment

Given the adverse effect of hearing impairment on WM, older adults with hearing loss should especially benefit from AV speech information. Recall from a previous section that AV speech was found to be associated with improved auditory perception. However, an ERP study suggested that individuals with hearing loss might have difficulty with the integration of auditory and visual speech cues (Musacchia, Arum, Nicol, Garstecki, & Kraus, 2009), which would prevent them from AV speech benefit. On the other hand, behavioural investigations did not find any difference between participants with normal hearing and those with hearing impairment in their ability to integrate auditory and visual speech cues (Grant, Tufts, & Greenberg, 2007; Tye-Murray, Sommers, & Spehar, 2007). In fact, the study by Grant and colleagues (2007) suggested that participants with hearing impairment may have derived a greater AV benefit than normal-hearing participants in terms of speech recognition. More specifically, while participants with hearing impairment performed lower in the A-only condition during a consonant recognition task, no group differences were evident in the AV condition. Other behavioural studies also found that visual speech cues improved speech recognition in individuals with hearing impairment (e.g., Bernstein & Grant, 2009; Grant et al., 1998).

Furthermore, older adults with hearing impairment also seem to derive AV speech benefit on a WM task. Specifically, the results of a study by Brault and colleagues (2010) indicated that among older adults, those with hearing loss and good lip-reading abilities seemed to particularly benefit from AV speech compared to A-only speech during a WM task when no background noise was included. When background noise was present, AV speech improved the WM performance regardless of the level of hearing impairment or lip-reading proficiency.

In summary, the research suggests that degradation of auditory processing in individuals with hearing loss requires a greater number of processing resources to be allocated toward speech perception, which results in insufficient resources for higher-order processing. The AV speech information was found to improve speech perception and there is evidence that it can help to offset the negative effect of hearing impairment on WM. However, further studies are needed to confirm this effect in hearing impaired population and examine the relationship between perceptual and WM processing in a more direct manner. To this end, we conducted an ERP investigation of WM performance under V-only, A-only and AV speech modalities in older adults with age-normal hearing and those with hearing impairment. Before presenting the results of this study (presented in Chapter Two), I will introduce the background information for the other clinical population investigated in this thesis, specifically older adults suffering from AD or MCI.

1.7 Alzheimer Disease and Mild Cognitive Impairment

In the previous section I have mentioned that effortful perceptual processing may have particularly detrimental effects on higher-order functions in populations with restricted processing resources. In addition to normal aging and hearing impairment, processing resources also become restricted due to neurodegenerative disorders, such as MCI or AD. Thus, individuals suffering from these conditions may especially benefit from AV speech information.

AD is the most prevalent form of dementia and with the increasing number of older adults it rapidly becomes a major source of concern in health care systems around the world. In Canada, 480,618 people or 1.5% of population lived with dementia in 2008, 63% of whom had AD. It is projected that by 2038, about 1.1 million of people or 2.8% of the Canadian population will suffer from dementia and 68.5% of these cases will have AD (Alzheimer Society of Canada, 2010). The cumulative economic burden of dementia by the year of 2038 was estimated to be $872 billion (Alzheimer Society of Canada, 2010). Despite significant research efforts, there is currently no cure for AD. It remains crucial that individuals suffering from AD, or other dementias experience the highest quality of life possible. One of the purposes of this thesis was to examine whether AV speech information could contribute to this goal.

1.7.1 Clinical and Neuropathological Characteristics

AD is a neurodegenerative disorder of the brain characterized by an insidious onset and progressive decline of symptomology, consisting of deficit in at least two cognitive domains, including memory, language, visuospatial skills or executive functioning, and an impaired ability to work or perform usual activities of daily living (G. M. McKhann et al., 2011). AD is often preceded by a clinical stage called mild cognitive impairment (MCI), which is characterized by a decline in a person's cognitive ability relative to the previous level of functioning and a confirmed deficit in one or more cognitive domains relative to other people similar in age and education. However, the deficit in the cognitive ability of MCI individuals is not severe enough to warrant the diagnosis of dementia and it does not affect their daily activities (Albert et al., 2011). Individuals with MCI are at increased risk for developing dementia, with the annual conversion rate between 9-30%, depending on specific neuropsychological characteristics (Mitchell, Arnold, Dawson, Nestor, & Hodges, 2009).

Neuropathologically, AD is characterized by amyloid plaques and neurofibrillary tangles. The typical progression of the amyloid plagues is from the basal isocortex in the frontal, temporal and occipital lobes towards the isocortical association areas and finally affecting the entire isocortex, including sensory and motor regions (Braak & Braak, 1991). Neurofibrillary tangles are first evident in the transentorhinal cortex, followed by the entorhinal cortex and other medial regions, and finally spreading to the entire isocortex (Braak & Braak, 1991). The cortical atrophy was reported to progress from temporal and parietal regions toward the frontal lobe, sparing the sensory motor area, and greater left than right hemispheric deficits (P. M. Thompson et al., 2003).

Importantly for the multisensory topic of this thesis, the STS, which has been shown to be involved in multisensory interaction (e.g., Calvert et al., 2000; L. M. Miller & D'Esposito, 2005; Sekiyama et al., 2003) is one of the areas affected early on in the AD stages. One study reported over 50% loss of neurons in the STS for patients with AD, and the amount of neural loss correlated positively with both the duration of the illness and severity of cognitive impairment (Gomez-Isla et al., 1997). Liu and colleagues (2012) reported a widening of the STS in patients with mild AD, and noted that the morphological changes in this region are negatively associated with global cognitive functioning as assessed by the Mini-Mental State Examination (MMSE). Nelissen and colleagues (2007) reported a decrease in the gray matter volume and an increase in amyloid deposition in the left STS for patients with AD. Furthermore, they observed on fMRI images that patients with AD had decreased activation in the left STS during a semantic association task. The atrophy in the STS region is evident even at the MCI stage, and can discriminate those MCI patients who are at risk of progression to AD (Killiany et al., 2000).

White matter changes represent another neuroanatomical characteristic of AD relevant to multisensory processing, as discussed in more detail later on. These changes interfere with effective communication among different cortical and subcortical regions. In regards to white matter changes in AD, a recent review has concluded that: (a) brain imaging research has clearly indicated white matter changes in AD and that these changes may be present even at the MCI stage; (b) white matter changes in AD were found in networks important for cognitive functioning; (c) the degree of white matter changes relates to cognitive functioning and may predict who will progress from MCI to AD (Radanovic et al., 2013). Studies published in the past two years continue to support these conclusions. For example, patients with AD were found to present with a significant annual decline of white matter within temporal lobes (Frings et al., 2014) and even individuals with MCI were found to show wide spread changes in white matter (J. Liu et al., 2013; Stricker et al., 2013). In MCI patients, the integrity of white matter underlying medial-temporal lobes was related to performance on memory tasks, whereas the integrity of white matter in parietal lobes related to executive functioning (Stricker et al., 2013).

1.7.2 Working Memory in Alzheimer Disease and Mild Cognitive Impairment

According to Schneider and Pichora-Fuller's theory (2000), a need to allocate extra processing resources toward perceptual functioning is likely to have an especially adverse effect on cognition when the task is challenging. Patients with AD have difficulties across a variety of cognitive functions but particularly relevant for this thesis is the observation of deficits in WM (e.g., Belleville, Chertkow, & Gauthier, 2007; Belleville, Rouleau, Van der Linden, & Collette, 2003; Egerhazi, Berecz, Bartok, & Degrell, 2007; Kalpouzos et al., 2005) (for reviews, see Huntley & Howard, 2010; Morris, 1994). Among other WM paradigms, difficulties were observed on the n-back task (e.g., Rombouts, Barkhof, Goekoop, Stam, & Scheltens, 2005; Waltz et al., 2004), which is the WM task used in the current research. In regards to the Baddeley and Hitch (1974) WM model presented earlier, the phonological loop seems to be affected only in the later stages of AD while the deficits in the central executive are seen early on (Huntley & Howard, 2010; Morris, 1994) and progress with the advancement of the disease (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991).

WM difficulties are evident even at the MCI stage. Difficulties were noted in a variety of commonly used neuropsychological measures of WM, including the Letter-Number

Sequencing (Griffith et al., 2006; Johns et al., 2012; Klekociuk & Summers, 2014a, 2014b), the Digit Span Backward (Chang et al., 2010; Klekociuk & Summers, 2014a, 2014b; Muangpaisan, Intalapaporn, & Assantachai, 2010; Zihl, Reppermund, Thum, & Unger, 2010), the Spatial Span (Egerhazi et al., 2007; Griffith et al., 2006; Saunders & Summers, 2010) and the Brown Peterson task (Belleville et al., 2007; Johns et al., 2012). Furthermore, WM deficits in MCI patients were also demonstrated by various experimental paradigms (e.g., (Gagnon & Belleville, 2011; Newsome, Pun, Smith, Ferber, & Barense, 2013; Zheng et al., 2012; Zheng et al., 2014) and are evident even after accounting for processing speed and cognitive reserve variables (Facal, Juncos-Rabadan, Pereiro, & Lojo-Seoane, 2014).

In terms of the n-back task specifically, MCI patients were found to have difficulties in the 2-back condition (Alichniewicz, Brunner, Klunemann, & Greenlee, 2012; Zheng et al., 2012) or they were generally slower (Borkowska, Drozdz, Jurkowski, & Rybakowski, 2009; Rombouts et al., 2005) and less accurate in their performance (Borkowska et al., 2009). One study found a decreased performance in the 1-back and the 2-back conditions, but only in those MCI patients who had severe white matter hyperintensities (Nordahl et al., 2005). Even in the absence of behavioural deficits on the n-back task, brain activation differences were reported in imaging studies (Migo et al., 2014; Niu et al., 2013). A very recent study found that a decrease in performance on the n-back task over time is related to the presence of amyloid in the brain of MCI patients as well as cognitively healthy controls at the baseline assessment (Lim et al., 2014). Thus, the n-back task appears to be a sensitive measure of WM even at the MCI stage and performance on this task seems to relate to AD pathology.

1.7.3 Auditory-Visual Speech in Alzheimer Disease and Mild Cognitive Impairment

A partial goal of this thesis is to examine the AV speech benefit on WM in patients with MCI and AD. Given that AV speech most likely requires communication among different brain regions and/or processing in multimodal areas, the findings presented on neurodegeneration in the STS and observation of white matter changes call into question whether patients with AD and MCI can benefit from AV speech. There is relatively little research with a direct focus on examining AV speech interaction in MCI and AD patients. One study (Delbeuck, Collette, & Van der Linden, 2007) reports a deficit in the integration of auditory and visual speech cues in patients with AD. In this study, the McGurk paradigm was used to assess the influence of visual speech information on auditory speech perception. It was found that patients with AD were less affected by the illusion than age, education and gender matched controls. Delbeuck and colleagues (2007) interpreted these results as support for the disconnection hypothesis of AD, in which cognitive deficits are caused by impaired communication among different brain regions.

However, two important factors need to be considered when making an interpretation about regular AV speech perception in AD patients based on the results from Delbeuck and colleagues' (2007) study. Firstly, auditory and visual speech cues are complementary rather than conflicting during regular speech. In Delbeuck and colleagues' (2007) study, patients and controls did not differ in their performance when auditory and visual speech cues were congruent. This suggests that multisensory processing involving more ecologically valid, complementary AV speech information may be intact in this population. Unfortunately, based on the study paradigm, it cannot be determined whether AV interaction actually occurred in either of the groups (i.e., patients and controls) for congruent trials. Secondly, visual abilities were not measured and compared across the groups. In a previous study done in our laboratory, AV speech perception correlated positively with levels of contrast sensitivity (Winneke & Phillips, 2011), highlighting the importance of matching the groups on basic visual functioning when examining AV effects. Delbeuck and colleagues (2007) reported that patients with AD had a higher proportion of auditory-based responses during incongruent AV trials compared to controls. Furthermore, there was a statistical trend of lower abilities for visual discrimination and lip-reading in the AD group, even though neither of these abilities correlated significantly with performance during incongruent AV trials. Nevertheless, the possibility that group differences in visual functions (e.g., contrast sensitivity) contributed to observed group differences in multisensory functioning cannot be completely ruled out.

Unfortunately, there is a scarcity of studies investigating congruent AV speech perception in either patients with AD or MCI. In a preliminary report from our laboratory, it was found that both patients with AD and healthy controls can benefit from visual speech cues in terms of speech perception (Phillips, Baum, & Taler, 2009). Studies examining AV interaction in MCI and AD patients using non-speech stimuli also yielded mixed results. One study reported an adequate, even though slightly delayed, interaction effect in AD patients (J. Wu et al., 2012), whereas another study reported a reduced interaction effect in both MCI and AD patients (Golob, Miranda, Johnson, & Starr, 2001). Overall, more studies are needed to clarify AV speech interaction and to explore its potential benefit on perception as well as on WM in these patient populations. This gap in the literature motivated the current research. We conducted an ERP investigation of WM performance under A-only and AV speech modalities in older adults with MCI or AD in comparison to cognitively healthy controls. Before presenting the results of this study (presented in Chapter Three), I will introduce the ERP methodology and its contribution to our understanding of AV speech benefit.

1.8 The Contribution of Event-related Potentials Methodology to Understanding of Auditory-Visual Speech Perception

This thesis examines the reallocation of processing resources between perceptual and higher-order information processing. A unique method to examine the relationship between these two processing stages is measuring ERPs. The ERPs are derived from EEG, or a continuous recording of rapid voltage changes in the brain. The activity is recorded by placing multiple electrodes on the scalp, which then can be amplified and plotted over time (Luck, 2005). At each electrode, the observed voltage changes are a result of summed post-synaptic potentials from a large number of neurons that have spatially aligned dipoles (Luck, 2005). In EEG, the neural activity associated with the processing of a specific perceptual or cognitive event is embedded among other EEG signals. To isolate the specific 'event-related' brain activity, one must average the signal elicited by the particular event over multiple trials. The assumption is that EEG activity that is not time-locked to the event occurs randomly in relation to the event and thus, will be cancelled out over multiple trials (Luck, 2005). The result of the averaging process is an ERP waveform, made of series of voltage deflections over time, which reflects stages of processing generally from low-level sensory/perception to higher-order cognition (Luck, 2005). The great temporal resolution of ERPs (in the range of milliseconds) makes it a unique tool for examining a direct relationship between perceptual functions and higher-order cognitive abilities.

The voltage deflections reflected in an ERP waveform are called components. Each of them is labeled based on whether it is a positive or negative deflection and its position within the waveform (Luck, 2005). For example, N1 refers to the first negatively-going component whereas P3 refers to the third positively-going component. Each component is characterized by the amplitude (measured in μV), which reflects the size of the component; latency (measured in ms), which reflects the timing of the component; and the topographical distribution of the component across the scalp (Luck, 2005). Through decades of research, the characteristics of some ERP components have become well understood in terms of amplitude, latency, and topographical distribution. Among well-recognized ERP components are the P1 and N1, which are associated with perceptual processing, and P3, which is associated with WM processing. Because these three components are integral to the current research, a brief description of their characteristics is presented in order to help the reader understand their role.

In response to auditory stimulation, the brain generates a series of responses that are reflected by different, though often overlapping, ERP components. The auditory P1 refers to a positive peak occurring approximately 50 ms after the onset of the stimulus, and it was proposed to originate from the primary auditory cortex (Liegeois-Chauvel, Musolino, Badier, Marquis, & Chauvel, 1994). The P1 is followed by the N1 wave, which is elicited by a sudden change in sensory input (Näätänen & Picton, 1987). The auditory N1 refers to a negativity peaking at approximately 100 ms after the onset of the stimulus and reaching its maximum voltage in frontal-central electrodes (Näätänen & Picton, 1987; Pantev et al., 1995; Woods, 1995). It has been suggested that the N1 wave may be affected by multiple cerebral sources (Giard et al., 1994; Liegeois-Chauvel et al., 1994; Näätänen & Picton, 1987;

Woods, 1995). However, activation of the secondary auditory cortex was proposed as an important contributor (Liegeois-Chauvel et al., 1994; Pantev et al., 1995). The N1 component is affected by physical stimuli characteristics, including intensity and tonal frequency (Näätänen & Picton, 1987).

The last component, the P3, refers to a broad-ranging positivity associated with cognitive processing, usually during a discrimination task (Polich & Kok, 1995). It was proposed to originate from temporo-parietal activity (Polich, 2007), reach its maximum at parietal sites (Polich & Kok, 1995; Walhovd, Rosquist, & Fjell, 2008) and peak approximately 300 ms after the stimulus presentation. However, the latency window varies greatly depending on the listener's age, modality of presentation, and task manipulations (Polich & Kok, 1995). P3 amplitude was reported to reflect the updating of working memory (Polich & Kok, 1995; Watter et al., 2001), with decrease in the amplitude as the cognitive demands increase (Polich, 2007; Watter et al., 2001). P3 latency is usually interpreted as reflecting the speed of processing and was found to increase with decreasing cognitive function (Fjell & Walhovd, 2003; Polich & Kok, 1995). The stimulus intensity is positively associated with P3 amplitude and negatively associated with P3 latency (Fjell & Walhovd, 2003; Polich, Ellerson, & Cohen, 1996). On the other hand, the target stimulus frequency is negatively associated with both amplitude and latency of the P3 (Polich et al., 1996). Aging was found to be associated with decreased amplitude and prolonged P3 latency, as well as a slight frontal shift in the topography (Walhovd et al., 2008). Overall, by looking at the pattern of changes in perceptual (i.e., P1 and N1) and higher-order (i.e. P3) components, different research questions can be addressed, including the effects of multisensory processing on WM as examined in this thesis.

Our understanding of multisensory interaction has been strongly improved by ERP methodology. This research indicates that the perceptual enhancement of auditory speech information by visual speech cues is accompanied by faster and/or more efficient auditory processing (Besle et al., 2008; Besle, Fort, Delpuech, & Giard, 2004; Frtusova et al., 2013; Stekelenburg & Vroomen, 2007; van Wassenhove et al., 2005; Winneke & Phillips, 2011). In scalp-recorded ERPs this is most commonly reflected as earlier peak (Frtusova et al., 2013; Pilling, 2009; Stekelenburg & Vroomen, 2007; van Wassenhove et al., 2005; Winneke & Phillips, 2011) and smaller amplitude (Frtusova et al., 2013; Stekelenburg & Vroomen, 2007; van Wassenhove et al., 2005) of the auditory N1 component during AV speech compared to A-only speech. A previous research from our laboratory provides evidence of a multisensory effect even earlier than N1. More specifically, a reduced amplitude was evident in the preceding auditory P1 component (Frtusova et al., 2013; Winneke & Phillips, 2011). Overall, these results suggest that multisensory interaction during AV speech perception occurs early in the processing stream, most likely at the level of the auditory cortex.

It has been suggested that the temporal AV facilitation (i.e., reduction of N1 latency) of perceptual processing is dependent on the predictability of either when the auditory signal is going to occur (Stekelenburg & Vroomen, 2007) or what the sound is going to be (van Wassenhove et al., 2005) by preceding visual speech cues. On the other hand, the resource facilitation (i.e., reduction of N1 amplitude) during AV speech, was found to be related to the potential of preceding visual cues to reliably predict when the sound is going to occur (Pilling, 2009; Stekelenburg & Vroomen, 2007) but not to the ability of visual cues to predict the identity of subsequent auditory input (van Wassenhove et al., 2005). An alternative explanation for resource facilitation is that visual information helps to filter out redundant information (Stekelenburg & Vroomen, 2007) and allows auditory processing to narrow the focus on relevant frequencies (van Wassenhove et al., 2005). Altogether, these results suggest that visual speech cues allow the brain to 'prepare' for incoming auditory input and subsequently, the brain is able to process the auditory information faster and more efficiently.

The differences in ERPs evoked by AV speech compared to A-only speech are not necessarily evidential of multisensory interaction, as the modulated AV waveform may simply reflect simultaneous but independent processing of auditory and visual stimuli, or reflect other processing differences between the conditions, such as attention cuing by the visual speech cues. However, the modulation of N1 amplitude and/or latency in AV compared A+V (i.e., sum of the ERPs evoked by A-alone and V-alone stimuli) waveforms suggests that the N1 changes in AV condition reflect a genuine multisensory interaction (Frtusova et al., 2013; Klucharev et al., 2003; Pilling, 2009; van Wassenhove et al., 2005; Winneke & Phillips, 2011). Furthermore, when the visual speech cues precede the auditory speech cues, but are out of synchrony with the onset of the sound, there is no modulation of the auditory N1 amplitude in AV compared to A-only condition, suggesting that the AV effect cannot solely be caused by attention cuing (Pilling, 2009).

The main purpose of this thesis is to examine how AV speech perception affects WM abilities in older adults with restricted processing resources. In a previous study, we examined the effect of AV speech perception on WM in cognitively and sensory healthy younger and older adults using a similar paradigm as in the projects presented in this thesis (Frtusova et al., 2013). More specifically, we measured ERPs while younger and older participants completed a WM n-back task. As previously mentioned, we found an improvement in reaction time across all memory loads (0-, 1-, 2-, and 3-back) and better accuracy in the most demanding WM conditions (2- and 3-back) when the speech stimuli were presented in the AV condition in comparison to A-only condition. Importantly, the ERP analysis showed that the AV modality was associated with a decrease in the auditory N1 amplitude for older adults and earlier auditory N1 latency for both older and younger adults. Furthermore, the reduction in N1 amplitude in the AV condition in comparison to A-only condition related to an improvement in certain behavioural and ERP measures of working memory. Thus, the study not only confirmed the benefit of AV speech information on WM but also provided a support for a direct link between perceptual functioning and WM performance.

1.9 Summary and Rational for the Current Research

In summary, it has been shown that taxing perceptual processing can have a negative effect on subsequent higher-order cognitive functioning, such as the processing of information in WM. This effect is especially evident during highly demanding tasks or when the overall processing resources are restricted, for example when the resources are restricted due to aging. Aging is associated with decline in sensory/perceptual functioning as well as WM. Thus, during speech processing, older adults need to devote more of their limited resources to decoding the speech signal, leaving them with fewer resources for higher-order cognitive processing and subsequently, resulting in inadequate memory for presented information.

AV presentation represents one possibility for facilitation of speech perception. Furthermore, electrophysiological studies suggest more efficient brain processing during AV in comparison to A-only speech presentation. More specifically, the auditory processing is faster (as suggested by an earlier auditory N1 latency) and requires fewer resources (as suggested by a smaller auditory N1 or P1 amplitude) during AV in comparison to A-only speech modality.

Previous research has found that both younger and older adults benefit from AV speech perception in terms of improved WM performance, supporting the notion that perceptual facilitation leads to improved WM. We showed this effect in an ERP paradigm (Frtusova et al., 2013), which allows for a more direct examination of multisensory processing associated with AV speech and its effect on WM. There is a scarcity of ERP research that would examine the AV speech benefit on WM in older adults with restricted processing resources due to hearing or cognitive impairment. This gap in the literature motivated the current investigation.

Older adults with hearing impairment need to devout extra processing resources into speech recognition and thus are especially likely to drain their available pool of processing resources. Whether this effect can be offset by AV speech presentation was examined in the study presented in Chapter Two. On the other hand, older adults with a neurodegenerative disorder due to MCI or AD, have a restricted number of overall processing resources. Thus, having to allocate a greater number of resources to perceptional processing can further exacerbate their memory difficulty. This suggests that these individuals could especially benefit from perceptual facilitation through AV speech. Currently, only very limited research on AV speech perception has been done with these populations and there is an indication in the existing literature that the nature of AD neuropathology in the brain may be affecting multisensory processing. To clarify these issues, we examined AV speech processing and its effect on WM in older adults suffering from MCI or AD. The results of this study are presented in Chapter Three.

Chapter 2: Study 1

The Auditory-Visual Speech Benefit on Working Memory in Older Adults with Hearing Impairment

Manuscript to be submitted to *Psychology and Aging*

2.1 Abstract

This study examined the effect of auditory-visual (AV) speech stimuli on working memory (WM) in hearing impaired participants (HIP), in comparison to age- and education-matched normal elderly controls (NEC). Participants completed a WM *n*-back task (0- to 2-back) in which sequences of digits were presented in visual-only (i.e., speech-reading), auditory-only (A-only), and AV conditions. Auditory event-related potentials (ERP) were collected to assess the relationship between perceptual and WM processing. The behavioural results showed that both groups responded faster in the AV condition in comparison to the unisensory conditions. The ERP data showed perceptual facilitation in the AV condition, in the form of reduced amplitudes and latencies of the auditory N1 and/or P1 components, in the HIP group. Furthermore, a WM-ERP component, the P3, peaked earlier for both groups in the AV condition compared to the A-only condition. In general, the HIP group showed a more robust AV benefit; however, the NECs showed a dose-response relationship between perceptual facilitation and WM improvement, especially for facilitation of processing speed. Two measures, RT and P3 amplitude, suggested that the presence of visual speech cues may have helped the HIP to counteract the demanding auditory processing, to the level that no group differences were evident during the AV modality despite lower performance during the A-only condition. Overall, this study provides support for the theory of an integrated perceptual-cognitive system. The practical significance of these findings is also discussed.

2.2 Introduction

Aging is associated with various physical and cognitive changes, including both structural and functional changes in the auditory system resulting in hearing difficulty. Hearing impairment is the third most common chronic condition in older adults, ranking just after arthritis and hypertension (Zhang et al., 2013) and it has a significant impact on older adults' quality of life (e.g., Dalton et al., 2003; Strawbridge et al., 2000). The most common cause of hearing impairment in older adults results from various structural and functional age-related changes in the cochlea (Schneider, 1997). In addition to elevated hearing thresholds, these changes affect the processing of temporal and spectral cues, which are important for speech perception (e.g., Baer & Moore, 1994; Pichora-Fuller et al., 2007; Schneider, 1997; Schneider & Pichora-Fuller, 2001). Research also indicates that older adults need to engage broader cortical networks to process speech compared to younger adults (Wong et al., 2009). Thus, age-related changes in the auditory system can have a negative effect on speech perception, making it more effortful and demanding in terms of cognitive resources.

In addition to hearing difficulty, one of the most common complaints of older adults is difficulty with remembering information. According to a model proposed by Schneider and Pichora-Fuller (2000), there is a direct link between perceptual and higher-order cognitive functioning, such as memory. More specifically, they have proposed that perceptual and cognitive functions share a common pool of processing resources. Under this theory, having to devote too many processing resources toward perception may result in insufficient residual resources for subsequent higher-order processing, such as encoding and storing of the information in memory. Thus, for older adults with hearing impairment, memory difficulty may be a secondary effect of having to devote too many processing resources to speech perception. This has been demonstrated by several studies, which have shown that hearing impairment as well as presentation of auditory information in background noise interferes with memory performance (e.g., McCoy et al., 2005; Pichora-Fuller et al., 1995; Rabbitt, 1968, 1991).

In contrast to a negative effect of hearing impairment, there is strong evidence indicating that auditory-visual (AV) speech, in which both auditory and visual speech cues (i.e., lip, tongue and face movements) are available, enhances speech recognition (e.g., Bernstein & Grant, 2009; Fraser et al., 2010; Klucharev et al., 2003; Ma et al., 2009; Sumby & Pollack, 1954; Tanaka et al., 2009; Winneke & Phillips, 2011). Importantly, AV speech is not only associated with behavioural improvements of speech perception, but also with more efficient brain processing. This effect is indicated by studies using event-related potential (ERP) methodology, which measures electrical brain activity associated with different stages of stimulus-related processing (Luck, 2005). Auditory ERP components relevant to speech perception include the P1, which refers to a positive-going waveform peaking approximately 50 ms after the onset of the stimulus, and that is proposed to originate from the primary auditory cortex (Liegeois-Chauvel et al., 1994). In addition, the N1, which is a negative-going waveform that peaks approximately 100 ms after the onset of a sound and is proposed to originate from the secondary auditory cortex (Liegeois-Chauvel et al., 1994; Pantev et al., 1995).

The data from ERP research suggest that the brain elicits earlier and smaller responses during AV speech in comparison to auditory-only (A-only) speech modality. More specifically, both amplitude (Frtusova et al., 2013; Stekelenburg & Vroomen, 2007;

van Wassenhove et al., 2005), and latency (Frtusova et al., 2013; Pilling, 2009; Stekelenburg & Vroomen, 2007; van Wassenhove et al., 2005; Winneke & Phillips, 2011) of the auditory N1 and/or P1 component are reduced during processing of AV compared to A-only speech. Overall, these results indicate that the brain is able to process auditory information more efficiently and produce better behavioural outcomes when visual speech cues are available.

According to the theory of an integrated perceptual-cognitive system proposed by Schneider and Pichora-Fuller (2000), the observed perceptual benefit of AV speech should lead to more resources being available for higher-order cognitive processes, such as encoding of information in memory, and thus improved behavioural performance. This has been confirmed by Pichora-Fuller (1996), who demonstrated that visual speech cues help to counteract the negative effect of noise on working memory (WM) performance. We have previously examined the effect of AV speech on WM using an *n*-back task while also measuring ERP responses (Frtusova et al., 2013). The *n*-back task has been found to be sensitive to age-related changes (e.g., Van Gerven et al., 2007; Van Gerven et al., 2008; Vaughan et al., 2008; Verhaeghen & Basak, 2005; Vermeij et al., 2012), and it has been examined by previous ERP research. It has been found that P3 amplitude decreases with increased WM load (i.e., higher n-back condition; Segalowitz, Wintink, & Cudmore, 2001; Watter et al., 2001), while P3 latency seems independent of *n*-back manipulation (Gaspar et al., 2011; Watter et al., 2001). These results were interpreted as a suggestion that P3 amplitude reflects demands related to updating of WM, with greater demands resulting in a lower P3 amplitude, while P3 latency reflects processing related to comparison of the current stimulus with the one preselected in WM as being presented *n*-trials before (Watter et al., 2001).

During the *n*-back task used in our previous experiment (Frtusova et al., 2013) with normal-hearing younger and older adults, spoken digits were presented in either the visual-only (V-only), A-only or AV modality. The results showed that participants were faster across all memory loads, and more accurate in the most demanding WM conditions (2- and 3-back) when stimuli were presented in the AV modality compared to in the A-only and the V-only modality. Furthermore, the AV modality was associated with facilitated perceptual processing as evidenced by an earlier-peaking auditory N1 component in both age groups, and a smaller auditory N1 amplitude in older adults in the AV condition compared to the A-only condition.

The aforementioned findings come mostly from studies of younger and older adults with normal hearing. There is evidence to suggest that individuals with hearing impairment also benefit from having speech presented in the AV modality in terms of improved speech recognition in noisy environment (Bernstein & Grant, 2009; Grant et al., 1998; Tye-Murray et al., 2007). Furthermore, Grant, Tufts and Greenberg (2007) found that, despite a lower performance in an A-only condition during a syllable recognition task, participants with hearing impairment performed similarly to normal-hearing individuals in an AV condition. Thus, there is an indication that visual speech cues can help older adults with hearing impairment to counteract the hearing difficulty experienced during A-only conditions.

There is a scarcity of ERP research examining AV speech perception in the hearing impaired population. In one study, Musacchia, Arum, Nicol, Garstecki, and Kraus (2009) measured auditory ERPs in a group of older adults with normal hearing, and those with mild to moderate hearing loss during A-only, V-only and AV speech perception. Participants were asked to watch and/or listen to a repeated presentation of a “bi” syllable. The results showed that the AV modality did not result in the same level of modulation of ERP components for the hearing impaired group as it did for the normal-hearing controls. Musacchia and colleagues (2009) interpreted these results as an indication that AV integration abilities are diminished in individuals with hearing impairment. Thus, the results of this study seem contradictory to the observed AV speech benefit reported in behavioural studies and more ERP studies are needed to clarify this issue.

Importantly, there is preliminary behavioural evidence that older adults with hearing impairment may derive a WM benefit from AV speech. Brault, Gilbert, Lansing, McCarley and Kramer (2010) asked older adults with normal hearing and those with mild/moderate hearing loss (defined as at least one behavioural threshold between 45-70 dB HL in the range of 2000 – 4000 Hz) to recall the last three words from word lists of unpredictable lengths. The word lists were presented in either the AV or the A-only modality. The results showed that when the stimuli were not perceptually degraded by white noise, older adults with hearing impairment and good lip-reading ability benefited from AV speech in comparison to A-only speech. On the other hand, when the stimuli were presented in background noise, the AV speech benefit in comparison to the A-only condition was evident independently of hearing impairment status or lip-reading proficiency. However, Brault and colleagues (2010) thought that these improvements were related more to perception than to WM as there was no significant interaction between AV benefit and the lag (i.e., serial position of the recalled word).

Overall, AV speech seems to improve speech recognition in individuals with hearing impairment (Bernstein & Grant, 2009; Grant et al., 1998; Grant et al., 2007; Tye-Murray et al., 2007), and there is preliminary evidence that it may also lead to better WM performance (Brault et al., 2010). However, more studies that include a combination of behavioural and electrophysiological measures are needed to provide information about the AV interaction effect in individuals with hearing impairment. ERP methodology, in particular, can help to clarify the timing and nature of the AV interaction in this population in comparison to normal-hearing controls. In addition, this methodology can also help to clarify to what extent the behavioural WM improvements are in fact related to perceptual facilitation of auditory processing during AV speech.

2.2.1 Present Study

This study examined the effect of AV speech on WM in older adults with hearing impairment in comparison to age- and education-matched controls. WM was tested using an *n*-back task with 0-, 1-, and 2-back conditions, and with A-only, V-only and AV stimuli. During the task, ERP responses were collected together with behavioural accuracy and reaction time (RT) measures.

Similar to our previous work (Frtusova et al., 2013), it was expected that participants would have higher accuracy and faster RT in the AV condition compared to the A-only and V-only conditions. In addition, both perceptual and WM facilitation was expected to be evident on ERP measures in the AV condition compared to the A-only condition. More specifically, participants were expected to have earlier-peaking and smaller amplitude auditory P1 and N1 components during the AV condition compared to the A-only condition, indicating perceptual facilitation. Furthermore, they were expected to have an earlier-peaking and greater amplitude P3 component during the AV condition compared to the A-only condition, indicating WM facilitation. Based on the hypothesis that strenuous perceptual processing caused by hearing impairment affords less available cognitive resource for higher-order functions, and the expectation that this effect can be counteracted by AV speech, we predicted a greater AV benefit for the hearing impaired population.

Furthermore, we examined whether a direct relationship between perceptual facilitation and improvement on WM could be found. A greater facilitation of N1 amplitude, indicating more efficient perceptual processing, was expected to be associated with higher accuracy. Additionally, a greater facilitation of N1 latency, indicating faster perceptual processing, was expected to be associated with faster RT.

2.3 Method

2.3.1 Participants

The sample in this study consisted of 16 hearing impairment participants (HIP) and 16 normal elderly controls (NEC). Participants were recruited through the community, mostly from an existing laboratory database, or through local advertisements and word of mouth by previous participants. Two HIPs were recruited through the Deaf and Hard-of-Hearing Program at the MAB-Mackay Rehabilitation Centre in Montreal and several were recruited through the Communicaid for Hearing Impaired Persons organization in Montreal. The data from ten participants in the NEC group came from a previous study (Frtusova et al., 2013) that used a nearly identical procedure (with the exception of eliminating the 3-back condition in the current study). All participants in this study were reasonably healthy, with no self-reported history of disease significantly affecting cognitive ability (e.g., stroke, dementia, Parkinson's disease, or epilepsy). All participants reported being completely fluent in English and right handed (one participant in the HIP group reported mixed handedness). Potential participants for the HIP group were included if they reported hearing difficulty and either wore a hearing aid or were eligible for hearing aids according to their self-report. This way we tried to limit our sample to participants with sensorineural hearing loss.

All participants completed a hearing screening that measured hearing thresholds for 250, 500, 1000, 2000, 4000 Hz (Welch Allyn, AM 232 Manual Audiometer). From these, we computed pure tone average (PTA) values for each ear by averaging across the thresholds obtained for 500, 1000 and 2000 Hz. Control participants had to have a PTA equal to or below 25 dB (Katz, 1985). The individuals in the HIP group had to have sufficient hearing to be able to correctly identify the stimuli in the A-only condition without a hearing aid. All participants completed a vision screening that measured contrast sensitivity using the Mars Contrast Sensitivity Test (by MARS Perceptrix; Arditi, 2005). In this test, participants were asked to read a series of large print letters that degraded in terms of background contrast. Contrast sensitivity, measured as logMAR scores, was obtained for each eye separately as well as binocularly. Lastly, cognitive screening was completed using the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). The groups were matched on age, education, gender, vision and general cognitive skills measured by the MoCA. The demographic characteristics of the two samples are presented in Table 1.

Table 1. Demographic characteristics

	NEC (n=16)	HIP (n=16)	
Males/Females	2/14	1/15	
Age (Years)	76.6 (4.93)	76.4 (9.57)	p > .05
Education (Years)	14.1 (2.53)	14.5 (3.45)	p > .05
MoCA[1]	27.5 (1.41)	26.3 (2.52)	p > .05
Binocular Vision (logMAR[2])	1.7 (0.06)	1.7 (0.07)	p > .05
PTA[3] Right Ear (dB)	15.6 (6.23)	47.8 (10.23)	p < .001
PTA[3] Left Ear (dB)	15.4 (5.59)	49.4 (11.75)	p < .001

[1] Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005)

[2] Contrast sensitivity scores on Mars Contrast Sensitivity Test (Arditi, 2005)

[3] The pure tone average (PTA) represents the average of hearing thresholds for 500 Hz, 1000 Hz, and 2000 Hz.

2.3.2 Stimuli

The stimuli consisted of short videos of a female speaking the digits 1, 2, 3, 4, 5, 6, 8, 9, and 10 with neutral facial expression. The digit 7 was omitted because it is bi-syllabic and thus more easily distinguishable from the other digits. The stimuli were recorded in a recording studio at the Department of Journalism, Concordia University, and subsequently edited using Adobe Premier (Video codec, Windows Media Video 9; frame size, 500 px 388 px; frame rate, 29.97 fps; Audio codec, Windows Media Audio; sample rate and size, 44,100 Hz 16-bit). The videos showed the full face and shoulders of the speaker against a green background. The videos were edited such that the first obvious lip movement occurred nine frames after the onset of the video and the last lip movement happened approximately nine frames before the video ended. Imperceptible triggers were inserted at the time of the first lip movement (i.e., visual trigger) and at the onset of the sound (i.e., auditory trigger), in order to signal these events to the recording electroencephalogram which was important for subsequent ERP analyses (as described later). The lag between the onset of the video and the onset of the sound was approximately 395.3 ms (*SD* = 103.24). The average length of the video was 2010 ms (*SD* = 160 ms), with inter-trial interval of 2400 ms. The sound was presented binaurally using insert earphones (EARLINK tube ear inserts; Neuroscan, El Paso, Texas) at the mean intensity of 70.2 dB (SPL, *SD*=2.59).

The AV stimuli included both video and audio channels, meaning that the participants could both see and hear the speaker. For the A-only stimuli, the video channel was deleted and only a white fixation point was presented on a black background to maintain eye fixation. For the V-only stimuli, the auditory channel was deleted and the participants needed to identify the digits based on the visual speech cues. Overall, the stimuli in the three modalities were identical with the exception of the presence of either both of the modalities or only one of the modalities. The stimuli were presented on a black screen 15-in. CRT monitor, using Inquisit (version 2.0; Millisecond Software, 2008). Participants were seated in a comfortable chair approximately 60 cm from the screen.

2.3.3 Procedure

Participants completed the *n*-back task in three modalities: V-only (where they could see the speaker presenting the digits but could not hear her voice); A-only (where they could hear the speaker presenting digits but could not see her face); and AV (where they could both hear and see the speaker presenting digits). There were three different levels of task difficulty ranging from 0-back to 2-back load in a blocked design. In the 0-back condition, participants had to decide whether the currently presented digit matched a target digit assigned at the beginning of the block. In the 1-back condition, participants had to decide whether the currently presented digit matched the one presented one trial before, and in the 2-back condition, participants had to decide whether the currently presented digit matched the one presented two trials before.

The sequences of digits were semi-random, each containing 40 'Match' trials and 60 'Non-Match' trials. In Match trials, the currently presented digit matched the one assigned at the beginning of the block (0-back) or the one presented one or two trials before (1- and 2-back, respectively). Participants completed the 0-back condition in each modality, followed by the 1-back condition in each modality and finished with the 2-back condition in each modality. The order of the modality presentations was varied across participants but remained the same for each n-back condition. Participants were presented with different sequences of digits in different modalities, but modality-sequence combinations were also varied across participants.

Participants practiced speech-reading and responding with the computer mouse before the experiment began. To practice speech-reading, participants had to identify the digits used in the experiment based on only seeing the speaker to utter these digits (similar to the V-only condition). Digits were first presented in numerical and then random order. This procedure was repeated if the participant made mistakes in the random practice condition. To practice responding with the computer mouse, participants were asked to hold the mouse in both of their hands and press the left or right button using their thumbs to indicate Match or Non-Match responses. The assignment of Match response to the left or right button was counterbalanced across participants. To practice responding, they completed ten trials that were identical to the AV 0-back condition. After this, the experimental tasks began. In order to ensure that each participant understood the task, they completed ten practice trials before each new *n*-back block (i.e., before beginning the 0-back, 1-back, and 2-back tasks). During these trials, feedback was provided by presenting a short low-frequency beep whenever participants made a mistake. The practice blocks were repeated if participants made more than a few mistakes and it appeared that they did not understand the task. For many participants, this was mostly necessary in the 2-back condition. Lastly, in order to give participants a chance to adjust to each new condition, five "Warm-Up" trials were included at the beginning of each sequence. These trials were not counted in the analyses.

Two behavioural measures were collected: the accuracy, defined as the percentage of correct Match responses, and RT, defined as the mean amount of time between the onset of the auditory trigger and the participant's button response for correct Match trials. Trials were excluded if the response occurred less than 200 ms after the first cue about the identity of the digit (i.e., the onset of the lip movement in the V-only and AV conditions or the onset of the sound in the A-only condition). This was done because such early responses were unlikely to represent a valid response.

2.3.4 Electroencephalography Data Acquisition and Processing

The electroencephalography (EEG) data were collected during the task using a Biosemi ActiveTwo system with 72 channels. Sixty-four electrodes were arranged on the head according to the extended International 10-20 system (Jasper, 1958). Electro-occulograms (EOG) were used to monitor eye movements: one electrode was placed above and one below the left eye to monitor vertical eye movements and one electrode was placed beside the outer canthi of each eye to monitor horizontal eye movements. The sampling rate during the recording was 2048 Hz but the files were down-sampled offline to 512 Hz to reduce the size of the files and facilitate data processing.

After down-sampling, the recorded data were converted to Neuroscan continuous data format using Polygraphic Recording Data Exchange (PolyRex; Kayser, 2003). The data were re-referenced to a linked left and right ear lobe reference and subsequently processed using Scan software (version 4.5; Compumedics Neuroscan, 2009). Vertical ocular artifacts were corrected using a spatial filtering technique (Method 1; NeuroScan Edit 4.5 manual, 2009). Next, the frequencies outside the range of 1-45 Hz were filtered using a bandpass filter. Continuous recordings were divided into separate epochs going from -100 to 1000 ms around the onset of auditory stimuli (i.e., auditory triggers) and baseline corrected based on the 100 ms prestimulus period (i.e., -100 ms to 0 ms before the auditory trigger). Epochs with excessive artifacts (i.e., activity larger than ± 75 μV in the active electrodes at and around the midline or EOG activity exceeding ± 60 μV) were excluded by the software program. The accepted epochs were subsequently inspected manually by the examiner to ensure that there was no excessive noise in the epochs that were to be used in the analyses. The mean number of accepted trials was 31.5 out of 40 for the Match condition (*SD* = 5.64).

The epochs were then sorted by the software based on the condition, and individual averages (i.e., average waveforms for each individual) for each condition were computed. In order to examine the AV interaction, the waveforms for A-only and V-only were added to create A+V waveforms (Frtusova et al., 2013; Klucharev et al., 2003; Pilling, 2009; van Wassenhove et al., 2005; Winneke & Phillips, 2011).

In this study, we were interested in three ERP components, namely P1, N1, and P3. These components were first detected by a semiautomatic procedure in Scan software (NeuroScan Edit 4.5 manual). For this purpose, the P1 was defined as the highest positive point occurring between 20 and 110 ms after the onset of the stimulus; the N1 was defined as the lowest negative point occurring between 60 and 170 ms after the onset of the stimulus; and the P3 was defined as the most positive point occurring between 300 and 700 ms after the onset of the stimulus. To ensure that correct peaks were identified, the detected peaks were subsequently inspected and manually adjusted, when necessary, by a trained examiner who was blinded to the modality and group factors.

2.4 Results

The data were analyzed by repeated measures ANOVAs using SPSS (version 22; IBM). For predicted interaction effects, significant main effects were followed by explorations of simple effects and pairwise comparisons. The reported results are significant at $\alpha \leq .05$ unless otherwise specified. For the main analyses, the Greenhouse-Geisser nonsphericity correction was used for interpreting results for within-subject factors with more than two levels. Based on the convention suggested by Jennings (1987), Greenhouse-Geisser epsilon (ε) values and uncorrected degrees of freedom are reported together with adjusted *p*-values and mean square error (*MSE*) values. Participants had to reach an accuracy of at least 60% during a particular condition in order to be included in the analyses; otherwise the value for that condition was replaced by the group mean. This criterion was imposed in order to ensure that participants were sufficiently engaged in the task so that the observed values indicated a valid representation of task-related performance. Eight values (out of 144) needed to be replaced in the NEC group and nine values (out of 141) needed to be replaced in the HIP group. In addition, one participant from the HIP group discontinued the 2-back condition because she found it too difficult and thus the missing values were replaced by group means.

2.4.1 Behavioural Results

Behavioural data were analyzed by repeated measures ANOVAs with modality (V-only, A-only, AV) and *n*-back load (0-, 1-, and 2-back) entered as within-subject variables and group (NEC and HIP) entered as a between-subject variable.

Accuracy. The accuracy data are shown in Figure 1. The analysis revealed a significant main effect of modality, $F(2, 60) = 9.7$; $MSE = 48.22$; $p < .001$; $\varepsilon = .86$; $\eta_p^2 = .25$, indicating that participants were more accurate in the A-only and AV conditions compared to the V-only condition but performance in the A-only and the AV condition did not differ. There was also a main effect of load, $F(2, 60) = 162.2$; $MSE = 53.23$; $p < .001$; $\varepsilon = .89$; $\eta_p^2 = .84$, showing that accuracy decreased as *n*-back load increased. Neither the main effect of group, $F(1, 30) = .6$; $MSE = 127.95$; $p = .43$; $\eta_p^2 = .02$, nor the Modality x Group interaction, $F(2, 60) = .4$; $MSE = 48.22$; $p = .66$; $\varepsilon = .86$; $\eta_p^2 = .01$, were significant.

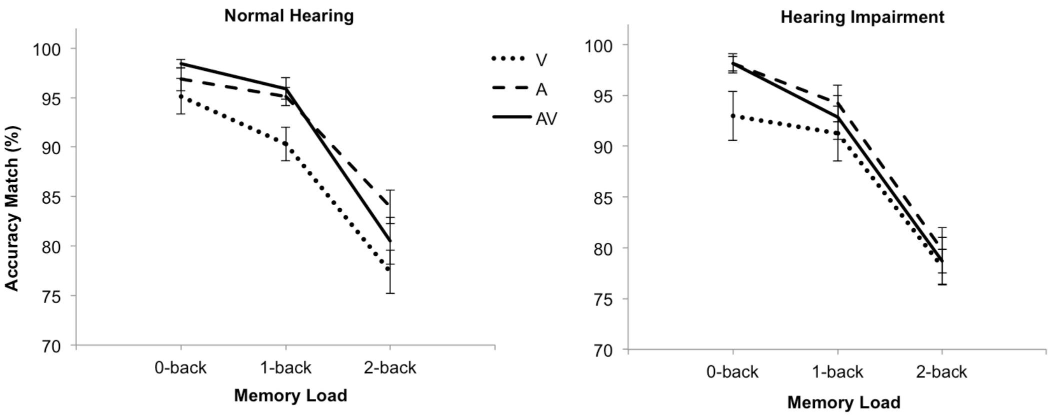

Figure 1. The mean percentage of correct responses and standard error bars for normal-hearing participants (left panel) and participants with hearing impairment (right panel).

Reaction Time. The mean RT data are shown in Figure 2. The analysis revealed a significant main effect of modality, $F(2, 60) = 42.6$; $MSE = 9946.64$; $p < .001$; $\varepsilon = .80$; $\eta_p^2 = .59$, load , $F(2, 60) = 29.7$; $MSE = 18372.55$; $p < .001$; $\varepsilon = .91$; $\eta_p^2 = .50$, as well as a significant Modality x Load interaction, $F(4, 120) = 7.8$; $MSE = 9575.33$; $p < .001$; $\varepsilon = .66$; $\eta_p^2 = .21$. Pairwise comparisons showed that participants were faster during the AV condition compared to the V-only and A-only conditions at all *n*-back loads, but they were faster in the A-only condition compared to the V-only condition only during the 0-back condition.

Furthermore, there was a statistical trend for the effect of group, $F(1, 30) = 3.6$; $MSE = 105309.68$; $p = .07$; $\eta_p^2 = .11$, indicating that the NEC group was faster than the HIP group. This effect was qualified by a Modality x Group interaction, $F(2, 60) = 4.6$; $MSE = 9946.64$; $p = .02$; $\varepsilon = .80$; $\eta_p^2 = .13$, which showed that the HIP group performed similarly to the NEC group in the V-only, $F(1, 30) = .8$; $p = .37$; $\eta_p^2 = .03$, and the AV, $F(1, 30) = 2.0$; $p = .17$; η_p^2

= .06, conditions but were significant slower in the A-only condition, $F(1, 30) = 12.6$; $p = .001$; $\eta_p^2 = .30$.

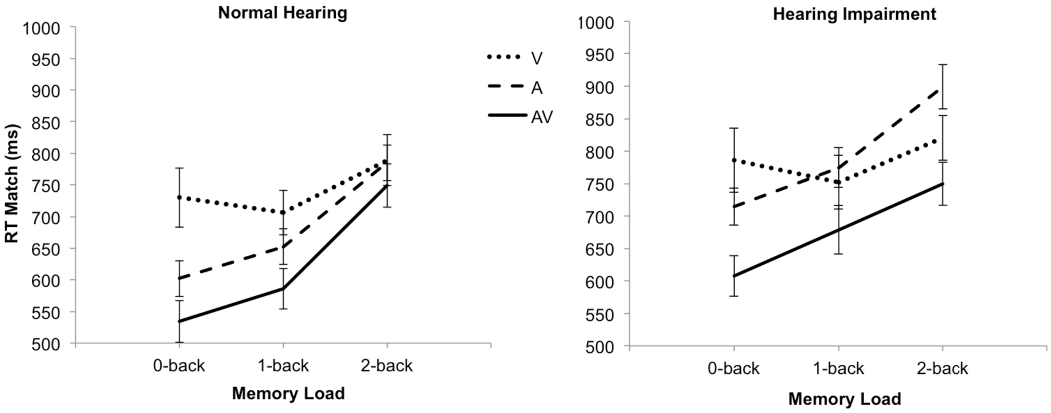

Figure 2. The mean reaction time and standard error bars for normal-hearing participants (left panel) and participants with hearing impairment (right panel). Note the faster responses during the AV condition in comparison to the A-only condition in both groups.

2.4.2 Electrophysiological Results: Perceptual Processing

For the electrophysiological results, the V-only condition was not included in the analyses because our analyses focused on the auditory evoked potentials. More specifically, we were interested in the comparison of auditory processing with and without the presence of visual speech cues. N1 amplitude was defined as an absolute voltage difference between the trough of the P1 and the peak of the N1, thus we refer to this component complex as P1-N1 when describing the amplitude data. In order to explore the possibility of multisensory effects occurring before the N1 component, we also analyzed the data from the P1 component separately. P1 amplitude was measured relative to the 0 μV baseline.

The P1 and N1 latencies were measured at the components' peaks relative to the onset of the auditory trigger. The data from the CZ electrode were used for the analyses as these components reach their maximum in mid-central electrodes (Näätänen & Picton, 1987) and no hemispheric differences were identified in a previous work in our laboratory (Winneke & Phillips, 2011).

To explore multisensory processing, the AV and the A-only conditions were compared to the A+V measure. This waveform was obtained by the summation of electrophysiological activity in the A-only and the V-only conditions locked to the onset of the auditory stimuli. For this purpose, we embedded imperceptible triggers into the V-only files at the time points where the onset of the sound would have occurred, if it had been presented (i.e., at the identical time point as in the A-only and the AV stimuli). This way we were able to assess whether the AV condition represented a multisensory interaction or merely the simultaneous processing of two independent modality channels (A-only and V-only). The values for the P1 and P1-N1 amplitudes and for the P1 and N1 latencies were analyzed by repeated measures ANOVAs with modality (AV, A-only, A+V) and *n*-back load (0-, 1-, and 2-back) conditions entered as within-subject variables and group (NEC and HIP) entered as a between- subject variable.

P1-N1 amplitude. The grand averages illustrating different modalities for the P1-N1 wave are presented in Figure 3. The mean values and standard deviations are also presented in Table 2. The ANOVA showed a main effect of modality, $F(2, 60) = 12.5$; $MSE = 4.74$; $p < .001$; $\varepsilon = .74$; $\eta_p^2 = .29$, such that the amplitude of the P1-N1 was smaller in the AV condition compared to both the A-only condition and the A+V measure, and smaller in the A-only condition compared to the A+V measure. Thus, the data provided evidence for a multisensory interaction in the AV condition. There was also a main effect of group, *F*(1, 30) = 10.5; *MSE* = 38.88; *p* = .003; η_p^2 = .26, with the HIP group having a smaller P1-N1 amplitude than the NEC group.

In order to test our main hypothesis, the planned simple effects, followed by pairwise comparisons, indicated that there was a significant decrease in P1-N1 amplitude in the AV condition compared to the A-only condition and the A+V measure, and in the A-only condition compared to the A+V measure for the HIP group, *F*(2, 29) = 7.4; *p* = .003; η_p^2 = .34. However, while a similar pattern of results was suggested in the NEC group, the mean differences did not reach the level of significance, *F*(2, 29) = 1.8; *p* = .19; η_p^2 = .11; see Table 2.

P1 amplitude. The grand averages illustrating different modalities for the P1 wave are presented in Figure 3. The mean values and standard deviations are also presented in Table 3. The ANOVA showed a main effect of modality, *F*(2, 60) = 10.2; *MSE* = 4.62; *p* = .001; ε = .76; η_p^2 = .25; the amplitude of P1 was smaller in the AV condition compared to the A-only condition and the A+V measure, while the A-only condition and the A+V measure did not significantly differ. These results indicate that the multisensory interaction effect is evident early in the information processing stream and modulation observed in the AV condition compared to the A-only condition cannot be explained by simultaneous but independent processing of visual and auditory speech information.

There was also a main effect of group, *F*(1, 30) = 4.4; *MSE* = 9.35; *p* = .04; η_p^2 = .13, with the HIP group having a smaller P1 amplitude than the NEC group. Furthermore, there was a significant Modality x Group interaction, *F*(2, 60) = 4.2; *MSE* = 4.62; *p* = .03; ε = .76; η_p^2 = .12, indicating that for the HIP group, *F*(2, 29) = 9.0; *p* = .001; η_p^2 = .38, P1 amplitude was smaller in the AV condition compared to the A-only condition and the A+V measure, and there was a statistical trend (p= .06) for the P1 to be smaller in the A-only condition compared to the A+V measure. However, no modality effect was indicated in the NEC group, F(2, 29) = .5; p = .61; η_p^2 = .03; see Table 3. The simple effects conducted on the interaction also revealed that the HIP group had a smaller P1 amplitude in the AV condition compared to the NEC group, F(1, 30) = 11.9; p = .002; η_p^2 = .28, while the two groups had similar P1 amplitudes in the A-only condition, F(1, 30) = 2.1; p = .16; η_p^2 = .07, and the A+V measure, F(1, 30) = .02; p = .90; η_p^2 = .00. Lastly, there was a main effect of load, F(2, 60) = 3.5; MSE = 4.86; p = .05; ε = .84; η_p^2 = .10, with P1 amplitude being smaller in the 1-back than the 0-back condition. No other differences were evident across different WM loads.

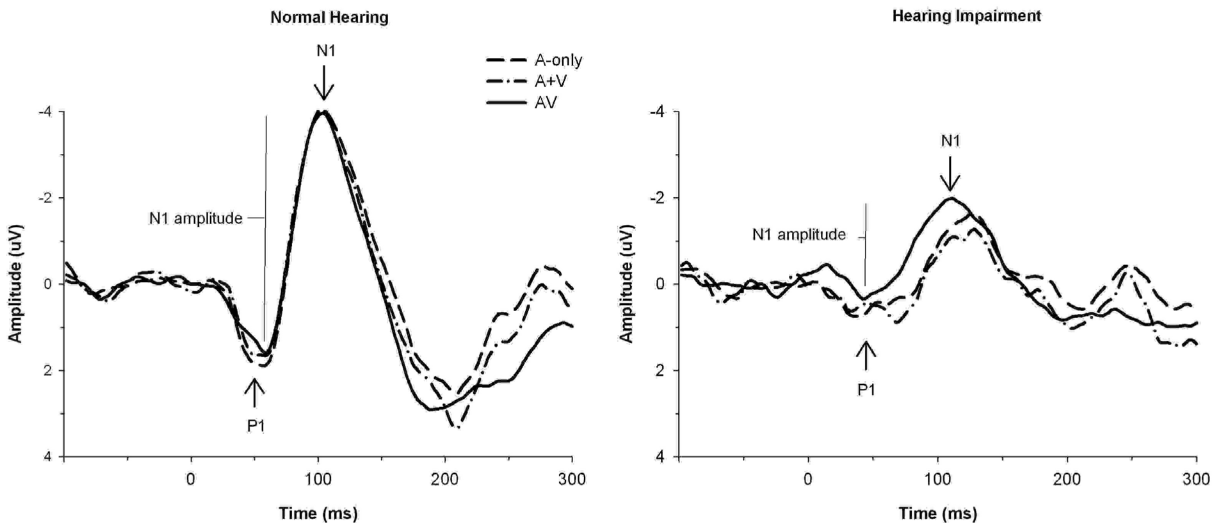

Figure 3. The grand average waveforms of auditory event-related potentials at the CZ electrode, illustrating the amplitudes and latencies of the P1 and N1 components for normal-hearing older adults (left panel) and older adults with hearing impairment (right panel). The data are collapsed across different *n*-back conditions. Note the smaller amplitude of P1 and N1, and earlier P1 in the AV in comparison to the A-only condition for participants with hearing impairment.

Table 2

The mean amplitudes (μV) and standard deviations (in parenthesis) of the P1-N1 component for normal-hearing participants and participants with hearing impairment at the CZ electrode

		Modality	
Load	A-only	A+V	AV
		Normal Hearing	
0-back	8.3(0.71)	8.8(0.74)	6.9(0.69)
1-back	7.1(0.61)	7.3(0.76)	6.7(0.61)
2-back	7.9(0.59)	8.0(0.66)	7.7(0.74)
		Hearing Impairment	
0-back	5.2(0.71)	5.9(0.74)	4.3(0.69)
1-back	5.5(0.61)	6.6(0.76)	4.5(0.61)
2-back	5.3(0.59)	5.8(0.66)	4.2(0.74)

Table 3

The mean amplitudes (μV) and standard deviations (in parenthesis) of the P1 component for normal-hearing participants and participants with hearing impairment at the CZ electrode

		Modality	
Load	A-only	A+V	AV
		Normal Hearing	
0-back	3.3(0.37)	3.4(0.53)	2.1(0.56)
1-back	1.9(0.47)	2.1(0.60)	2.0(0.57)
2-back	3.0(0.33)	2.9(0.55)	3.2(0.42)
		Hearing Impairment	
0-back	2.4(0.37)	2.8(0.53)	1.1(0.56)
1-back	1.8(0.47)	2.8(0.60)	0.5(0.57)
2-back	2.2(0.33)	2.7(0.55)	0.8(0.42)

P1 latency. The grand averages illustrating different modalities for the P1 wave are presented in Figure 3. The mean values and standard deviations are also presented in Table 5. The data showed the main effect of modality, $F(2, 60) = 6.0$; $MSE = 373.14$; $p = .01$; $\varepsilon = .86$; $\eta_p^2 = .17$; the P1 peaked earlier in the AV condition compared to the A-only condition and the A+V measure, while the A-only condition and the A+V measure did not significantly differ. The main effect of group was not significant, $F(1, 30) = 2.9$; $MSE = 854.68$; $p = .10$; $\eta_p^2 = .09$, but there was a statistical trend toward a Modality x Group interaction, $F(2, 60) = 3.2$; $MSE = 373.14$; $p = .06$; $\varepsilon = .86$; $\eta_p^2 = .10$, indicating that the P1 peaked earlier in the AV condition compared to the A-only condition and the A+V measure for the HIP group, $F(2, 29) = 7.1$; $p = .003$; $\eta_p^2 = .33$, but the differences in the NEC group did not reach statistical significance, $F(2, 29) = .3$; $p = .78$; $\eta_p^2 = .02$.

N1 latency. The grand averages illustrating different modalities for the N1 wave are presented in Figure 3. The mean values and standard deviations are presented in Table 4. The main effect of modality did not reach statistical significance, $F(2, 60) = 3.0$; $MSE = 600.15$; $p = .09$; $\varepsilon = .61$; $\eta_p^2 = .09$. There was a statistical trend toward the main effect of group, $F(1, 30) = 3.8$; $MSE = 1311.89$; $p = .06$; $\eta_p^2 = .11$, with the N1 peaking later in the HIP group than the NEC group. There was a main effect of load, $F(2, 60) = 5.6$; $MSE = 482.81$; $p = .01$; $\varepsilon = .95$; $\eta_p^2 = .16$, which was qualified by a Load x Group interaction, $F(2, 60) = 4.3$; $MSE = 482.81$; $p = .02$; $\varepsilon = .95$; $\eta_p^2 = .13$, and further by a Modality x Load x Group interaction, $F(4, 120) = 2.8$; $MSE = 376.14$; $p = .05$; $\varepsilon = .69$; $\eta_p^2 = .09$. The simple effects and pairwise comparisons indicated that there were no statistical differences in the NEC group (all $Fs < 1.9$; all $ps > .16$). For the HIP group, no differences across different modalities were observed in the 0-back, $F(2, 29) = .2$; $p = .81$; $\eta_p^2 = .02$, condition, but the N1 peaked earlier in the AV condition compared to the A-only condition and the A+V measure during the 1-back load, *F*(2, 29) = 6.5; p = .01; η_p^2 = .31, and earlier in the A-only condition compared to the A+V measure during the 2-back load, *F*(2, 29) = 3.1; p = .06; η_p^2 = .18.

Table 4

The mean latencies (ms) and standard deviations (in parenthesis) of the N1 component for normal-hearing participants and participants with hearing impairment at the CZ electrode

		Modality	
Load	A-only	A+V	AV
		Normal Hearing	
0-back	101.2(7.16)	102.8(6.97)	99.8(4.60)
1-back	104.5(5.68)	103.1(5.15)	102.4(4.64)
2-back	102.2(4.08)	100.3(4.53)	94.5(3.31)
		Hearing Impairment	
0-back	118.5(7.16)	121.7(6.97)	119.9(4.60)
1-back	115.0(5.68)	115.0(5.15)	90.9(4.64)
2-back	97.7(4.08)	105.4(4.53)	101.9(3.31)

Table 5

The mean latencies (ms) and standard deviations (in parenthesis) of the P1 component for normal-hearing participants and participants with hearing impairment at the CZ electrode

	Modality		
Load	A-only	A+V	AV
		Normal Hearing	
0-back	47.1(4.89)	45.0(4.36)	49.2(3.74)
1-back	50.6(4.92)	50.4(6.06)	48.6(4.57)
2-back	50.2(3.31)	53.4(4.61)	44.1(4.16)
		Hearing Impairment	
0-back	59.5(4.89)	66.5(4.36)	52.6(3.74)
1-back	54.7(4.92)	60.6(6.06)	40.3(4.57)
2-back	51.9(3.31)	58.6(4.61)	46.6(4.16)

2.4.3 Electrophysiological Results: Working Memory Processing

P3 amplitude was measured relative to the 0 μV baseline and P3 latency was measured at the components' peaks relative to the onset of the auditory trigger. The data from the PZ electrode were used for the analyses as this component reaches its maximum in mid-posterior sites (Frtusova et al., 2013; Watter et al., 2001). The P3 is considered to reflect WM processes (i.e., higher-order) rather than perceptual processing and thus for this condition we only compared the AV and A-only modalities. The values from the P3 components were analyzed by repeated measures ANOVAs with the modality (A-only and AV) and *n*-back load (0-, 1-, and 2-back) conditions entered as within-subject variables and group (NEC and HIP) entered as a between-subject variable.

P3 amplitude. The grand averages illustrating different modalities for the P3 wave are presented in Figure 4. The mean values and standard deviations are also presented in Table 6. The ANOVA showed that neither the main effect of modality, $F(1, 30) = .5$; $MSE = 2.69$; $p = .50$; $\eta_p^2 = .02$, nor the main effect of group, $F(1, 30) = 3.0$; $MSE = 15.58$; $p = .10$; $\eta_p^2 = .09$, was significant. However, there was a significant Modality x Group interaction, $F(1, 30) = 4.1$; $MSE = 2.69$; $p = .05$; $\eta_p^2 = .12$. The two groups had similar P3 amplitudes in the AV condition, $F(1, 30) = .6$; $p = .43$; $\eta_p^2 = .02$, but the HIP group had significantly smaller P3 amplitude in the A-only condition compared to the NEC group, $F(1, 30) = 5.8$; $p = .02$; $\eta_p^2 = .16$. As expected, there was a main effect of load, $F(2, 60) = 11.3$; $MSE = 5.04$; $p < .001$; $\varepsilon = .79$; $\eta_p^2 = .27$, with P3 amplitude being greater in the 0-back condition compared to the 1-back and 2-back conditions, while the 1-back and 2-back conditions did not significantly differ.

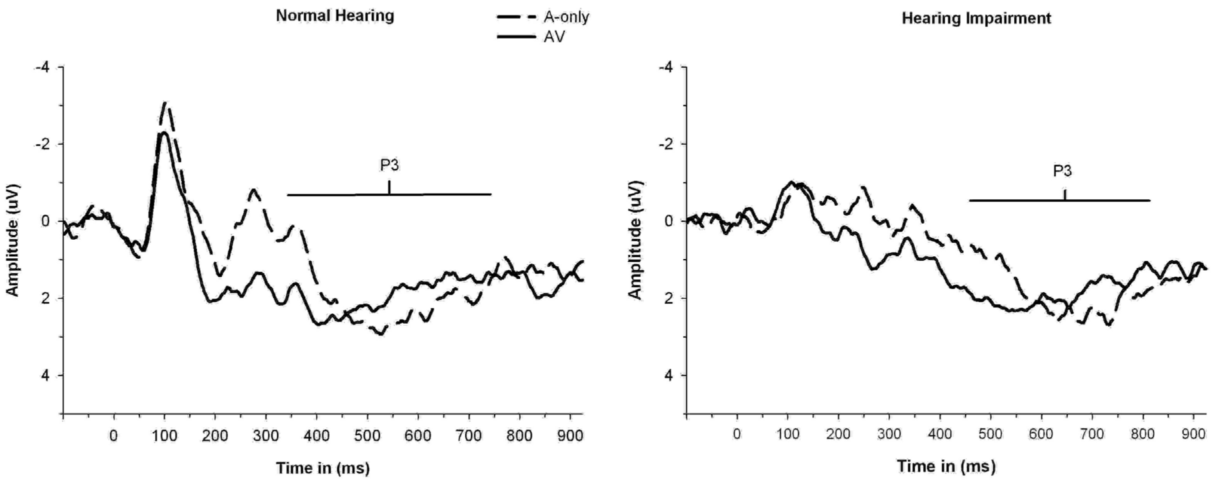

Figure 4. The grand average waveforms of auditory event-related potentials at PZ electrode, illustrating the amplitudes and latencies of P3 component for normal-hearing older adults (left panel) and older adults with hearing impairment (right panel). The data are collapsed across different *n*-back conditions. Note the smaller P3 amplitude in participants with hearing impairment for the A-only condition but similar P3 amplitudes in both groups for the AV condition. Also note the earlier peaking P3 in the AV in comparison to the A-only condition in both groups and later peaking P3 in both modalities for participants with hearing impairment.

Table 6

The mean amplitudes (µV) and standard deviations (in parenthesis) of the P3 component for normal-hearing participants and participants with hearing impairment at the PZ electrode

	Modality	
Load	A-only	AV
	Normal Hearing	
0-back	6.4(0.66)	5.8(0.70)
1-back	4.7(0.52)	4.7(0.55)
2-back	4.5(0.47)	4.2(0.51)
	Hearing Impairment	
0-back	4.4(0.66)	5.6(0.70)
1-back	3.7(0.52)	3.9(0.55)
2-back	3.2(0.47)	3.8(0.51)

P3 latency. The grand averages illustrating the different modalities for the P3 wave are presented in Figure 4. The mean values and standard deviations are presented in Table 7. The data showed a main effect of modality, $F(1, 30) = 11.3$; $MSE = 5319.22$; $p = .002$; $\eta_p^2 = .27$, with the P3 peaking earlier in the AV condition compared to the A-only condition. There was also a main effect of group, $F(1, 30) = 14.2$; $MSE = 13022.67$; $p = .001$; $\eta_p^2 = .32$, with the P3 peaking later in the HIP group compared to the NEC group. The interaction between Modality x Group was not significant, $F(1, 30) = .02$; $MSE = 5319.22$; $p = .88$; $\eta_p^2 = .00$.

Table 7

The mean latencies (ms) and standard deviations (in parenthesis) of the P3 component for normal-hearing participants and participants with hearing impairment at the PZ electrode

	Modality	
Load	A-only	AV
	Normal Hearing	
0-back	473.9(15.20)	423.9(17.75)
1-back	487.2(17.49)	476.0(22.61)
2-back	507.0(13.25)	456.8(14.96)
	Hearing Impairment	
0-back	557.8(15.20)	509.4(17.75)
1-back	536.3(17.49)	512.1(22.61)
2-back	555.1(13.25)	526.3(14.96)

2.4.4 Correlation Between Facilitation of Perceptual Processing and Improvement in Working Memory Performance

We examined whether there is a relationship between the amount of perceptual facilitation (i.e., a decrease in the amplitude of the P1-N1 and the latency of the auditory N1) and the level of behavioural improvement on the WM task in the AV condition compared to the A-only condition. Firstly, we examined whether there is a positive relationship between the facilitation of the auditory P1-N1 amplitude (A-only – AV) and higher accuracy (AV – A-only). Secondly, we examined whether there is a positive relationship between facilitation of the auditory N1 latency (A-only – AV) and faster RT (A-only – AV). We reasoned that participants with greater perceptual facilitation should have greater behavioural improvement. The results are presented in Table 8 (note that positive correlations always reflect a relationship in the expected direction).

Table 8

Zero-order correlations between the facilitation of P1-N1 amplitude and improvement in accuracy (on the left) and facilitation of N1 latency and improvement in reaction time (RT; on the right) during the AV condition in comparison to A-only condition

	P1-N1 Amplitude		N1 Latency	
	NEC ACCURACY	HIP ACCURACY	NEC RT	HIP RT
0-back	.26	-.09	.13	.02
1-back	.16	-.11	.31	.05
2-back	.13	.34	.43*	.10

* significant at α ≤ .05 one-tailed

2.5 Discussion

This study examined the effect of AV speech on WM in older adults with hearing impairment compared to normal-hearing NECs. The results showed that both groups were faster in the AV condition compared to the unisensory conditions even though the accuracy was comparable between the AV and A-only conditions. Participants with hearing impairment were slower compared to controls during the A-only condition but the two groups performed similarly in the AV and the V-only conditions. These results suggest that group differences in the A-only condition are due to more demanding perceptual processing for the HIP group rather than differences in WM, and that visual speech cues can help to counteract this more demanding auditory processing.

The electrophysiological results revealed facilitation of perceptual processing in the HIP group, indicated by smaller and faster perceptual ERP responses during the AV condition compared to the A-only condition. Furthermore, the ERP data showed facilitation of WM processing, indicated by earlier P3 components in both groups. For P3 amplitude, the HIP group had smaller P3 amplitude than the NEC group in the A-only condition but no group differences were observed in the AV condition, supporting the suggestion that visual speech cues can help to counteract the negative effect of more demanding perceptual processing on WM.

2.5.1 Auditory-Visual Speech Interaction in Older Adults with Hearing Impairment

The results of the current study indicate that older adults with hearing impairment show a more robust multisensory interaction effect compared to older adults with age-normal hearing. More specifically, the amplitudes of the auditory P1 and the P1-N1 were significantly reduced in the AV condition compared to the A-only condition and the A+V measure for participants with hearing impairment but these effects did not reach statistical significance in participants with normal hearing. Similarly, there was a reduction in the auditory P1 latency during the AV condition, compared to the A-only condition and the A+V measure, evident in hearing impaired participants while in those with normal hearing these differences were not statistically significant. Lastly, for the auditory N1 latency, a reduction in the AV condition compared to the A-only condition and the A+V measure, was observed in the 1-back load for the hearing impaired group while no significant differences were seen in controls. Overall, our results suggest intact AV multisensory interaction in older adults with hearing impairment. These effects were observed early in the processing stream (i.e., the level P1 component), suggesting that the multisensory interaction is occurring as early as at the level of the primary auditory cortex (Liegeois-Chauvel et al., 1994).

These results stand in contrast to those by Musacchia and colleagues (2009) who found that older adults with hearing impairment may not be able to integrate auditory and visual speech information to the same extent as older adults with age-normal hearing. There are several methodological differences between the current study and that conducted by Musacchia and colleagues (2009) that may have contributed to the differences in the results. For example, Musacchia and colleagues (2009) assessed speech perception by repetition of the same syllable, participants were not actively involved in the task, which may have affected their attention to the stimuli, and lastly, they equalized the auditory input across the groups by adjusting the intensity level of the stimuli. Our results confirmed the observation of improved perceptual functioning during AV speech reported by behavioural studies examining speech recognition in older adults with hearing impairment (e.g., Bernstein & Grant, 2009; Grant et al., 1998; Tye-Murray et al., 2007).

2.5.2 The Effect of Auditory-Visual Speech on Working Memory

The behavioural results showed faster RT during the AV condition compared to the unisensory conditions in both groups, suggesting facilitation of WM processing. Furthermore, while the WM performance of individuals with hearing impairment was slower in comparison to normal-hearing individuals during the A-only condition, no group differences were observed during the AV condition. Thus, it appears that visual speech cues may help to counteract the slowing of information processing caused by hearing impairment.

Surprisingly, no difference between the AV and the A-only condition was evident in the accuracy data suggesting that despite the facilitation of processing speed, the AV speech did not seem to influence overall WM capacity. There was also no effect of group on accuracy. Overall, these results indicate that both older adults with hearing impairment and those with normal hearing are able to achieve similar levels of accuracy during A-only and AV speech, however they are able to achieve these levels of accuracy at faster RTs when visual speech cues are available.

On electrophysiological correlates of WM, facilitation of processing speed (indicated by P3 latency) was observed in both groups and facilitation of WM resources (indicated by P3 amplitude) was observed in the individuals with hearing impairment. More specifically, both older adults with hearing impairment and those with normal hearing showed earlier P3 latency in the AV condition compared to the A-only condition, further validating the finding of improved processing speed during AV speech observed in the behavioural RT data. Overall, there seems to be a disproportionate gain on WM processing speed when perceptual processing speed is facilitated. That is, the average facilitation of P1 latency was 5.0 ms (*SD* = 11.33) and N1 latency was 3.8 ms (*SD* = 18.28) whereas the average facilitation was 35.5 ms (*SD* = 53.40) for P3 latency and 82.6 ms (*SD* = 53.35) for RT. In addition, we observed that P3 amplitude was smaller during the A-only condition in hearing-impaired participants compared to controls but no group differences were evident in the AV condition. Thus, similar to the RT data, it appears that visual speech cues may help to counteract the negative effect of more demanding perceptual processing caused by hearing impairment.

2.5.3 Do Older Adults with Hearing Impairment Show a Greater Auditory-Visual Speech Benefit?

The results of this study have confirmed that perceptual processing was more demanding for older adults with hearing impairment compared to those with normal hearing. This was suggested by a significantly smaller amplitude of the auditory P1-N1 component in older adults with hearing impairment compared to normal-hearing controls. N1 amplitude is known to be affected by stimuli characteristics, such as intensity and tonal frequency (Näätänen & Picton, 1987). Thus, it appears that physically similar stimuli become “tuned down” and less perceptible in the context of hearing impairment. Furthermore, there was a statistical trend for a delayed auditory N1 latency in the older adults with hearing impairment in comparison to the normal-hearing controls, suggesting prolonged perceptual processing time. These results agree with the finding of Oates, Kurtzberg and Stapells (2002) who found an increased latency and a decreased N1 amplitude with increasing hearing loss during a syllable discrimination task. In contrast, studies using more ambiguous stimuli during speech discrimination tasks, found increased N1 amplitudes in individuals with hearing impairment (Harkrider, Plyler, & Hedrick, 2006; Tremblay, Piskosz, & Souza, 2003). In the current study, the effects of hearing impairment were also evident on WM measures. Older adults with hearing impairment had smaller P3 amplitude and longer RT during the A-only condition compared to the control group. In addition, the group with hearing impairment had generally greater P3 latency, regardless of modality.

When comparing the overall results between normal-hearing older adults and those with hearing impairment, the pattern suggests that older adults with hearing impairment are deriving a greater AV speech benefit than normal-hearing older adults. Firstly, older adults with hearing impairment showed greater facilitation of perceptual processing, as evidenced by the greater reduction in P1 and N1 latency and P1 and P1-N1 amplitudes in the AV condition compared to the A-only condition. Furthermore, both behavioural RT data and electrophysiological P3 amplitude data suggest greater facilitation of WM processing in older adults with hearing impairment. More specifically, the group differences were observed in the baseline (i.e., A-only) condition but not during the AV condition, indicating that visual speech cues helped older adults with hearing impairment to compensate for the difficulty that they experienced during the more demanding A-only condition. The observed findings are in agreement with previous behavioural research reporting improved speech recognition under AV conditions in individuals with hearing impairment (Bernstein & Grant, 2009; Grant et al., 1998; Tye-Murray et al., 2007). Furthermore, these results support the indication of greater AV benefit in older adults with hearing impairment compared to those with normal hearing observed in a syllable recognition paradigm by Grant and colleagues (2007) as well as in a behavioural WM paradigm by Brault and colleagues (2010). Overall, the greater AV benefit in older adults with hearing impairment supports the inverse-effectiveness hypothesis, which proposes that the benefit from multisensory interaction increases as the functioning of unisensory channels decreases (Stein & Meredith, 1993).

When examining the direct relationship between perceptual facilitation (i.e., facilitation of P1-N1 amplitude and N1 latency during the AV condition in comparison to A-only condition) and behavioural improvement (i.e., higher accuracy and faster RT in the AV in comparison to A-only condition), we found that normal-hearing older adults showed a stronger and more consistent dose-response relationship between these variables, especially for facilitation of processing speed. A significant relationship was found between greater facilitation of N1 latency in the AV condition compared to the A-only condition and greater improvement in RT during the 2-back condition. Similar trends were observed across other conditions. Interestingly, the NEC group did not show a significant AV benefit for either N1 latency nor P1-N1 amplitude in the group ANOVA analyses. Taken together these results suggest that even though older adults with normal hearing may have shown more inconsistent perceptual facilitation as a group, those who derived a perceptual benefit from the AV speech were also able to benefit at the WM level, especially in terms of facilitation of processing speed.

On the other hand, participants with hearing impairment showed more robust perceptual AV benefit, as indicated by facilitation of N1 latency in the 1-back condition and overall facilitation of P1-N1 amplitude evident in the group ANOVAs, but they did not show dose-response relationship between perceptual facilitation and WM performance (i.e., the correlation analyses). This may be related to the fact that perceptual facilitation helps individuals to reach their WM capacity but not necessarily to expand its limits. Thus, participants may gain a variable level of perceptual facilitation but regardless of this variability may achieve similar improvement on behavioural measures. This hypothesis is supported by the observation that no behavioural differences were observed between the groups in the AV condition. For reaction time specifically, individuals with hearing impairment were slower in comparison to controls in the A-only condition but not in the AV condition. Thus, visual speech cues appeared to improve their WM capacity to the point that their performance no longer differed from those with normal hearing.

2.5.4 Practical Implications

The statistics clearly highlight the high prevalence of social and psychological difficulties in the hearing impaired population (e.g., Dalton et al., 2003; Strawbridge et al., 2000). AV speech represents one possibility for facilitation of information processing and thus improved communication abilities for older adults with hearing impairment. Furthermore, numerous speech comprehension training programs have been developed over the years (see Pichora-Fuller & Levitt, 2012) and previous research has found that speech-reading training can improve speech perception of individuals with hearing impairment (e.g., Richie & Kewley-Port, 2008; Walden, Erdman, Montgomery, Schwartz, & Prosek, 1981). The results of the current study indicate that such training may be beneficial not only for enhancement of perceptual but also for higher-order functioning.

In addition to speech comprehension training, the current results have implications for technology adaptation and future development. For example, despite their increased popularity in commercial companies and government institutions, research has shown that older adults find it very challenging to use interactive voice response (IVR) services (D. Miller, Gagnon, Talbot, & Messier, 2013), Capitalization on AV speech may provide one method for making future technology user-friendlier for older adults, especially those with hearing impairment.

2.5.5 Limitations

Several methodological and statistical limitations of the current study need to be acknowledged. Firstly, a larger sample size would decrease error variance and provide greater statistical power. In a previous study with a similar design (Frtusova et al., 2013) but a greater sample size, we found AV facilitation of both N1 latency and P1-N1 amplitude in older adults with normal hearing. In the current study, the modality effect on these perceptual measures did not reach statistical significance for this group even though the means pointed in the right direction (see Tables 2 and 4). Secondly, a consideration needs to be given to our sample of older adults with hearing impairment. Individuals in the hearing impaired group were quite heterogeneous in terms of their level of hearing impairment (average PTA ranging from 31.67 – 73.33 dB), and their general cognitive ability as estimated by the MoCA (overall score ranging from 21 to 30 points). However, exploratory analyses showed that these factors were not systematically associated with the level of AV benefit. On the other hand, a significant correlation between higher contrast sensitivity and a lower AV benefit on P1-N1 amplitude was observed for the 1-back (r= -

.49) and the 2-back (*r*= -.48) conditions. Thus, those older adults with hearing impairment who also have poorer visual ability seem to derive the largest AV benefit. Another consideration is that we were unable to confirm for all the participants the exact nature of their hearing impairment; some participants were unsure of the cause and did not have an audiology report available. However, all participants reported wearing or being eligible for hearing aids, which is most commonly prescribed for older adults with sensorineural hearing loss.

2.6 Conclusions

This study provides evidence that older adults derive WM benefit from AV speech. Importantly, these effects were found to be even more robust in older adults with hearing impairment compared to those with normal hearing. In the context of an integrated perceptual-cognitive system, these results indicate that AV speech facilitates perceptual processing that is otherwise very demanding for older adults with hearing impairment. The perceptual facilitation results in more resources available for subsequent WM processing. The evidence of processing facilitation afforded by AV speech has important practical implications for helping to improve the quality of life for older adults with hearing impairment.

Chapter 3: Study 2

The Auditory-Visual Speech Benefit on Working Memory in Individuals with Mild Cognitive Impairment and Alzheimer Disease

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3.1 Abstract

Perception and cognition are believed to draw on a common pool of processing resources. Thus, facilitation of perceptual processing through means such as auditory-visual (AV) speech perception can positively impact higher-order cognitive functions, such as working memory (WM). This would be especially important for individuals with WM deficits. This study examined the effect of AV speech cues on WM in older adults with Alzheimer disease (AD) or mild cognitive impairment (MCI) in comparison to controls matched on age, education, and sensory functioning. Participants completed a WM *n*-back task (0-, 1-, and 2-back) in two modalities: auditory-only (A-only), in which they could hear a speaker presenting sequences of digits and see a still picture of the speaker's face, and AV, in which they could hear and see the speaker pronounce the digits. Event-related brain potentials (ERP) were measured during the task to examine perceptual facilitation and its effect on WM. The behavioural results showed improved accuracy for the patient group, and faster reaction time in the AV condition compared to the A-only condition for both groups. Facilitation of WM processing during the AV condition was also found in both groups, as indicated by an earlier P3 component. Furthermore, the AV condition was also associated with facilitation of perceptual processing, indicated by earlier and smaller ERP responses related to auditory perception (i.e., P1 and N1) in both patients and controls. Overall, the results suggest that patients with MCI/AD benefit from AV speech in terms of improved WM performance. The results are interpreted as support for an integrated perceptual-cognitive model, suggesting that perceptual facilitation afforded by AV speech allowed more resources to be available for subsequent memory processing and thus helped to improve patients' WM skills. Practical implications of these findings in relation to

cognitive testing and methods for improving the quality of life for patients with MCI/AD or their caregivers are discussed.

3.2 Introduction

In the literature on cognitive aging, it has become increasingly recognized that there is a strong interconnection between perceptual and cognitive processes (e.g., K. Z. Li & Lindenberger, 2002; Schneider & Pichora-Fuller, 2000). More specifically, there is evidence from both hearing and vision research that degradation of perceptual stimuli can have a negative effect on cognitive performance. For example, degradation of auditory input by noise was found to interfere with memory performance for verbally presented material (Rabbitt, 1968). Similarly, in the visual domain, it has been found that even a relatively minor distortion of visual acuity (i.e., 20/40 vision) affects performance on non-verbal neuropsychological tests that use small size/high spatial frequency items and/or require visual scanning (Bertone et al., 2007). According to Schneider and Pichora-Fuller (2000), perceptual and cognitive processes are a part of an integrated information processing system and thus share a certain number of processing resources. Under this theory, the number of resources that needs to be allocated to perceptual processing affects how many resources remain available for higher-order cognitive processes. To illustrate this process during speech comprehension, if a substantial number of processing resources needs to be devoted to decoding a speech signal, then there may be insufficient resources for storing of the information in memory (Schneider & Pichora-Fuller, 2000). The need to allocate extra resources to perceptual processing is particularly problematic for older adults suffering from neurodegenerative disorders, such as dementia, due to their reduced processing resources. Given that a sensory decline in both vision and hearing is an inevitable part of aging for most individuals, it is important to identify ways to minimize the effect of sensory deterioration on cognitive function.

One function that is directly affected by age-related sensory decline is speech perception (Grant et al., 1998). Speech is an important part of social interaction and hearing difficulties can lead to a feeling of social isolation (Strawbridge et al., 2000). One possibility to enhance speech perception is through an auditory-visual (AV) modality, where both auditory (i.e., the speaker's voice) and visual (i.e., lip, tongue, and face movements) speech cues are available. Visual speech information was found to be complementary to auditory speech information, by helping to disambiguate the phonemic information (Summerfield, 1979; van Wassenhove et al., 2005). Researchers have identified that having visual speech cues presented in a noisy environment significantly improves speech perception (e.g., Ross et al., 2007; Sumby & Pollack, 1954). Moreover, perceptual enhancement by visual speech cues has been demonstrated even in the absence of background noise (Klucharev et al., 2003). Importantly, AV speech does not only lead to perceptual improvement but also to more efficient information processing. More specifically, cognitive neuroscience research using event-related brain potentials (ERP) has found that AV speech is associated with reduced amplitude and latency of ERP components that reflect auditory processing (Frtusova et al., 2013; Stekelenburg & Vroomen, 2007; van Wassenhove et al., 2005; Winneke & Phillips, 2011).

The ERP methodology provides a unique method to examine electrical brain activity associated with different stages of stimulus processing, reflected in a sequence of positive and negative deflections (Luck, 2005). Given the importance of this methodology for current research, a brief description of relevant components is provided. In response to auditory stimulation, the brain elicits a series of components including the P1, which is a positive-going waveform that peaks approximately 50 ms after the onset of the stimulus, and the N1, which is a negative-going waveform that peaks approximately 100 ms after onset of the stimulus. These components reflect auditory perceptual processing and are suggested to be associated with activation of the primary and secondary auditory cortices (Liegeois-Chauvel et al., 1994; Pantev et al., 1995). Higher-order cognitive functions, such as working memory (WM) examined in this study, are reflected in the later occurring ERP components. In particular, WM processing is associated with changes in the P3, a broad positively-going waveform that peaks approximately 300 ms after the onset of a stimulus (although the latency can range greatly depending on factors such as participant age and task characteristics; Polich & Kok, 1995). This component is proposed to originate from temporo-parietal activity (Polich, 2007).

In addition to perceptual enhancement and more efficient auditory processing, the provision of AV speech cues was associated with better WM performance compared to WM performance when provided with A-only cues (e.g., Frtusova et al., 2013; Pichora-Fuller, 1996). Supporting Schneider and Pichora-Fuller's (2000) theory of integrated processing resources, there is evidence to suggest that this memory improvement is related to the facilitation of perceptual processing by AV speech. More specifically, in our previous study we examined how perceptual facilitation during an AV speech condition, reflected as earlier and smaller auditory N1 in the AV condition compared to the A-only condition, relate to WM performance (Frtusova et al., 2013). We used an *n*-back task, in which sequences of spoken digits were presented to healthy younger and older adults in the AV and A-only modalities. Participants had to decide whether the digit in the current trial matched the one presented in the previous trial (1-back), two trials before (2-back), three trials before (3-back) or the one assigned at the beginning of the block (0-back). To assess the level of perceptual facilitation and its effect on WM, ERP responses were collected during the task. We found that the AV speech compared to the A-only speech led to earlier N1 latency in both younger and older adults, and reduced N1 amplitude in older adults. Behaviourally, the AV modality was associated with faster reaction time (RT) across all WM loads, and improved accuracy in the most demanding WM conditions. Importantly, the amount of reduction in N1 amplitude during the AV speech condition in comparison to the A-only condition positively correlated with the enhancement of WM performance in certain conditions. Thus, the study demonstrated that perceptual facilitation afforded by AV speech can enhance WM processing.

A variety of WM models have been proposed (e.g., Baddeley & Hitch, 1974; Cowan, 2010; Kane, Conway, Hambrick, & Engle, 2007), which generally posit a storage capacity and a processing capacity. For example, a model proposed by Baddeley and Hitch (1974) presents one of the most prominent explanations of WM. According to this model, WM represents a limited work-space consisting of temporary storage of information through a phonemic buffer and processing of stored information through a central executive. The phonemic buffer represents a passive component but when it becomes overloaded, greater demands are put on the central executive to manage the information (e.g., through chunking or recoding of information into a simpler form) in order to optimize the buffer and also to reconstruct the information during retrieval. In addition, because there is a limited capacity for the overall system, there is a trade-off between required resources for storage and available resources for information processing. Considering this general model, the perceptual facilitation puts fewer processing demands on storing the information in the phonemic buffer and thus affords better capacity for subsequent stages of information processing (e.g., updating of information in WM). The improvement of WM through facilitated perceptual functioning is also in agreement more recent models of WM that stress the quality of input information (Ma, Husain, & Bays, 2014; Rönnberg et al., 2013).

A common experimental task to measure WM is the *n*-back task, where participants need to match the currently presented stimulus to the one held in short-term memory and presented *n*-trials before. This task was found to be sensitive to age-related changes in WM performance (e.g., Van Gerven et al., 2007; Van Gerven et al., 2008; Vaughan et al., 2008; Verhaeghen & Basak, 2005; Vermeij et al., 2012). Age differences on the *n*-back task are generally interpreted as reflecting the difficulties of older adults to switch the focus of attention in WM (Van Gerven et al., 2007; Van Gerven et al., 2008; Vaughan et al., 2008; Verhaeghen & Basak, 2005), a concept introduced in a WM framework by Cowan (1988). In addition to behavioural studies, the *n*-back task has been used in ERP paradigms. ERP studies have generally found that the amplitude of the P3 decreases with increasing *n*-back load (Segalowitz et al., 2001; Watter et al., 2001) but this effect may be dependent on WM capacity (Daffner et al., 2011). P3 latency was found to remain constant with increasing WM load (Frtusova et al., 2013; Gaspar et al., 2011; Watter et al., 2001) but it tends to peak later in those with lower WM capacity compared to those with higher WM capacity (Daffner et al., 2011).

Under Schneider and Pichora-Fuller's (2000) theory, the reallocation of processing resources between perceptual and cognitive functions is especially important during a highly demanding task. This implies that having to allocate too many processing resources to perception would affect people with cognitive deficits more than cognitively healthy individuals. Thus, people with neurodegenerative disorders affecting cognition may especially benefit from facilitated perceptual processing provided through such means as AV speech.

Dementia is a prevalent neurodegenerative disorder in older adults, with Alzheimer disease (AD) being the most common type. According to a report by the Alzheimer's Association (2014), one in nine Americans aged 65 years old or older suffers from AD, amounting to 5.2 million cases. Alzheimer's disease is characterized by a progressive decline in cognitive abilities that affect individuals' activities of daily living (G. M. McKhann et al., 2011). Importantly, WM is affected in early stages of the disease (e.g., Belleville et al., 2007; Belleville et al., 2003). In fact, WM deficits are often evident in a pre-clinical stage of AD, called mild cognitive impairment (MCI).

Individuals with MCI have some degree of cognitive impairment in one or more cognitive domains but the functional impact is not sufficient to warrant diagnosis of dementia and it does not generally interfere with activities of daily living (Albert et al., 2011). An impairment in episodic learning and memory is considered the most common cognitive characteristic of MCI cases who subsequently progress to AD but other cognitive domains, such executive functioning, are also frequently affected at this stage (Albert et al., 2011). Importantly for this study, impairment in WM at the MCI stage has been demonstrated using a variety of WM tasks. For example, Johns and colleagues (2012) found that over 65% of individuals with MCI in their sample were impaired on the Brown Petersen task, which requires holding information in WM while performing a distraction task, and over 50% of individuals with MCI were impaired on Letter-Number Sequencing, which requires re-ordering of information held in WM. A deficit on Letter-Number

Sequencing has been reported in other studies (e.g., Griffith et al., 2006; Klekociuk & Summers, 2014a, 2014b). In addition, MCI patients were found to have difficulties repeating digits in a backward order (e.g., Chang et al., 2010; Muangpaisan et al., 2010; Zihl et al., 2010) and remembering the sequence of spatial positions in both forward and backward order (e.g., Egerhazi et al., 2007; Griffith et al., 2006; Saunders & Summers, 2010). Most pertinently to the current research, WM deficits in MCI patients have also been observed on the *n*-back task (Alichniewicz et al., 2012; Borkowska et al., 2009; Zheng et al., 2012).

Given the WM difficulties experienced by patients with MCI and AD, these individuals are likely to benefit from the perceptual facilitation provided by AV speech during a WM task to an even higher extent than cognitive healthy individuals. In other words, it could be expected that AV speech will lead to facilitated perceptual processing, and subsequently, to more of the limited resources being available for higher-order processing. Thus, AV speech may help to improve the WM ability of individuals with MCI and AD.

However, given that AV speech perception is a form of multisensory processing, this potential benefit is based on the assumption that multisensory processing is not affected in these patient populations. Although studies are relatively sparse, some evidence suggests that individuals with MCI and AD may have difficulties integrating multisensory information. A common design to examine multisensory processing is a McGurk paradigm (McGurk & MacDonald, 1976), in which one spoken syllable, such as /ba/, is paired with a visual speech cues from a different syllable, such as /ga/, which can result in a fused perception of a different illusionary syllable, in this case commonly /da/. Using this paradigm, it has been found that the fused or combined perception is less likely to occur in AD patients than in cognitive healthy controls, suggesting difficulties with multisensory processing in this population (Delbeuck et al., 2007). Another study found that MCI and AD patients did not show the same amount of amplitude reduction in auditory ERP components (such as the N1), when non-speech visual information (a flash) preceded non-speech auditory information (a tone) compared to controls (Golob et al., 2001). Overall, these results suggest that visual information may not have the same level of influence on auditory processing in patients with MCI and AD than in healthy controls. However, it is important to note that Delbeuck and colleagues' (2007) findings relied on McGurk stimuli, which are anomalous and not ecologically valid, and the stimuli used by Golob and colleagues (2001) were not speech stimuli. This latter consideration is important as there is evidence suggesting that the interaction of AV speech cues may differ from the interaction of non-speech AV stimuli (Tuomainen, Andersen, Tiippana, & Sams, 2005).

A study assessing the integration of visual features also indicated affected multisensory processing in AD (Festa et al., 2005). More specifically, patients with AD were found to have difficulty integrating different features of visual information (i.e., colour and motion) that required communication between separate cortical regions (ventral and dorsal visual streams in this case), even though the patients did not have difficulties integrating information processed in the same cortical region (e.g., motion and luminance, both processed by the dorsal stream). Overall, it has been suggested that AD pathology affects cortico-cortico communication, which interferes with multisensory processing (Delbeuck et al., 2007; Delbeuck, Van der Linden, & Collette, 2003; Festa et al., 2005). Supporting the hypothesis of affected communication across different cortical regions, white matter changes have been reported in both MCI and AD individuals (e.g., Frings et al., 2014; J. Liu et al., 2013; Radanovic et al., 2013; Stricker et al., 2013). In addition, it has been shown that the superior temporal sulcus, a multimodal area important for the integration of auditory and visual speech information, is affected in MCI and AD (e.g., Gomez-Isla et al., 1997; Killiany et al., 2000; Nelissen et al., 2007). Taken together, disruption of structural and functional networks involved in multi-sensory processing could interfere with the AV speech benefit in MCI and AD patients.

However, on-going work in our laboratory indicates that these patients actually benefit from AV speech to a similar extent as healthy older adults (Phillips et al., 2009). Specifically, when patients with MCI and AD were asked to recognize words presented in background noise, they performed significantly better during AV speech than during A-only speech, and the size of the AV speech benefit was comparable to that of healthy controls. The differences in the findings of this study and the work of other researchers presented earlier may be due to the type of stimuli used. The patients with MCI and AD may have difficulties fusing incongruent AV information (as shown in Delbeuck et al., 2007), or to process one stimulus presented shortly after another stimulus (as shown in Golob et al., 2001) because these tasks require resolution of ambiguous information or inhibiting interference, which is an extra challenge for patients with MCI and AD due to their impairment in executive functioning (e.g., Collette, Schmidt, Scherrer, Adam, & Salmon, 2009; Fernandez-Duque & Black, 2006; Johns et al., 2012). On the other hand, when the stimuli are unambiguous and more ecologically valid, such as when visual speech cues match with the produced speech sounds (Phillips et al., 2009), MCI and AD patients may be able to integrate AV speech information to a similar extent as healthy older adults. This is consistent with Delbeuck and colleagues' (2007) observation that AD patients performed as well as controls during congruent AV speech. But what is not clear from their study is how much influence the visual information had on auditory processing in the congruent trials. It could be argued that no multisensory interaction took place, and AD patients based their responses solely on the auditory input. An electrophysiological investigation paired with behavioural task performance can be helpful in clarifying the multisensory processing during congruent AV speech information in individuals with cognitive impairment.

3.2.1 Present Study

The purpose of this study was to examine the AV speech benefit in patients with cognitive impairment. Specifically, this study aimed to clarify whether (1) individuals with MCI and AD show better WM performance (higher accuracy and faster RT) during AV speech in comparison to A-only speech; (2) whether individuals with MCI and AD show facilitation of perceptual processing during AV speech, as reflected by reduced amplitude and/or shorter latency of early auditory ERP components (i.e., P1 and N1); and (3) whether improvement in behavioural performance during AV speech is related to facilitation of perceptual processing. Under the assumption that the reallocation of information processing resources is especially important when the task is demanding, we predict that the patients will benefit from AV speech information during the WM task to an even greater extent than cognitive healthy older adults.

3.3 Method

3.3.1 Participants

Nineteen MCI and eight AD patients were recruited from the memory clinic at the Jewish General Hospital in Montreal. From the MCI patients, one participant found the task too difficult and discontinued the study, one participant did not pass the study criteria, and one participant was excluded during the data processing due to extensive noise in the electroencephalography (EEG) recording. From the AD patients, two participants did not meet the study criteria. Thus, the final sample consisted of 16 MCI and six AD patients. Both patient groups were diagnosed at the memory clinic based on a standardized mental status assessment and physical evaluation by a trained neurologist or geriatrician. The diagnosis of MCI was made using agreed-upon criteria (Petersen et al., 2009; Winblad et al., 2004). All AD patients met the diagnosis of probable AD based on the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition criteria (American Psychiatric Association, 1994) and the National Institute of Neurological and Communicative Disorders and Stroke/Alzheimer's Disease and Related Disorders Association criteria (G. McKhann et al., 1984). For the purposes of this study, which is to examine AV speech benefit in individuals with cognitive impairment, participants with MCI and AD were combined to form a Patient group to achieve a sufficient sample size and also to recognize that there is a certain level of overlap between a late MCI stage and an early AD stage. The range of scores on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), a screening tool of cognitive functioning, was 16 to 26 for the participants with MCI, and 17 to 22 for the participants with AD.

Twenty-two older adults were recruited for the study from the community to serve as a control group. Their cognitive status was assessed using the MoCA. Furthermore, they all completed comprehensive neuropsychological testing in a separate session. For the participants who scored below the suggested cut off (score of 26) on the MoCA, the neuropsychological profile was reviewed by a clinical neuropsychologist in order to determine their cognitive status. Two participants were excluded from the study because they did not meet the study inclusion criterion for normal cognition. The final sample consisted of 20 normal elderly controls (NEC).

In order to be eligible for the study, all participants had to be completely fluent in English and could not suffer from any neurological condition that could significantly affect cognition, other than MCI or AD. They also needed to have adequate vision and hearing. Vision abilities were assessed by the Mars Contrast Sensitivity Test (by MARS Perceptrix; Arditi, 2005). In this test, participants were asked to read a chart with large print letters that progressively decrease in contrast from the background. Both monocular and binocular contrast sensitivity scores, expressed as logMAR values, were obtained for each participant. The auditory screening measured hearing threshold for 250, 500, 1000, 2000, 4000 Hz in each ear (Welch Allyn, AM 232 Manual Audiometer). To compare the groups, pure tone averages (PTA) were computed for each ear by averaging hearing threshold for 500, 1000, 2000 Hz.

The participants in this sample were quite variable in terms of visual functioning, with binocular contrast sensitivity ranging from 1.36 to 1.64 logMAR. Most of the participants had monocular vision in a stronger eye within the age-normal limits (Haymes et al., 2006) with only 6 out of 42 participants (2/20 NECs and 4/22 Patients) having vision below this range. The hearing thresholds also varied, with the average binaural PTA ranging from 10.83 to 65.83 dB. Most of the participants, 31 out of 42 (12/20 NECs and 19/22 Patients), had PTA in the stronger ear higher than typically considered normal (i.e., >25 dB; Katz, 1985). However, the hearing screening was not conducted in a sound-proof room and thus the obtained hearing thresholds may be an underestimation of true hearing acuity. Importantly, the patient and control groups were matched on hearing acuity. As expected, the two groups differed on the overall MoCA scores as well as on the scores on Letter-Number Sequencing (LNS), a neuropsychological test of WM from the Wechsler Adult Intelligence Scale Fourth Edition (WAIS-IV; Wechsler, 2008). This latter observation confirms WM difficulties in the Patient group. The demographic information on the final samples of participants is presented in the Table 1.

Table 1. Demographic information.

	NECs (n=20)	Patients (n=22)	
Males/Females	9 (45%)/11	10 (45%)/12	
Right-handed/Other	16 (80%)/4	17 (77%)/5	
Age (Years)	79.05 (6.23)	80.32 (4.50)	n.s.
Education (Years)	14.15 (3.20)	13.14 (2.68)	n.s.
MoCA[1]	26.90 (2.32)	21.18 (2.99)	$p < .001$
LNS[2]	19.2 (1.98)	13.7 (3.30)	$p < .001$
Binocular Vision (logMAR[3])	1.67 (.11)	1.66 (.11)	n.s.
PTA[4] Right Ear (dB)	31.58 (16.80)	37.80 (10.50)	n.s.
PTA[4] Left Ear (dB)	30.25 (13.83)	35.61 (9.79)	n.s.

[1] Montreal Cognitive Assessment (Nasreddine et al., 2005)

[2] Letter-Number Sequencing raw scores (Weschler, 2008)

[3] Contrast sensitivity scores on Mars Contrast Sensitivity Test (Arditi, 2005)

[4] The pure tone average (PTA) represents the average of hearing thresholds for 500 Hz, 1000 Hz, and 2000 Hz.

3.3.2 Stimuli

The stimuli were nine single syllable digits (1, 2, 3, 4, 5, 6, 8, 9, 10) spoken by a female speaker with a neutral facial expression. The digit seven was omitted because it has two syllables and thus it would be easily recognizable among one-syllabus words. The stimuli were audio-video recorded with auditory digitization rate of 48,000 Hz in a recording studio and they show a full face and head of the speaker against a green background. They were subsequently edited in Adobe Premiere. Each digit was presented as a short video clip (Videocodec, Windows Media Video 9; framerate, 29.97 fps; Audiocodec, Windows Media Audio 2; sample rate and size, 44 100 Hz 16-bit) edited such that nine still frames of the speaker's face were added before the first and after the last lip movement. In addition, each clip had a six-frame fade in/fadeout segment. The A-only stimuli were identical to the AV stimuli except that the motion picture of the speaker was replaced by a still picture of the speaker's face. Thus, in the A-only condition participants could hear the speaker's voice and saw a picture of her face but they could not identify the digits from visual speech cues.

Imperceptible triggers signaling the onset of lip movement (i.e., visual triggers) and the speech signal (i.e., auditory triggers) were embedded in the video files. These triggers consisted of short transistor-transistor logic (TTL) pulses that were sent to the recording electroencephalogram amplifiers so that the onset of these events could be later identified and used in the analysis. The average length between the onset of the first lip movement and the onset of the sound was 395.33 ms (SD=103.24) and the average length of the entire video clip was 2413.53 (SD=160.89 ms). The loudness of each clip was equalized using Praat (version 5.1.30; Boersma & Weenink, 2010). The sound was presented through earphones (EARLINK tube ear inserts; Neuroscan, El Paso, Texas) at the mean intensity of approximately 67 dB(A), and peak intensity of approximately 71 dB(A). The stimuli were presented using Inquisit (version 2.0; Millisecond Software, 2008) on a 14-inch monitor against a black background, with the participant sitting approximately 50 cm from the screen. The size of the stimuli on the computer screen was 14 cm x 18 cm. The inter-stimulus interval was 1400 ms, consisting of a 1,100 ms post-stimuli response window and a 300 ms pre-trial pause.

3.3.3 Procedure

Before starting the experiment, participants were first trained in speech-reading (i.e., recognition of the digits from visual speech cues, without the presence of sound) in order to make sure that they can adequately recognize visual speech cues for each digit. During the training, the digits were first presented in the sequential and then random order. The training was repeated until participants could recognize all digits in the random order.

Each participant completed the WM *n*-back task across three different WM loads (0-back, 1-back and 2-back) and two sensory modalities (A-only and AV). In the 0-back condition, participants had to decide whether the currently presented digit matched the digit assigned at the beginning of the block. In the 1-back and 2-back conditions, participants had to decide whether the currently presented digit matched the digit presented one trial (1-back) or two-trials (2-back) before. Participants indicated their responses by pressing, “Match” or “Non-Match” buttons on a computer mouse. They were asked to hold the mouse in both of their hands and use only their thumbs to make the response. The assignment of Match to either left-handed or right-handed response was varied across the participants. Participants practiced responding with the mouse and the response assignment before the experiment began. In addition, they were given ten practice trials at the beginning of each new WM load condition in order to make sure that they understood the task.

For each WM load, participants competed four blocks of 50 trials (20 Match and 30 Non-Match) with alternating modality (e.g., A-only, AV, A-only, AV). Each block consisted of a different semi-random trial sequence and the assignment of a particular sequence to a particular modality was counterbalanced across participants. Blocks started with five "Warm Up" trials in order to allow the participants to get used to the task. The responses to warm up trials were not included in the analysis.

The order of the modality conditions was the same for each WM load but counterbalanced across the participants. The order of the WM load conditions was the same for all participants and began with 1-back, followed by 2-back and ended with 0-back. In order to improve the patients' tolerance for the task, the 0-back condition was left to be completed at the end as this was the least demanding condition and thus participants were likely to perform well on it even if they were slightly fatigued. Furthermore, digits assigned as targets in the 0-back block would become more salient due to frequent repetition. Completing the 0-back condition at the end of the experiment avoided having the 1- and 2-back conditions affected by this saliency effect. The target digits were three, four, six or nine. The assignment of the target digits to the modality conditions was counterbalanced across the participants.

Four behavioural measures were collected during the study: accuracy of Match and Non-Match responses and RT for Match and Non-Match responses. The accuracy was defined as the percentage of correct identification of the current digit as matching the target digit (i.e., correct Match) or the percentage of correct identification of the current digit as not matching the target digit (i.e., correct Non-Match). RT was defined as the mean time elapsed (in ms) between the onset of the auditory-trigger and the participant's button response for correct responses. Any response earlier than 200 ms from the first cue about the digit's identity (i.e., the visual trigger for AV trials and A trigger for A-only trials) was excluded from the analysis as this latency was considered to be too short to reflect a valid decision.

3.3.4 Electroencephalography Data Acquisition and Processing

Participants' brain activity during the task was monitored using the Neuroscan SynAmps EEG system. Twenty-nine electrodes (midline: FPZ, FZ, FCZ, CZ, CPZ, PZ; left lateral: FP1, F3, F7, FC3, FT7, C3, T3, CP3, TP7, P3, T5, O1; right lateral: FP2, F4, F8, FC4, FT8, C4, CP4, TP8, P4, T6, O2) were attached to a nylon cap (EasyCap; Brain Vision LLC). The arrangement of the electrodes on the cap corresponded with the International 10/20 system (Jasper, 1958), extended for 29 electrodes. Electro-oculogram (EOG) activity was monitored by electrodes positioned above and below the left eye (vertical EOG) and beside the outer canthi of each eye (horizontal EOG). The right ear electrode served as the on-line reference and a midline electrode located between FPZ and FZ served as a ground. The sampling rate for the EEG recording was 500 Hz and the bandwidth was DC to 100 Hz.

The offline data processing was performed using Scan (version 4.5; Compumedics Neuroscan, 2009). Activity from all sites was re-referenced to a linked ear reference using linear derivation. The excessive vertical EOG activity caused by eye blinks was removed by spatial filtering (Method 1; NeuroScan Edit 4.5 manual, 2009). The continuous files were filtered using a zero-phase-shift band pass filter, with high pass set to 1 Hz and low pass set to 45 Hz. The auditory ERPs were created by epoching the files into -100 to 1000 ms windows locked to the onset of the auditory trigger (defines as 0 ms). Epochs with excessive noise or movement activity were rejected. This was done through a two-step procedure, first by the Scan software (with rejection of a trial if the EOG activity exceeded ±75 μV or if the activity in or next to the channels of interest exceeded ±100 μV), followed by inspection of each accepted trial. The mean number of accepted trials was 32.2 (*SD* = 6.08) out of a possible 40 for the Match trials, and 49.1 (*SD* = 9.34) out of a possible 60 for the Non-Match trials. The epochs were averaged separately for each modality and the *n*-back conditions and separately for Match and Non-Match trials.

To obtain the latency and amplitude measures for the components of interest (P1, N1, and P3) the averaged waveforms underwent peak detection performed by the Scan software. To remove the noise-related activity, the averaged waveforms were first filtered using a zero-phase-shift band pass filter, with low pass set to 1 Hz and high pass set to 30 Hz. The P1 component was defined as the highest positive point occurring between 20 and 110 ms whereas the N1 component was defined as the lowest negative point occurring between 75 and 170 ms. The P3 component was defined as the most positive point occurring between 300 and 600 ms. The identified peaks were inspected and manually adjusted if necessary. This was performed by a trained individual blinded to the modality and group condition of a particular waveform.

3.4 Results

The data were analyzed using SPSS Statistics version 20 (IBM, 2011). The Match and Non-Match trials were analyzed separately as there is evidence that these represent different aspects of WM processing (Chen, Mitra, & Schlaghecken, 2008), and they were found to have a differential effect on the P3 in the current study. The effects were tested by an ANOVA for repeated measures, with modality (A-only and AV) and load (0-, 1-, and 2-back) entered as within-subject factors and group (NEC and Patient) entered as a between-subject factor. Significant interactions were explored by pairwise comparison. Predicted interaction effects of modality and group were explored by examination of simple effects. The Greenhouse-Geisser nonsphericity correction was applied when analysis involved within-subject factors with more than two levels, and reported *p* and mean square error (*MSE*) values reflect this adjustment. To follow the convention proposed by Jennings (1987), the reported data include Greenhouse-Geisser epsilon (ε) values and uncorrected degrees of freedom. All reported results are significant at $\alpha = .05$, unless stated otherwise. Only the performances reaching the accuracy of 60 percent or higher for a particular condition were included in the analysis. This threshold was set in order to ensure that only people sufficiently engaged in the task (i.e., performing above the chance level) were considered in the comparison. This was important so that the effects are not confounded by invalid performance due to factors such as inability to understand the task, especially in the case of the patients. This minimum level of accuracy was the only criterion for exclusion based on performance. Participants were not excluded based on the deviation of their performance from a group mean because the main focus of the study was to examine the AV benefit and within-subject variability in performance can provide useful information about the nature of the benefit.

3.4.1 Behavioural Results

Accuracy for Match Trials. The data describing accuracy performances for the Match trials are shown in Figure 1. There was a main effect of modality, $F(1, 40) = 4.3$; *MSE*

= 21.33; p = .05; η_p^2 = .10, with accuracy being higher in the AV condition than the A-only condition. Furthermore, there was a main effect of load, F(2, 80) = 69.2; MSE = 52.32; p < .001; ε = .81; η_p^2 = .63, with accuracy being lower in the 2-back condition than in 0-back and 1-back conditions, which did not differ from each other. The main effect of group was not significant, F(1, 40) = 1.3; MSE = 96.64; p = .27; η_p^2 = .03. The Modality x Group interaction was not significant, F(1, 40) = 1.4; MSE = 21.33; p = .24; η_p^2 = .03.

In order to test our main hypothesis, the planned simple effects indicated that there was a significant increase in accuracy in the AV condition compared to the A-only condition for Patients, F(1, 40) = 5.5; $M_{difference}$ = 1.89; p = .02; η_p^2 = .12, but not for NECs, F(1, 40) = .4; $M_{difference}$ = .52; p = .55; η_p^2 = .01.

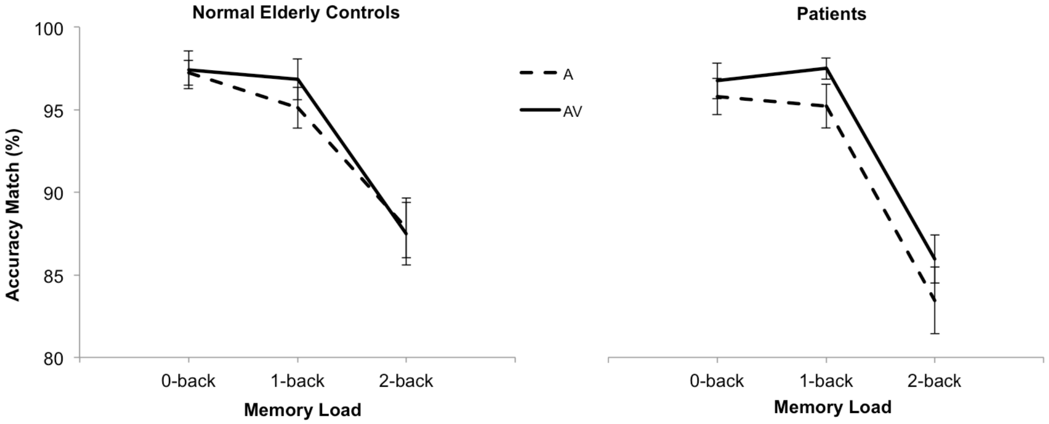

Figure 1. Mean percentage of correct responses and standard error bars for the Match trials for Normal Elderly Controls (left panel) and Patients (right panel) during auditory-only (A-only) and auditory-visual (AV) conditions. Note the improved performance during the AV condition, especially for the patient group.

Accuracy for Non-Match Trials. The data describing accuracy performance for the Non-Match trials are shown in Figure 2. There was no main effect of modality, $F(1, 40) = .1$; $MSE = 19.99$; $p = .71$; $\eta_p^2 = .00$. There was a main effect of load, $F(2, 80) = 51.2$; $MSE = 53.63$; $p < .001$; $\varepsilon = .94$; $\eta_p^2 = .56$, with accuracy being lower in the 2-back condition than in the 0-back and 1-back conditions, which did not differ from each other. There was also a main effect of group, $F(1, 40) = 4.7$; $MSE = 94.52$; $p = .04$; $\eta_p^2 = .10$, which was qualified by a Load x Group interaction, $F(2, 80) = 6.4$; $MSE = 53.63$; $p < .01$; $\varepsilon = .94$; $\eta_p^2 = .14$. There was no significant difference between the groups during the 0-back and 1-back loads, but during the 2-back load, the Patient group performed less accurately than the NEC group. The

Modality x Group interaction was not significant, $F(1, 40) = 2.3$; $MSE = 19.99$; $p = .14$; $\eta_p^2 = .06$.

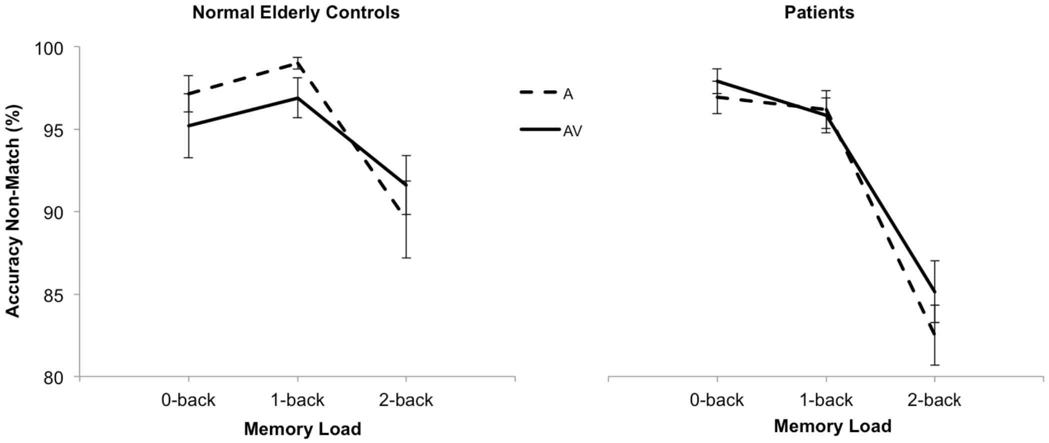

Figure 2. Mean percentage of correct responses and standard error bars for the Non-Match trials for Normal Elderly Controls (left panel) and Patients (right panel) during auditory-only (A-only) and auditory-visual (AV) conditions.

RT for Match Trials. The data describing mean RT performance for the Match trials are shown in Figure 3. There was a main effect of modality, $F(1, 40) = 86.8$; $MSE = 3979.65$; $p < .001$; $\eta_p^2 = .68$, with faster RT in the AV condition than in the A-only condition. There was also a main effect of load, $F(2, 80) = 79.3$; $MSE = 38731.08$; $p < .001$; $\varepsilon = .61$; $\eta_p^2 = .67$, such that RT significantly increased with each increase in the WM load. The main effect of group was not significant, $F(1, 40) = .02$; $MSE = 103857.64$; $p = .89$; $\eta_p^2 = .00$. There was also no significant Modality x Group interaction, $F(1, 40) = .2$; $MSE = 3979.65$; $p = .63$; $\eta_p^2 = .01$.

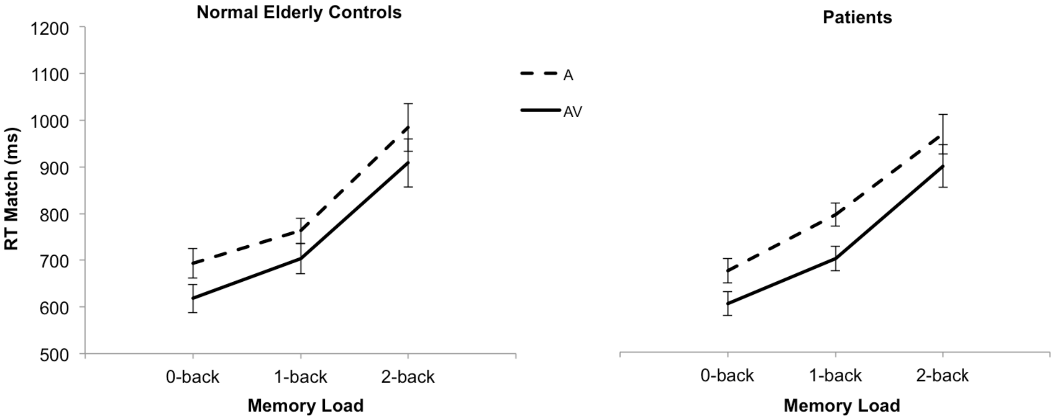

Figure 3. Mean reaction time (RT) and standard error bars for the Match trials for Normal Elderly Controls (left panel) and Patients (right panel) during auditory-only (A-only) and auditory-visual (AV) conditions. Note faster responses during the AV modality in both groups and across all memory load conditions.

RT for Non-Match Trials. The data describing mean RT performance for the Non-Match trials are shown in Figure 4. There was a main effect of modality, $F(1, 40) = 174.8$; $MSE = 2896.62$; $p < .001$; $\eta_p^2 = .81$, with faster RT in the AV condition than in the A-only condition. There was also a main effect of load, $F(2, 80) = 77.4$; $MSE = 34118.54$; $p < .001$; $\varepsilon = .82$; $\eta_p^2 = .66$, such that RT significantly increased with each increase in the WM load. The main effect of group was not significant, $F(1, 40) = .08$; $MSE =138509.69$; $p = .78$; $\eta_p^2 = .00$. There was a statistical trend for a Modality x Group interaction, $F(1, 40) = 3.5$; $MSE =$

2896.62; $p = .07$; $\eta_p^2 = .08$. Simple effects showed that the Patient group tended to benefit from the AV information more, $F(1, 40) = 119.4$; $M_{difference} = 102.35$; $p < .001$; $\eta_p^2 = .75$, than the NEC group, $F(1, 40) = 61.6$; $M_{difference} = 77.13$; $p < .001$; $\eta_p^2 = .61$. There was also a statistical trend suggesting a Modality x Load interaction, $F(2, 80) = 3.0$; $MSE = 4393.31$; $p = .06$; $\varepsilon = .97$; $\eta_p^2 = .07$, such that the largest improvements were observed in the 2-back condition, followed by the 0-back and then the 1-back condition.

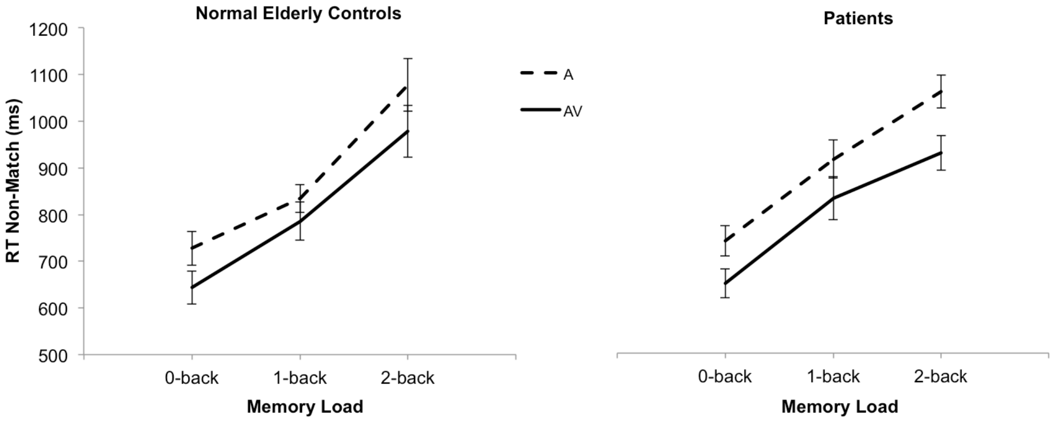

Figure 4. Mean reaction time and standard error bars for the Non-Match trials for Normal Elderly Controls (left panel) and Patients (right panel) during auditory-only (A-only) and auditory-visual (AV) conditions. Note faster responses during the AV modality, especially in the patient group, and during the 2-back memory load condition.

3.4.2 Electrophysiological Results

The P1 and N1 components are parts of a sensory-driven complex of related ERPs (Eggermont & Ponton, 2002). To recognize their inter-relationship, we defined N1 amplitude as an absolute difference between the trough of the P1 component and the peak of the N1 component; thus we refer to this component complex as P1-N1 when describing the amplitude data. To examine how early in auditory processing the AV benefit occurs, we also analyzed data from the P1 component separately. P1 and P3 amplitudes were measured relative to the 0 μV baseline. P1, N1, and P3 latencies were measured at the components' peaks relative to the onset of the auditory trigger. For P1, N1 and P1-N1, the data from the CZ electrode were analyzed because these components reach their maximum midcentrally (Näätänen & Picton, 1987) and a previous work from our laboratory did not find any hemispheric differences (Winneke & Phillips, 2011). For P3, the data from the PZ electrode were analyzed as this component reaches its maximum in mid-posterior sites (Frtusova et al., 2013; Watter et al., 2001).

3.4.2.1 Perceptual Processing

P1-N1 amplitude for Match trials. The waveforms illustrating P1-N1 amplitude during the Match trials are shown in Figure 5. There was a main effect of modality, $F(1, 40) = 39.9$; $MSE = 2.37$; $p < .001$; $\eta_p^2 = .50$. As predicted, P1-N1 amplitude was smaller during the AV condition than the A-only condition. There was also a main effect of load, $F(2, 80) = 3.7$; $MSE = 3.60$; $p = .04$; $\varepsilon = .87$; $\eta_p^2 = .09$. P1-N1 amplitude was significantly smaller during the 0-back than during the 1-back, and there was a statistical trend for P1-N1 amplitude to be smaller in the 0-back than in the 2-back (p = .07). The main effect of group was not significant, $F(1, 40) = 1.4$; $MSE = 20.10$; $p = .25$; $\eta_p^2 = .03$, nor was the Modality x Group interaction, $F(1, 40) = .4$; $MSE = 2.37$; $p = .53$; $\eta_p^2 = .01$.

P1 amplitude for Match trials. The waveforms illustrating P1 amplitude during the Match trials are shown in Figure 5. There was a main effect of modality, $F(1, 40) = 30.4$; $MSE = 1.25$; $p < .001$; $\eta_p^2 = .43$. P1 amplitude was smaller during the AV condition than the A-only condition. The main effect of group was not significant, $F(1, 40) = .5$; $MSE = 4.57$; $p = .48$; $\eta_p^2 = .01$, nor was the Modality x Group interaction, $F(1, 40) = .7$; $MSE = 1.25$; $p = .42$; $\eta_p^2 = .02$.

P1 latency for Match trials. The waveforms illustrating P1 latency during the Match trials are shown in Figure 5. The main effect of modality was not significant, $F(1, 40) = .02$; $MSE = 144.75$; $p = .90$; $\eta_p^2 = .00$. The main effect of group was also not significant, $F(1, 40) = .01$; $MSE = 404..62$; $p = .91$; $\eta_p^2 = .00$, nor was the Modality x Group interaction, $F(1, 40) = .01$; $MSE = 144.75$; $p = .94$; $\eta_p^2 = .00$.

N1 latency for Match trials. The waveforms illustrating N1 latency during the Match trials are shown in Figure 5. There was a main effect of modality, $F(1, 40) = 15.0$; $MSE = 303.09$; $p < .001$; $\eta_p^2 = .27$. N1 amplitude peaked earlier during the AV condition than during the A-only condition. There was also a main effect of load, $F(2, 80) = 9.9$; $MSE = 278.74$; $p < .001$; $\varepsilon = .92$; $\eta_p^2 = .20$, which was qualified by Load x Group interaction, $F(2, 80) = 3.7$; $MSE = 278.74$; $p = .03$; $\varepsilon = .92$; $\eta_p^2 = .09$. For the NEC group, the N1 peaked earlier during the 2-back condition in comparison to the 0-back and 1-back conditions. For the Patient group, the N1 peaked earlier during the 1-back and the 2-back conditions in comparison to the 0-back condition. The main effect of group was not significant, $F(1, 40)$

= .1; MSE = 574.77; p = .82; η_p^2 = .00, nor was the Modality x Group interaction, $F(1, 40)$ = .3; MSE = 303.09; p = .60; η_p^2 = .01.

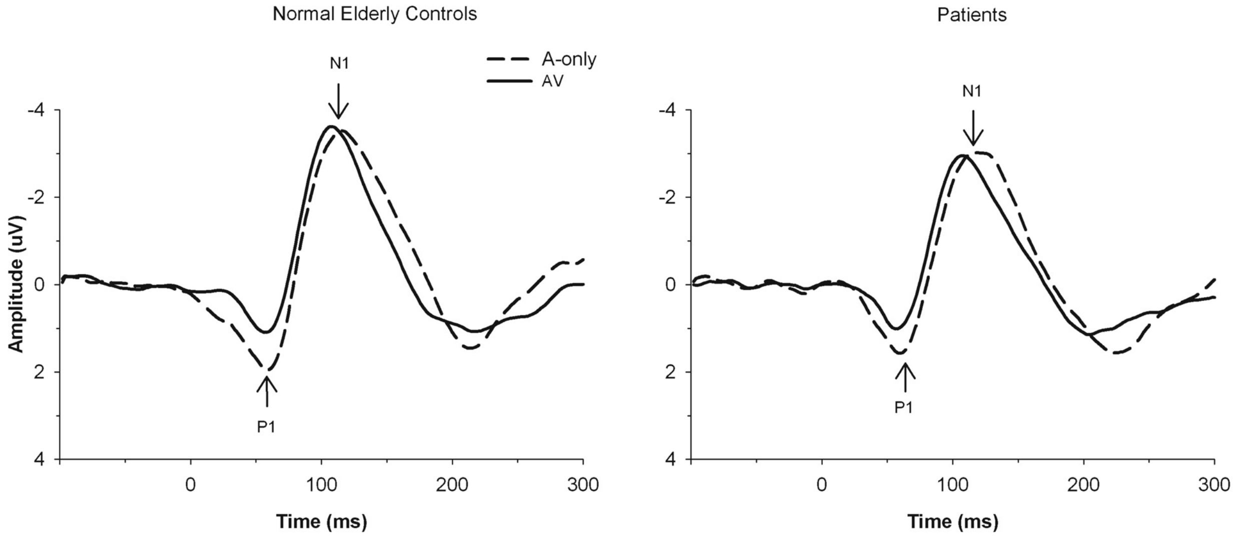

Figure 5. The grand average waveforms of auditory event-related potentials at the CZ electrode, illustrating the amplitudes and latencies of the P1 and N1 components during the Match trials for Normal Elderly Controls (left panel) and Patients (right panel). The data are collapsed across different *n*-back loads. Note a smaller voltage change (i.e., the absolute difference between the trough of P1 and peak of N1) and an earlier peak of the N1 in the auditory-visual (AV) modality than in the auditory-only (A-only) modality for both age groups.

P1-N1 amplitude for Non-Match trials. The waveforms illustrating P1-N1 amplitude during the Non-Match trials are shown in Figure 6. There was a main effect of modality, $F(1, 40) = 47.5$; $MSE = 1.42$; $p < .001$; $\eta_p^2 = .54$. Similar to the Match trials, P1-N1 amplitude was smaller during the AV condition than the A-only condition. The main effect of group was not significant, $F(1, 40) = .2$; $MSE = 21.50$; $p = .69$; $\eta_p^2 = .00$, nor was the Modality x Group interaction, $F(1, 40) = .00$; $MSE =1.42$; $p = .96$; $\eta_p^2 = .00$.

P1 amplitude for Non-Match trials. The waveforms illustrating P1 amplitude during the Non-Match trials are shown in Figure 6. There was a main effect of modality, $F(1, 40) = 11.7$; $MSE = 1.03$; $p = .001$; $\eta_p^2 = .23$. Similar to the Match trials, P1 amplitude was smaller during the AV condition than the A-only condition. The main effect of group was not significant, $F(1, 40) = .5$; $MSE = 5.92$; $p = .50$; $\eta_p^2 = .01$, nor was the Modality x Group interaction, $F(1, 40) = .8$; $MSE = 1.03$; $p = .38$; $\eta_p^2 = .02$.

The planned simple effects indicated that P1 amplitude was smaller in the AV condition compared to the A-only condition for the NEC group, $F(1, 40) = 8.8$; $M_{difference} = -.55$; $p = .01$; $\eta_p^2 = .18$, but while the same trend was suggested in the Patient group, the modality effect did not reach significance, $F(1, 40) = 3.4$; $M_{difference} = -.32$; $p = .07$; $\eta_p^2 = .08$.

P1 latency for Non-Match trials. The waveforms illustrating P1 latency during the Non-Match trials are shown in Figure 6. There was a main effect of modality, $F(1, 40) = 13.5$; $MSE = 119.92$; $p = .001$; $\eta_p^2 = .25$. P1 peaked earlier during the AV condition than the A-only condition. The main effect of group was not significant, $F(1, 40) = .8$; $MSE = 257.78$; $p = .39$; $\eta_p^2 = .02$, nor was the Modality x Group interaction, $F(1, 40) = 2.0$; $MSE = 119.92$; $p = .16$; $\eta_p^2 = .05$.

The planned simple effects indicated that the P1 peaked earlier in the AV condition in comparison to the A-only condition for the Patient group, $F(1, 40) = 13.7$; $M_{difference} = -$

7.05; $p = .001$; $\eta_p^2 = .26$, but no significant modality effect was evident in the NEC group, $F(1, 40) = 2.4$; $M_{difference} = -3.10$; $p = .13$; $\eta_p^2 = .06$.

N1 latency for Non-Match trials. The waveforms illustrating N1 latency during the Non-Match trials are shown in Figure 6. There was a main effect of modality, $F(1, 40) = 38.4$; $MSE = 148.33$; $p < .001$; $\eta_p^2 = .49$. Similar to the Match trials, N1 amplitude peaked earlier during the AV condition than the A-only condition. The main effect of group was not significant, $F(1, 40) = .3$; $MSE = 668.19$; $p = .57$; $\eta_p^2 = .01$, nor was the Modality x Group interaction, $F(1, 40) = .5$; $MSE = 148.33$; $p = .47$; $\eta_p^2 = .01$.

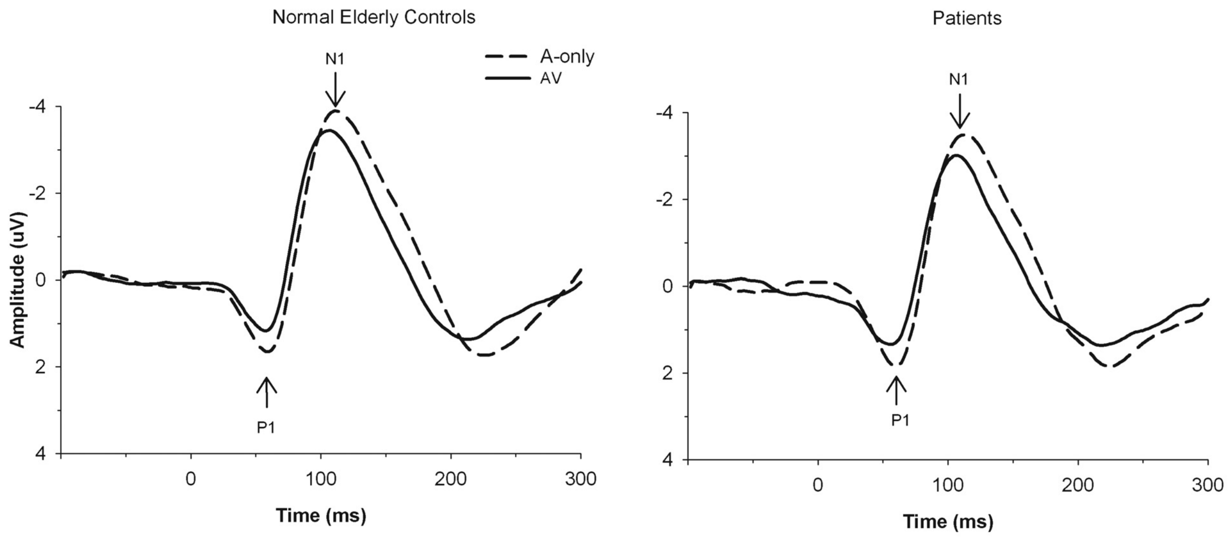

Figure 6. The grand average waveforms of auditory event-related potentials at CZ electrode, illustrating the amplitudes and latencies of P1 and N1 components during the Non-Match trials for Normal Elderly Controls (left panel) and Patients (right panel). The data are collapsed across different *n*-back loads. Note a smaller voltage change (i.e., the absolute difference between the trough of P1 and peak of N1) and an earlier peak of P1 (in Patients) and N1 (both groups) in the auditory-visual (AV) modality than in the auditory-only (A-only) modality.

3.4.2.2 Working Memory Processing

P3 amplitude for Match trials. The waveforms illustrating P3 amplitude during the Match trials are shown in Figure 7.The main effect of modality was not significant, $F(1, 40) = .8$; $MSE = 1.07$; $p = .39$; $\eta_p^2 = .02$. There was a main effect of load, $F(2, 80) = 18.3$; $MSE = 1.32$; $p < .001$; $\varepsilon = .93$; $\eta_p^2 = .31$. P3 amplitude was larger during the 0-back condition in comparison to the 1-back and 2-back conditions. The main effect of group was not significant, $F(1, 40) = .1$; $MSE = 4.31$; $p = .82$; $\eta_p^2 = .00$, nor was the Modality x Group interaction, $F(1, 40) = .1$; $MSE =1.07$; $p = .81$; $\eta_p^2 = .00$.

P3 latency for Match trials. The waveforms illustrating P3 latency during the Match trials are shown in Figure 7. There was a main effect of modality, $F(1, 40) = 11.2$; $MSE = 4850.97$; $p = .002$; $\eta_p^2 = .22$. P3 peaked earlier during the AV condition than during the A-only condition. The main effect of group was not significant, $F(1, 40) = .5$; $MSE = 12364.92$; $p = .48$; $\eta_p^2 = .01$, nor was the Modality x Group interaction, $F(1, 40) = 3.1$; $MSE = 4850.97$; $p = .09$; $\eta_p^2 = .07$.

The planned simple effects indicated that the P3 peaked earlier in the AV condition in comparison to the A-only condition for the NEC group, $F(1, 40) = 12.5$; $M_{difference} = -44.89$; $p = .001$; $\eta_p^2 = .24$, but no significant modality effect was evident in the Patient group, $F(1, 40) = 1.3$; $M_{difference} = -13.84$; $p = .26$; $\eta_p^2 = .03$.

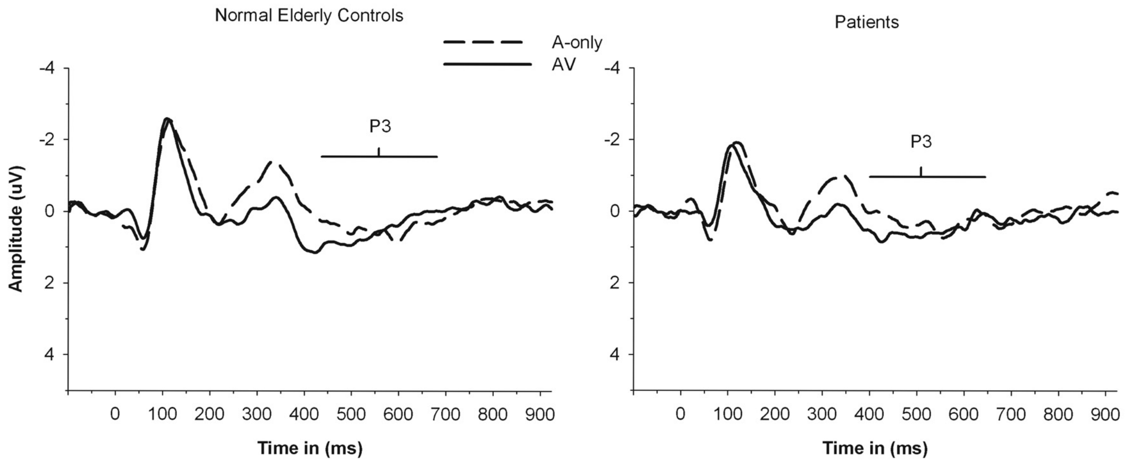

Figure 7. The grand average waveforms of auditory event-related potentials at PZ electrode, illustrating the amplitudes and latencies of P3 component during the Match trials for Normal Elderly Controls (left panel) and Patients (right panel). The data are collapsed across different *n*-back loads. Note an earlier P3 in the auditory-visual (AV) condition than in the auditory-only (A-only) condition, especially in the control group.

P3 amplitude for Non-Match trials. The waveforms illustrating P3 amplitude during the Non-Match trials are shown in Figure 8. The main effect of modality was not significant, $F(1, 40) = .1$; $MSE = 1.14$; $p = .74$; $\eta_p^2 = .00$. The main effect of group was not significant, $F(1, 40) = .01$; $MSE = 3.13$; $p = .91$; $\eta_p^2 = .00$, nor was the Modality x Group interaction, $F(1, 40) = .01$; $MSE = 1.14$; $p = .92$; $\eta_p^2 = .00$.

P3 latency for Non-Match trials. The waveforms illustrating P3 latency during the Non-Match trials are shown in Figure 8. There was a main effect of modality, $F(1, 40) = 16.6$; $MSE = 8405.40$; $p < .001$; $\eta_p^2 = .29$. The P3 peaked earlier during the AV condition than during the A-only condition. There was also a main effect of load, $F(2, 80) = 3.4$; $MSE =$

3473.14; $p = .05$; $\varepsilon = .87$; $\eta_p^2 = .08$. The P3 peaked earlier during the 0-back condition in comparison to the 2-back condition. The main effect of group was not significant, $F(1, 40) = .1$; $MSE = 25255..86$; $p = .72$; $\eta_p^2 = .00$, nor was the Modality x Group interaction, $F(1, 40) = .3$; $MSE = 8405.40$; $p = .60$; $\eta_p^2 = .01$.

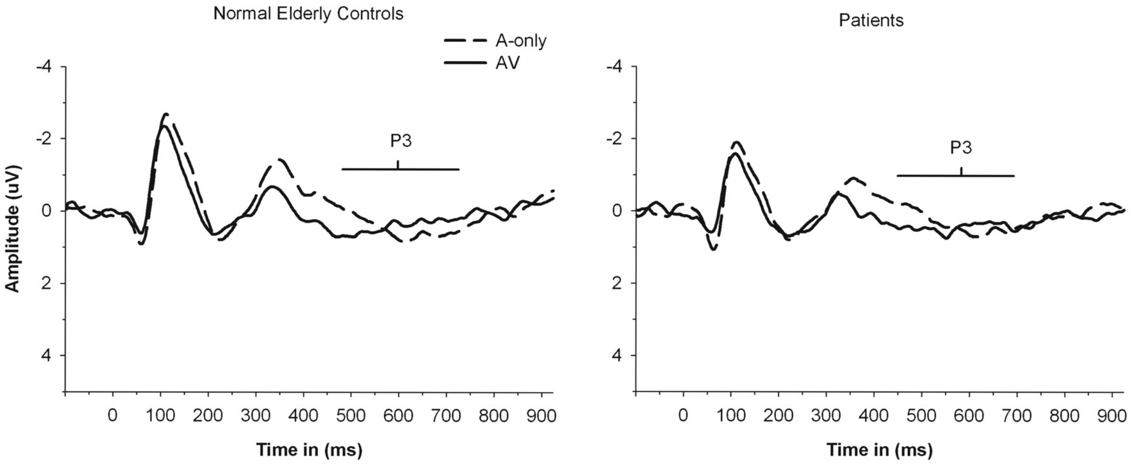

Figure 8. The grand average waveforms of auditory event-related potentials at PZ electrode, illustrating the amplitudes and latencies of P3 component during the Non-Match trials for Normal Elderly controls (left panel) and Patients (right panel). The data are collapsed across different *n*-back loads. Note an earlier P3 in the auditory-visual (AV) modality than in the auditory-only (A-only) modality for both age groups.

3.4.3 Correlation Between the Facilitation of Perception Processing and Improvement in Working Memory Performance

The results in the previous section indicated perceptual facilitation in both groups, shown by a smaller P1-N1 amplitude and an earlier N1 latency during the AV condition in comparison to the A-only condition for both Match and Non-Match trials. In order to examine whether there is an association between the amount of perceptual facilitation and enhancement of WM performance during AV speech, the correlations between the AV benefit on P1-N1 amplitude/N1 latency and WM were examined. In other words, we examined whether there is a relationship between the amount of reduction in P1-N1 amplitude or N1 latency and the amount of behavioural improvement on the *n*-back task during the AV speech condition in comparison to the A-only speech condition. To illustrate, let's say that Participant A had a P1-N1 amplitude of 4 μV in the AV condition and 4.7 μV in the A-only condition and Participant B had a P1-N1 amplitude of 4.3 μV in the AV condition and 4.7 μV in the A-only condition. In this example, Participant A showed greater perceptual facilitation (difference of 0.7 μV) than Participant B (difference of 0.4 μV), and thus was expected to perform better on the WM task in the AV condition in comparison to the A-only condition. For N1 latency, let's say that Participant A had n N1 latency of 70 ms in the AV condition and 100 ms in the A-only condition and Participant B had an N1 latency of 80 ms in the AV condition and 100 ms in the A-only condition. Participant A showed greater perceptual facilitation (difference of 30 ms) than Participant B (difference of 20 ms), and thus was expected to perform better on the WM task in the AV condition in comparison to the A-only condition than Participant B.

The AV benefit was defined as better performance in the AV condition in comparison to the A-only condition and was calculated as: (AV – A-only)/A-only for accuracy and (A-only – AV)/A-only for RT, P1-N1 amplitude and N1 latency. Defined this way, larger positive values always reflect a larger AV benefit relative to the A-only condition. To reduce the chances of Type I error, we only examined this relationship for the 1-back condition. We chose this condition as the best estimate of WM performance, reasoning that the 0-back does not put much demand on WM and 2-back may have been too difficult for some MCI/AD participants. We expected a positive correlation between the facilitation of P1-N1 amplitude and improvement in accuracy (Table 2) and a positive correlation between the facilitation of N1 latency and an improvement in RT (Table 3). The data revealed a significant positive correlation between the facilitation of P1-N1 amplitude and improvement in accuracy for Match trials, and a statistical trend for improved accuracy in Non-Match trials for the Patient group. There was no statistically significant relationship between the facilitation of N1 latency and improvement in RT but there was a statistical trend toward significance for the Non-Match condition in the NEC group.

Table 2. Zero-order correlations between the facilitation of P1-N1 amplitude and improvement in accuracy during the 1-back AV in comparison to A-only condition

	NECs		Patients	
	Match	Non-Match	Match	Non-Match
1-back	.14	.08	.41*	.32~

* significant at α = .05, one-tailed

~ trend toward statistical significance (p < .08)

Table 3. Zero-order correlations between the facilitation of N1 latency and improvement in RT during the 1-back AV in comparison to A-only condition

	NECs		Patients	
	Match	Non-Match	Match	Non-Match
1-back	.02	.41~	-.11	-.22

~ a statistical trend toward significance (p < .08)

3.4.4 Correlation Between the Facilitation of Perception Processing and Sensory Functioning

We examined whether sensory functioning (i.e., binocular contrast sensitivity and binaural hearing acuity) affected the perceptual benefit from AV speech (i.e., smaller P1-N1 amplitude and earlier N1 latency in the AV condition relative to the A-only condition). Given that the Patients and NECs did not significantly differ in terms of sensory functioning we collapsed the data across the groups to gain greater power to detect significant relationships. We examined the relationship between binocular contrast sensitivity (measured by logMAR scores) or average hearing threshold (measured as PTA in dB, averaged across the right and left ear) and the facilitation of P1-N1 amplitude or N1 latency in the AV condition in comparison to the A-only condition, calculated as (A-only - AV)/A-only. The data are presented in Table 4 for P1-N1 amplitude and in Table 5 for N1 latency. In general, higher hearing thresholds were associated with reduced perceptual facilitation of P1-N1 amplitude but hearing thresholds did not seem to significantly affect the facilitation of N1 latency. Higher contrast sensitivity was less reliably associated with greater facilitation of both P1-N1 amplitude and N1 latency.

Table 4. Zero-order correlations between the hearing threshold and visual contrast sensitivity and facilitation of P1-N1 amplitude

	Hearing Threshold		Contrast Sensitivity	
	Match	Non-Match	Match	Non-Match
0-back	-0.14	-0.22~	0.04	0.01
1-back	0.05	-0.28*	0.29*	0.01
2-back	-0.41*	-0.30*	0.03	0.25~

* significant at α = .05, one-tailed

~ a statistical trend toward significance (p < .10)

Table 5. Zero-order correlations between the hearing threshold and visual contrast sensitivity and facilitation of N1 latency

	Hearing Threshold		Contrast Sensitivity	
	Match	Non-Match	Match	Non-Match
0-back	-0.08	0.15	-0.01	0.24~
1-back	-0.15	-0.06	0.02	0.27*
2-back	0.01	0.08	0.10	-0.03

~ a statistical trend toward significance (p < .10)

3.5 Discussion

This study examined how the perception of congruent AV speech cues affects WM performance of individuals with cognitive impairment relative to age- and education-matched controls. In general, the results showed that AV speech stimuli led to higher accuracy in the Patient group (Match trials) and faster responses (Match and Non-Match trials) in both groups. Furthermore, the AV speech condition resulted in the clear facilitation of perceptual processing, indicated by smaller and earlier peaking ERP components associated with perceptual processing. The following discussion is organized around the three main questions of this study and concludes with highlights on practical implications of the findings and considerations of both strengths and limitations in order to direct the future research.

3.5.1 Do Patients with Cognitive Impairment Show Facilitation of Perceptual Processing During Auditory-Visual Speech?

The results of this study suggest that, compared to older adults with normal cognition, patients with cognitive impairment gain a similar level of perceptual facilitation (i.e., decrease in the amplitude of P1 and P1-N1 and earlier latency for P1 and N1) during AV speech in comparison to A-only speech. This is suggested by non-significant interaction effects between the group and modality factors for any of the ERP measures of perceptual processing (i.e., the amplitude of P1 and P1-N1 and the latency of P1 and N1), and as evident during the inspection of Figure 5 and 6. However, we must acknowledge that this interpretation is based on null findings, which may be affected by a low power to detect a significant interaction if it were present.

Nevertheless, these results suggest that patients with MCI and AD benefit from congruent AV speech cues at the perceptual level. The findings of this study stand in contrast to those by Delbeuck and colleagues' (2007) who suggested that individuals with AD have difficulty integrating auditory and visual speech information. A comparison of methodological differences between the current and Delbeuck and colleagues' (2007) study provides valuable insights in regards to AV speech perception in individuals with MCI and AD. The current study used a WM paradigm with whole-word, congruent AV speech, which represents ecologically-valid stimuli. On the other hand, Delbeuck and colleagues (2007) employed incongruent AV phoneme pairs that are relatively impoverished and that may require a very different type of multi-sensory processing in comparison to congruent AV speech. Thus, individuals with cognitive impairment may be able to integrate congruent but not incongruent AV speech cues.

It is possible that the integration of incongruent AV speech cues relies on different processes than the integration of congruent AV speech cues and that these two types of information processing are differentially affected by AD pathology. Incongruent AV speech cues elicit stronger responses from the superior-temporal sulcus as well as inferior frontal gyrus in comparison to congruent AV speech cues (Nath & Beauchamp, 2012). These results suggest that processing incongruent McGurk-type AV speech cues relies more heavily on the multimodal areas and frontal regions that are both affected by AD pathology (e.g., Braak & Braak, 1991; Gomez-Isla et al., 1997; Killiany et al., 2000; T. Liu et al., 2012; Nelissen et al., 2007).

Furthermore, processing differences between congruent and incongruent trials in the McGurk paradigm begin to occur at approximately 175 ms (Saint-Amour, De Sanctis, Molholm, Ritter, & Foxe, 2007) after the stimuli onset, whereas, in the current study, there was evidence of multisensory processing for congruent word-level AV speech information occurring as early as 50 ms (as indexed by the P1 component). This is consistent with the results of other ERP research that used word-level stimuli and found modulation of auditory processing by congruent visual speech cues at the level of the P1 and N1 components (Frtusova et al., 2013; Winneke & Phillips, 2011), which generally implies involvement of the primary or secondary auditory cortex (Liegeois-Chauvel et al., 1994; Pantev et al., 1995). Functional magnetic resonance imaging (fMRI) research using congruent word-level AV stimuli also provides evidence for modulation of activity in the primary and secondary auditory cortices (Callan et al., 2003; Calvert et al., 1999; Calvert et al., 2000) while the involvement of the superior-temporal sulcus is less consistent. More specifically, some research found significantly enhanced activity in this region during processing of congruent AV stimuli (Calvert et al., 2000) whereas other research found no significant involvement (Callan et al., 2003).

Overall, the difficulties that AD patients have with processing McGurk stimuli may be related to either affected multisensory processing at a later stage than the one involved in processing of word-level AV congruent speech and/or difficulty with executive functioning, such as resolution of conflicting information (Collette et al., 2009; Fernandez-Duque & Black, 2006). It is also likely that the patients in the current study were in a less progressed stage of AD than patients in Delbeuck and colleagues' (2007) study. The patient group in this study consisted primarily of individuals with MCI, some of which may not actually progress to AD. Even among those who suffer from early AD pathology, this pathology may not be sufficient enough to cause functional disruption in AV speech perception.

3.5.2 Do Patients with Cognitive Impairment Benefit from Auditory-Visual Speech during a Working Memory Task?

The current data suggest that patients with MCI/AD benefit from AV speech information in terms of improved WM performance. The improvement was observed on both accuracy (Match trials) and RT (Match and Non-Match trials). In fact, several patterns in the data indicated that that AV speech may be particularly beneficial for patients with cognitive impairment. Firstly, improved accuracy (Match trials) was evident in the Patient group but not in the NEC group. Secondly, there was an indication (i.e., a statistical trend) that speed of responding during Non-Match trials may have been facilitated more for Patients than for healthy controls. Overall, the results suggest that patients with WM difficulties, as confirmed by the lower performance on a neuropsychological test of WM (i.e., LNS), benefit from AV speech information in terms of improved WM performance, and there is some indication that this effect may be even stronger in this group than in cognitively healthy older adults.

Although the AV condition did benefit the RT of the NECs, the lack of an AV effect on accuracy was unexpected, considering that we found an AV benefit on accuracy in healthy older adults in our previous work (Frtusova et al., 2013). However, it may be that adaptations of the task for this patient population (e.g., increasing the inter-stimulus period for responding, using shorter blocks of trials), made the task less sensitive to the AV benefit in normal aging. In our previous study we found the AV effect on accuracy only during the most demanding WM conditions (Frtusova et al., 2013). Thus, by making the task easier in order for it to be manageable for individuals with WM deficits, we may have reduced a need for visual speech cues in healthy older adults. This hypothesis is supported by the observation that accuracy during the A-only 2-back condition seemed higher in the current study that in our previous work (Frtusova et al., 2013).

In addition, another modification of the task in comparison to our previous study (Frtusova et al., 2013) was using a still picture (i.e., without any visual speech cues) of the speaker's face during the A-only condition. We added the still picture to better control for attention cuing as to when a new trial begins as well as for any vision-related processes outside of processing visual speech cues. However, we would not expect this modification to significantly affect the results as in a previous study conducted in our laboratory no substantial differences were found in the ERP responses between the A-only condition with or without a still picture of the speaker's face (Winneke & Phillips, 2011).

3.5.3 Is the Behavioural Improvement on the Working Memory Task Related to Facilitation of Perceptual Processing?

The results of this study support the suggestion that AV speech cues lead to facilitation of perceptual processing as well as improved WM performance in older adults, including both cognitively healthy individuals as well as those with cognitive difficulties. In this study, we have also tried to establish whether the amount of WM enhancement (i.e., behavioural improvement in the AV condition compared to the A-only condition) is directly related to the amount of perceptual facilitation during AV speech (i.e., reduced amplitude of P1-N1 and latency of N1 in the AV condition compared to the A-only condition). For this purpose, we have examined correlations between perceptual facilitation and improvement in WM performance in the AV condition relative to the A-only condition. The reduction in the number of processing resources devoted to speech perception (indicated by changes in P1-N1 amplitude) and improved accuracy was found during the 1-back condition (a significant relationship for Match trials and a statistical trend for Non-Match trials) in the Patient group. There was also an indication (i.e., statistical trend) that facilitation of processing speed (indicated by changes in N1 latency) was related to faster behavioural responses during the 1-back condition (Non-Match trials) in the NEC group. Overall, it seems that those MCI/AD patients who derive greater facilitation of perceptual resources during AV speech are able to perform more accurately on the WM task. On the other hand, for NECs, those who derive greater facilitation of perceptual speed during AV speech are able to perform faster during WM tasks.

3.5.4 Practical Implications of the Findings

This study provides evidence that individuals with cognitive impairment can benefit from AV speech in terms of improved WM. WM is involved in many activities of daily living such as, remembering medical instructions or understanding directions. Teaching individuals with MCI and early AD to take advantage of this perceptual facilitation by facing and watching the person they interact with, may help them to better cope with their cognitive challenges. In the later stages of AD, caregivers could receive training in the facilitation of face-to-face conversation. Based on the results of this study, this form of communication could allow for optimization of cognitive resources toward the encoding of the information rather than perception. The small existing literature suggests that caregivers already tend to engage in this form of communication with AD patients even though they do not seem consciously aware of it (Small & Gutman, 2002; Small, Gutman, Makela, & Hillhouse, 2003). The effect of a direct training in these communication skills needs to be assessed by future research.

Another important implication of the current research relates to neuropsychological testing. This research shows that perceptual functioning has an effect on cognitive performance. In particular, this study suggests that whether or not an examinee has a chance to benefit from visual speech cues may affect his/her cognitive performance. Thus, clear face-to-face interaction should be routinely implemented in cognitive testing. More broadly, completing cognitive assessments in perceptually facilitated conditions seems imperative to get a valid estimate of higher-order cognitive skills (Pichora-Fuller, Dupuis, Reed, & Lemke, 2013).

Lastly, there has been an increase in the use of interactive voice response (IVR) services. For example, voice commands or keyboard presses are used to navigate almost any phone directory for a store or health clinic. However, a recent study by Miller, Gagnon, Talbot and Messier (2013) suggests that using this technology is very challenging for the older adults. In their community-based sample of 185 older adults, approximately 20.5% could not complete any of the IVR tasks. Furthermore, WM and auditory memory abilities were significant predictors of performance on the IVR tasks. Thus, using IVR systems may be especially challenging for people with MCI or AD.

In addition to difficulty with using IVR systems, even a regular conversation over the telephone may be challenging for individuals with MCI and AD. Speech perception over the telephone is difficult because of the restricted bandwidth, including compression of high frequencies important for distinguishing speech sounds (e.g., different consonants), and thus making the listener rely on context to make sense of the conversation (Rodman, 2003). This process puts higher demands on WM (Rönnberg et al., 2008) and thus may be particularly challenging for these patients. The results of this study suggest that AV systems may lead to less frustration and improved functionality in the older adult population, with likely greater benefit in those with diminished cognitive abilities. Given the expected increase in the older adult population, further research on AV speech perception and use of AV technology is strongly warranted.

3.5.5 Strengths and Limitations

The current study has some notable methodological strengths. Firstly, the two groups of older adults (i.e., Patients and NECs) in this study were carefully matched on multiple important variables, including age, education, sex, handedness, and vision and hearing abilities. Furthermore, the study used behavioural assessment of WM combined with ERP technology, allowing a direct examination of the relationship between perceptual processes (reflected by the P1 and N1 ERP components) and behavioural WM outcome.

Despite the careful control of important variables, the study has a few limitations. Firstly, both the NEC and Patient sample used in this study consisted of highly educated individuals screened for a variety of health conditions. How the results generalize to people with lower levels of education or those with more complex clinical presentation, such as comorbidity of MCI or AD with other neurological conditions, remains to be determined in future research.

Secondly, while participants in this study were quite variable in their visual functioning (binocular contrast sensitivity ranging from 1.36 to 1.64 logMAR) and hearing abilities (average binaural PTA ranging from 10.83 to 65.83 dB), those with significant visual and hearing conditions were generally excluded from the study. Most of the participants in this study had age-normal contrast sensitivity. Hearing thresholds for a substantial proportion of the participants were above the normal range but, as previously noted, this was likely affected by environmental conditions that did not allow for ideal screening (i.e., testing in a sound-proof or sound-attenuated room). Our correlation analysis showed that elevated hearing threshold seems to reduce the level of the AV benefit on P1-N1 amplitude. Higher contrast sensitivity seems to have a positive relationship with greater facilitation of both P1-N1 amplitude and N1 latency, even though these effects are less reliable across different *n*-back loads. Whether AV speech information leads to reliable perceptual facilitation in a group of older adults with clinically diagnosed hearing impairment and to what extent AV speech affects their WM performance is the focus of our other study.

Lastly, in the current study the AV benefit was similar for participants with MCI/AD in comparison to cognitive healthy older adults. Combining MCI and AD patients together may have masked differences in the AV effect between these two patient groups, which may be related to differences in the neuropathological stage of the disease. The analyses of the data using only MCI patients and NECs yielded a pattern of scores similar to using the complete patient sample. Future studies could explore differences in the AV effect between MCI and AD using larger samples for each patient population[1].

3.6 Conclusion

The current study explored the relationship between perceptual processing during AV speech and WM performance in individuals with MCI/AD. On a WM *n*-back task, Patients were more accurate (Match trials) and both Patients and NECs were faster (Match and Non-Match trials) during an AV condition compared to an A-only condition. Both groups also showed a clear perceptual facilitation, indicated by smaller and earlier ERP components related to perceptual processes. Overall, the study provided evidence that individuals with MCI and AD benefit from the presentation of congruent AV speech tokens in terms of improved WM. This observation has important implications for planning behavioural interventions and making technological adjustments that would help individuals with cognitive impairment to optimize their functionality and improve their quality of life.

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[1] Visual inspection of the waveforms for AD patients suggested facilitation of the N1 latency, P1 amplitude and P1-N1 amplitude for Match trials, and facilitation of the N1 latency and P1 amplitude for Non-Match trials in the AV compared to A-only condition.

Chapter 4: General Discussion

4.1 Purpose of the Current Research and Summary of Results

According to the theory of an integrated perceptual-cognitive systems (Schneider & Pichora-Fuller, 2000), perceptual and cognitive processing share a certain number of processing resources, which can be flexibly allocated to either perception or higher-order cognition. Considering this theory and the assumption that there is a limited amount of overall capacity (Baddeley, 2010; Baddeley & Hitch, 1974; Cowan, 2010; Logie, 2011), it is implied that if a significant number of resources need to be allocated to perception there may not be enough left-over resources for subsequent higher-order processing, such as encoding of information in memory. The reallocation of processing resources seems particularly important when either the memory task is demanding (Frtusova et al., 2013; Pichora-Fuller et al., 1995) or when the auditory signal is degraded (Pichora-Fuller et al., 1995). Thus, the effect of perceptual burden on higher-order processing should be especially evident in individuals suffering from cognitive or hearing impairment. On the other hand, facilitation of perceptual processing through auditory-visual (AV) speech should allow a greater number of resources to be available for higher-order processing, such as memory, and thus lead to improved performance in these individuals.

The purpose of this thesis was to examine the implications of the integrated perceptual-cognitive system model (Schneider & Pichora-Fuller, 2000) by examining how AV speech affects working memory (WM) processing in older adults whose information processing is affected by neurodegenerative disorder or hearing impairment. More specifically, the two studies described in this thesis aimed to clarify whether older adults suffering from (Study 1) hearing impairment or (Study 2) mild cognitive impairment

(MCI)/Alzheimer disease (AD) can derive perceptual benefit through AV speech and whether this benefit would subsequently lead to improved WM performance. Both behavioural and electrophysiological responses were collected in the two studies, allowing for a more sensitive assessment of the relationship between perceptual processing and WM performance. In this section, a brief summary of the observed findings is presented followed by a discussion of the theoretical and practical implications of the results. The thesis concludes with remarks on the strengths and limitations of the current research, and suggestions for future research.

The first study examined the AV speech benefit on perceptual and WM performance in older adults with hearing impairment in comparison to age- and education-matched controls. The results showed perceptual facilitation, indicated by smaller and earlier event related potentials (ERP) components related to perceptual processing in the AV condition compared to A-only condition, in participants with sensorineural hearing impairment. Furthermore, facilitation of WM processing was also indicated by electrophysiological responses, in the form of faster processing in both groups and improved WM capacity in older adults with hearing impairment during the AV condition compared to the auditory-only (A-only) condition. Behaviourally, no effects on accuracy were observed but participants were faster during the AV speech condition. In fact, despite lower performance in the A-only condition for older adults with hearing impairment in comparison to controls, no group differences were noted during the AV speech condition. Overall, the results indicated that older adults with hearing impairment derive an AV speech benefit, and that this effect seems to be even more robust in this population than in normal-hearing elderly. Furthermore, under the condition of facilitated perceptual processing afforded by the AV speech, older adults with hearing impairment were as efficient as normal-hearing older adults on the WM task.

The second study compared perceptual processing and WM performance of older adults suffering from MCI or AD in comparison to age- and education-matched cognitively healthy controls. The results confirmed auditory perceptual facilitation, indicated by smaller and earlier ERP components related to perceptual processing, evident in both cognitively healthy and cognitively impaired individuals during the AV condition compared to the A-only condition. Furthermore, facilitation of WM processing was also indicated by electrophysiological responses, in the form of faster processing in the AV compared to the A-only condition for both groups. There was also behavioural improvement on a WM task, indicated by higher accuracy in the patients and lower reaction times (RT) in both groups. Overall, the second study confirmed that individuals suffering from MCI or AD benefit from AV speech information, at both perceptual and higher-order processing levels.

4.2 Theoretical Implications

4.2.1 Resource Integration Between Perception and Cognition

The results of the two studies presented in this thesis support the theory of an integrated perceptual-cognitive system (Schneider & Pichora-Fuller, 2000). The first study examined WM performance of individuals with hearing impairment, a population in which sensory functioning was found to affect higher order abilities (e.g., Cervera et al., 2009; McCoy et al., 2005; Rabbitt, 1991; Stewart & Wingfield, 2009). The results showed improved perceptual and WM functioning during the AV speech condition compared to the A-only speech condition that was similar to or even greater than that of normal-hearing older adults. More specifically, older adults with hearing impairment showed more robust perceptual facilitation in the AV condition, indicated by smaller P1 and P1-N1 and earlier P1. Furthermore, on the WM RT measure, older adults with hearing impairment were slower than controls during the A-only condition but their performance was similar to that of controls during the AV condition. Similarly, for P3 amplitude, which reflects attention and processing capacity (Watter et al., 2001), older adults with hearing impairment had smaller P3 amplitude than controls during the A-only condition but there were no P3 amplitude differences across the groups during the AV condition.

The second study examined WM performance of individuals with MCI and AD, patient populations with well documented WM difficulties (e.g., Alichniewicz et al., 2012; Belleville et al., 2007; Belleville et al., 2003; Borkowska et al., 2009; Chang et al., 2010; Egerhazi et al., 2007; Facal et al., 2014; Gagnon & Belleville, 2011; Griffith et al., 2006; Huntley & Howard, 2010; Johns et al., 2012; Kalpouzos et al., 2005; Klekociuk & Summers, 2014b; Muangpaisan et al., 2010; Newsome et al., 2013; Nordahl et al., 2005; Rombouts et al., 2005; Saunders & Summers, 2010; Waltz et al., 2004; Zheng et al., 2012; Zheng et al., 2014; Zihl et al., 2010). The results of Study 2 showed that these individuals benefit from AV speech information to a similar or even higher extent than cognitively healthy older adults. More specifically, patients with MCI and AD showed a similar level of perceptual facilitation in the AV condition compared to the A-only condition, indicated by smaller P1/P1-N1 and earlier N1, as cognitively healthy older adults. Furthermore, on behavioural WM measures, patients' accuracy was higher in the AV condition compared to the A-only condition for the Match trials, whereas no significant modality effect was evident in the healthy control group. There was also an indication in the Non-match trial RT data that patients benefited from the AV condition compared to the A-only condition more than the control group.

Overall, the results of these two studies provide evidence that patients with MCI and AD as well as older adults suffering from hearing impairment show facilitated perceptual processing during AV speech. Furthermore, AV speech information seems to provide one method for helping to maximize WM potential. Importantly for both studies, the observed AV benefit on WM is not attributable to difficulties with perceiving the stimuli during the A-only condition. The stimuli were presented in a quiet environment and participants reported that they could hear the speech. This was also confirmed by high accuracy (over 95%) during the A-only 0-back condition observed in both studies and for all groups of participants. In context of the integrated perceptual-cognitive processing theory, these results indicate that facilitated perceptual processing during an AV speech condition allows greater number of resources to be available for WM. The reallocation of processing resources from perceptual toward higher-order processing is especially important if an individual does not have enough available resources. Thus, the observation of greater effects in older adults whose processing resources are restricted by cognitive or sensory decline supports the theory of an integrated perceptual-cognitive system.

While the current research concentrated mostly on testing the assumptions from the integrated perceptual-cognitive model (Schneider & Pichora-Fuller, 2000), another relevant theory comes from the WM system for ease of language understanding (ELU; Rönnberg et al., 2013; Rönnberg et al., 2008). According to this model, in ideal listening conditions processing occurs implicitly.: multimodal information enters the processing system and, after the different components are bound, the phonological representations are rapidly matched in long-term memory, leading to understanding of speech input. In less optimal listening conditions, an explicit process is demanded; the degraded speech information does not match any phonological representation during the rapid implicit processing, and thus explicit WM processing is required. Here, the stored phonological representations and semantic knowledge are used to compensate for missing information (i.e., the degraded phonological representation). Both the implicit and explicit processing are influenced by the individual's WM capacity. Based on this model, facilitated perceptual processing by AV speech increases the likelihood that the speech signal will match the representation in long-term memory, and thus will leave more WM processing capacity for subsequent mental functions, such as encoding of information in memory. From this model's perspective, AV speech facilitation would be particularly important for individuals with hearing impairment, by helping them to rely more on implicit speech processing rather the more resource-demanding explicit processing. On the other hand, a greater AV benefit would also be expected in MCI/AD patients because they have more restricted WM resources and thus the reliance on more demanding explicit processing would be particularly detrimental for the subsequent cognitive processes. Overall, the current research supports the assumptions derived from the ELU model by finding a greater AV benefit in older adults with hearing impairment and those with MCI/AD.

4.2.2 Multisensory Processing

The results from previous research raised a concern that multisensory functioning may be affected in older adults with AD (Delbeuck et al., 2007; Golob et al., 2001) and hearing impairment (Musacchia et al., 2009). However, the results of the two studies presented in this thesis suggest that both of these groups derive perceptual benefit from AV speech information. I examined the multisensory processing in individuals with hearing impairment by comparing auditory ERPs during the AV condition with the summed activity during unisensory conditions, A-only and visual-only (V-only), as described in previous research (Frtusova et al., 2013; Klucharev et al., 2003; Pilling, 2009; van Wassenhove et al., 2005; Winneke & Phillips, 2011). My analyses indicated effective multisensory processing in this group of hearing impaired older adults. I was not able to conduct the same analyses for individuals with MCI and AD because the V-only condition was not included in that study. Including an extra V-only condition would have been difficult from a practical standpoint, given an already lengthy paradigm for the MCI/AD population. Nevertheless, the fact that I observed facilitation of perceptual processing in the AV condition compared to the A-only condition in this population and that these effects were similar to those observed in the control group suggest that they have adequate multisensory processing related to AV speech perception.

The reason for the discrepancy between the results of the current study and previous research is likely related to differences in the nature of the stimuli and in the processing required during the task. For example, most of the previous studies that found affected multisensory processing in MCI or AD populations did not use AV speech stimuli (e.g., Festa et al., 2005; Golob et al., 2001) and there is an indication that AV speech represents a special form of multisensory interaction (Tuomainen et al., 2005). One study (Delbeuck et al., 2007) that used AV speech stimuli found inefficient binding of auditory and visual speech information in AD patients using a McGurk paradigm, in which visual and auditory speech syllables are incongruent. However, we are rarely, if ever, required to process incongruent syllabic-level AV information in our daily lives, and thus processing of these ecologically invalid stimuli is a very unnatural process for our brain. On the other hand, congruent AV information is a common occurrence and in this case visual information is considered to be complementary to auditory speech information. Thus, processing of incongruent, syllabic-level AV stimuli (used by Delbeuck et al., 2007) may be different from processing of the word-level congruent AV stimuli used in the current research (see alsoZekveld, Rudner, et al., 2011).

There is research evidence to support the notion of processing differences between congruent and incongruent AV stimuli. For example, Nath and Beauchamp (2012) tested processing differences between congruent and incongruent syllabic-level stimuli in an functional magnetic resonance imaging (fMRI) paradigm. They found a significantly greater activation in the left superior temporal sulcus (STS) to incongruent compared to congruent AV stimuli. Also, greater activation of the STS was associated with greater likelihood of the McGurk fusion. In addition, the inferior frontal gyrus showed a preferential activation for the incongruent compared to congruent AV speech information. In an ERP study, Saint-Amour and colleagues (2007) compared activation elicited by congruent and incongruent McGurk stimuli using an oddball paradigm. They found processing differences that began approximately 175 ms after the onset of the stimulus. Taken together, there seem to be processing differences between congruent and incongruent AV perception.

The current research tested AV speech perception in individuals with MCI/AD using whole-word congruent AV information. The modulation of ERP activity in the AV condition compared to the A-only condition was observed at a very early stage of auditory processing, at the level of P1 and N1 components. More specifically, the P1 and N1 components generally peaked earlier and had smaller amplitudes during the AV condition compared to the A-only condition. These early effects were mostly comparable to those observed in cognitively healthy controls in the current research, and they also agree with the AV modulation effects in cognitively healthy individuals observed in previous studies that used word-level congruent AV stimuli (Frtusova et al., 2013; Winneke & Phillips, 2011). In general, such early effects are consistent with modulation of auditory processing at the level of primary and/or secondary auditory cortex (Liegeois-Chauvel et al., 1994; Pantev et al., 1995). This is further supported by fMRI research that compared brain activation during the AV condition compared to the A-only condition using word-level congruent AV stimuli. These studies consistently found modulation of activity in the primary and/or secondary auditory cortex (Callan et al., 2003; Calvert et al., 1999; Calvert et al., 2000). On the other hand, the modulation of activity in the STS was observed only inconsistently across different studies (Callan et al., 2003; Calvert et al., 2000).

Overall, AV speech perception during processing of congruent word-level stimuli seems to differ from AV speech perception during incongruent syllabic-level McGurk stimuli. Thus, it is possible that these two processes may be differentially affected by AD pathology. For example, AD pathology was found to affect STS and frontal regions (e.g., Braak & Braak, 1991; Gomez-Isla et al., 1997; Killiany et al., 2000; T. Liu et al., 2012; Nelissen et al., 2007), which were implicated in processing incongruent AV stimuli (Nath & Beauchamp, 2012). Furthermore, it is also possible that the difficulties that patients with AD have processing incongruent McGurk stimuli are secondary to their cognitive difficulties, such as decline in WM or executive functioning. One plausible explanation can be derived from the ELU model, discussed earlier. The ecologically invalid incongruent AV stimuli is unlikely to match any phonological representation in long-term memory and thus explicit processing that is taxing on WM is required. This is especially problematic for AD patients due to their restricted WM resources (e.g., Belleville et al., 2007; Belleville et al., 2003). In addition, AD patients also experience difficulty with resolving conflicting information (e.g., Collette et al., 2009; Fernandez-Duque & Black, 2006) and thus may be more likely to rely solely on the auditory modality (as the main modality for speech). In fact, when fusion or combination of AV information did not occur in the Delbeuck and colleagues' (2007) study, the patients with AD were more likely to rely on the auditory modality than controls.

Another important consideration is that the groups (AD versus controls) in Delbeuck and colleagues' (2007) study were not tested and matched on basic visual functions, which could have possibly influenced the observed group differences. In their study, there was a statistical trend indicating poorer lip-reading and visual discrimination abilities in AD patients, suggesting possible group differences in visual functioning. Basic visual abilities, such as contrast sensitivity, were found to be important for AV speech perception (Winneke & Phillips, 2011). In the current study, the group of MCI/AD patients was carefully matched to controls on visual functioning, measured by contrast sensitivity scores. Taken together, the current findings indicate that patients with MCI/AD show facilitated perceptual processing during AV speech that involves processing of congruent auditory and visual speech cues. The level of perceptual facilitation was similar to that observed in the control group that matched the patient group not only on age and education but also on visual abilities.

Methodological differences may have also contributed to discrepancies between current findings and prevous research in the hearing impairmed populaton. For example, a prevous ERP study suggested that individuals with hearing impairment showed a decreased level of AV speech interaction (Musacchia et al., 2009). In that study, participants passively listened to (i.e., A-only condition), watched (i.e., V-only), or watched and listened to (i.e., AV condition) repeated presentation of the same syllable. The multisensory effect was examined by comparing the ERP responses during the AV speech condition to the sum of the ERP responses elicited during the unisensory conditions (A-only plus V-only). The results showed that in comparison to older adults with normal hearing, those with hearing impairment did not show the same level of latency and amplitude facilitation of the P1 and N1 components in the AV condition compared to the A+V measure. In contrast, the current research showed more robust facilitation of the P1 and N1 components (both amplitude and latency) in older adults with hearing impairment compared to normal-hearing older adults.

There are several methodological differences that may have contributed to discrepant results between the two studies. For example, a consideration needs to be given to the stimuli and task differences. Musacchia and colleagues (2009) assessed speech perception using repetition of the same synthetically created auditory syllable, which was imposed on the video recording of a human speaker pronouncing the same syllable. In comparison, the current study used a more ecologically valid task by employing sequences of constantly changing digits, in which both auditory and visual speech information was recorded from the same human speaker. Similarly, in Musacchia and colleagues' (2009) study, the stimuli were not as task-relevant as they were in the current study, which could have contributed to processing differences caused, for example, by reduced attention to speech information. Musacchia and colleagues (2009) tried to control attention by random presentation of visual 'catch' trials (i.e., presentation of a red asterisk) that participants needed to count. However, this could have in fact driven attention away from the speech perception toward this secondary task.

Most importantly, Musacchia and colleagues (2009) used an individually adjusted intensity level for auditory stimuli presentation to equalize the auditory input across the groups. In contrast, we were interested in perceptual processing differences across the groups in regular environmental conditions, where sound intensity adjustment is commonly not an option. Thus, we presented the stimuli at the same intensity for both groups. While all participants reported that they could hear the stimuli, which had been also confirmed by adequate performance during the A-only condition, the perceptual processing was expected to be more demanding for hearing impaired participants. While we did not directly measure the listening effort, the more demanding perceptual processing for older adults with hearing impairment was suggested by smaller P1-N1 amplitude and indication of delayed N1 latency in comparison to normal-hearing older adults.

Overall, the results of the current study suggest that under the perceptually demanding conditions that require detection of unpredictable speech information, older adults with hearing impairment show evidence of effective AV interaction.

The observed AV benefit in individuals with hearing impairment is in agreement with the results from behavioural studies. For example, Grant and colleagues (1998) measured consonant and sentence recognition in individuals with hearing impairment. The stimuli were presented under 0 dB signal-to-noise ratio (S/N), with speech-shaped background noise. The results showed improved speech recognition under the AV condition compared to the A-only condition. Similarly, Bernstein and Grant (2009) assessed speech intelligibility by presenting sentences under various types of background noise (i.e., interfering talker, modulated noise and stationary noise). The results suggested that participants with normal hearing as well as those with hearing impairment performed better in the AV condition compared to the A-only condition under all types of background noise. Another study that assessed speech perception by presenting consonants, words, and sentences masked by a multi-talker background babble found that after controlling for baseline differences in the A-only condition, older adults with hearing impairment benefited from visual speech cues during the AV speech to a similar extent as normal hearing older adults (Tye-Murray et al., 2007). Lastly, Grant and colleagues (2007) found that despite lower performance in the A-only condition during a syllable recognition task, participants with hearing impairment performed similarly to normal-hearing individuals in the AV condition. Taken together, these results suggest that individuals with hearing impairment benefit from AV speech.

Overall, the two studies presented in this thesis contributed in an important way to the existing literature. Firstly, the current research clarified the AV speech benefit in older adults with cognitive and hearing impairment using ecologically valid stimuli. Secondly, the current research provides unique electrophysiological and behavioural support for the theory of an integrated perceptual-cognitive system and thus further highlights the intimate relationship between perception and higher-order processing.

4.3 Practical Implications for Older Adults

In addition to having strong theoretical significance, the presented findings yield several suggestions for improving the quality of life for older adults suffering from either cognitive or hearing impairment. Both dementia and hearing impairment are associated with social interaction difficulties (e.g., Arlinger, 2003; Crews & Campbell, 2004; Dalton et al., 2003; Kolanowski & Litaker, 2006; Strawbridge et al., 2000), which can result in frustration or feelings of social isolation. Moreover, hearing impairment has been found to be particularly prevalent in individuals with cognitive impairment, such as AD (Gold, Lightfoot, & Hnath-Chisolm, 1996), making social interaction even more challenging. Communication difficulties not only affect the individual with cognitive or hearing impairment but they may also have direct (i.e., inability to communicate effectively) or indirect (i.e., having to deal with the person's frustration and mood difficulties) negative consequences for family members (Pichora-Fuller et al., 2013). For example, caring for a patient with dementia was found to be associated with psychological distress for the caretaker (Haley et al., 1995). Communication difficulties were identified as the major contributor to the caregiving burden because they tend to be related to problematic behaviours in patients with dementia, such as restlessness and irritability (Savundranayagam, Hummert, & Montgomery, 2005). Similarly, hearing impairment was found to be associated with decreased physical, psychological, and social well-being of the spouse (Wallhagen, Strawbridge, Shema, & Kaplan, 2004). Social interaction difficulties can be at least in part related to demanding speech processing, which requires both adequate perceptual and higher-order cognitive functions (Grant et al., 1998). Social interaction plays a significant role in human life and increased social engagement has been found to be associated with decreased risk of developing dementia (Wang, Karp, Winblad, & Fratiglioni, 2002). Thus, addressing social interaction problems in older adults is very important.

AV speech communication (i.e., through face-to-face interaction) presents one avenue of how to make speech processing less demanding, which may lead to greater social involvement. Individuals with hearing impairment and those in the early stages of dementia could be educated and trained to take advantage of this benefit. Furthermore, family members, especially those interacting with dementia patients, could be educated about this benefit and advised to face the patients during conversations as well as to direct the patients to look at them while they speak. The facilitated perceptual processing during AV speech is expected to allow more resources to be available for higher-order processing involved in verbal communication.

Several methods for improving speech comprehension have been developed, with various levels of emphasis put on use of visual speech cues or integration of auditory and visual speech cues (Pichora-Fuller & Levitt, 2012). The information from this study provides support for such programs. While the current studies suggest that even people without training are able to derive an AV speech benefit, it can be assumed that the more proficient individuals become in integrating auditory and visual speech information, the greater benefit they will experience. The results of my studies also indicate that training methods with a focus on improving AV speech functioning may not only lead to better speech identification but also to improved ability to remember the presented information. This assumption is based on the observation that facilitated AV speech processing is associated with better WM performance.

The current results also have important practical implications for many daily activities of older adults. The results of my studies indicate that older adults have a better chance of understanding and remembering information when it is presented face-to-face. Thus, tasks such as communicating complex medical information should be done face-to-face, with the health care provider arranging the environment so that the patient can benefit from visual speech cues. For some individuals, especially those living in rural areas, in-person visits to health clinics are not a viable option and tele-medicine systems are used to provide health care services. In these scenarios, using AV technology, rather than A-only systems, represents a better option for older adults. Allowing older adults to benefit from visual speech in health care settings is important as some of them, especially those with cognitive or hearing impairment, may have difficulty with processing complex information presented by medical professionals. For example, a review of literature indicated that the ability to provide informed consent declined with age, due to diminished ability to understand required information (Sugarman, McCrory, & Hubal, 1998). The same applies to other settings, such as banks, insurance companies, law offices, and as further discussed in the next section, neuropsychological assessments. Noisy environments, such as airports or train stations, are especially challenging for older adults. In such settings, having television screens so that speaker's face would be visible during announcements would likely be beneficial and less frustrating for older adults. Future studies could examine the benefits of AV speech in these settings.

Lastly, the current results provide guidelines for technological innovation that would be user-friendly for older adults. Research shows that older adults have significant difficulty using interactive voice response (IVR) systems that have become very popular in recent years (D. Miller et al., 2013). My results suggest that older adults may have less difficulty if visual speech cues were available in these programmed systems. As discussed in the following section, AV speech-based technology has shown promising results in school settings with children who are hard of hearing (Gagne, 2001). Thus, various AV devices could also be designed for older adults. Already existing technology, such as Skype or FaceTime, provide opportunities to benefit from AV speech cues during phone conversations.

4.4 Practical Implications in General

In a more general sense, the current results provide evidence that perceptual processing can affect higher-order cognitive abilities. Thus, optimization of sensory/perceptual functioning would likely lead to maximization of higher-order cognitive abilities. This has various practical implications. For example, during neuropsychological testing we are interested in assessing different domains of higher-order cognitive ability. It is evident from the presented results that a careful consideration should be given to sensory abilities of the examinee and perceptual conditions of the environment. Factors such as whether or not the examinee is wearing a hearing aid or eye glasses may be influencing the results. To illustrate, one study (van Boxtel et al., 2000) examined the effect of hearing acuity on verbal learning memory performance, using a common neuropsychological test. The task is to learn a list of 15 words over five learning trials, and then recall as many as possible twenty minutes later. In the study, 453 participants were tested, ranging in age from 23 to 82 years. The results showed that after accounting for demographic variables, such as age, sex, education, and processing speed, a

10 dB loss in hearing acuity was comparable to a cognitive age that is 5.7, 8.4, and 7.1 years older than actual chronological age for overall immediate recall, the maximum score within five learning trials, and delayed recall, respectively. These effects were observed despite the fact that the volume of the stimuli was individually adjusted and the background noise was reduced so that the participants could hear the words. Thus, it seems that the observed effects should not be completely attributable to the difficulties with perceiving the words. Rather, similar to the current results, the need to recruit more processing resources toward perception may have interfered with adequate resources for memory processing.

Additional consideration in regards to neuropsychological testing is the effect of environment. While we may try our best to test in quiet and well-lit conditions, we may not always have an option to chose or change the environment, for example, when doing bedside assessments. In these cases, a careful thought should be given to how these factors could influence results when making interpretations about higher-order cognitive abilities.

Another setting for which the current results have significant implications, both direct and indirect, is education. The direct implications are that children (or adults) would likely benefit from visual speech cues during learning. This may be particularly relevant for children who are hard of hearing as well as those who have cognitive dysfunction or a learning disability. In fact, it has been already described that children who are hard of hearing and require assistive listening devices, such as auditory FM transmission systems, performed better at school when the system provided both auditory and visual speech cues than if it provided only auditory speech cues (Gagne, 2001). The indirect or more general implications are that sensory/perceptual functioning can affect learning and development of skills. For example, profoundly deaf children with cochlear implants were found to have lower digits span, both forward and backward, than normally hearing age-matched peers even during AV speech (Burkholder & Pisoni, 2003). While a combination of different factors may have played a role in this affect, it is possible that demanding perceptual processing consumed resources that would otherwise be available for higher-order abilities.

Lastly, findings of a close relationship between perceptual and cognitive abilities have implications for driving. If speech perception takes away resources needed for higher-order processing than it can be hypothesized that activities such as having a conversation or listening to the radio while driving could be taking up resources needed for making a quick reaction in face of an unexpected situation on the road. Although hazards of distracted driving have been recognized, including a ban on texting while driving, the arguments raised were mostly related to keeping eyes on the road. The results of the studies presented in this thesis suggest that even if the driver uses hands-free devices or just listens to the radio, there may be an increased risk of accident. This concept has already been introduced in previous research. For example, one study (Just, Keller, & Cynkar, 2008) found that listening to spoken sentences while completing a simulated driving task interfered with driving skills, as indicated by errors such as increased number of hitting the berm and deviation from an ideal path. Furthermore, the brain imaging data collected during the task showed decreased activation in brain regions involved in spatial processing. The results were interpreted as an indication that listening to speech takes mental resources away from driving (Just et al., 2008). Even though I did not test driving skills directly, the current results support the notion that perceptually demanding situations may affect higher-order functions, such as those involved in driving.

One challenge is to identify more quantifiable measures of listening effort or processing load (i.e., outside of an fMRI scanner or ERP machine) so that the relationship between perception and cognition could be examined during daily-living activities, such as driving. A few methodologies so far present promising options. One possibility is through a dual-task paradigm where speech recognition is assigned as the primary task and performance on the secondary, concurrently performed task is considered to reflect listening effort. It is assumed that if the speech recognition task exceeds the available processing capacity, the performance on the secondary task will decline and the level of decline can be interpreted as the level of listening effort (Fraser et al., 2010). Relevant to my previous discussion, this paradigm was used to determine the effect of listening effort on driving performance in older adults with hearing impairment (Y. H. Wu et al., 2014). In this experiment, participants performed speech recognition tasks while also performing a simulated driving task. Both tasks were assigned equal priority because in a real world driving situation speech recognition would unlikely take priority over driving. The results showed a decline in driving performance when participants simultaneously performed the speech recognition task compared to the driving-only condition. In another study that used the dual-task paradigm, Fraser and colleagues (2010) tried to equate the AV and A-only conditions in terms of behavioural accuracy on a speech recognition task by decreasing the S/N in the AV condition (i.e., there was more noise in the AV than A-only condition). The secondary task was tactile pattern recognition. The results showed that AV perception was more effortful than A-only perception, as indicated by a greater decline in accuracy and RT on the secondary task. These results are consistent with the idea that more demanding perceptual processing created by poor S/N, took away resources available for the secondary task.

The second promising method for examining the processing effort is through measuring pupil dilation. For example, Zekveld, Kramer, and Festen (2010) found that as speech intelligibility during a sentence recognition task decreased due to poorer S/N ratio, the dilation of the pupil increased, indicating greater listening effort. The same group of researchers also found that hearing impairment is associated with a reduced change in pupil dilation with a change in speech intelligibility (Zekveld, Kramer, & Festen, 2011). Zekveld and colleagues (2011) speculated that this might be related to processing overload even in a relatively favorable S/N in those with hearing impairment. One interesting avenue for future research would be to combine ERP technology with these methodologies, a dual-task paradigm and/or pupil dilation, to further validate the sensitivity of these measures in reflecting processing load.

4.5 Strengths, Limitations and Future Directions

Most of the practical implications described in the last two sections will need to be tested by future studies to confirm the effect of AV speech or perceptual processing on daily functioning. One of the key issues for future research will be to design tasks that mimic daily activities to examine how well the effects found in this thesis generalize to practical settings. For example, one study may look at improvement in understanding and remembering conversations taking place over audio-video communication systems (e.g., Skype, Facetime, Videoconferencing) in comparison to regular phones. It is expected that older adults with normal hearing and cognition would perform better using the AV speech technology, and that even greater improvement would be expected in those with hearing or cognitive impairment.

The current research tested participants under optimal listening conditions. The fact that the AV speech benefit was still evident indicates the strength of this effect. However, in real life scenarios, we are often required to comprehend speech while other noise is happening in the background, whether coming from television, radio, traffic, or other speakers. It would be expected that in these more difficult listening conditions, an even greater AV speech benefit would be observed (e.g., Ross et al., 2007; Sumby & Pollack, 1954). A previous study from our laboratory supports this assumption by showing greater perceptual facilitation in noise for young adults (Frtusova, Amarsi, & Phillips, 2011) in comparison to our results obtained in a no-noise experiment (Frtusova et al., 2013). It would be interesting to examine how the background noise would affect the AV speech benefit in older adults, especially those suffering from cognitive or hearing impairment. Related to the limitation of testing in ideal listening conditions, the current research did not directly measure listening effort. Future studies could incorporate either subjective (e.g., participants ratings) or objective (e.g., pupil dilation) measures of effortful listening.

An important strength of the studies presented in this thesis is a combination of behavioural and electrophysiological methods. Temporal resolution of the ERP methodology and its ability to image different stages of information processing provides a unique opportunity to examine a direct relationship between perceptual and higher-order cognitive functioning. On the other hand, behavioural performance validates that the assumed cognitive function is taking place and that the effect of the experimental manipulation is strong enough to influence behaviour. However, ERP components can be affected by multiple generators and the methodology does not allow for the exact localization of the source generators. For example, the fact that observed effects were evident in the P1 and N1 components suggests that multisensory processing is happening as early as at the level of the primary and secondary auditory cortices (Liegeois-Chauvel et al., 1994; Pantev et al., 1995). However, it has been recognized that these components are affected by multiple source generators (Giard et al., 1994; Liegeois-Chauvel et al., 1994; Näätänen & Picton, 1987; Woods, 1995) and thus one has to make these intepretations with caution. This limitation can be somewhat reduced by replicating the findings by using magnetoencephalography (MEG). This would be especially informative for comparison of healthy older adults with clinical populations (e.g., cognitive or hearing impairment) to examine how speech modality affects different sources of brain activity and whether these influences differ across the groups.

It is also important to acknowledge for both studies presented in this thesis that although all participants were fluent in English, not all of them have learned English as their first language. Less stringent requirements were applied in these studies given that they focused on clinical populations that are difficult to recruit with too restrictive criteria. Nevertheless, it is important to consider how these characteristics could have affected the results. AV speech perception skills were found to develop early in life, even in pre-linguistic infants (Burnham & Dodd, 2004). Whether or not these skills generalize across different languages as they are acquired, and whether the age of language acquisition affects the quality of AV speech perception will need to be addressed by future studies. The fact that I observed the AV speech benefit even in studies with less strict language criteria, points to the robustness of this effect and generalizability of the results. However, the stimuli used in the current studies (i.e., digits) represent relatively simple language material that may be less dependent on second language proficiency than more complex language stimuli may have been (e.g., less common words, grammatically complex sentences).

In addition, the sample sizes of both studies were relatively small, which decreased statistical power to detect between-group differences as well as interaction effects between different variables if they were to exist. This is especially relevant when studying clinical populations, such as patients with MCI, who tend to represent very heterogeneous groups. For example, participants within the same MCI group may have different levels of AD pathology or may suffer from either single-domain or multi-domain cognitive deficits, which may have an influence on the AV benefit. Based on the integrated perceptual-cognitive model it would be hypothesized that those with multiple-domain cognitive deficits should benefit from the AV condition more than single domain MCIs because they have more restricted processing resources. Furthermore, participants in both studies were quite variable in terms of their sensory functioning. For this reason, I have performed correlational analyses between the levels of the AV benefit and visual or hearing abilities (as discussed in more detail in the following paragraph). However, these analyses were again limited by small sample sizes. Larger-scale studies could further qualify these effects by stratifying the samples (e.g., to mild, moderate and severe loss) and comparing the AV benefit across the subgroups.

One important avenue for future research would be to examine the relationship between sensory/perceptual and cognitive functions within a more comprehensive model. For example, Study 2 showed that the benefit from AV speech is affected by both hearing acuity and visual contrast sensitivity. More specifically, those with higher hearing acuity and contrast sensitivity seemed to show greater perceptual facilitation (i.e., reduction in P1-N1 amplitude and N1 latency) than those with lower sensory functions. However, paradoxically, Study 1 showed that participants with clinically significant hearing impairment benefited from AV speech more than those with normal hearing. Furthermore, among individuals with hearing impairment those with poorer contrast sensitivity showed greater reduction of P1-N1 amplitude in the AV condition compared to the A-only condition than those with higher contrast sensitivity.

To further examine the effect of hearing and vision across different levels of cognitive function, a large-scale study that would be able to stratify participants based on these functions would be needed. That is, participants with varying levels of vision, hearing, and cognitive ability would be recruited and divided into different groups and subgroups. For example, NECs would be subdivided into those with normal hearing/normal vision, normal hearing/poor vision, impaired hearing/normal vision and impaired hearing/impaired vision. The same grouping would apply for MCI and AD patients. By stratifying the sample, the influence of vision, hearing, and cognitive status on the AV benefit could be examined in an experimental paradigm.

Based on previous research (Winneke & Phillips, 2011) and the results of Study 2, those with better visual functioning would be expected to benefit from the AV speech more than those with poor visual functioning. The same prediction would also follow from the integrated perceptual-cognitive model (Schneider & Pichora-Fuller, 2000) in that visual impairment would be expected to create more demands on perceptual processing and thus interfere to some extent with the AV benefit on WM. Furthermore, those with hearing impairment would be expected to benefit more than those with normal hearing due to the fact that visual speech cues seem to be particularly beneficial when auditory processing is demanding (as indicated in Study 1). Lastly, it would be expected that those with cognitive difficulties would benefit more in terms of WM that those with normal cognition (as indicated in Study 2) due to the more restricted processing resources caused by neurodegenerative disorder. Overall, the largest AV benefit on WM would be expected in AD patients with relatively good vision but poor hearing. This prediction is based on the assumption that these individuals have especially restricted processing resources and thus demanding perceptual processing caused by hearing impairment would be particularly detrimental to their WM performance. Adequate visual functioning would provide them an opportunity to benefit from visual speech cues. However, it is important to note that even impoverished visual information was found to be associated with an AV benefit (e.g., Munhall, Kroos, Jozan, & Vatikiotis-Bateson, 2004) . The proposed design could clarify the exact nature of the relationship between visual functioning and the AV benefit.

In addition to expanding and stratifying the study sample, future research could examine the generalizability of the AV benefit across different cognitive tasks. For example, difficulties with episodic learning and memory are considered the hallmark of MCI patients who are at risk of converting to AD (Albert et al., 2011) and patients with AD also experience difficulty with semantic memory (e.g., Giffard et al., 2001; Hodges & Patterson, 1995; Hodges, Salmon, & Butters, 1992). Electrophysiological studies could examine how perceptual facilitation through AV speech affects performance on episodic and semantic memory tasks, while behavioural studies could examine how different speech modalities (A-only and AV) affect cognitive performance during neuropsychological testing.

Lastly, an interesting opportunity for future research would be to examine the effect of AD pathology on the AV benefit. One possibility to address this issue would be to examine the level of amyloid deposition in the brain regions important for AV speech integration (e.g., auditory cortex, visual cortex, and STS) by using a positron emission tomography (PET) scan with a ligand that binds to amyloid in the brain, such as the Pittsburgh Compound-B (PiB; Wolk & Klunk, 2009). This measure was found to distinguish AD patients from MCI patients (Forsberg et al., 2008; Y. Li et al., 2008) and healthy controls (Klunk et al., 2004; Y. Li et al., 2008). One could examine how the levels of amyloid in the regions of interest affect the levels of the AV benefit. Alternative options for examining the effect of AD pathology on the AV speech benefit would be either measuring cortical thickness in the regions of interest or examining electroencephographic (EEG) coherence. This latter possibility is especially appealing as AD was proposed to represent a disconnection syndrome. EEG coherence allows quantifying the synchronization of activity in different brain regions (e.g., visual and auditory cortical areas) during the task and it was proposed to reflect functional connectedness (Guevara & Corsi-Cabrera, 1996). It would be interesting to examine whether there is a certain level of "asynchrony" during AV speech perception in patients with MCI and AD and how this relates to the AV perceptual benefit as well as the AV benefit on WM. In fact, this type of analysis could be conducted with the current paradigm and they represent the most immediate option for expanding the current research.

4.6 Conclusion

Overall, the research presented in this thesis indicates that older adults with restricted processing resources due to cognitive or hearing impairment benefit from AV speech information, both in terms of facilitation of processing resources and improvement of WM. The results are interpreted in the context of an integrated perceptual-cognitive system (Schneider & Pichora-Fuller, 2000) to suggest that AV speech facilitated perceptual processing, which led to more resources being available for the WM task. These findings have several important implications for helping to improve the quality of life for older adults and their families. However, in a more general sense the results also bear suggestions for improvement of performance in other settings, such as education and neuropsychological evaluations, and helping to avoid accidents during driving. Exploring the effects of AV speech perception on daily life activities would be a vital goal for future research and it would provide ecological validity to the current findings. Furthermore, we need to improve our understanding of factors that influence the AV speech benefit, such as interaction effects between vision, hearing, and cognitive impairment or the effect of AD pathology, so that the target populations for AV speech rehabilitation programs could be identified.

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