Examining the relationship between cognitive abilities and auditory-visual cross-modal activation

Amanda-Mei Fullerton

Department of Linguistics

Faculty of Human Sciences

Macquarie University, Sydney, Australia

This thesis is submitted in fulfilment of the requirements for the degree of Master of Research (Linguistics)

October 2016

Table of contents

Abstract

Considerable variability exists in speech perception outcomes after cochlear implantation, particularly in adults with post-lingual hearing loss. Electroencephalography (EEG) studies have demonstrated that the extent of cross-modal plasticity (i.e. competitive take-over of the auditory cortex by the visual cortex), measured by the activity of the visual-evoked potential (VEP) activity in the cortical regions, is significantly correlated with performance measures of speech perception-in-noise. This trend is observed in adults with a cochlear implant (CI) and therefore, it is of interest to understand how cross-modal plasticity changes with time in adults with severe-profound hearing loss once audition is restored with a CI.

As speech perception in noise is influenced by cognitive and linguistic processes, and hearing loss is strongly associated with ageing and cognition, we need to better understand the role of each in influencing cross-modal activation and plasticity. Therefore, the aim of this pilot study was to assess the relationship between cognition, speech perception (using words and sentences in background noise) and activation of cortical areas, specifically the occipital (visual) and temporal (auditory) cortices, in response to visual stimuli, in older adults with normal hearing. It compared speech perception outcomes and a novel behavioural measure of cognition, Cogstate, (which does not rely on audition) with the P1, N1 and P2 components of the VEP responses, measured using EEG and MEG simultaneously. This study provides normative data for a future longitudinal study, which aims to investigate brain changes following cochlear implantation in older adults with post-lingual hearing loss. Results showed that while no correlations were found between speech and cognitive measures, significant correlations and relationship trends were observed between VEP responses (in both occipital and temporal regions) and speech perception and cognitive measures. While expansion of this cohort is needed to verify these trends, the results support the need to consider cognition as a potential influencing factor in broader topographical cortical representations in adults with hearing loss and/ or a cochlear implant.

Declaration

I declare that this thesis has not been submitted for a higher degree to any other university or institution. The sources of information used and the extent to which the work of others has been utilised have been indicated in this thesis in a manner conventionally approved within its relevant field of research.

The research in this thesis has been approved by the Macquarie University Faculty of Human Sciences Research Ethics Committee (reference: 5201600151).

Amanda-Mei Fullerton

10/10/16

Acknowledgement

I would firstly like to express my sincerest thanks and gratitude to my principal supervisor, Associate Professor Catherine McMahon, for her continued guidance and support throughout the year. Thank you Catherine for your encouragement and insightful advice, and for the opportunity to pursue this research with you and your team. I also acknowledge and thank my co-supervisors, Associate Professor Blake Johnson and Professor Greg Savage, for their knowledge and input in the design of this study.

I also wish to thank Dr Ronny Ibrahim for his direction, knowledge and extensive help with processing and interpretation of my data and to Mr David Meng for his helpful advice regarding MEG testing and assistance in creating the visual paradigm for this study. In addition, I would like to thank Ms Elizabeth Magdas and Dr Stan Tarnavskii from the KIT-Macquarie MEG laboratory for their assistance during the testing process, and for acquainting me with the world of MEG and EEG.

Special thanks must also go to Mr Chi Yhun Lo and Ms Kelly Miles for their immense help, support and counsel throughout the year. I would also like to thank Dr Isabelle Boisvert and fellow members of the Macquarie University Audiology Hearing and Research (AHRG) group, as well as other colleagues and friends, too numerous to list here, who have assisted me this year. Thank you for your support, friendship and for being so generous with your time.

Thank you also to the staff of the Macquarie University Speech and Hearing Clinic and to the clinic staff at Neurosensory, St. Vincent's Hospital in Darlinghurst, for their support of this study during the recruitment phase. I also acknowledge the financial support of this study, provided by both Cochlear Ltd. and the HEARing CRC. Importantly, I would also like to thank those who volunteered to be a part of this study – your participation has been vastly appreciated!

And last, but not least, thank you to my family for their unconditional love and support.

Acronyms and abbreviations

BKB	Bamford-Kowal-Bench
CI	cochlear implant
CNC	consonant-nucleus-consonant
EEG	electroencephalography
EOG	electrooculogram
4F-PTA	four frequency pure tone average
GMLT	‘Groton Maze Learning Task’ (a Cogstate subtest)
ICA	independent component analysis
MEG	magnetoencephalography
MSR	magnetically-shielded room
SD	standard deviation
SNR	signal-to-noise ratio
VEP	visual-evoked potential

Figures

Tables

1.0 Overview

1.1 Background

The cochlear implant (CI) is a remarkably successful neuroprosthetic device, with the ability to restore hearing to severely and profoundly deaf individuals through delivering direct electrical stimulation to the peripheral auditory neurons in the inner ear. In many cases, adults with a CI are able to use mobile telephones which rely on audition alone (i.e. no visual cues) and enjoy good speech understanding in quiet listening conditions. However, considerable variability exists in speech perception outcomes post cochlear implantation in adults with post-lingual hearing loss, after controlling for duration of deafness, which is the only significant predictor of speech perception outcomes in this population (Holden et al., 2013; Blamey et al., 1996).

It is not yet clear to what extent the ability of the brain to plastically adapt to the CI signal (a vocoded signal) is a limiting factor in obtaining good speech perception performance. Certainly, auditory deprivation is associated with degradation of the phonological map, whereby individuals who have had longer durations of deafness show poorer ability to match visually presented words which rhyme verbally but not visually (Lazard et al., 2010). Further, cross modal plasticity, competitive take-over of a 'deprived' sensory area of the brain by another (intact) sensory modality, has been suggested to limit speech perception outcomes post-cochlear implantation. Specifically, neuroimaging studies in adults with a CI show a correlation between auditory-visual cross-modal plasticity (whereby deprived auditory regions are recruited by the visual cortex in cases of severe to profound hearing loss, and even in milder forms of hearing loss) and speech perception outcomes (Chen, 2016; Kim et al., 2016; Campbell & Sharma, 2014; Buckley & Tobey, 2010; Doucet et a., 2006; (Giraud et al., 2001). In addition, PET studies have shown that the activation pattern of the brain for adults with CI during speech tasks is significantly different to normally-hearing adults, even when speech perception scores are similar, suggesting that more complex or effortful processing is required to make sense of the vocoded speech signal (Giraud et al., 2000). Understanding how brain plasticity might support or inhibit speech perception outcomes might enable more targeted interventions to be developed to optimize auditory rehabilitation or better predict outcomes, after cochlear implantation. Importantly, however, as speech perception in noise is influenced by cognitive and linguistic processes (Wayne & Johnsrude, 2015; A Wingfield & Tun, 2007), and age is strong associated with hearing loss and cognition (Lin et al., 2014), a better understanding of the role of each (i.e. hearing loss and cognition) in influencing cross-modal plasticity in older adults is needed.

Finally, magnetoencephalography and electroencephalography are complementary physiological techniques known for their high temporal resolution, which is advantageous in consideration of the complexity of the multiple synaptic transmissions occurring with brain activity (Proudfoot et al., 2014). Thus far, the investigation of outcomes in CI recipients using functional neuroimaging techniques has been limited due to incompatibilities with the implant itself. However, a novel technique using magnetoencephalography (MEG), currently under validation, has been designed to enable measurements of auditory cortical function, with a view to significantly reducing interference from electromagnetic artefacts of the implant (Johnson et al., 2013). Therefore, this pilot study intends to utilise both MEG and EEG concurrently to assess cortical visual-evoked potentials (VEPs) in a normally hearing older adult ‘control’ population, with a view to employing these methods in a follow-up study with older adult cochlear implant recipients, to further investigate how cross-modal plasticity might adaptively change over time in this population.

However, as much of the existing literature examining cross-modal plasticity to date has focussed on EEG, only EEG data will be discussed in this thesis and compared to previous studies. The combined assessment of MEG with EEG will enable us to compare this normative MEG data with future data from the prototype MEG system at Macquarie University, which will be analysed and discussed in a follow-up study.

1.2 Objectives

- To investigate cortical visually-evoked potentials (VEPs), measured using concurrent MEG and EEG techniques, in normally-hearing older adults using a validated visual paradigm, as utilised by Doucet et al. (2006). This will provide normative data for a future longitudinal study, which aims to investigate cross-modal plasticity following cochlear implantation in older adults with post-lingual hearing loss, using the same paradigm.
- To explore whether a relationship exists between speech perception ability in noise and performance on a novel behavioural measure of cognition (Cogstate Ltd.), which does not rely on auditory cues.
- To explore whether a relationship exists between cognitive factors, specifically processing speed, attention and working memory (measured using Cogstate), and/or speech perception in noise measures, and cortical VEP activation (i.e. occipital vs. temporal) in older adults.

1.3 Outline

This thesis comprises of five chapters:

Chapter 1 provides an overview of the background and research objectives for the study.

Chapter 2 gives a broad overview of cross-modal plasticity and its relevance in auditory rehabilitation with cochlear implants. It will also review the literature on various visual stimuli used to elicit cortical VEPs, as well as electrophysiological techniques used to examine these cortical responses and considerations for future CI studies, for which the present study is intended as a pilot. Finally, this section will also discuss the role of cognition and hearing loss and how this may relate to speech perception in an older population (relevant to this study cohort), as well as assessment of cognitive domains. Lastly, this section will summarise the rationale of the study in light of the reviewed literature.

Chapter 3 will detail the participants, test stimuli, procedures and statistical methods used in the study.

Chapter 4 presents the results of the current study.

Chapter 5 provides general discussion of the results of this study in light of other studies in the field, limitations of the present study, future directions and conclusions.

2.0 Introduction

2.1 Cross-modal plasticity

Cross-modal plasticity is a form of cortical neuroplasticity that demonstrates the remarkable capacity of the human cortex to adapt to change (Sharma & Glick, 2016). It involves the compensatory reorganization of neural structures in response to a reduction or deprivation of input to a sensory modality, whereby cortical areas of the affected modality become susceptible to recruitment from remaining functional sensory modalities (Sharma & Glick, 2016; Finney et al., 2003). This recruitment can lead to functional enhancement in the residual sensory systems – a phenomenon that has been studied extensively in both animals (see Sur, Angelucci, & Sharma, 1999, for review), and in human studies involving blind and deaf individuals (Kim et al., 2016). For example, a notable study in congenitally deafened cats demonstrated an example of visual-auditory cross-modal plasticity, whereby the deafened cats showed superior visual abilities in comparison to normally-hearing cats. In particular, the study showed that motion detection and peripheral visual localization were enhanced compared to the normal hearing controls (Lomber et al., 2010).

Several human studies have found evidence of cross-modal plasticity in cases of auditory deprivation resulting from hearing loss, resulting in recruitment of the auditory cortex for visual or somatosensory processing (Chen et al., 2016; Kim et al., 2016; Stropahl et al., 2016; Campbell & Sharma, 2014; Buckley & Tobey, 2010; Giraud & Lee, 2007; Doucet et al., 2006; Finney et al., 2003; Giraud et al., 2001). Specifically, convincing evidence from electrophysiological, behavioural and neuroimaging studies in humans has demonstrated compensatory cross-modal expansion and enhanced capabilities in visual function in deaf individuals (Sandmann et al., 2012; Doucet et al., 2006; Lambertz et al., 2005) and also enhanced tactile sensitivity (Sandmann et al., 2012; Levanen & Hamdorf, 2001). Interestingly, findings from a recent study by Campbell and Sharma (2014) using EEG have suggested that cross-modal recruitment by the visual cortex can occur in individuals with mild-moderate, age-related hearing loss.

In addition, while the recruitment of regions of the auditory cortex for visual processing has been well-documented in adults with both pre-lingual and post-lingual deafness, there has also been particular interest in investigating cross-modal plasticity in adults with profound hearing loss, who are recipients of cochlear implants (CI) (Campbell & Sharma, 2014; Kim et al., 2016; Sandmann et al., 2012; Buckley & Tobey, 2010; (Finney et al., 2003). While cortical reorganisation in deaf individuals may provide beneficial compensatory effects during the period of deafness, it has been suggested that this could have detrimental consequences for the process of adaptation to the unfamiliar cochlear implant signal, post-implantation (Sandmann et al., 2012; Bavelier et al. , 2006).

2.2 Cochlear implants, cross-modal plasticity and functional outcomes

The CI has enabled the restoration of hearing and oral communication in individuals with severe to profound hearing loss through direct stimulation of the auditory nerve (Fallon et al., 2008; Giraud et al., 2000; Lazard et al., 2012). However, despite evidence of successful outcomes, CI recipients display a wide spectrum of speech perception abilities, and a range of factors have been identified which could influence this performance (Blamey et al., 1996; Holden et al., 2013). It has been proposed that duration of auditory deprivation largely accounts for CI outcomes in congenitally deaf children (O'Donoghue et al., 2000; Sarant et al., 2001) , however this appears to be more ambiguous when predicting future performance with speech understanding in post-lingually deafened adults (Blamey et al., 1996; Green et al., 2007). The role of cross-modal plasticity in auditory rehabilitation with CI and how this may relate to speech perception outcomes is yet to be clearly elucidated and may also be a contributor to this observed variability in functional outcomes.

A significant study by Giraud et al. (2000) found differences in cerebral activation between normal control subjects and post-lingually deafened rehabilitated CI recipients measured using PET under various speech conditions of different linguistic complexity. They found that different brain activation patterns were elicited despite almost similar speech recognition performance in recipients and control subjects. Specifically, they found that more brain regions were required to process speech for the CI group, suggesting that speech comprehension can be assisted by recruitment of additional cortical areas. Giraud and colleagues (2000) proposed that the CI group showed activation of cortical regions associated with attention, suggesting that this probably reflects specific auditory attentional strategies used to compensate for degraded speech signals and monaural stimulation. They also noted increased activation in areas of the brain associated with episodic verbal retrieval and memory-related imagery, which the authors hypothesised may reflect an enhanced sensitivity in the visual modality expressed during deafness, as a result of cross-modal compensation (Giraud et al., 2000). In a follow-up study, Giraud and colleagues (2001) examined cross-modal plasticity in four functional neuroimaging experiments and found early recruitment of the visual cortex when CI users listened to sounds with their eyes closed. They observed that this recruitment occurred more in CI users than in control subjects and that this activation increased the longer they used the implant, which they hypothesized underpinned their language recovery post-implantation. Ultimately, Giraud and colleagues identified the need for further study of the longitudinal development of these patterns, post-CI activation.

Doucet et al. (2006) used EEG to investigate cross-modal reorganisation in relation to speech perception abilities in CI patients with profound bilateral hearing loss. They found that the group of CI users with limited speech perception abilities showed a more profound cross-modal reorganisation in response to visual stimuli, in comparison to a group of better CI performers, which showed enhanced brain activity within the preserved visual cortex. They proposed that the latter group was able to make better use of visual cues to compensate for the impoverished auditory signal of the CI, whereas the former group required recruitment of additional cortical areas to carry out visual tasks (Doucet et al., 2006). These findings were supported by another EEG study by Buckley and Tobey (2010). They found that poor speech perception outcomes in CI recipients were related to increased amplitudes of visual-evoked brain activity over temporal and anterior scalp regions, however noted this primarily in pre-lingually deafened CI users. Lazard et al. (2012) also discussed the creation of supplementary compensation in the development of visual responses within the auditory cortex in cases of low performance with CI due to insufficient auditory cues. Hence, this collective evidence suggests that despite the restoration of auditory input provided by a CI, poorly performing CI users may continue to recruit additional regions in the auditory cortex for processing visual information. Accordingly, Champoux et al. (2009) proposed that extensive cross-modal reorganisation of the auditory cortex may become detrimental to speech understanding, as it was observed that poorly-performing implanted subjects showed deterioration in word recognition scores in the presence of visual stimuli that appeared to compete with auditory recognition tasks. This contrasted with CI subjects with good performance and normal hearing control subjects, who were not affected by visual distractors (Champoux et al., 2009).

The benefits of audio-visual speech have been recognised in prior studies (see review by Peelle & Sommers, 2015), with evidence to suggest that visual information complements auditory information through providing cues to both the timing of the incoming acoustic signal and its content. This effective multisensory integration of audio-visual speech cues has been found to improve recognition accuracy, particularly for speech in noise, and may reduce the cognitive demands placed on listeners by increasing the precision by which predictions can be made. However, multiple stages of integration are involved in this process and are supported by distinct neuroanatomical mechanisms (Peelle & Sommers, 2015). It is not yet fully understood how the phenomenon of cross-modal reorganisation may interact with the process of audio-visual integration, particularly in new cochlear implant users who are required to adapt to a degraded speech signal. Perhaps it is more effective audio-visual integration that may explain cases of cross-modal adaptations or 'plasticity' in hearing-impaired individuals following CI implantation, which have led to successful speech perception outcomes. Clearly, more studies are needed to elucidate this potential interaction.

2.3 Auditory-visual cross modal plasticity in CI users

With respect to purely visual processing in CI recipients, several studies have examined cortical VEPs in pre-lingually deaf (Buckley & Tobey, 2010) and post-lingually deaf CI recipients (Kim et al., 2016; Doucet et al., 2006), and have observed increased VEP amplitudes over the auditory (temporal) cortex in response to visual stimuli. Findings from Finney and colleagues (2001) suggest that increased cortical activation in response to visual motion stimuli in deaf participants is mediated by a region of the right auditory cortex. Furthermore, these increased VEP amplitudes appear to be negatively correlated with speech perception abilities in quiet and noise, which further suggests that cross-modal reorganisation can also occur in cases of adult onset hearing loss (Sharma & Glick, 2016). In addition, findings from Buckley and Tobey (2010) suggest that auditory deprivation alone may be sufficient to induce cross-modal reorganisation, rather than the duration of auditory deprivation prior to CI, having found no significant correlation between N1 VEP amplitude in either pre-lingually or post-lingually deafened adults and duration of deafness (Sharma & Glick, 2016). A recent study by Sandmann et al. (2012) also examined cortical VEPs in a group of CI recipients with adult onset hearing loss (some whose onset of deafness was as recent as a year prior to CI), and in a group of normally hearing adults. They observed significant correlations in the CI group between speech perception and the extent of activation in the right auditory cortex, as well as increased activation in the auditory cortex compared to the normal hearing group, which further supports this observed trend.

Further findings from studies by Kim et al. (2016) and Doucet et al. (2006) have found that some groups of CI recipients show more extensive cross-modal reorganisation than others. Recently, Kim et al. (2016) investigated two groups of post-lingually deafened adult CI recipients – one with poor phonetically-balanced monosyllabic word scores (<40%) and the other with good word scores (>60%). They observed that in comparison to the good CI performers, the poor CI performers showed larger VEP amplitudes to checkerboard pattern reversals in the right temporal cortex. Furthermore, cross-modal plasticity was evident in the P1 VEP amplitude over the right temporal cortex which was significantly negatively correlated with speech perception scores, whereas the P1 VEP amplitude over the occipital cortex showed a significant positive correlation with speech perception scores (Kim et al., 2016). Similarly, Doucet et al. (2006) showed that in both pre-lingually and post-lingually deafened CI adults with good speech perception abilities, cortical activation patterns were restricted to the visual cortex in response to visual motion stimuli, whereas CI recipients that showed poorer speech perception outcomes demonstrated more extensive cortical activity which spread in an anterior direction into the temporal cortices.

In summary, these studies have demonstrated decreased activity over the temporal cortex, viewed as evidence of cross-modal reorganisation, and increased activity over the occipital cortex, evidence of 'intra-modal' plasticity, in successful CI users (Kim et al., 2016; Sharma & Glick, 2016). Given these findings, a greater understanding of this phenomenon, particularly in regards to longitudinal cortical changes over time post-CI, could be of significant clinical value – with the potential to benefit CI rehabilitation through enabling better prediction and/or optimisation of speech perception outcomes post-implantation.

2.4 Eliciting the cortical visual-evoked response

As mentioned, several studies have investigated visual processing in CI recipients to evaluate the presence or extent of cross-modal plasticity, however there is variability among the studies in terms of the specific visual stimuli used to assess this. Several studies have focused on motion stimuli (Buckley & Tobey, 2010; Armstrong et al., 2002; Finney et al., 2001; Bavelier, 2001); some have employed checkerboard patterns (e.g. Sandmann et al., 2012) and even a video sequence of a human face utterly an incongruent word (visual-auditory stimuli) (Champoux et al., 2009).

However, the present study recreated a validated paradigm used by Doucet et al. (2006), which utilised concentric stimuli that undergo radial transformations (see Figure 1 of section 3.2.1). These stimuli were also utilised in a later study by Campbell and Sharma (2014) (also mentioned in section 2.1), which investigated cortical VEPs in adults with mild to moderate hearing loss and a group of normal hearers, and found a significant difference in VEP amplitudes and latencies between the two groups. Doucet et al. (2006) proposed that these stimuli are ideal for measuring visual reorganisation following a period of auditory deprivation, because they activate the visual ventral stream up to at least the fusiform (occipito-temporal) gyrus, which chiefly includes structures involved in high-level vision and also complex visual processing, such as processing of faces (Wilkinson et al., 2000); they also active the dorsal stream due to the 'transformational' pattern, and they are relatively simple to recreate. Furthermore, they are completely neutral, in that they avoid engagement of emotional responses or familiarity effect, in comparison to the use of faces or other similar stimuli (Doucet et al., 2006).

2.5 Electrophysiological techniques for examining ERPs and considerations for CI studies

In recent years, recruitment of the auditory cortex for visual-motion processing has been examined in deaf adults and adult CI users using various techniques, such as electroencephalography (EEG) (Buckley & Tobey, 2010; Doucet et al., 2006) , functional near-infrared spectroscopy (fNIRS) (Chen, 2016; Dewey & Hartley, 2015); and functional magnetic resonance imaging (fMRI) (Shiell et al., 2016). However, the investigation of outcomes in CI recipients using functional neuroimaging techniques has been limited due to incompatibilities with the implant itself. To address this issue, a novel technique using magnetoencephalography (MEG), currently under validation, has been designed to enable routine measurements of auditory cortical function by measuring this function in the hemisphere contralateral to the CI, thus reducing interference from electromagnetic artefacts of the implant (Johnson et al., 2013). Therefore, this pilot study intends to utilise both MEG and EEG concurrently to assess cortical VEPs in a normally hearing 'control' population, with a view to employing these methods in future follow-up studies involving cochlear implant recipients, in the investigation of cross-modal plasticity.

While functional MRI and PET imaging modalities offer good spatial resolution and enable rapid quantification of structure at a given time-point, MEG and EEG provide excellent temporal resolution (Darvas et al., 2004; Hämäläinen et al., 1993). This is of particular importance considering the nature of multiple synaptic transmissions and physical distance covered by brain activity (Proudfoot et al., 2014).

Furthermore, both techniques also have advantages of being non-invasive, safe and comfortable for the subject (Proudfoot, 2014), which makes them ideal for examining brain activity in clinical populations.

The primary source of both MEG and EEG signals is believed to be in the apical dendrites of pyramidal cells in the cerebral cortex, however both techniques have their own unique differences. While EEG measures the potential differences over the scalp resulting from currents produced by electrical brain activity, MEG measures the magnetic field changes induced by intracellular current flow (Darvas et al., 2004). EEG measurement involves a set of scalp electrodes coupled to high-impedance amplifiers and a digital data acquisition system, whereas MEG requires the use of superconductive, high sensitive magnometers, housed in a magnetically shielded room. A caveat to EEG measurement is that it is highly sensitive to the conductivity of the skull, brain and extracranial tissue, given that the electrical signals being produced in head are required to pass through these complex mediums to be measured. Thus, interpretation of EEG signals requires precise knowledge of the conductivity and thicknesses of different mediums, in order to localize regions of neural activation. Unlike EEG, as MEG measures the magnetic field outside the head produced by current flow inside the brain, the issue of conductivity does not apply, therefore allowing a comparatively higher spatial resolution (Darvas et al., 2004). Another consideration is that in comparison to EEG, MEG is more subject to cortical structure (Hämäläinen et al., 1993), the surface of which is densely folded and can therefore form different orientations to the primary currents. While MEG is sensitive to the tangentially oriented primary currents (relative to the spherical model of the head), which arise in the sulci, it is insensitive to the radially oriented primary currents originating in the gyri. Consequently, MEG is thought to be relatively insensitive to signals from deep brain structures. However, EEG has the ability to detect currents induced by both radial and tangential primary currents (Nunez & Srinivasan, 2009). Therefore, as a result of their combined advantages, MEG and EEG are becoming more commonly viewed as complementary rather than competing techniques, and most MEG protocols routinely include concurrent acquisition of multichannel EEG data, as utilised in the present study (Darvas et al., 2004)

2.6 Cognition, speech comprehension and hearing loss in an older population

In addition to cross-modal plasticity, several studies have also speculated about the effect of cognitive factors on CI outcomes (Holden et al., 2013; Friedland et al., 2010; Heydebrand et al. , 2007; Collison et al., 2004). Past studies have highlighted the role of cognitive abilities such as knowledge and working memory in supporting speech comprehension, particularly in cases where the signal is degraded due to background noise, unfamiliar talker characteristics, e.g. accents, or semantic ambiguity (Wayne & Johnsrude, 2015; Heald & Nusbaum, 2014; Wingfield & Tun, 2007). Similarly, the phenomenon of cognitive ageing has long been observed, however still remains insufficiently understood (Salthouse, 2010). While there are some cognitive functions that appear to be maintained with age, such as semantic memory, several studies have shown that older adults demonstrate increased difficulty with certain higher level 'executive' functions. These functions include difficulties with working memory skills, attention and task switching. Other age-related differences that have been observed are difficulties with 'episodic memory', such as a reduced ability to retrieve and learn both verbal and non-verbal material (Grady, 2012). Furthermore, past studies have shown that older adults demonstrate slower processing speed on average and are more prone to distractions when completing cognitive tasks (Salthouse, 1996; Healey et al., 2008). A significant challenge has been to understand which specific brain mechanisms might underlie or explain better or worse performance in older adults (Grady, 2012).

Many studies have therefore employed structural and function neuroimaging techniques to address this challenge, and in recent years, various functional MRI studies have provided evidence of age differences in task-related brain activity (Grady, 2012; Spreng et al., 2010; Eyler et al., 2011). However, interpretation of these differences has been difficult due to variability in performance, i.e. sometimes brain activity is reduced in older adults relative to younger adults and vice versa (Grady, 2012). In general, decreased levels of brain activity have been assumed to reflect cognitive deficits in older adults, whereas increased brain activity has been interpreted as compensatory (Grady et al., 1995; Grady et al., 1994). Other mechanisms have also been proposed to explain increases in brain activity, including dedifferentiation (reduction in selectivity of responses) or a lack of efficiency in the use of neural resources. For example, a study by Peelle et al. (2010) investigated the cortical network underlying speech comprehension of syntactically complex sentences in healthy older adults using fMRI. Their findings showed that while both young and older adults activated components of a core sentence-processing network during sentence comprehension, the older adults showed decreased activation of specialised processing regions and also a limited ability to coordinate activity between these regions. Peelle and colleagues (2010) therefore concluded that these factors contribute to the difficulties that older adults experience with sentence comprehension under difficult listening conditions. Furthermore, Peelle & Wingfield, (2016) highlight that, despite widespread declines in hearing ability in older adulthood, speech comprehension in older adults is generally good. They propose that in order to maintain high levels of successful speech comprehension, listeners with hearing loss recruit systems outside the typical speech-processing network to compensate for a poor auditory signal. This therefore results in additional cognitive effort being required when listening to a degraded speech signal, which can impact other important operations, such as remembering the information that has been heard, e.g. working memory. Hence, in light of such evidence, we are particularly interested in the influence of cognition on cortical activity in older adults.

2.6.1 Working memory, processing speed and attention

The association between adult ageing with changes in cognitive domains such as working memory and processing speed have great implications for speech comprehension, particularly in challenging listening environments, and it has been suggested that these age-related changes are due to a complex combination of both perceptual and cognitive influences (Wingfield et al., 2005).

Working memory refers to an individual's ability to store and process information simultaneously (Ronnberg et al., 2013). Hence, it is thought to be involved in the allocation of resources in complex tasks, evidenced by correlations observed between performance on language understanding tasks and verbal working memory capacity (measured using reading-span tasks), as well as performance on reasoning tasks (Lunner, 2003; Just & Carpenter, 1992; Carpenter, Just, & Shell, 1990). Working memory has also been identified as a key factor in speech understanding, as proposed in the 'Ease of Language Understanding' (ELU) model by Ronnberg and colleagues (2013). Therefore, it has been proposed that age-related deficits in working memory may exacerbate the communication difficulties experienced by older adults in complex listening environments. This is even more relevant to individuals with a hearing loss, in that there is additional load on working memory, whereby context is required to interpret degraded auditory information to derive its meaning (Ronnberg et al., 2013) and this is certainly also relevant in cochlear implantation, where recipients are exposed to a vocoded signal.

Another influential cognitive domain on speech comprehension is processing speed, specifically, verbal information-processing speed, which refers to how efficiently lexical information can be accessed from long-term memory (Lunner, 2003). Processing speed is known to correlate with skills such as reading comprehension (Baddeley et al., 1985), general verbal ability and sentence-based speech reading (Lyxell & Rönnberg, 1992) and also with age (Salthouse, 2004; Lunner 2003). Salthouse (1996) hypothesised that increased age in adults is associated with a decrease in the speed with which task-processing can be performed, and that this 'slowing down' leads to impairments in cognitive functioning. He proposed that cognitive performance is compromised due to slower processing because relevant tasks cannot be successfully executed in time due to a delay in the products of earlier processing, which may no longer be available by the time the later processing is complete (Salthouse, 1996). This skill is certainly important for conversational speech, particularly in group situations or in background noise and certainly, for individuals with hearing loss, who do not receive auditory cues with clarity (Lunner, 2003).

Lastly, attention has also been identified as an important factor influencing speech comprehension, and also one that is susceptible to age related changes (Grady, 2012). It has been found that older adults may more susceptible to distractions than younger adults, and that they may experience difficulties in dividing their attention between two simultaneous tasks (McDowd & Shaw, 2000). This is particularly relevant in situations where there is more than one talker, in that the listener is required to monitor several aspects: the overall dialogue being spoken, as well as the content of the dialogue and timing for each person involved. In addition, further perceptual demands may be placed on the listener as a result of the location and spatial arrangement of the speakers. Therefore, it has been proposed that older adults could be prone to difficulties imposed by the extra cognitive/ attentional demands of following group conversation and the added perceptual demands of integrating auditory information from spatially separate locations (Pichora-Fuller & Singh, 2006). This is also of particular interest in older adult CI users, who may experience even further difficulties with attentional demands, in having to listen through a vocoded signal.

2.6.2 Hearing loss and cognitive decline

There has also been recent evidence to suggest a link between untreated hearing loss and increased risk for cognitive decline in older adults, however the exact relationship and potential causal mechanisms remain to be clearly understood (Contrera et al., 2016; Lin et al., 2014; Peelle et al., 2011; Lin et al., 2011). Proposed mechanistic pathways through which hearing impairment could contribute to poorer cognitive function include the effect of hearing impairment on brain structure, cognitive load and decreased social engagement (Lin et al., 2014). Studies by Rabbitt (1968) and Tun, McCoy and

Wingfield (2009) have demonstrated the effect of poor peripheral encoding of sound as a result of cochlear damage, whereby greater cognitive resources are necessary for auditory perceptual processing in conditions where there is a degraded auditory signal, which proves detrimental to other cognitive processes such as working memory. Lin et al. (2014) notes that for an individual with hearing loss, such a constant demand on cognitive load could affect an individual's performance in usual daily activities and cognitive tasks, which is among the criteria for the diagnosis of dementia. Pichora-Fuller and Macdonald (2009) also addressed the correlation between sensory and cognitive ageing, noting that difficulties experienced by older listeners in understanding spoken language in complex listening condition may be exacerbated as a result of declines in abilities such as working memory and attention. This is likely to worsen as the listening condition become more adverse, as such a task becomes more cognitively demanding for listeners of any age to process.

2.7 Assessment of cognitive domains

The use of various measurement tools to assess cognitive functions varies across studies and ranges from general cognitive screening tests to test batteries that selectively assess specific processes such as memory, language, processing speech, attention and other executive functions (Wayne & Johnsrude, 2015). Common screening tests include the Mini-Mental State Exam (MMSE) , the Modified Mini-Mental State Test (3MS) (Teng & Chui, 1987) and the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). However, it has been noted that the sole use of cognitive screening tools such as the aforementioned tests may not capture the full variability in a normally ageing (i.e. non 'clinical') population, as 'ceiling effects' may underestimate the true relationship between cognitive decline and hearing loss (Wayne & Johnsrude, 2015).

An additional challenge in adults with hearing loss is the difficulty in measuring cognition without requiring sufficient hearing ability, and vice versa. For example, several test items rely on good audition, therefore poor performance for adults with hearing loss might result from either poor cognitive performance, or increased effort needed to listen to what was said, reducing the ability to store items in working memory for later recall (Rabbitt, 1968); inability to hear the instructions or what was said (Dupuis et al., 2015; Wayne & Johnsrude, 2015), or a combination of the above.

In consideration of these factors, the present study used a visual-only computerized program for assessment of cognitive domains called 'Cogstate' (Cogstate Ltd, Melbourne, Australia), which has been suggested to be an appropriate tool for cognitive assessment in older individuals (see Lim et al., 2012; Fredrickson et al., 2010). The selected battery aims to assess psychomotor, attentional, working memory and visual learning ability, as well as executive function, which as discussed, may be susceptible to age-related declines and are thus relevant to our population of interest. For this study, the predominant advantage lies in the completely visual interface for administering tests, without reliance on auditory cues, and hence it is particularly appropriate for use in individuals with severe to profound hearing impairment and CI users, needed for a subsequent follow-up study.

2.8 Rationale and research questions for the current study

The current literature on cross-modal plasticity is fraught with differences in the selection of speech materials, categorisation of speech performance and differences in the visual stimuli used to evoke cortical VEPs. In addition, the term cross-modal plasticity has been used to refer to an assumed plastic change of the cortex. However, as these studies have been cross-sectional, it is unclear whether the cortical activation patterns represent a change or are associated with a measure of speech perception. In addition, evidence of cross-modal plasticity has been assumed to be captured by either an increase in the activation of the temporal region (e.g. Kim et al., 2016; Doucet et al., 2006) for an auditory stimulus or an increase in the activation of the occipital region (e.g. Campbell & Sharma, 2014). We are therefore interested in assessing whether reductions in cognitive ability are associated with reduced activation in the visual cortex (i.e. the occipital cortex) or increased activation in the auditory cortex (T7 / T8). Multiple studies have shown that speech perception (in noise) is significantly correlated with cognitive ability (see Lunner, 2003), and that age is highly correlated with cognitive ability (Salthouse, 2004). However, it is becoming clear that speech perception abilities in adults with CIs may be limited by cross-modal plasticity. Specifically, the extent of activation of the auditory cortex by a visual stimulus or the reduction of activation of the visual cortex is correlated with speech perception outcomes. Despite this, it is not clear whether cognitive ability (or declines in the case of older adults) is also associated with cross-modal plasticity, or a greater distribution of cortical activity.

While the association between cognition and VEPs (i.e. cortical activation to visual stimuli) has not yet been investigated, different brain activation patterns in older adults, compared with younger adults, during auditory processing of speech have been observed (Peelle et al., 2010). Specifically, decreased activations of specialised speech processing regions have been seen in older adults, who also showed recruitment of frontal areas outside the core speech processing network, which is thought to play a compensatory role (Peelle et al., 2010). Hence, it is of interest to examine whether a spread of activation is seen for visual processing in this population. Furthermore, as cognition is associated with speech processing, it is also of interest to understand how cognition may relate to these cortical activations. We are therefore interested in whether cognition influences cortical representations in response to visual stimuli in an older adult population, given that we intend to investigate potential cross-modal representations in an older adult population with CI. We hypothesise that ‘cross-modal’ activations will not occur within a normal hearing population.

This pilot study aims to answer the following key research question:

Does a relationship exist between cognitive ability and cortical activity in the occipital and temporal cortical regions, in response to a visual stimulus?

Sub-questions include:

1. Is there a relationship between specific components of the VEP (i.e. P1, N1 and P2 components) at occipital and/or temporal electrode sites, and cognitive abilities and/or speech perception in noise abilities in older adults?
2. Is there an association between speech perception abilities in noise (using word recognition and sentence recognition scores) and cognitive capacity measured visually (specifically processing speed, attention and working memory using Cogstate) in older adults?

3.0 Materials and Methods

3.1 Participants

13 adults (12 females, 1 male) aged 55-75 years (mean = 62 years) participated in this study, with demographic information summarised in Table 1. Air conduction thresholds were screened using an Affinity 2.0 audiometer (AC440; Interacoustics, Middelfart, Denmark). Twelve of the thirteen participants had clinically ‘normal’ hearing levels in at least the better ear, which was defined in this study as a four-frequency pure tone average (4F-PTA) at 0.5, 1, 2 and 4 kHz, of ≤ 25 dBHL. However, one participant presented with ‘mild’ hearing loss in at least the better ear, with a 4F-PTA of ≤40 dBHL. Given the limited number of participants that could be recruited for this study within a short time-frame, we chose to include this participant in the analysis. Participants were not receiving clinical intervention at the time of involvement in the study and the participant with a mild hearing loss had already received a diagnosis from recent consultation with a clinical audiologist.

Table 1. Subject Characteristics.

Participant	Age (years)	Gender	4F-PTA in better ear
1	58	F	8.75
2	59	F	1.25
3	65	F	7.5
4	61	F	7.5
5	66	F	21.25
6	67	F	10
7	56	F	3.75
8	63	F	27.5*
9	67	F	21.25
10	66	M	22.5
11	58	F	8.75
12	62	F	16.25
13	59	F	23.75

*Mild hearing loss

Otoscopic examination was performed prior to testing, to identify potential contraindications to audiometric testing. All participants showed normal middle ear pressure and compliance, as measured with standard 226 Hz tympanometry, using a Titan middle ear analyser (Interacoustics, Middelfart, Denmark). None of the participants showed evidence of significant cognitive impairment, as measured by a range of computerized cognitive tests (Cogstate Ltd, Melbourne, Australia), where impairment was categorised using Z scores that were compared with aggregated age group norms (see section 3.1.4.).

All participants reported good general health at the time of testing and had normal or corrected-to-normal vision. The recruitment, information consent process and test procedures were approved by the Human Research Ethics Committee (Medical Sciences) of Macquarie University (Reference number: 5201600151).

3.2 Stimuli

3.2.1 Visual stimuli

The visual stimuli consisted of a high contrast sinusoidal concentric grating which alternated with a similarly radially modulated star-shaped grating (see Figure 1) for a duration of 500 ms each, adapted with written permission from Doucet et al. (2006). The circle and star stimuli were presented 150 times, with the intention of inducing the percept of shape transformation, which is known to active the ventral visual pathway in humans (Doucet et al, 2006). The displays were generated using Presentation software (Neurobehavioral Systems Inc.). Participants were instructed to focus their gaze on the centre of the concentric circle/ star pattern for the duration of the testing. There were a total of 300 stimulus presentations, with an overall test duration of three minutes.

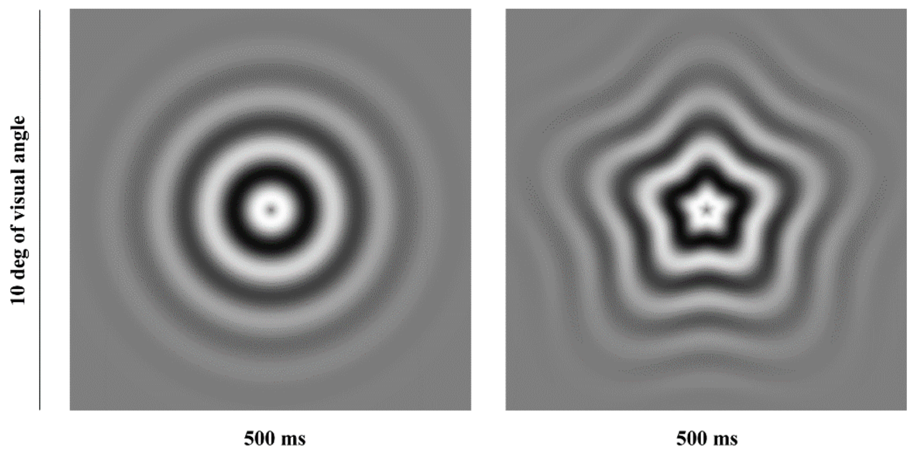


Figure 1. Visual stimuli, as used by Doucet et al. (2006), consisting of a high contrast sinusoidal concentric grating, alternating with a similar star-shaped grating, every 500 ms.

3.2.2 Speech perception stimuli

Speech perception was assessed using both sentence (high linguistic redundancy) and word materials (lower linguistic redundancy), presented with 4-talker babble noise at a signal-to-noise ratio (SNR) of + 0 dB. The noise used for both the sentence and word materials was speech shaped noise. Bamford-

Kowal-Bench (BKB) sentences adapted for Australian speakers (BKB-A) (Bench & Doyle, 1979) were used for the sentence condition, and the open-set, monosyllabic consonant-nucleus-consonant (CNC) word tests (Peterson & Lehiste, 1962) were used for the word condition. Both sentence and word tasks were presented through inserts at a comfortable listening level of 75 dB SPL. Participants were presented with two lists of 16 BKB sentences and one list of 50 CNC words, and were instructed to repeat the sentences and words as best they heard. Sentences were scored for percentage of key words correct and words were scored for percentage of whole words correct.

3.3 MEG and EEG data acquisition and processing

Brain activity was continuously recorded using a whole-head MEG system consisting of 160 axial gradiometers with a 50 mm baseline (Model PQ1160R-N2, KIT, Kanazawa, Japan), housed in a magnetically shielded room (MSR) (Fujihara Co. Ltd, Tokyo, Japan). EEG recordings were also made concurrently, using a 64-electrode MEG-compatible whole head EEG system (BrainProducts GmbH, Gilching, Germany). EEG was performed using Ag/AgCl sintered electrodes attached to an EasyCap®, over which the MEG marker coils were secured prior to concurrent MEG/EEG data acquisition. Vertical electrooculogram (EOG) and heartbeat signals were collected by placing an electrode at below the right eye and at the back. The EEG electrode positions, MEG marker coil positions and head shape were measured using a pen digitiser (Polhemus Fastrack, Cochester, VT). All measurements were performed with the participant lying in a supine position, looking up at the image projected on the ceiling. Both MEG and EEG recordings were collected using a sampling rate of 1000 Hz, with a high pass filter of 0.03 Hz and low pass filter of 200 Hz.

Offline EEG data were processed using Fieldtrip toolbox (Maris & Oostenveld, 2007) implemented in MATLAB (R2014 b). The data were re-referenced to the common average. Ocular artefact and heartbeat artefact correction to the EEG signals were performed using Independent Component analysis (ICA) which utilises a statistical blind source separation approach (Jung et al., 2000). The function of ICA was to identify components that presented maximal temporal statistical independency. This appeared, a priori, as a valid approach to separate neuronal EEG and ocular artefacts because these signals are generated by different uncorrelated processes (Grouiller et al., 2007).

After removal of ocular artefacts, the continuous EEG was band-pass filtered with a frequency cut-off between 0.5 to 35 Hz. Further, the resulting EEG was divided into trials/epochs of 600 ms with 100 ms baseline. Therefore, each epoch represented the evoked response to the morphing visual changes of the presented stimuli. The epochs were then baseline corrected between -100 ms to 0 ms. In order to remove noisy trials, trials which had absolute amplitude greater than 75µV between -100 ms up to 500 ms, were excluded from further analysis. The remaining trials were averaged to obtain the event related potentials (ERP) waveform. P1, N1 and P2 peaks were identified and marked through visual inspection prior to analysing cognitive and speech scores, to avoid potential bias. The P1 peak component was identified as the first positive peak occurring within the latency window of approximately 90-120 ms. The N1 component was identified as the second peak occurring in the negative direction, within a latency window of approximately 120-170 ms. Lastly, the P2 component was observed as the third peak occurring in the positive direction, with a latency window approximately within 220-270 ms. If a peak component was identified outside of the prescribed latency ranges, it was still marked as the closest corresponding peak depending on its order of appearance in the waveform. P1 amplitudes were defined from the onset of the wave to the P1 peak value; N1 amplitudes as the peak of the N1 component to the peak of the P2 component and the P2 amplitude as the peak of the P2 component to the offset value of the waveform. Wave latencies were marked at the highest amplitude of the peak.

3.4 Cognitive tests

Cognitive domains were assessed using a game-like computerized test battery, the Cogstate Brief Battery (Cogstate Ltd, Melbourne, Australia), which has been designed to test psychomotor, attentional, working memory and visual learning ability. An additional test, called the Groton Maze Learning Task (GMLT) (Cogstate Ltd, Melbourne, Australia) was also added to the battery to provide a measure of executive function and spatial memory. There were a total of five subtests in the battery that were administered with the same laptop and the same test conditions for each of the participants. The tester was present at all times during the test sessions and gave verbal instructions prior to each subtest. Participants were required to complete the whole test battery twice, to encompass both a practice and baseline measure.

Baseline measures (the second completion of battery following the initial practice) were used to calculate Z scores using the following formula, which accounted for age-related norms provided by Cogstate Ltd., in order to exclude any participants who showed evidence of cognitive impairment:

$$\text{Z\_DET\_current} = \left(\frac{(x_{\text{current}} - \overline{X})}{SD}\right) * \text{Multiplicand}$$

where

Z_DET_current = Standardised current score

xcurrent = individual performance on the Detection task for the current assessment

$\overline{X}$ = age specific normative mean performance

SD = age specific normative standard deviation

Multiplicand = -1 when the task variable involves speed for the 'Detection', 'Identification' and 'One Back' tasks or for errors on the GMLT (as a lower score indicates improved performance)

Multiplicand = +1 when the task variable involves total correct and accuracy for 'One Card Learning' task (as a higher score indicates improved performance)

Cognitive impairment was identified when 50% or more of the tasks in the battery were impaired at -1.00, i.e. a Z score of <-1.00 on three or more tasks were needed to categorize cognitive impairment. All participants were found to be within the normative range.

Furthermore, a combined 'composite' cognitive score was computed for each individual as a measure of their overall cognitive performance. Firstly, the mean and standard deviation (SD) of the baseline scores for each subtest was calculated for the group and the difference in score from the group mean baseline was calculated for each individual, across the five subtests. Standardised scores were then computed using the following formula, whereby the difference from the group mean baseline scores are standardized by dividing the difference by the relevant baseline SD for each subtest:

$$z - score\ (z_t) = \frac{\left(x_{jt} - \bar{x}_{1t}\right) \times -1}{\sigma_{1t}}$$

Where *j*= assessment, 1=baseline, t=task. Note that "x -1" was only applied for subtests where lower scores indicate improvement (i.e. the GMLT, Detection, Identification and One Back tests)

A combined cognition score was then calculated by taking the average of the standardised scores across all tasks at each assessment for each individual:

$$combined\ cognition\ score\ (ccs_{ij}) = \sum_{t=1}^{N} z_t \Big/ N$$

Where i=individual, j=assessment, t=task, N= number of tasks

3.4.1 Groton Maze Learning Test (GMLT) – test of executive function

The GMLT is a computerized neuropsychological task, primarily designed to assess executive function and spatial memory ability (Snyder et al., 2005). The task takes around 7 minutes to administer in healthy individuals. Participants were instructed to find a 'hidden' pathway to navigate through a 10 x 10 grid of grey tiles (see Figure 2), from the top left corner to the bottom right corner. A 28-step pathway was therefore hidden among these 100 potential locations.

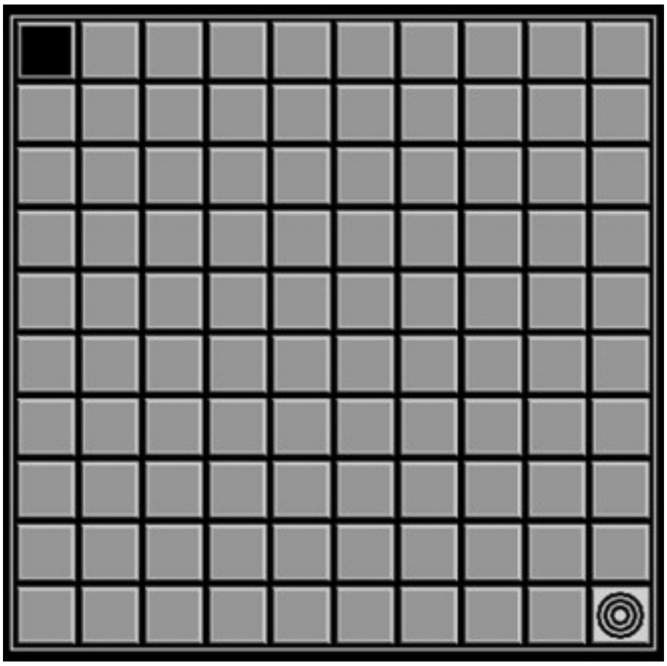


Figure 2. A monochromatic example of the computerized GMLT. Participants were instructed to navigate from the top left tile (shaded tile) to the bottom right tile (with concentric circle pattern) by finding a 'hidden pathway'.

The subjects were required to learn the pathway through trial and error feedback. Upon completion of one trial, the participant was returned to the start location and needed to repeat the test with the same pathway four more times, with the instruction to try and remember the pathway they had just completed. A practice trial (with a different hidden pathway) was initially administered to allow familiarisation with the task, using a smaller 6 x 6 grid. Participants were also instructed to make their moves as quickly and accurately as possible, and each trial was timed – starting from the moment the first move was made. The main outcome measure of interest for this test was total number of errors made over the five successive learning trials.

3.4.2 Simple Reaction Time

This task, called the 'Detection Test', was designed to assess psychomotor function using a simple reaction time paradigm to measure processing speed. The task usually takes three minutes to administer in healthy individuals. A single card was presented in the centre of the screen facing down and participants were required to press the 'K' key as soon as the card turned over. A beep would sound if the participants made a response too soon or if they failed to respond. The main outcome measure for this test was speed of performance, which was calculated using the mean of the log10 transformed reaction times for correct responses (in ms), where a lower score indicated better performance.

3.4.3 Choice Reaction Time

This task, called the 'Identification test', uses a choice reaction time paradigm to measure attention and takes around three minutes to complete in healthy individuals. Once again, a single card was presented in the centre of the screen facing down, and participants were required to decide 'Is the card red?' If the card was red, they needed to press the 'K' key for a 'yes' response and if it wasn't red, they needed to press the 'D' key to indicate a 'no' response. A beep would sound if the participants made a response error. Participants were encouraged to work as quickly and as accurately as possible when completing the task. The main outcome measure for this test was also speed of performance, which was calculated using the mean of the log10 transformed reaction times for correct responses (in ms), where a lower score indicated better performance.

3.4.4 Pattern Separation

This task, called the 'One Card Learning Test', uses a pattern separation time paradigm to measure visual memory and takes around six minutes to complete in healthy individuals. A single card was presented in the centre of the screen facing down, and participants were required to consider the question, 'Have you seen this card before in this test?' Each time a card was revealed, the participant needed to decide if he/she had been shown that card before in this test and press the 'K' key for a 'yes' response and the ‘D’ key to indicate a ‘no’ response. A beep would sound if the participants made a response error. Participants were again encouraged to work as quickly and as accurately as possible when completing the task. The main outcome measure for this test was accuracy of performance, which was calculated using the arcsine (the inverse of a sine function) transformation of the square root of the proportion of correct responses, where a higher score indicated better performance.

3.4.5 Working memory using an n-back paradigm

This task, called the ‘One Back Test’, uses an ‘n-back’ paradigm to measure working memory performance and takes around four minutes to complete in healthy individuals. A single card was presented in the centre of the screen facing down, and participants were required to consider the question, ‘Is the previous card the same’? Each time a card was revealed, the participant needed to decide if the card was identical to the one shown just before and press the ‘K’ key for a ‘yes’ response and the ‘D’ key to indicate a ‘no’ response. A beep would sound if the participants made a response error. Once again, participants were encouraged to work as quickly and as accurately as possible when completing the task. The main outcome measure for this test was speed of performance, which was calculated using the mean of the log10 transformed reaction times for correct responses (in ms, as per the ‘Detection’ and ‘Identification’ tests), where a lower score indicated better performance.

3.5 Statistical Methods and Analyses

Statistical analysis was performed using IBM SPSS Statistics version 22. Three of the thirteen total participants were excluded from the EEG analysis due excessive noise or contraindications to EEG testing. For analysis of the amplitudes and latencies for each of the VEP components (P1, N1 and P2), various data exclusions for certain participants were also necessary due to either excessive noise and/or absence of an identifiable waveform.

Relationships between the speech perception measures, cognitive domains, and VEP measures, were visually explored using scatterplots. To assess the strength and direction of association between the variables, a two-tailed Spearman’s rank-order correlation was performed. Due to the limited sample size, the non-parametric Spearman’s rank-order correlation was selected instead of the Pearson product-moment correlation coefficient as the sample did not meet the assumption of bivariate normality. A Bonferroni adjustment was applied to account for multiple comparisons. It is expected that further expansion of this cohort will permit more robust statistical modelling to assess potential predictive relationships and certainly, verify the trends that have emerged from this small sample.

The correlational analysis was used to address the key research questions as follows:

1. Is there a relationship between specific components of the VEP (i.e. P1, N1 and P2 components) at occipital and/or temporal electrode sites, and cognitive abilities, in older adults?

Spearman's rank-order correlation was used to investigate whether a relationship exists between variables of the amplitudes and latencies of P1, N1 and P2 components at Oz, T7 and T8 electrode sites and both 'combined cognition score' and individual subtest scores from the Cogstate cognitive test battery.

2. Is there a relationship between specific components of the VEP (i.e. P1, N1 and P2 components) at occipital and/or temporal electrode sites, and speech perception in noise abilities, in older adults?

Spearman's rank-order correlation was used to investigate whether a relationship exists between variables of the amplitudes and latencies of P1, N1 and P2 components at Oz, T7 and T8 electrode sites and sentence (BKB) and word (CNC) scores, presented in noise.

3. Is there an association between speech perception abilities in noise (using word recognition and sentence recognition scores) and cognitive capacity measured visually (specifically processing speed, attention and working memory using Cogstate) in older adults?

Spearman's rank-order correlation was again used to explore the relationship between variables of CNC word score, BKB sentence score and both 'combined cognition score' and individual subtest scores from the Cogstate cognitive test battery.

4.0 Results

4.1 Visual-evoked potentials

ERP waveforms were successfully elicited in response to the morphing visual changes of the alternating concentric visual stimuli. The grand average ERP waveforms are shown in Figure 3, at the frontal (Fz), central (Cz), occipital (Oz) and left (T7) and right (T8) temporal electrode sites. Individual topographical VEP plots, as well as individual data for VEP component amplitudes and latencies for all subjects at Oz, T7 and T8 can be found in Appendices A and B. VEPs were characterized by a P1 positive deflection occurring at approximately 100ms after the onset of the stimulus, followed by a negative deflection (N1) at about 150 ms and a positive peak (P2) at approximately 220 ms.

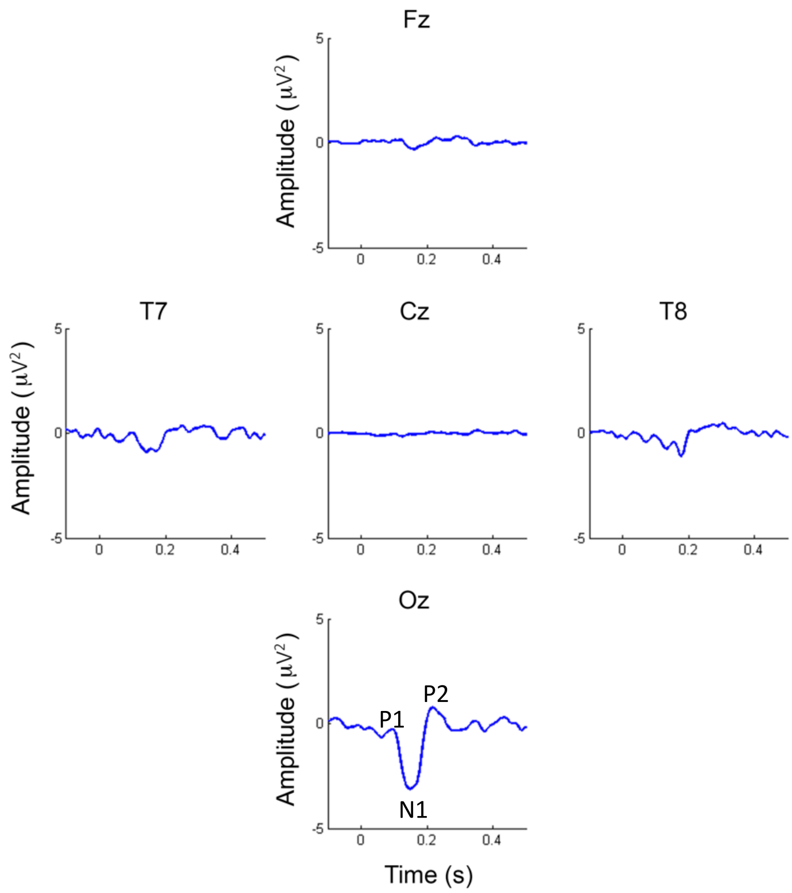


Figure 3. Average waveforms of the group (n=10) at five electrode locations. (Fz, Cz, Oz, T7 and T8). Voltage (μV) is displayed on the y-axis and time (ms) relative to the stimulus change on the x-axis.

Figure 4 depicts the mean amplitudes and latencies of the P1, N1 and P2 VEP components over the Oz, T7 and T8 electrode sites. It is evident that the greatest peak amplitude is the N1 VEP component over Oz, as would be expected for a visual task, however similar strengths in amplitude were not seen for P1 or P2 components over the Oz region. The mean P2 latencies were shortest over Oz in comparison to P2 latencies at T7 and T8. The smallest response activation was the P1 component over all three electrode sites, in comparison to the N1 and P2 components.

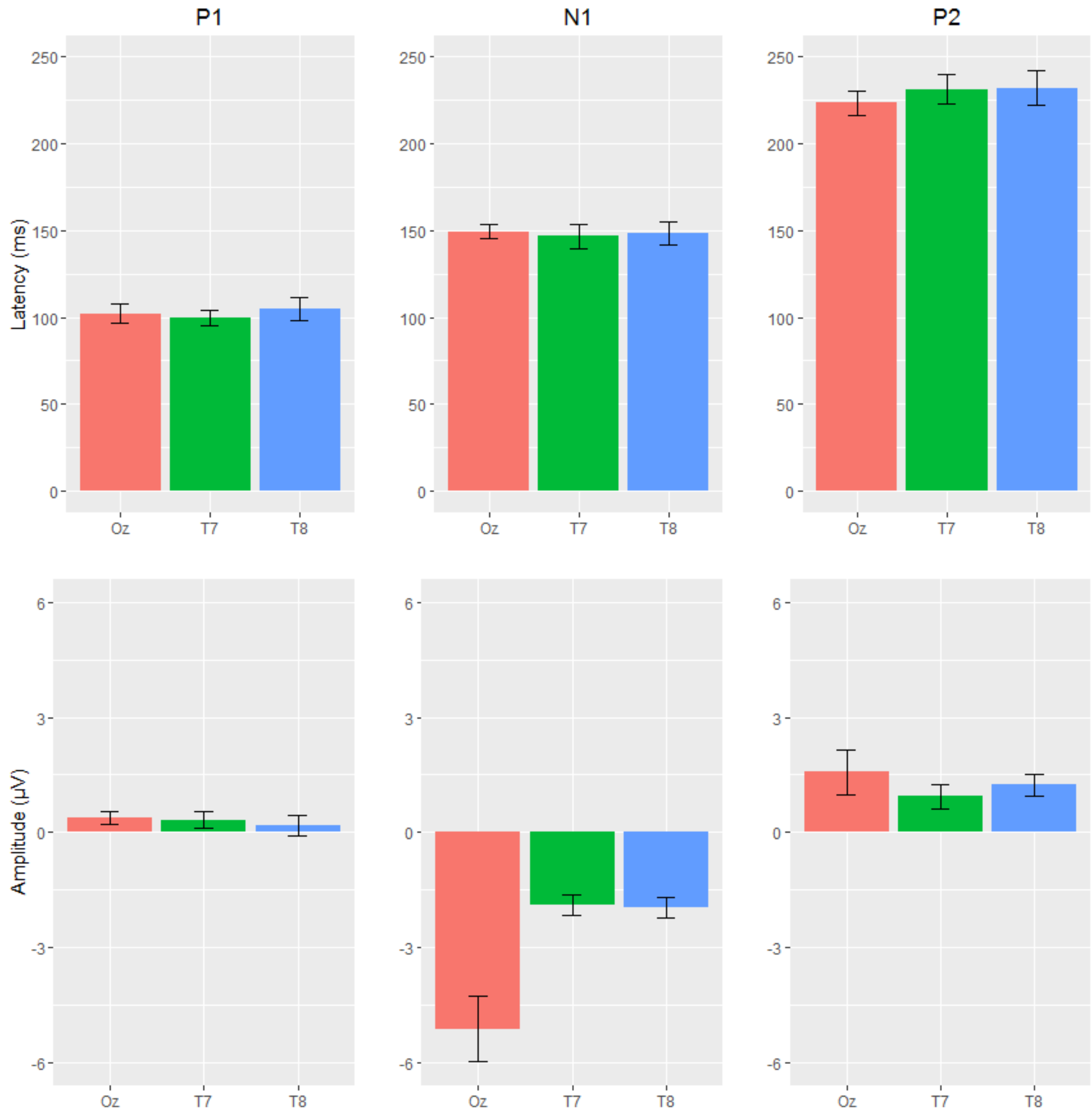


Figure 4. Graphical representation of the mean amplitudes and latencies for P1, N1 and P2 components at Oz, T7 and T8, with standard error bars.

Figure 5 shows the grand average EEG topographical plots for P1, N1 and P2 VEP components. This further demonstrates that the average N1 response in the occipital region shows the strongest activation across the cohort, with comparatively decreased activation from the P1 and P2 VEP components.

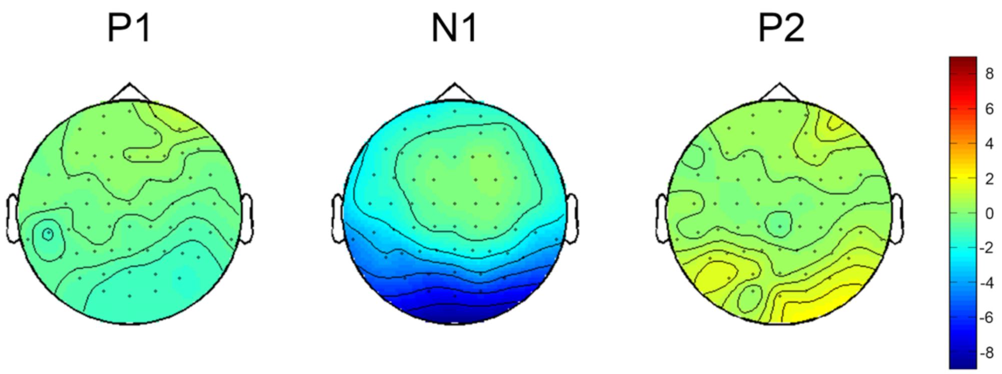
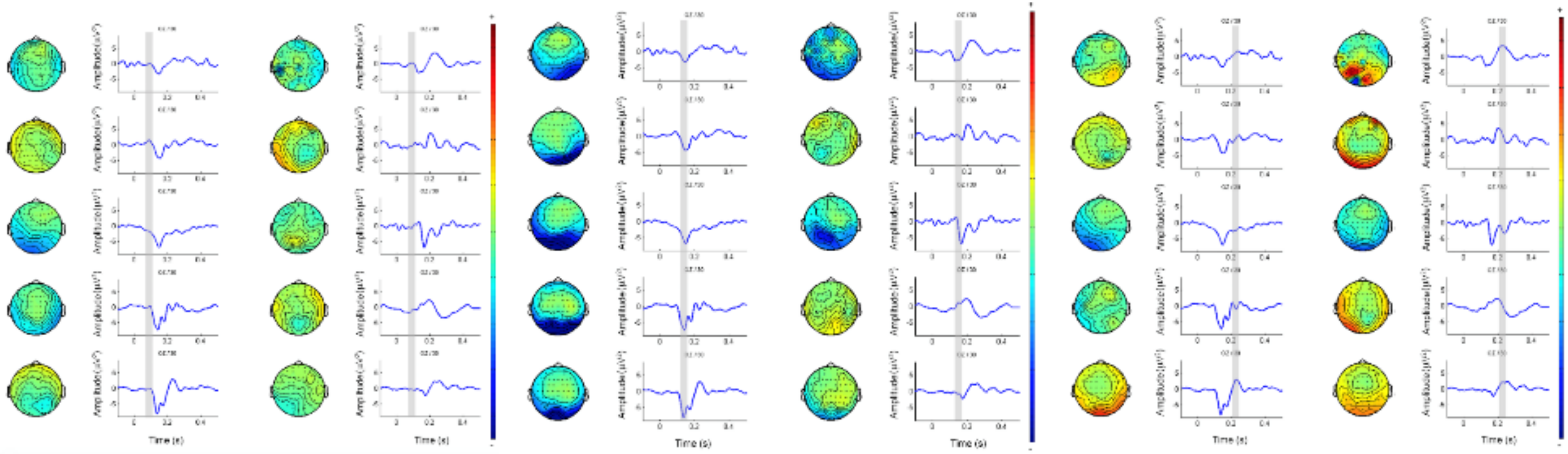


Figure 5. Topographical maps of the mean voltage amplitudes (μV), at the maximum amplitude of the Oz P1, N1 and P2 components, respectively. The most negative value is depicted as dark blue on the colour scale, running to dark red as the most positive value.

Individual topographic response distributions scaled across the participants to show the P1, N1 and P2 VEP responses are shown in Figure 6. The P1 topographical plots show very limited P1 response activation, let alone in the occipital region. The N1 response is clearly discernible in most of the participants, with the main activity dispersed predominantly in the occipital region, however N1 responses for two participants show considerably delayed latencies, resulting in limited visible activation in the topographical plot. In addition, a few participants show activity extending from the occipital region slightly into the temporal regions and one participant demonstrates some left parietal and frontal activation. For the P2 response, about half of the participants show occipital activation, however some responses are skewed towards the left hemisphere and into the temporal regions. The remaining half of the group show limited P2 responses and even demonstrate more negative responses, which is unexpected.



A B C

Figure 6. Individual topographic response maps (n=10), scaled across the participants to highlight (A) the P1 VEP response, (B) the N1 VEP response, and (C) the P2 VEP response. The most negative value is depicted as dark blue on the colour scale through to dark red as the most positive value.

4.2 Cognitive scores and relationship to speech perception and VEP measures

Individual speech and cognitive scores for all subjects are summarised in Table 2.

Table 2. Individual speech perception and cognitive scores for each participant

	SPEECH PERCEPTION		**COGSTATE**					
ID no.	**CNC word score (%)**	**BKB sentence score (%)**	**DET (processing speed)**	**IDN (attention)**	**ONB (working memory)**	**OCL (visual memory)**	**GML (executive function)**	**Combined Cognition Score**
			LMN (speed)	LMN (speed)	LMN (speed)	ACC (accuracy)	TER (total errors)	
1	50	n/a	2.50	2.67	2.76	0.91	65	0.29
2	62	83	2.53	2.76	2.90	1.00	47	-0.02
3	48	82	2.61	2.79	2.96	1.05	44	-0.39
4	62	90	2.59	2.75	2.86	0.92	57	-0.36
5	38	56	2.51	2.70	2.96	0.84	69	-0.58
6	60	76	2.46	2.69	2.86	1.07	68	0.58
7	58	80	2.48	2.73	2.79	1.13	32	0.98
8	46	55	2.56	2.72	2.96	1.01	52	-0.22
9	56	69	2.56	2.86	2.98	1.10	29	-0.28
10	36	47	2.53	2.77	2.97	1.09	35	0.06
11	48	88	2.62	2.79	2.94	1.06	30	-0.18
12	48	56	2.67	2.77	2.86	1.00	54	-0.49
13	40	76	2.43	2.66	2.83	1.19	36	1.34

A Spearman's rank-order correlation was used to determine the relationship between speech perception scores (BKB sentences and CNC words) and the five Cogstate subtests however, there were no statistically significant correlations found, either with each individual subtest score or with 'combined cognition score'. As expected, a significant positive correlation was found between BKB sentence and CNC words score at 0 dB SNR ($r_s = 0.704$, p=0.033), which indicates that BKB sentence scores increased with CNC word scores. A significant negative correlation was found between 4F-PTA in the better ear with both BKB sentence scores (r_s = -0.746, p=0.009) and CNC word scores ($r_s =$ -0.783, 0.009), indicating that speech perception scores for both BKB sentences and CNC words improved with decreasing 4F-PTA values (i.e. better hearing thresholds), despite 12 of the 13 participants showing clinically normal hearing thresholds. Age was positively correlated with working memory score, which was calculated using a 'speed of performance' measure, therefore higher score = poorer performance (r_s = 0.671, p=0.036), indicating that with increasing age, working memory ability tended to be poorer (i.e. slower 'speed of performance measures').

Correlational trends were also found using Spearman's rank-order correlation between various VEP measures at Oz, T7 and T8, and both speech perception and cognitive domains, summarised in Table 3. Table 3 includes both unadjusted and Bonferroni-adjusted p-values. For the purposes of this thesis, only the cognitive domains of processing speed, attention and working memory will be discussed. These domains are of particular interest given the known changes in both working memory and processing speed with age (Salthouse, 2004), with a correlation between working memory and age also observed in this cohort, and we are also interested in the influences of attentional mechanisms on brain activation in adults with CI. Furthermore, although not all correlations were significant following Bonferroni-adjustment, many were trending towards significance. As such, general trends observed in the data will also be discussed, with acknowledgement of the small sample size (and low statistical power). It is intended that the current cohort will be expanded, in order to further verify these trends. For clarity, when describing observed relationship trends in this section, Bonferroni-adjusted p-values are stated where the reported relationship has been found to be 'statistically significant' post-adjustment.

Table 3. Summary of significant (unadjusted) Spearman's rank-order correlations between VEP components and speech perception and cognitive measures, with p-values post-Bonferroni adjustment

Variables tested	Spearman's correlation coefficient	p-value (2-tailed)	Bonferroni-adjusted p-value	N
P1 amplitude over Oz BKB sentence score	-0.762	0.028	0.056	8
P1 latency over Oz BKB sentence score	-0.714	0.047	0.094	8
P1 latency over Oz CNC word score	-0.892	0.003	0.006*	8
P2 latency over Oz BKB sentence score	0.806	0.005	0.01*	10
P2 latency over Oz CNC word score	0.823	0.003	0.006*	10
N1 amplitude over T8 Attention	-0.810	0.015	0.075	8
N1 amplitude over T8 Working memory	-0.786	0.021	0.105	8
N1 latency over Oz Attention	-0.917	0.01	0.05	9
N1 latency over Oz Processing speed	-0.750	0.02	0.1	9
P2 latency over Oz Working memory	-0.806	0.005	0.025*	9
P2 latency overT7 Working memory	-0.867	0.001	0.005*	9
P2 latency over T8 Working memory	-0.800	0.01	0.05	9

*Significant at 0.05 level, post-Bonferroni adjustment (p<0.05)

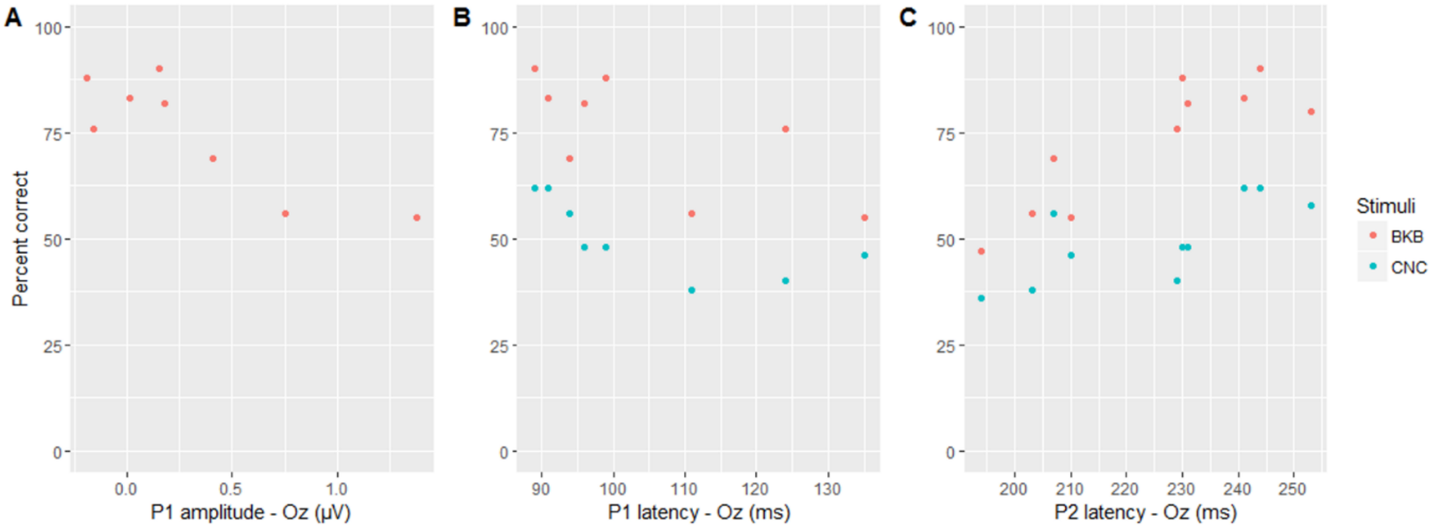


Figure 7. Scatterplots depicting relationships between A): P1 amplitude over Oz and BKB sentence score, B): P1 latency over Oz and both BKB sentence and CNC word scores and C): P2 latency over Oz with both BKB sentence and CNC word scores.

Correlations were found between VEP measures and speech perception scores. A negative relationship between P1 amplitude over Oz and BKB sentence score can be seen in plot A of Figure 7, which shows that as BKB sentence score decreased, P1 amplitudes over Oz increased. Negative relationships were also found between the P1 VEP latency over Oz and CNC words (r_s =-0.892, p=0.006) and BKB sentence scores, indicating that as P1 VEP latencies shortened, CNC word and BKB sentence scores improved (see plot B of Figure 7). Finally, in contrast, significant positive correlations were found between P2 latency over Oz and BKB sentence scores (r_s = 0.806, p=0.01) and CNC word scores (r_s = 0.823, p=0.006) (see plot C in Figure 7). This shows that P2 latencies increased with high speech perception scores and also decreased with poorer performance.

In terms of cognitive domains, no statistically significant correlations were found between VEP measures and overall ‘combined cognition’ scores for each subject, however correlations were found between VEP measures and individual subtest scores. A negative relationship was observed between N1 amplitude over T8 and both attention and working memory, which indicates that as attention and working memory ability increased (evidenced by a decrease in ‘speed of performance’ measure, i.e. faster speed), the N1 amplitude over T8 decreased (see plots A and B in Figure 8).

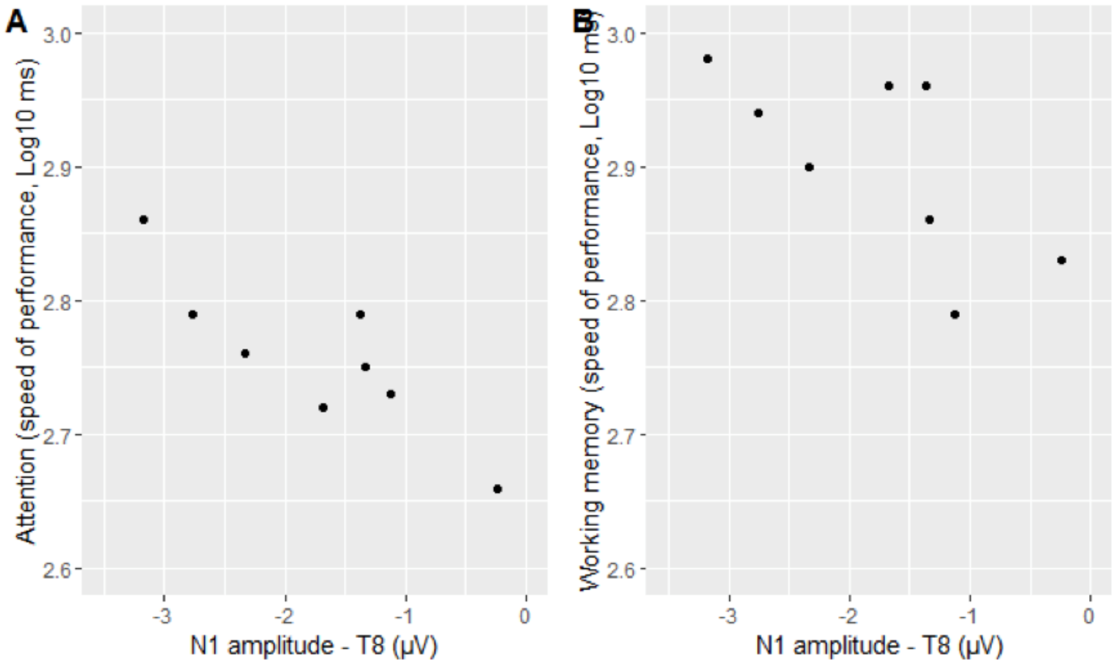


Figure 8. Scatterplot showing relationships between the N1 amplitude over T8 electrode site and both attention and working memory, (calculated using 'speed of performance' measure, therefore lower score = better performance).

Negative relationships were also found with VEP latency measures. Figure 9 depicts the relationship between the N1 latency over Oz with both attention and processing speed. As attention and processing speed are both determined via a 'speed of performance' measure, the correlation demonstrates that as attention and processing speed improve (i.e. 'speed of performance measure decreases'), the N1 latencies over Oz increase.

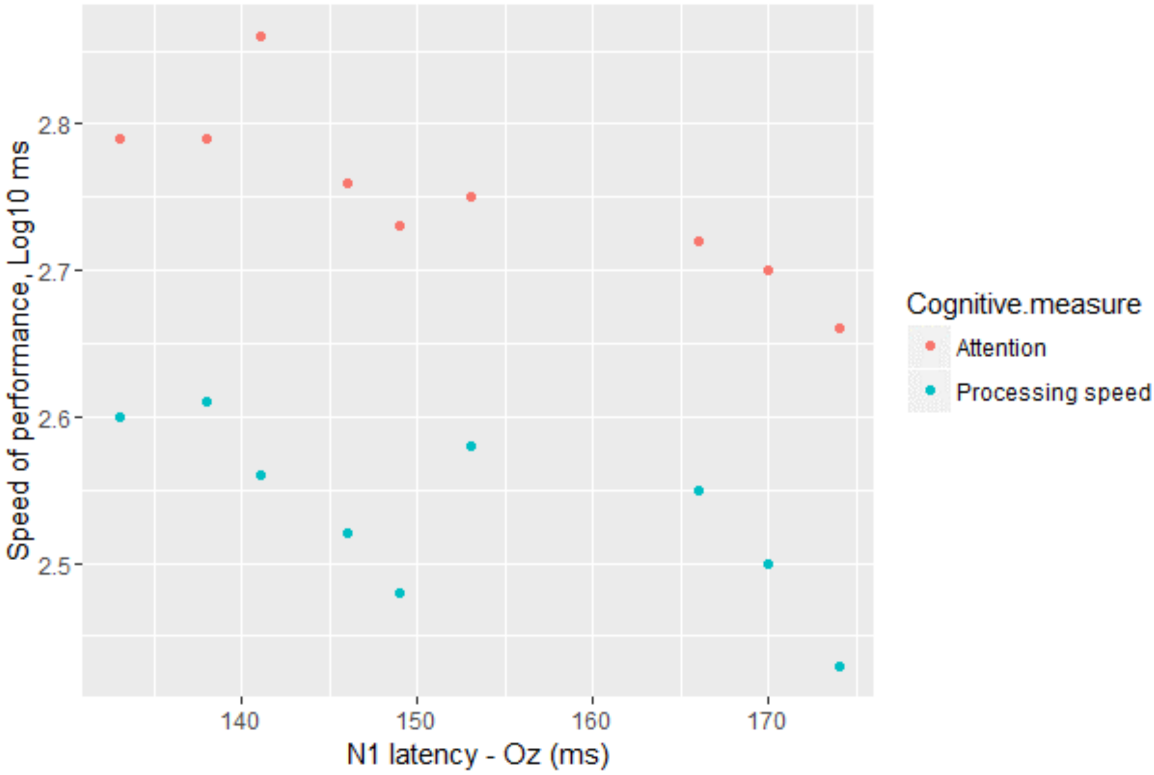


Figure 9. Scatterplot showing relationship between N1 latency over Oz electrode site with attention and processing speed (calculated using 'speed of performance' measure, where lower score = better performance).

Finally, negative relationships were found between working memory and the P2 latencies over Oz (r_s = -0.806, p=0.025), T7 (r_s = -0.867, 0.005) and T8 electrode sites. These relationships are depicted together in Figure 10 and indicate that as working memory ability improved (i.e. 'speed of performance' measures become faster, or decrease), the P2 latencies over Oz, T7 and T8 increased.

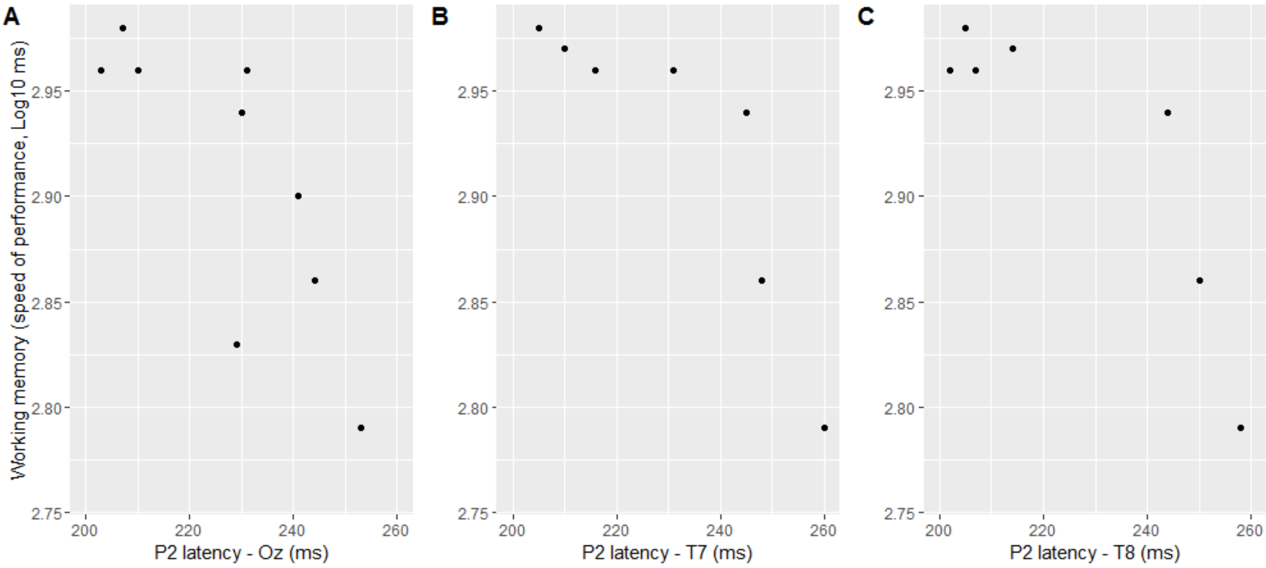


Figure 10. Scatterplot showing relationship between P2 latency over Oz, T7 and T8 electrode sites with working memory (calculated using 'speed of performance' measure, therefore lower score = better performance).

5.0 Discussion and Conclusion

This study investigated cortical VEPs measured concurrently using MEG and EEG techniques in a group of 13 normally-hearing older adults using a visual paradigm developed by Doucet et al. (2006). For the purposes of this thesis, however, we will discuss EEG results only. As expected in a normal hearing cohort with normal or corrected vision, grand average EEG topographical plots showed that the strongest activation occurred for the N1 component over the occipital region, with lower comparative activation at all other electrode sites (Sandmann et al., 2012). Nonetheless, temporal activations were observed at the auditory T7 and T8 electrode sites in response to the visual stimulus. Furthermore, while correlations were not found between speech perception and cognitive measures, correlational trends were found between cognitive measures and N1 and P1 VEP amplitudes, as well as P1, N1 and P2 latencies in the temporal regions, suggesting that VEP measures could be influenced by cognitive ability, in terms of spread of cortical activation. However, it is important to note that due to the small cohort size and restricted age range, these aspects will be considered as suggested trends and limitations of this study will be discussed. This section will firstly outline the nature of cortical VEP activations found in this pilot group and specifically discuss the individual N1, P1 and P2 VEP components observed, in light of other relevant studies. Secondly, findings relating to VEP measures and cognitive and speech perception scores will be discussed in consideration of the key research questions. Lastly, this section will address the limitations of the present study and considerations for future research.

While it was hypothesised that we would not expect to see ‘cross-modal’ representations in the VEP measures, given that this cohort is ‘normally-hearing’, it appears that a broader topographical activation has been observed, extending in to the temporal regions. An early study by (Clark et al., 1995) sought to investigate the cortical sources of the early components (50-250 ms) of the pattern-onset VEP, relevant to the present study. Despite using fewer EEG channels (i.e. 32 channels) than the current study and averaging across 28°arcs , the topographical distribution of the VEP in a group of young adults (n=24; 18-35 years) with normal or corrected-to-normal visual acuity showed broad activation across the cortex, similar to the current study. That is, Clark and colleagues identified a P1 wave (composed of two sub-deflections, P75 and P100) elicited at the occipito-temporal electrode site. While there was limited P1 activity noted topographically in the present study, these activations appeared to be spread fairly evenly over the Oz, T7 and T8 electrode sites. Clark and colleagues showed that the N1 component, present between 120 –180 ms post-stimulus, arose from multiple sources in the occipito-parietal, occipito-temporal and possibly frontal cortex. The N1 VEP showed strongest activation over the occipital region in the present study, with a mean latency of around 150 ms. However, slight temporal activation was also noted higher in the T7 and T8 (temporal) electrode sites. In addition, the study reported a P210 wave which was largest over the occipito-parietal region. The present study identified a P2 wave with a mean latency of around 224 ms in the occipital region (Oz).

The N1 VEP component

In this study, the N1 VEP component showed the strongest response in comparison to P1 and P2 components, and was predominantly active over the occipital region. This finding is consistent with the study by Doucet et al. (2006), who examined VEPs in normally hearing subjects (n=16) and CI users (n=13) using the same visual paradigm. In their study, CI users were grouped as either 'good' performers' or 'poor performers' in terms of auditory performance. Their results showed that the VEP responses in the normal hearers were localised more around the primary visual cortex, i.e. in the occipital area, and that this pattern of more modality-specific activity was also found in the 'good' CI performers. Furthermore, they found that VEP responses were more anteriorly distributed in the 'poor' CI performers in comparison to the normal hearers and 'good' CI performers. However, while the present study saw strongest occipital activation in the N1 VEP component only, Doucet et al. (2006) observed VEP responses across all electrode sites (Fz, Cz, T5, T6 and Oz), even in the normal hearing cohort. Although, some noted differences between this study and the Doucet et al (2006) study include the lower age range of the normal hearing group (18-52 years), as well as a different EEG protocol and electrode montage in the Doucet study. It should also be noted that Doucet et al. (2006) referred to electrodes T5 and T6 in their analysis, however the present study referred to electrodes T7 and T8 given differences in EEG cap configuration, therefore such differences in methods would account for discrepancies in findings. Also of note is a difference in age range of the control group, which ranged from 18 to 52 years of age, as opposed to 56 to 67 in the present study.

Campbell and Sharma (2014) also investigated the N1 VEP in both normal hearing individuals (n=8) and subjects with mild to moderate hearing loss (n=9) to investigate cortical cross-modal plasticity, using the same visual paradigm as Doucet et al., (2006) and the present study. The study compared amplitudes and latencies for the P1, N1 and P2 VEP components between the normal hearers (NH) and hearing loss (HL) group, focussing on electrodes in the occipital region of interest. The mean N1 amplitude for the NH group was noticeably smaller, around 1.8 μV, in comparison to 4.8 μV in the present study. Again, there were noted differences in EEG methodology and age range of the participants, with the use of high density, 128 channel EEG, as well as an age range of 37 to 68 years. Overall, the study found a trend of increased amplitudes and decreased latencies across the three VEP components (P1, N1 and P2) in the occipital region in the hearing loss group, compared to the normal hearing group.

While the present study observed the most activation at the occipital region across subjects, Buckley and Tobey (2011) examined the N1 VEP response to peripheral visual motion over the right temporal lobe. Their study aimed to investigate the association between auditory deprivation, visual/auditory cross-modal plasticity and speech perception abilities in post-lingual deafened CI users, and the right temporal lobe was selected to examine the extent to which visual/auditory cross-modal plasticity in this auditory cortical region might influence speech perception outcomes with a cochlear implant. Indeed, past studies have shown that individuals who achieve greater speech perception abilities with a CI appear to recruit the right temporal cortices for speech processing (Mortensen et al., 2006). Moreover, studies by Fine et al. (2005) and Finney et al. (2001) have demonstrated that the right temporal cortical regions show evidence of visual/ auditory cross-modal plasticity in deaf individuals, being responsive to visual stimuli.

The study by Buckley and Tobey (2011) involved 22 cochlear implant users with severe to profound sensorineural hearing loss (SNHL) (10 with prelingual deafness and 12, post-lingual onset) and 10 normally hearing individuals, with an age range of 22 to 40 years. A key difference from the present study was in the visual stimuli, which consisted of moving visual gradients located in a square pattern on a grey background, with still pictures of cartoon characters located in the centre. The paradigm was designed to evoke visual peripheral motion, therefore subjects were instructed to keep their eyes focussed on the centre of the image throughout the task and were also asked to press a button in response to the appearance of a black box at one of the corner gradient positions – this was to ensure that they were also monitoring the entire screen as well as fixating on the centre of the image (Buckley & Tobey, 2011). EEG recordings were made using a 68 electrode cap, referenced to a single reference on the head in the centre line between Cz and CPz, apart from the bipolar eye-monitoring channels. Their results showed discernible and replicable N1 VEP responses in all individuals, with a mean latency of 219.09 ms for the normal hearing group. The amplitude of the N1 VEP recorded over the right temporal lobe in the normal hearing group was -0.725 μV. These findings differ slightly from the present study in normally hearing individuals, which showed a shorter mean N1 VEP latency over the right temporal region of 152 ms and a larger amplitude of -1.75μV. Interestingly, the study found no significant differences in N1 VEP response amplitude or latencies between the normally hearing, prelingually deaf and post-lingually deaf groups, however it was also noted that there were large age differences, with the normal hearing group being significantly younger than the post-lingually deaf group. Intriguingly, this appears to contradict previous research findings, which have shown that N1 VEP response latencies in response to motion is shorter in young individuals in comparison to older individuals (Jiang et al., 2009; Langrová et al., 2006).

Furthermore, the topographical distributions in the normally hearing group in the Buckley and Tobey (2011) study appeared to be distributed over the left parietal lobe, with some responses also over the occipital lobe, and this pattern of response activation appeared to be mostly consistent within the normal group. This response distribution pattern of the N1 VEP slightly differs with that seen in the normally hearing cohort of the present study, where activation of the N1 VEP was largely seen in the occipital region, with only some individuals showing evidence of parietal activation. These differences may be attributed to factors such as the nature of visual stimuli used, as well as differences in mean age of the normal hearers, i.e. approximately 29 years, in comparison to a mean of 62 years of age in the present study.

The P1 and P2 VEP components

In the present cohort, both the P1 and P2 VEP amplitudes appeared to be much smaller in comparison to the N1 VEP amplitude and while some individual topographic maps showed slight evidence of occipital activations for the P2 component, very limited activity was seen from the P1 VEP in response to the stimulus. The P1 and P2 VEP components have been discussed to a lesser extent in studies examining visual/auditory cross-modal plasticity, however certainly, there have been studies which have shown responses from both components to a greater extent than found in the present cohort. The aforementioned study by Campbell and Sharma (2014) in CI users and normal hearers, while having focussed predominantly on the N1 VEP, noted that mean P1 and P2 VEP amplitudes over the occipital were increased for the HL group in comparison to the normally hearing group. The mean P1 VEP amplitudes were much larger in this study's normally hearing cohort, with a mean P1 amplitude of approximately 2.25 μV, compared to 0.32 μV in the present study. However, the mean amplitudes for P2 in the NH group appeared to be more similar, with the Campbell and Sharma (2014) study showing a mean of about 1μV for the P2 amplitude, which was closer to a mean of 1.64 μV, in the present cohort. Furthermore, the study found the presence of an additional P2 VEP component in a subset of the HL group. Their findings of greater P2 VEP amplitudes in the HL group are consistent with other studies in deaf individuals e.g. Doucet et al. (2006), however this was particularly noted in 'good' CI performers.

While the present study elected to replicate a visual paradigm used by Doucet et al. (2006), some studies have opted to use different visual stimuli. Sandmann and colleagues (2012) used parametrically modulated reversing checkerboard images and EEG source localisation to investigate cross-modal reorganisation in the auditory cortex of post-lingually deafened CI users (n=11), and compared this to a group of normally hearing controls (n=11). Interestingly, their findings revealed smaller amplitudes P1 VEP amplitudes and reduced activation in the visual cortex in CI users, in comparison to the normally hearing controls. Furthermore, CI users also showed recruitment of the right auditory cortex to purely visual stimuli, which suggests a visual 'take-over' cortical reorganisation pattern in the auditory cortex of CI users, which importantly, was found to be inversely related to speech perception ability in right ear implanted CI users. Their finding of smaller P1 VEP amplitudes and smaller visual cortex activation in CI users appears to contrast with results of other studies showed enhanced VEP amplitudes e.g. Neville and Lawson (1987) and more recently, Campbell and Sharma (2014) and larger recruitment of the visual cortex in deaf subjects compared to normally hearing controls (Fine et al., 2005; Bavelier, 2001). Campbell and Sharma (2014) speculated that given the more complex pattern of visual stimulation relative to their study (and also the present study), the checkboard pattern stimulus may have 'tapped in' to a different stage of visual processing. Their argument for using the checkerboard stimuli included that in contrast to motion stimuli, checkerboard reversals elicit strong, high SNR VEPs, even at shorter latencies, and that VEPs elicited by this type of stimuli are less variable in waveform morphology and latency than responses to other types of stimulation, evidenced in previous studies (Sandmann et al., 2012). This raises an important point in consideration of future studies examining cortical VEPs, in that the type of visual stimuli used has the potential to influence the nature of the VEPs elicited, and thus should be taken into account when making comparisons between studies.

VEPs and correlations with speech perception and cognitive measures

The present study assessed speech perception-in-noise ability using two widely-utilised clinical speech tests – BKB sentences and CNC words, presented at a comfortable listening level with +0dB SNR 4-talker babble. A novel, computerized cognitive test battery, designed to assess five cognitive domains was also used to investigate cognitive abilities. A key research question of this study involved whether there is an association between speech perception abilities in noise and cognitive capacity (measured visually) in older adults. Surprisingly, no significant correlations were found between speech perception scores for either sentences or words and any of the five cognitive domains assessed, particularly given that cognitive domains such as working memory and processing speed are known to be critical for speech comprehension, and are susceptible to declines in older adults (Peelle et al., 2010); Wingfield et al., 2005). The potential limitations of these tests and study in general will be discussed later in this section. However, correlations were found between some components of the cortical VEPs with specific cognitive measures, namely attention and working memory, and also between VEP response latencies and speech perception scores.

In addition to having the aim of evoking cortical VEPs to examine cross-modal plasticity in subjects with hearing loss and/or CI users, several studies have attempted to investigate associations between cortical VEPs and speech perception performance. However, no studies have examined the potential effect of cognitive domains on VEPs. Given that multiple studies have demonstrated that speech perception-in-noise is significantly correlated with cognitive ability (see Lunner, 2003) and that age is highly correlated with cognitive declines (Salthouse, 2004), it may be of interest to better understand the role of cognitive domains in influencing speech perception and potentially, VEP measures in older adults. Findings thus far in studies of CI users increasingly suggest that speech perception abilities post-cochlear implantation may be limited by cross-modal plasticity. That is, the extent of activation of the auditory cortex by a visual stimulus or the reduction of activation of the visual cortex appears to be correlated with speech perception outcomes. Despite this, it is not clear whether cognitive ability (or declines in the case of older adults) is also associated with cross-modal plasticity or rather, a greater distribution of cortical activity.

A key aim of this study was to examine whether a relationship exists between specific components of the VEP (i.e. P1, N1 and P2 components) at occipital and/or temporal electrode sites, and speech perception in noise abilities, in this cohort. Significant positive correlations were found between the P2 latency over Oz and BKB sentence scores (r_s = 0.806, p=0.01) and CNC word scores (r_s = 0.823, p=0.006). This shows that P2 latencies increased with high speech perception scores and also decreased with poorer performance. Campbell and Sharma (2014) found a similar trend in their study, however in a different component – the N1 VEP. Campbell and Sharma (2014) investigated the relationship between the latency of the N1 VEP component with speech perception performance, as the N1 VEP has been implicated as a marker of cross-modal reorganisation in deafness (Buckley & Tobey, 2011; Armstrong et al., 2002). They utilised the QuickSIN ™ clinical test to assess speech perception-in-noise ability, which reports an SNR threshold as an outcome measure; with a lower threshold or score indicating better performance. They included both the NH group and HL group together in the correlation analysis, given that hearing loss consists of a gradual increase in auditory threshold from 0 dB HL. Their findings showed a negative correlation between N1 latency and QuickSIN scores across the group (r_s=-0.701, p=0.001), indicating that higher QuickSIN scores (i.e. worse performance) were associated with shorter N1 latencies. Hence, whilst the present study did not find significant correlations between speech perception (in noise) scores and the N1 VEP component, there was a significant positive trend between VEP latency in the occipital region and speech perception score, i.e. P2 latency and both sentence and word scores.

Another key aim was to investigate whether a relationship exists between specific components of the VEP (i.e. P1, N1 and P2 components) at occipital and/or temporal electrode sites, and cognitive abilities (measured by Cogstate), in this cohort. There were some observed relationships between N1 and P2 VEP components and cognitive domains assessed using the Cogstate cognitive test battery. Of particular interest, a relationship was observed with VEPs over the right temporal region. The N1 VEP amplitude over T8 (the right temporal region) showed a negative relationship with 'speed of performance' measures of attention and working memory (i.e. lower scores = better performance). Therefore, as attention and working memory improved, the N1 VEP amplitude over T8 decreased. This is an interesting trend given that more widespread activation patterns in response to visual stimulation were associated with poorer speech perception outcomes in CI users, whereas better performing CI users showed more enhanced and concentrated brain activity within the visual cortex, a similar pattern to that seen in normal-hearers (Doucet et al., 2006). Furthermore, age-related mechanisms may be implicated here, given that increased brain activity has been interpreted as a 'compensatory' effect in studies involving older adults (Grady et al., 1995; Grady et al., 1994), which has been proposed to be a result of factors such as reduction in selectivity of responses or a lack of efficiency in neural resources.

Further interesting correlations were found between N1 and P2 VEP latencies with attention, processing speed and working memory. The N1 VEP latency over Oz showed a negative relationship with attention and processing speed (both 'speed of performance' measures, i.e. lower score = better performance), indicating that as attention and processing speed improve (reflected in a lower 'speed of performance' score), the longer the N1 VEP latencies. Similarly, a negative relationship was seen in the P2 latencies over Oz, T7 and T8 with working memory, in that as working memory improved, the P2 latencies over all three electrode sites increased. While longer VEP latencies have not been specifically correlated with cognitive measures in other studies interested in cross-modal plasticity, shorter VEP latencies have been significantly related to individuals with hearing loss in the study by Campbell and Sharma (2014). Given the link between hearing loss in older adults and cognitive decline, the potential role of cognitive ability in this trend in an older adult population remains to be addressed and hence may be of interest. Further studies in older adults examining cognitive abilities in addition to speech perception performance and correlation to VEPs are therefore required to shed further light on this trend.

In summary, it is clear that there are considerable variations in the literature in terms of the classification of cross-modal plasticity and its relationship to speech perception outcomes, particularly in the selection of speech perception measures, categorisation of speech perception performance and differences in visual stimuli used to investigate the cortical VEPs. While cross-modal plasticity has been assumed to be a *plastic* change that has occurred in the cortex, it cannot be reliably assumed that the cortical activation patterns measured within the cross-sectional studies are a true reflection of this compensatory change, or simply an observed association with a speech perception measure. Furthermore, this pilot study has shown evidence of a potentially 'broader' activation pattern in older adults that may relate to measures of cognitive ability, which may be important to consider when investigating evidence of cross-modal activity in clinical populations. Therefore, the results of the current study (while from a limited number of participants) suggest a need to consider cognition and perhaps age as a potential source of variability when examining cross-modal activations in adults with hearing loss and/or a cochlear implant.

Limitations and future directions

This study had several limitations. The small sample size, given the restricted age range and time restraints, limited our ability to examine the strength and reliability of the observed trends and hence, they have been presented as such. Although not all relationships were found to be 'statistically significant' following adjustment for multiple comparisons in correlational analysis, observed relationship trends were still discussed, with the intention to expand this cohort to further verify these trends. In addition, there was a large gender bias in the cohort, with only one male participant and twelve female participants. This study did not find any significant correlations between speech perception-in-noise measures and cognitive abilities, as might have been expected given that speech comprehension, particularly in adverse listening conditions, relies on aspects of cognition (Peelle et al., 2010; Wingfield et al., 2005). Whilst there was a spread of speech perception-in-noise abilities within the cohort, the cognitive abilities appeared to be comparatively more homogenous (i.e. smaller standard deviations noted, than for speech perception scores).

Furthermore, this study also screened participants using the Cogstate tests (in reference to age-related normative data) to exclude individuals with evidence of cognitive impairment. Perhaps a larger cohort with a greater age range or range of cognitive abilities may have yielded an effect. Furthermore, the sensitivity of the Cogstate cognitive tests has mainly been shown in studies within clinical populations, e.g. cognitive impairment in mild traumatic brain injury and schizophrenia. However, studies have noted the feasibility and validity of the use of the Cogstate tests in ageing adults with no evidence of dementia (Mielke et al., 2015). The present study has also assessed the feasibility of using Cogstate to both assess and screen cognitive domains in an older adult population. The battery certainly shows promise as a visual-only assessment of specific cognitive domains in an older population, particularly for use future studies in individuals with a hearing loss and/or CI. An additional benefit of the test design is the applicability to longitudinal cohort studies given the predominantly 'game-like' interface, which can be randomised across trials/ test sessions to avoid a familiarity effect. This would be particularly useful in investigating brain changes over time following cochlear implantation. Further verification of the suitability of this test paradigm will continue with future follow-up studies.

The choice of visual task in this study is another factor to consider, in acknowledgement of the variability in stimuli used in other studies. The visual paradigm used in this pilot was mainly selected as it has been previously validated and utilised in earlier studies investigating cross-modal plasticity in CI recipients and was also fairly simple to recreate. In view of the literature regarding audiovisual integration and its benefits for speech understanding, perhaps incorporation of both visual and auditory elements into a test paradigm would yield for an interesting investigation of how visual and auditory processing interact.

In addition, differences in speech perception-in-noise tests have been noted across various studies. In the present study, an SNR of +0dB was used as a standardised way of assessing speech-perception-in noise ability in a normally-hearing group. This SNR has been found in the literature to yield a roughly 50% speech perception performance or speech reception threshold (SRT) using CNC word tests in noise (Boothroyd, 2008), hence +0dB SNR was chosen to avoid ceiling effects. Additionally, it was expected that the cohort would perform better on the BKB sentences at the same SNR given the higher linguistic redundancy due to contextual cues, however a fair spread of performance was also seen for this task amongst the cohort. Again, perhaps further studies in a larger cohort, where there may be a greater range of performance would yield an effect. Furthermore, dedicated speech-in-noise perception tests such as the QuickSIN™, utilised by Campbell and Sharma (2014) may yield more sensitive measures of performance, in that the level of noise is varied for each individual to determine their individual SNR threshold.

In summary, this pilot study has yielded several considerations for prospective studies. Although MEG data from this study was not presented and discussed in this thesis, it is intended that future analysis will take place to combine both MEG and EEG findings to take advantage of their complementary information, as well as further expansion of this cohort/ study to include individuals with untreated hearing loss and eventually, CI users.

Conclusion

To conclude, this pilot study investigated cortical VEPs measured concurrently using MEG and EEG techniques in a small group of older adults with normal hearing abilities. EEG findings have corroborated the visual paradigm used, having successfully elicited an identifiable VEP waveform across the cohort. Grand averaged VEP responses have shown strongest activation of the N1 component over the occipital region in comparison to the frontal and temporal regions, which is consistent with other literature in normal hearing individuals showing stronger activations concentrated in the visual cortex, in comparison to CI users. However, temporal activations were also noted in this cohort.

While the present study found no significant correlations between speech perception-in-noise performance and cognitive abilities, correlations were found between cognitive test measures and VEP components in the temporal regions. Importantly, this trend suggests that there may be a relationship between VEP measures and cognitive domains, in terms of spread of cortical activation in an older population. While it is becoming clear that speech perception abilities in adult CI users may be limited by cross-modal plasticity, i.e. the extent of activation of cortical temporal (auditory) regions by visual stimuli is correlated with poorer speech perception outcomes, it is still not clear whether cognitive ability is also associated with cross-modal plasticity, or a greater distribution of cortical activity. Certainly, further studies in both normally hearing and hearing-impaired older adults are required to further verify these trends.

6.0 References

Armstrong, B. A., Neville, H. J., Hillyard, S. A., & Mitchell, T. V. (2002). Auditory deprivation affects processing of motion, but not color. *Cognitive Brain Research*, *14*(3), 422–434. http://doi.org/10.1016/S0926-6410(02)00211-2

Baddeley, A., Logie, R., Nimmo-Smith, I., & Brereton, N. (1985). Components of fluent reading. *Journal of Memory and Language*, *24*(1), 119–131. http://doi.org/10.1016/0749-596X(85)90019-1

Bavelier, D. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *J. Neurosci.*, *21*, 8931–8942.

Bavelier, D., Dye, M. W., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends Cogn Sci*, *10*(11), 512–518. http://doi.org/10.1016/j.tics.2006.09.006

Bench, R., & J, D. (1979). The BKB/A (Bamford-Kowal-Bench/Australian version) sentence lists for hearing-impaired children. Victoria: La Trobe University.

Blamey, P., Arndt, P., Bergeron, F., Bredberg, G., Brimacombe, J., Facer, G., … Whitford, L. (1996). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiology & Neuro-Otology*, *1*(5), 293–306. http://doi.org/10.1159/000259212

Boothroyd, A. (2008). The performance/intensity function: an underused resource. *Ear and Hearing*, *29*(4), 479–491. http://doi.org/10.1097/AUD.0b013e318174f067

Buckley, K. A, & Tobey, E. A. (2011). Cross-modal plasticity and speech perception in pre- and postlingually deaf cochlear implant users. *Ear and Hearing*, *32*(1), 2–15. http://doi.org/10.1097/AUD.0b013e3181e8534c

Campbell, J., & Sharma, A. (2014). Cross-modal re-organization in adults with early stage hearing loss. *PLoS ONE*, *9*(2). http://doi.org/10.1371/journal.pone.0090594

Carpenter, P. A, Just, M. A., & Shell, P. (1990). What one intelligence test measures: a theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological Review*, *97*(3), 404–431. http://doi.org/10.1037/0033-295X.97.3.404

Champoux, F., Lepore, F., Gagné, J.-P., & Théoret, H. (2009). Visual stimuli can impair auditory processing in cochlear implant users. *Neuropsychologia*, *47*(1), 17–22. http://doi.org/10.1016/j.neuropsychologia.2008.08.028

Chen, L. (2016). *Enhanced visual adaptation in cochlear implant users revealed by concurrent EEG-fNIRS. Manuscript in preparation*. Elsevier. http://doi.org/10.1016/j.neuroimage.2016.09.033

Clark, V., Fan, S., & Hillyard, S. A. (1995). Identification of early visually evoked potential generators by retinotopic and topographic analysis. *Hum. Brain Mapp.*, *2*, 170–187.

Collison, E. A., Munson, B., & Carney, A. E. (2004). Relations among linguistic and cognitive skills and spoken word recognition in adults with cochlear implants. *Journal of Speech, Language, and Hearing Research*, *47*(3), 496–508. http://doi.org/10.1044/1092-4388(2004/039)

Darvas, F., Pantazis, D., Kucukaltun-Yildirim, E., & Leahy, R. M. (2004). Mapping human brain function with MEG and EEG: methods and validation. *NeuroImage*, *23*, S289–S299. http://doi.org/10.1016/j.neuroimage.2004.07.014

Dewey, R. S., & Hartley, D. E. H. (2015). Cortical cross-modal plasticity following deafness measured using functional near-infrared spectroscopy. *Hearing Research*, *325*, 55–63. http://doi.org/10.1016/j.heares.2015.03.007

Doucet, M. E., Bergeron, F., Lassonde, M., Ferron, P., & Lepore, F. (2006). Cross-modal reorganization and speech perception in cochlear implant users. *Brain*, *129*(Pt 12), 3376–3383. http://doi.org/10.1093/brain/awl264

Dupuis, K., Pichora-Fuller, M. K., Chasteen, A. L., Marchuk, V., Singh, G., & Smith, S. L. (2015). Effects of hearing and vision impairments on the Montreal Cognitive Assessment. *Aging, Neuropsychology and Cognition*, *22*(4), 413–437. http://doi.org/10.1080/13825585.2014.968084

Eyler, L. T., Sherzai, A., Kaup, A. R., & Jeste, D. V. (2011). A review of functional brain imaging correlates of successful cognitive aging. *Biological Psychiatry*. http://doi.org/10.1016/j.biopsych.2010.12.032

Fallon, J. B., Irvine, D. R., & Shepherd, R. K. (2008). Cochlear implants and brain plasticity. *Hear Res*, *238*(1-2), 110–117. http://doi.org/10.1016/j.heares.2007.08.004

Fine, I., Finney, E. M., Boynton, G. M., & Dobkins, K. R. (2005). Comparing the effects of auditory deprivation and sign language within the auditory and visual cortex. *J. Cogn. Neurosci.*, *17*, 1621–1637. Retrieved from http://dx.doi.org/10.1162/089892905774597173

Finney, E. M., Clementz, B. A, Hickok, G., & Dobkins, K. R. (2003). Visual stimuli activate auditory cortex in deaf subjects: evidence from MEG. *Neuroreport*, *14*(11), 1425–7. http://doi.org/10.1097/01.wnr.0000079894.11980.6a

Finney, E. M., Fine, I., & Dobkins, K. R. (2001). Visual stimuli activate auditory cortex in the deaf. *Nature Neurosci.*, *4*, 1171–1173. Retrieved from http://dx.doi.org/10.1038/nn763

Fredrickson, J., Maruff, P., Woodward, M., Moore, L., Fredrickson, A., Sach, J., & Darby, D. (2010). Evaluation of the Usability of a Brief Computerized Cognitive Screening Test in Older People for Epidemiological Studies. *Neuroepidemiology*, *34*(2), 65–75. http://doi.org/10.1159/000264823

Friedland, D. R., Runge-Samuelson, C., Baig, H., & Jensen, J. (2010). Case-control analysis of cochlear implant performance in elderly patients. *Archives of Otolaryngology--Head & Neck Surgery*, *136*(5), 432–438. http://doi.org/10.1001/archoto.2010.57

Giraud, A. L., & Lee, H. J. (2007). Predicting cochlear implant outcome from brain organisation in the deaf. *Restor. Neurol. Neurosci.*, *25*, 381–390.

Giraud, A. L., Price, C. J., Graham, J. M., & Frackowiak, R. S. (2001). Functional plasticity of language-related brain areas after cochlear implantation. *Brain*, *124*(Pt 7), 1307–1316. http://doi.org/10.1093/brain/124.7.1307

Giraud, A.-L. L., Truy, E., Frackowiak, R. S., Gregoire, M. C., Pujol, J.-F. F., Collet, L., … Collet, L. (2000). Differential recruitment of the speech processing system in healthy subjects and rehabilitated cochlear implant patients. *Brain*, *123 (Pt 7*(7), 1391–1402. http://doi.org/10.1093/brain/123.7.1391

Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews: Neuroscience*, *13*, 491–505.

Grady, C. L., Maisog, J. M., Horwitz, B., Ungerleider, L. G., Mentis, M. J., Salerno, J. A., … Haxby, J. V. (1994). Age-related changes in cortical blood flow activation during visual processing of faces and location. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *14*(3 Pt 2), 1450–1462. http://doi.org/10.1080/09541440042000304

Grady, C. L., McIntosh, A. R., Horwitz, B., Maisog, J. M., Ungerleider, L. G., Mentis, M. J., … Haxby, J. V. (1995). Age-related reductions in human recognition memory due to impaired encoding. *Science (New York, N.Y.)*, *269*(5221), 218–221. http://doi.org/10.1126/science.7618082

Green, K. M. J., Bhatt, Y. M., Mawman, D. J., O'Driscoll, M. P., Saeed, S. R., Ramsden, R. T., & Green, M. W. (2007). Predictors of audiological outcome following cochlear implantation in adults. In *Cochlear Implants International* (Vol. 8, pp. 1–11). http://doi.org/10.1002/cii.326

Grouiller, F., Vercueil, L., Krainik, A., Segebarth, C., Kahane, P., & David, O. (2007). A comparative study of different artefact removal algorithms for EEG signals acquired during functional MRI. *NeuroImage*, *38*(1), 124–137. http://doi.org/10.1016/j.neuroimage.2007.07.025

Hämäläinen, M., Hari, R., Ilmoniemi, R. J., Knuutila, J., & Lounasmaa, O. V. (1993). Magnetoencephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. *Reviews of Modern Physics*, *65*(2), 413–497. http://doi.org/10.1103/RevModPhys.65.413

Heald, S. L. M., & Nusbaum, H. C. (2014). Speech perception as an active cognitive process. *Frontiers in Systems Neuroscience*, *8*(MAR), 35. http://doi.org/10.3389/fnsys.2014.00035

Healey, M. K., Campbell, K.L., Hasher, L. (2008). *Progress in Brain Research Vol. 169: The Essence of Memory*. (S. Sossin, W., Lacaille, J.C., Castellucci, V.F., Belleville, Ed.).

Heydebrand, G., Hale, S., Potts, L., Gotter, B., & Skinner, M. (2007). Cognitive predictors of improvements in adults' spoken word recognition six months after cochlear implant activation. *Audiology and Neurotology*, *12*(4), 254–264. http://doi.org/10.1159/000101473

Holden, L. K., Finley, C. C., Firszt, J. B., Holden, T. A., Brenner, C., Potts, L. G., … Skinner, M. W. (2013). Factors affecting open-set word recognition in adults with cochlear implants. *Ear Hear*, *34*(3), 342–360. http://doi.org/10.1097/AUD.0b013e3182741aa7

Jiang, Y., Luo, Y.-J., & Parasuraman, R. (2009). Neural correlates of age-related reduction in visual motion priming. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *16*(2), 164–82. http://doi.org/10.1080/13825580802348588

Johnson, B. W., Tesan, G., Meng, D., & Crain, S. (2013). A custom-engineered MEG system for use with cochlear implant recipients. In *Front Hum Neurosci*.

Jung, T.-P., Makieg, S., Humphries, C., Lee, T.-W., McKeown, M. J., Iragui, V., & Sejnowski, T. J. (2000). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology*, *37*(2), S0048577200980259. http://doi.org/10.1017/S0048577200980259

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, *99*(1), 122–149. http://doi.org/10.1037/0033-295X.99.1.122

Kim, M.-B., Shim, H.-Y., Jin, S. H., Kang, S., Woo, J., Han, J. C., … Hong, S. H. (2016). Cross-Modal and Intra-Modal Characteristics of Visual Function and Speech Perception Performance in Postlingually Deafened, Cochlear Implant Users. *PloS One*, *11*(2), e0148466. http://doi.org/10.1371/journal.pone.0148466

Lambertz, N., Gizewski, E. R., de Greiff, A., & Forsting, M. (2005). Cross-modal plasticity in deaf subjects dependent on the extent of hearing loss. *Brain Res Cogn Brain Res*, *25*(3), 884–890. http://doi.org/10.1016/j.cogbrainres.2005.09.010

Langrová, J., Kuba, M., Kremláček, J., Kubová, Z., & Vít, F. (2006). Motion-onset VEPs reflect long maturation and early aging of visual motion-processing system. *Vision Research*, *46*(4), 536–544. http://doi.org/10.1016/j.visres.2005.06.024

Lazard, D. S., Giraud, A. L., Gnansia, D., Meyer, B., & Sterkers, O. (2012). Understanding the deafened brain: implications for cochlear implant rehabilitation. *Eur Ann Otorhinolaryngol Head Neck Dis*, *129*(2), 98–103. http://doi.org/10.1016/j.anorl.2011.06.001

Lazard, D. S., Lee, H. J., Gaebler, M., Kell, C. A., Truy, E., & Giraud, A. L. (2010). Phonological processing in post-lingual deafness and cochlear implant outcome. *Neuroimage*, *49*(4), 3443–3451. http://doi.org/10.1016/j.neuroimage.2009.11.013

Levanen, S., & Hamdorf, D. (2001). Feeling vibrations: enhanced tactile sensitivity in congenitally deaf humans. *Neurosci. Lett.*, *301*, 75–77. Retrieved from http://dx.doi.org/10.1016/S0304-3940(01)01597-X

Lim, Y. Y., Ellis, K. A., Harrington, K., Ames, D., Martins, R. N., Masters, C. L., … the AIBL Research Group. (2012). Use of the CogState Brief Battery in the assessment of Alzheimer's disease related cognitive impairment in the Australian Imaging, Biomarkers and Lifestyle (AIBL) study. *Journal of Clinical and Experimental Neuropsychology*, *34*(4), 345–358. http://doi.org/10.1080/13803395.2011.643227

Lin, F. R., Ferrucci, L., An, Y., Goh, J. O., Doshi, J., Metter, E. J., … Resnick, S. M. (2014). Association of hearing impairment with brain volume changes in older adults. *Neuroimage*, *90*, 84–92. http://doi.org/10.1016/j.neuroimage.2013.12.059

Lin, F. R., Ferrucci, L., Metter, E. J., An, Y., Zonderman, A. B., & Resnick, S. M. (2011). Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. *Neuropsychology*, *25*(6), 763–70. http://doi.org/10.1037/a0024238

Lomber, S. G., Meredith, M. A., & Kral, A. (2010). Cross-modal plasticity in specific auditory cortices underlies visual compensations in the deaf. *Nat Neurosci*, *13*(11), 1421–1427. Retrieved from http://dx.doi.org/10.1038/nn.2653

Lunner, T. (2003). Cognitive function in relation to hearing aid use. *International Journal of Audiology*, *42*(s1), 49–58. http://doi.org/10.3109/14992020309074624

Lyxell, B., & Rönnberg, J. (1992). The relationship between verbal ability and sentence-based speechreading. *Scandinavian Audiology*, *21*(2), 67–72. http://doi.org/http://dx.doi.org/10.3109/01050399209045984

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. http://doi.org/10.1016/j.jneumeth.2007.03.024

McDowd, J. M., & Shaw, R. J. (2000). Attention and aging: A functional perspective. In *The handbook of aging and cognition* (pp. 221–292).

Mielke, M. M., Machulda, M. M., Hagen, C. E., Edwards, K. K., Roberts, R. O., Pankratz, V. S., … Petersen, R. C. (2015). Performance of the CogState computerized battery in the Mayo Clinic

Study on Aging. *Alzheimer's and Dementia*, *11*(11), 1367–1376. http://doi.org/10.1016/j.jalz.2015.01.008

Mortensen, M. V., Mirz, F., & Gjedde, A. (2006). Restored speech comprehension linked to activity in left inferior prefrontal and right temporal cortices in postlingual deafness. *NeuroImage*, *31*(2), 842–852. http://doi.org/10.1016/j.neuroimage.2005.12.020

Nasreddine, Z. S., Phillips, N. A., B??dirian, V., Charbonneau, S., Whitehead, V., Collin, I., … Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695–699. http://doi.org/10.1111/j.1532-5415.2005.53221.x

Nunez, P. L., & Srinivasan, R. (2009). *Electric Fields of the Brain: The neurophysics of EEG*. *Electric Fields of the Brain: The neurophysics of EEG*. http://doi.org/10.1093/acprof:oso/9780195050387.001.0001

O'Donoghue, G. M., Nikolopoulos, T. P., & Archbold, S. M. (2000). Determinants of speech perception in children after cochlear implantation. *Lancet*, *356*(9228), 466–468. http://doi.org/10.1016/S0140-6736(00)02555-1

Peelle, J. E., & Sommers, M. S. (2015). Prediction and constraint in audiovisual speech perception. *Cortex*, *68*, 169–181. http://doi.org/10.1016/j.cortex.2015.03.006

Peelle, J. E., Troiani, V., Grossman, M., & Wingfield, A. (2011). Hearing loss in older adults affects neural systems supporting speech comprehension. *J Neurosci*, *31*(35), 12638–12643. http://doi.org/10.1523/JNEUROSCI.2559-11.2011

Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2010). Neural processing during older adults' comprehension of spoken sentences: Age differences in resource allocation and connectivity. *Cerebral Cortex*, *20*(4), 773–782. http://doi.org/10.1093/cercor/bhp142

Peelle, J. E., & Wingfield, A. (2016). The Neural Consequences of Age-Related Hearing Loss. *Trends in Neurosciences*, *39*(7), 486–497. http://doi.org/10.1016/j.tins.2016.05.001

Peterson, G., & Lehiste, I. (1962). Revised CNC lists for auditory tests. *Journal of Speech and Hearing Disorders*, *27*, 62–70.

Pichora-Fuller, M. K., & Singh, G. (2006). Effects of Age on Auditory and Cognitive Processing: Implications for Hearing Aid Fitting and Audiologic Rehabilitation. *Trends in Amplification*, *10*(1), 29–59.

Proudfoot, M., Woolrich, M. W., Nobre, A. C., & Turner, M. R. (2014). Magnetoencephalography. *Practical Neurology*, *14*(5), 336–343. http://doi.org/10.1136/practneurol-2013-000768

Rabbitt, P. M. (1968). Channel-capacity, intelligibility and immediate memory. *The Quarterly Journal of Experimental Psychology*, *20*(3), 241–248. http://doi.org/10.1080/14640746808400158

Ronnberg, J., Lunner, T., Zekveld, A., Sorqvist, P., Danielsson, H., Lyxell, B., … Rudner, M. (2013). The Ease of Language Understanding (ELU) model: theoretical, empirical, and clinical advances. *Front Syst Neurosci*, *7*, 31. http://doi.org/10.3389/fnsys.2013.00031

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*(3), 403–428. http://doi.org/10.1037/0033-295X.103.3.403

Salthouse, T. A. (1996). The processing speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403–428.

Salthouse, T. A. (2004). What and When of Cognitive Aging. *Current Directions in Psychological Science*, *13*(4), 140–144.

Salthouse, T. A. (2010). Selective review of cognitive aging. *Journal of the International Neuropsychological Society : JINS*, *16*(5), 754–60. http://doi.org/10.1017/S1355617710000706

Sandmann, P., Dillier, N., Eichele, T., Meyer, M., Kegel, A., Pascual-Marqui, R. D., … Debener, S. (2012). Visual activation of auditory cortex reflects maladaptive plasticity in cochlear implant users. *Brain*, *135*(2), 555–568. http://doi.org/10.1093/brain/awr329

Sarant, J. Z., Blamey, P. J., Dowell, R. C., Clark, G. M., & Gibson, W. P. (2001). Variation in speech perception scores among children with cochlear implants. *Ear and Hearing*, *22*(1), 18–28. http://doi.org/10.1097/00003446-200102000-00003

Sharma, A., & Glick, H. (2016). Cross-Modal Re-Organization in Clinical Populations with Hearing Loss. *Brain Sciences*, *6*(1), 4. http://doi.org/10.3390/brainsci6010004

Shiell, M. M., Champoux, F., & Zatorre, R. J. (2016). The Right Hemisphere Planum Temporale Supports Enhanced Visual Motion Detection Ability in Deaf People: Evidence from Cortical Thickness. *Neural Plasticity*, *2016*. http://doi.org/10.1155/2016/7217630

Snyder, P. J., Bednar, M. M., Cromer, J. R., & Maruff, P. (2005). Reversal of scopolamine-induced deficits with a single dose of donepezil, an acetylcholinesterase inhibitor. *Alzheimer's & Dementia : The Journal of the Alzheimer's Association*, *1*(2), 126–35. http://doi.org/10.1016/j.jalz.2005.09.004

Spreng, R. N., Wojtowicz, M., & Grady, C. L. (2010). Reliable differences in brain activity between young and old adults: A quantitative meta-analysis across multiple cognitive domains. *Neuroscience and Biobehavioral Reviews*. http://doi.org/10.1016/j.neubiorev.2010.01.009

Stropahl, M., Chen, L.-C., & Debener, S. (2016). Cortical reorganization in postlingually deaf cochlear implant users: Intra-modal and cross-modal considerations. *Hearing Research*. http://doi.org/10.1016/j.heares.2016.07.005

Sur, M., Angelucci, A., & Sharma, J. (1999). Rewiring cortex: The role of patterned activity in development and plasticity of neocortical circuits. *Journal of Neurobiology*, *41*(1), 33–43. http://doi.org/10.1002/(SICI)1097-4695(199910)41:1<33::AID-NEU6>3.0.CO;2-1

Teng, E. L., & Chui, H. C. (1987). The Modified Mini-Mental State (3MS) examination. *The Journal of Clinical Psychiatry*, *48*(8), 314–8. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3611032

Tun, P. A., McCoy, S., & Wingfield, A. (2009). Aging, hearing acuity, and the attentional costs of effortful listening. *Psychol Aging*, *24*(3), 761–766. http://doi.org/10.1037/a0014802

Wayne, R. V, & Johnsrude, I. S. (2015). A review of causal mechanisms underlying the link between age-related hearing loss and cognitive decline. *Ageing Res Rev*, *23*(Pt B), 154–166. http://doi.org/10.1016/j.arr.2015.06.002

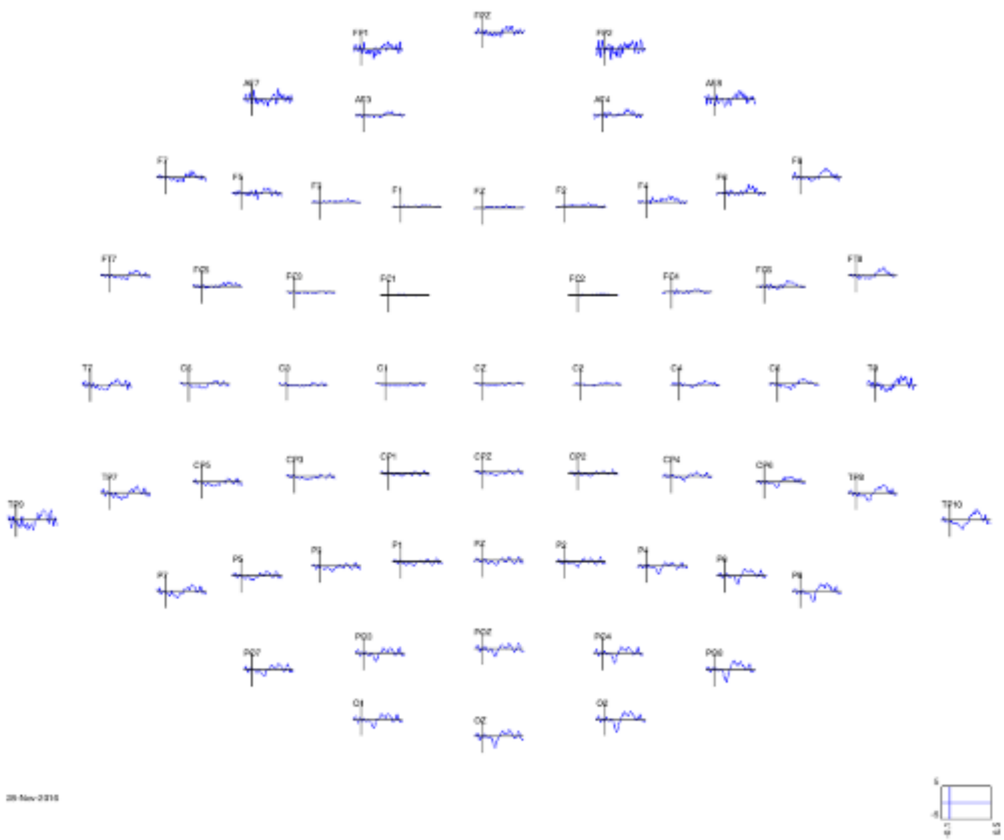
Wilkinson, F., James, T. W., Wilson, H. R., Gati, J. S., Menon, R. S., & Goodale, M. A. (2000). An fMRI study of the selective activation of human extrastriate form vision areas by radial and concentric gratings. *Current Biology*, *10*(22), 1455–1458. http://doi.org/10.1016/S0960-

9822(00)00800-9

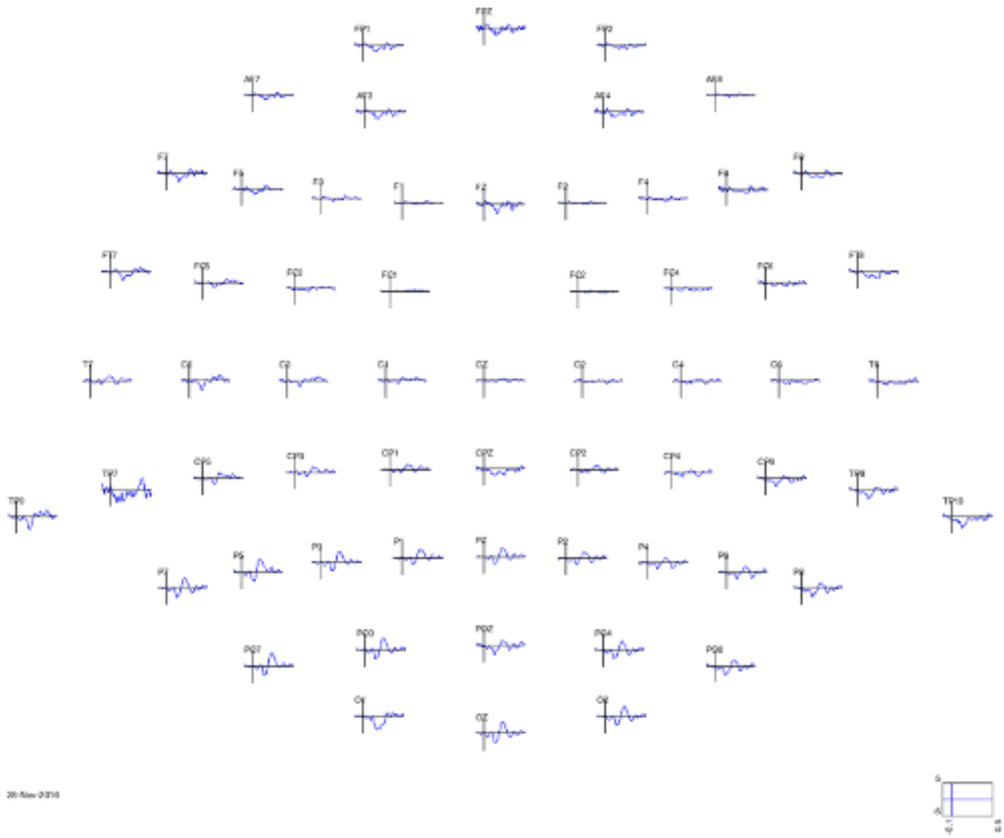
Wingfield, A., & Tun, P. A. (2007). Cognitive supports and cognitive constraints on comprehension of spoken language. *Journal of the American Academy of Audiology*, *18*(7), 548–558. http://doi.org/Doi 10.3766/Jaaa.18.7.3

Wingfield, A., Tun, P. A., & McCoy, S. L. (2005). Hearing loss in older adulthood: What it is and how it interacts with cognitive performance. *Current Directions in Psychological Science*. http://doi.org/10.1111/j.0963-7214.2005.00356.x

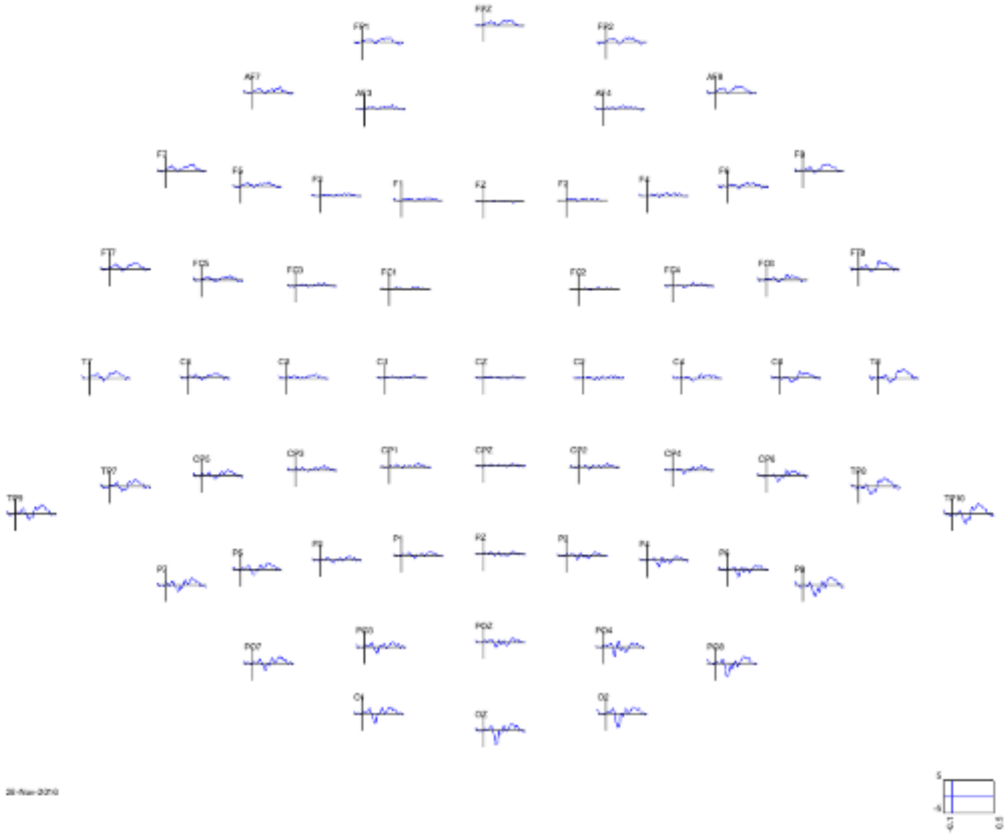
7.0 Appendix A – Individual topographical VEP plots for each participant (excluding participants 1, 6 and 12, who either had data that could not be analysed due to excessive noise or could not complete EEG testing).



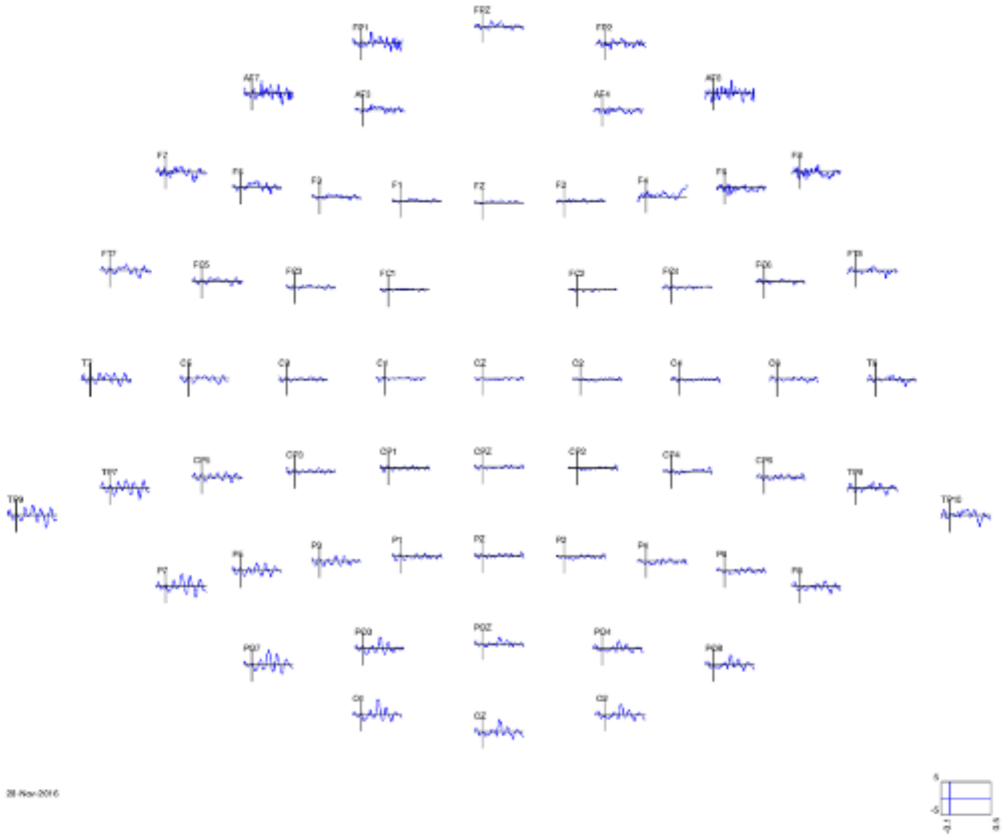
Participant 2



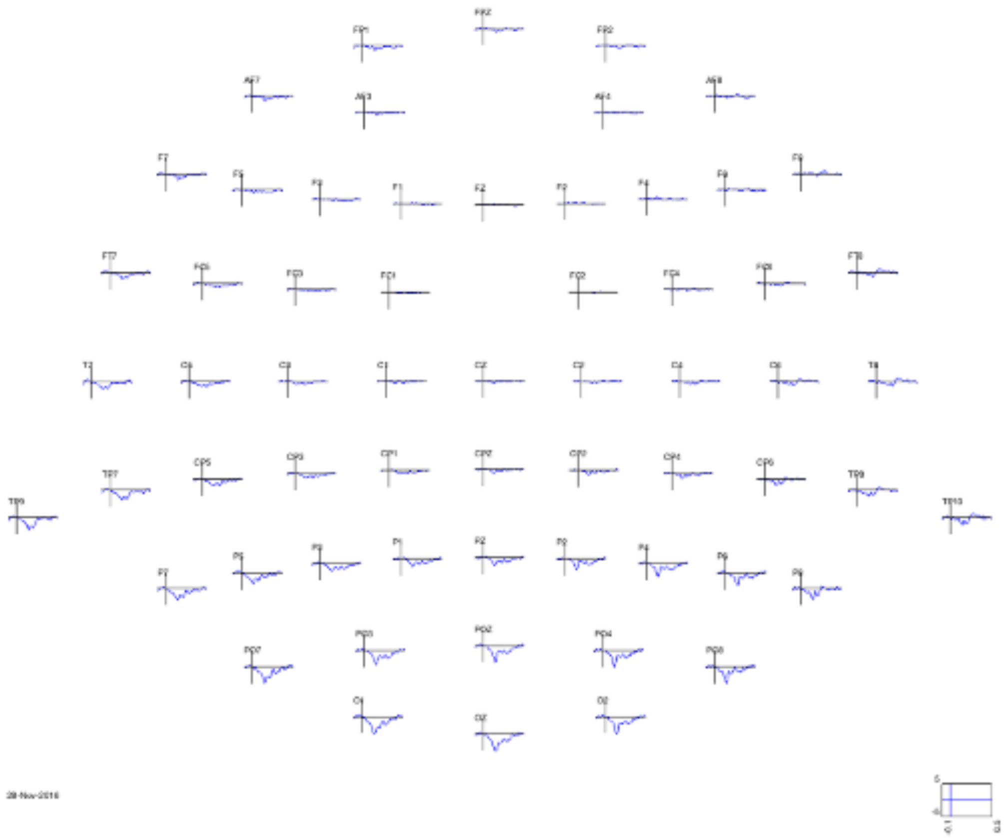
Participant 3



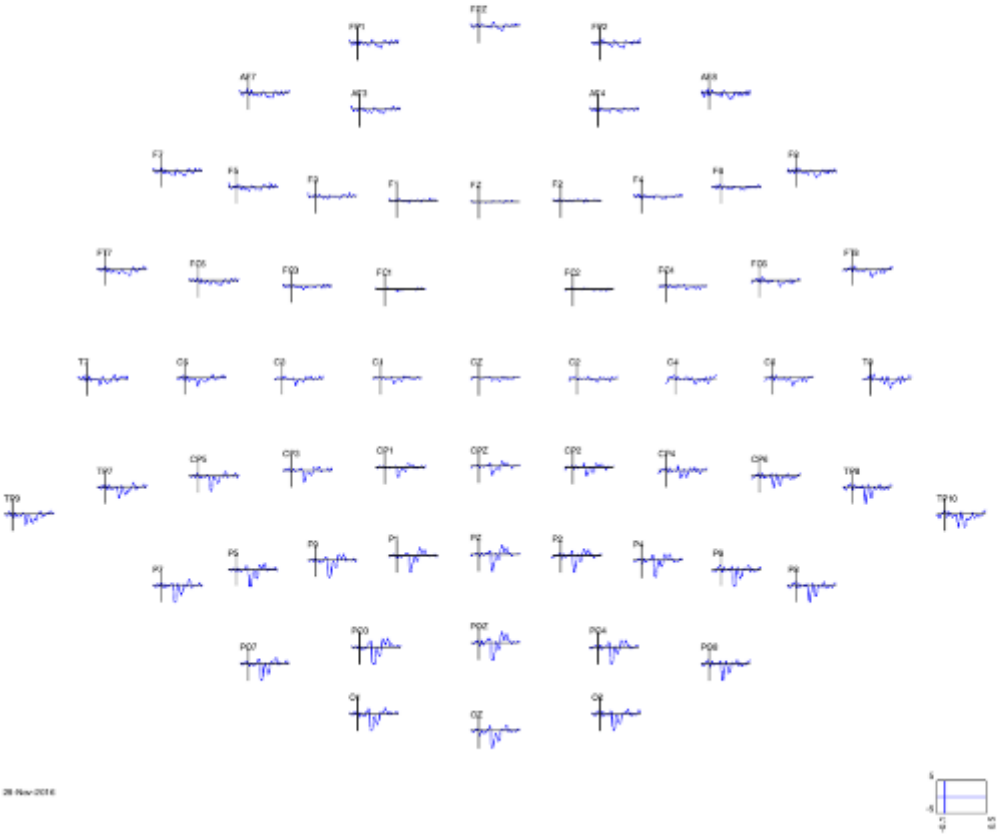
Participant 4



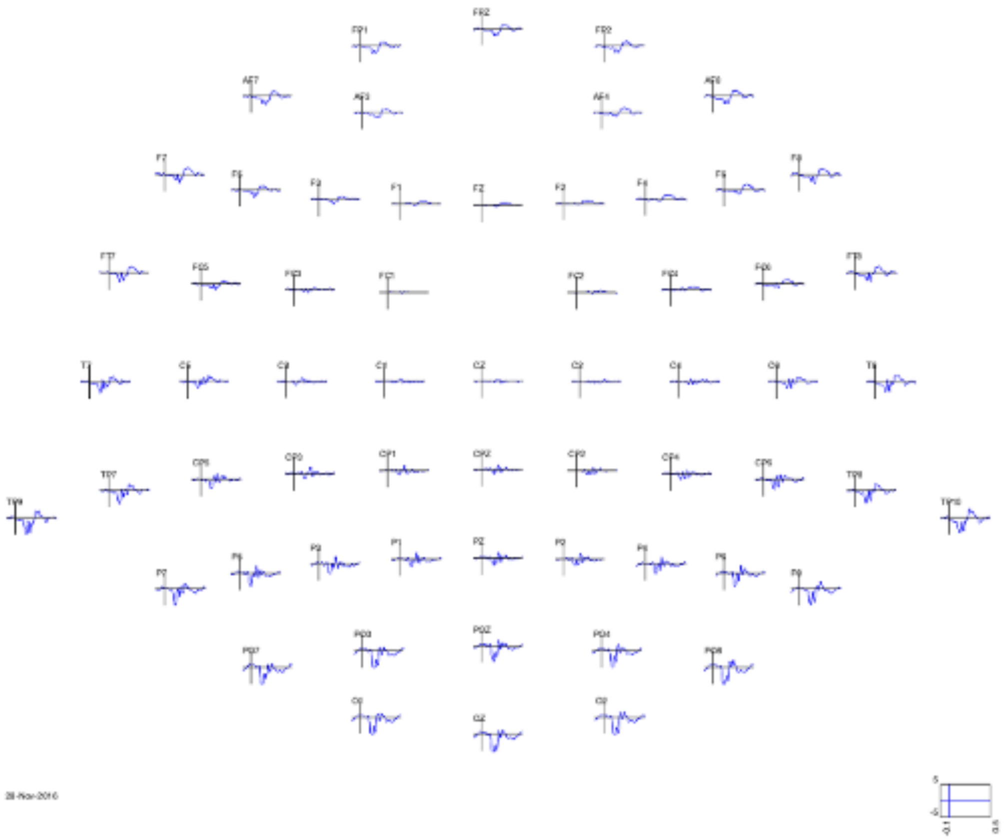
Participant 5



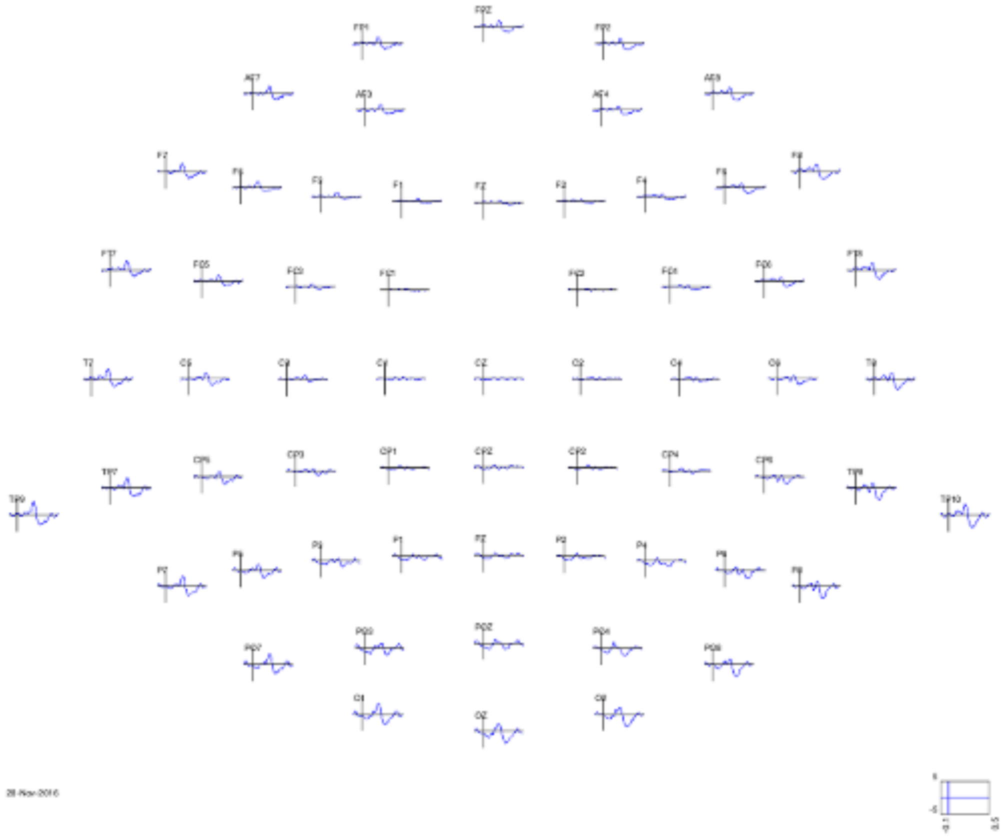
Participant 7



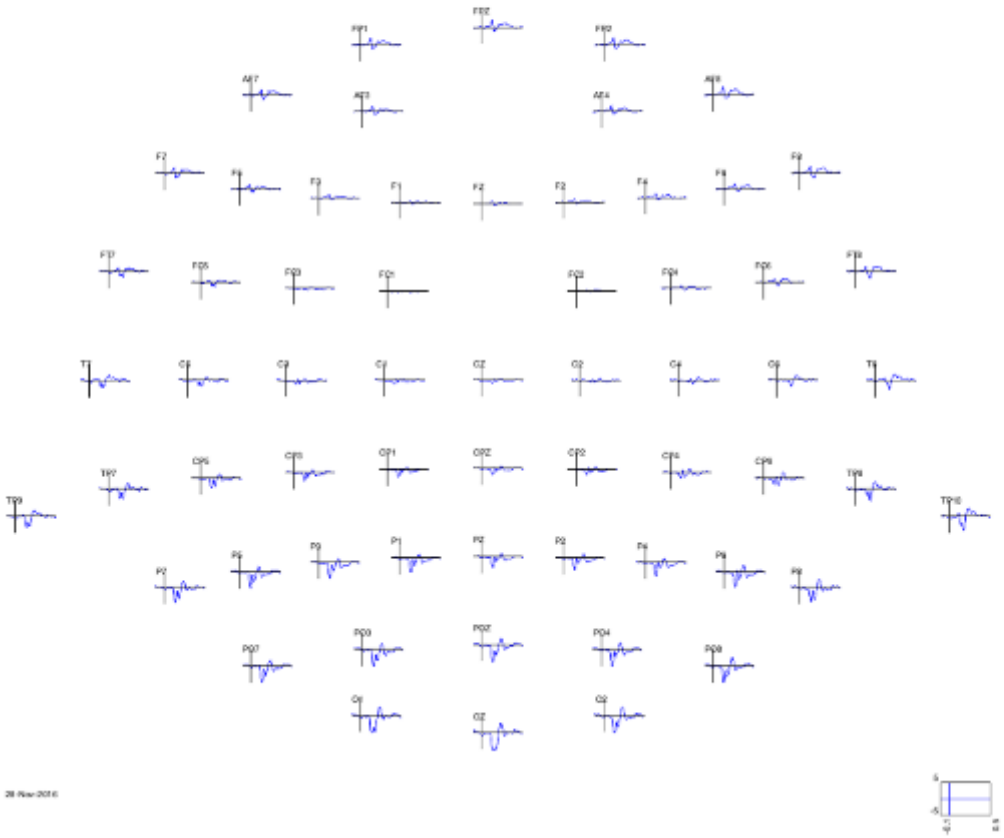
Participant 8



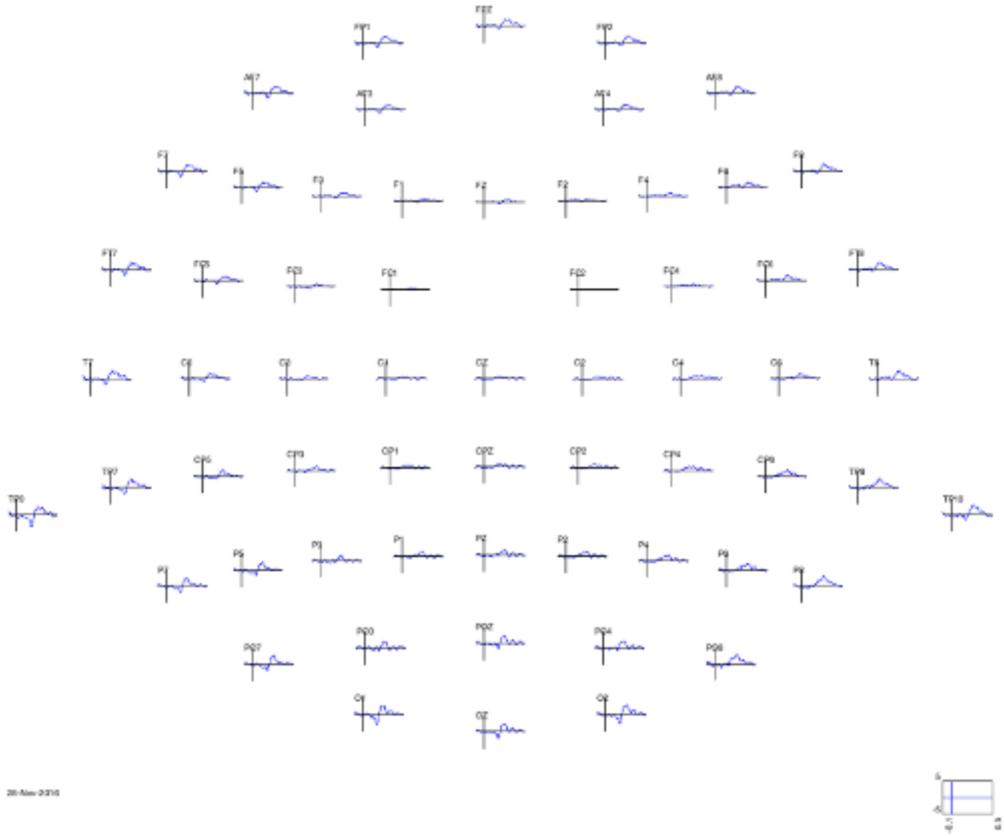
Participant 9



Participant 10



Participant 11



Participant 13

Appendix B – Individual VEP component amplitudes and latencies for all subjects at Oz, T7 and T8

	EEG																	
	P2						N1						P1					
ID no.	Latency (ms)			Amplitude (microV)			Latency (ms)			Amplitude (microV)			Latency (ms)			Amplitude (microV)		
	Oz	T7	T8	Oz	T7	T8	Oz	T7	T8	Oz	T7	T8	Oz	T7	T8	Oz	T7	T8
1																		
2	241	270	278	1.72	0.66	1.85	146	117	128	-3.26	-1.52	-2.33	91	84	93	0.01	-0.12	-0.56
3	231	216	N/A	3.42	1.23	N/A	133	128	126	-2.88	-1.23	-1.37	96	99	N/A	0.18	0.28	N/A
4	244	248	250	1.37	1.45	2.39	153	163	157	-4.27	-0.93	-1.34	89	90	90	0.15	1.34	0.91
5	203	231	207	3.68	0.51	0.69	170	N/A	N/A	-1.18	N/A	N/A	111	N/A	N/A	0.75	N/A	N/A
6																		
7	253	260	258	-1.31	0.21	0.87	149	147	148	-6.95	-1.71	-1.13	N/A	N/A	97	N/A	N/A	-0.18
8	210	198	202	-0.83	0.51	0.47	166	161	171	-6.95	-2.21	-1.68	135	115	137	1.38	-0.20	0.27
9	207	205	205	1.02	-0.55	0.04	141	136	133	-7.29	-3.43	-3.17	94	89	81	0.41	-0.43	-0.94
10	194	210	214	2.26	2.9	1.79	N/A	N/A	N/A	N/A	N/A	N/A	N/A	101	115	N/A	1.05	1.14
11	230	245	244	2.89	1.47	1.79	138	176	176	-8.18	-2.23	-2.76	99	120	121	-0.19	0.30	0.66
12																		
13	229	261	262	2.16	2.4	2.45	174	182	177	-2.28	-1.97	-0.24	124	100	N/A	-0.16	0.07	N/A

Appendix C

Office of the Deputy Vice-Chancellor
(Research)

Research Office
Research Hub, Building C5C East
Macquarie University
NSW 2109 Australia
T: +61 (2) 9850 4459
http://www.research.mq.edu.au/
ABN 90 952 801 237

MACQUARIE University
SYDNEY·AUSTRALIA

25 May 2016

Dear Associate Professor McMahon

Reference No: 5201600151

Title: *Brain processing of speech and spatial tasks in older adults with hearing loss*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Medical Sciences)).

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated May 2015) (the *National Statement*).

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the *National Statement,* which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. All adverse events, including events which might affect the continued ethical and scientific acceptability of the project, must be reported to the HREC within 72 hours.

4. Proposed changes to the protocol and associated documents must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Medical Sciences) Terms of Reference and Standard Operating Procedures are available from the Research Office website at:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Medical Sciences) wishes you every success in your research.

Yours sincerely

Professor Tony Eyers
Chair, Macquarie University Human Research Ethics Committee (Medical Sciences)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice.*