Auditory and cognitive skills in adults with reported listening in noise difficulties

by

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Declaration

I certify that the work in this thesis entitled – **Auditory and cognitive skills in adults with reported listening in noise difficulties** has not been previously submitted for a degree nor it has been submitted as a part of requirements for a degree to any other university or institution other than Macquarie University. I also certify that thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. The research presented in the thesis was approved by Macquarie University Ethics Review Committee, reference number: 5201600438 on 19th July 2016.

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Thesis Abstract

Some adults with and without hearing loss struggle to understand speech in adverse listening situations. In a US and UK based prevalence study, speech understanding in noise difficulty in adults with clinically normal audiograms was reported to be 2.9% and 4% respectively. Similarly, there are a several survey studies that have shown dissatisfaction with hearing aids particularly in the presence of noise. What causes adults with and without hearing loss to experience listening difficulties in noise? The motivation of the current research comes from the auditory-cognitive interactions framework and its subsequent model Framework for Understanding Effortful Listening (FUEL). The models have proposed that both auditory and cognitive skills are pre-requisites for understanding speech particularly in the presence noise. The objective of the first study (study 1) was to investigate the auditory and cognitive skills in adults with clinically normal hearing sensitivity and reported listening in noise difficulties. The second objective was to assess the auditory and cognitive skills in individuals with bilateral mild-moderate to moderately severe sensorineural hearing loss with reported speech understanding in noise difficulty (study 2). The Speech Spatial and Qualities Hearing Scale 12 (SSQ12) was used to evaluate the listening difficulties in 12 different listening scenarios.

Study 1 included twenty adults with normal hearing and reported listening in noise difficulties and study 2 included 10 adults with hearing loss. In addition, there was a control group of twenty-two adults with normal hearing with no reported listening in noise concerns. Both studies assessed auditory skills using behavioural and electrophysiological measures (Cortical evoked potentials; CAEPs). Behavioural measures of auditory processing and cognitive measures showed no differences between adults with and without listening difficulties in noise, irrespective of hearing loss. Electrophysiological responses, however, showed distinct differences in both studies. Study 1 investigated N400 to semantically congruent-incongruent sentences and adults with listening difficulties showed small or absent

N400 in quiet compared to the control group based on area under the curve. Cluster permutation analysis conducted within the groups across congruent-incongruent sentences using dependent samples t-test confirmed the presence of clusters in the centro-frontal electrodes only for the control group. Presence of N400 response indicates one's ability to accurately predict key words based on the context. There was no difference for the onset responses (P1-N1-P2) to the sentences across the two groups, indicating similar percept across the two groups to the start of the sentence. In-addition, time frequency analysis carried out showed stronger synchronised alpha oscillations in the control group when compared to the group having individuals with listening in noise concerns. These strong alpha oscillations for the control group may indicate that the control group have a better ability to maintain their attention throughout the task.

In study 2 the group with hearing loss showed similar results to study 1, there were differences in the time-frequency analysis of the electrophysiological data (/da/ in quiet and 8dB SNR). Within group analysis showed significant synchronised alpha oscillations only in the control group, indicating that the control group provided more attention and displayed more inhibition during the passive listening task.

The current research cannot fully explain the listening difficulties. For instance, one of the aspects that we have not considered is assessment of listening difficulties in realistic situations. One factor recommended in the FUEL model is motivation, which we have not explored in the current research. Listening effort is another aspect that has not been considered in the current research on why some adults struggle to understand speech in everyday listening situations. Nevertheless, the current project has provided some insight. The significant differences on the electrophysiological measures that implicate cognitive skills, are promising.

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Chapter 1: Introduction

In everyday life, speech is encountered in both somewhat noisy and very challenging listening conditions. Most adults with normal hearing sensitivity can cope easily in these conditions. Some adults, however, report difficulty understanding speech in adverse conditions such as an office space or a shopping mall. Often these spaces have compromised acoustics such as a long reverberation time and loud background noise (refer to Mattys, Davis, Bradlow, & Scott, 2012 for a review).

In the recent past, there have been several studies in adults with clinically normal audiograms that have reported difficulty understanding speech in adverse listening conditions (Alvord, 1983; Kujala et al. 2004; Kumar, Ameenudin, & Sangamanatha, 2012; Hope, Luxon, & Bamiou, 2013; Prendergast et al. 2017; Yeend et al. 2017). Individuals reporting such listening in noise concerns whilst having clinically normal audiograms have been studied under various labels. For instance initially, since there was no apparent cause, such as the presence of peripheral hearing loss, it was considered a psychological issue and therefore defined as psychogenic hearing loss (King, 1954). Subsequently, several investigators have defined individuals with a similar profile with other names such as; obscure auditory dysfunction, King-Kopetzky syndrome, cochlear synaptopathy, auditory processing disorder, and more recently hidden hearing loss (Saunders & Haggard 1989; Hinchcliffe 1992; Kujawa & Liberman, 2009; British Society of Audiology APD Special Interest Group 2011; Schaette & McAlpine, 2011). These terminologies were based on the individual findings by each of the investigators. For instance, “cochlear synaptopathy” was coined as the investigators noted that listening in noise concerns were an outcome of suprathreshold processing deficits occurring due to disruption of the ribbon synapses that exist between the inner hair cells and primary auditory neurons (for review, see Kujawa & Liberman, 2015; Liberman, Epstein, Cleveland, Wang, & Maison, 2016).

A prevalence study by Hind et al. (2011) showed 4% of 1025 adults attending hearing evaluation in clinics between the age ranges of 17-60 years had normal hearing sensitivity, and yet reported listening in noise difficulties. Similarly, a retrospective study carried out by Shinn et al. (2016) showed that 13% adults who attended clinics for a hearing check reported hearing difficulties despite normal audiograms. Even though there are a number of studies trying to investigate this concern, the cause and pathophysiology still remain unclear. Some of the earlier studies exploring individuals with clinically normal audiograms but having speech understanding in noise difficulty (Alvord 1983; Kujala et al. 2004; Kumar, Ameenudin, & Sangamanatha, 2012; Hope et al. 2013), comprised indviduals with occupational noise exposure. However, this is not representative of the population of individuals reporting such concerns, indeed the present research cohort were adults exposed to generic day to day environmental noise, having speech understanding in noise difficulty and clinically normal audiograms. Therefore, it is not clear whether the findings from the existing literature can be applied to the speech understanding concerns of the present research cohort or other similar populations.

The presence of a peripheral hearing loss can make speech perception challenging especially in noise (Plomp & Duquesnoy, 1982; Smoorenburg, de Laat, & Plomp, 1982; Dubno, Dirks, & Morgan, 1984). Earlier research studies in adults with hearing loss found that peripheral hearing loss was an important contributor to speech understanding difficulty (refer Humes & Dubno, 2010 for a review). The most common approach to address peripheral hearing loss is to provide amplification using hearing devices. Frequencies between 1 kHz to 4 kHz were reported to be most important for speech perception abilities (Van Rooij & Plomp, 1990; Van Rooij & Plomp, 1992; Jerger et al., 1991; Dubno & Dirks, 1992; Dubno & Ahlstrom, 1995a,b). Consequently, in the presence of hearing loss, providing appropriate amplification across the frequency range was thought to result in adequate speech perception abilities.

Studies evaluating self-reported satisfaction using hearing aid devices, however, have shown satisfaction in quiet but, largely, not in the presence of noise (Kochkin, 2000; Kochkin, 2005).

It appears that irrespective of hearing loss, there exists a common concern that clinical practice is battling with, i.e. why some people with and without hearing impairment report difficulty understanding speech in noise.

Speech understanding in noise

The report given by the Committee on Hearing, Bioacoustics and Biomechanics (CHABA, 1988), emphasized evaluating auditory and cognitive factors and its contribution to speech understanding particularly in the presence of noise. Subsequent to the CHABA report, there have been several studies that have focused on evaluating the contribution of auditory and cognitive skills such as working memory, cognitive spare capacity and attention on speech understanding, particularly in individuals with hearing loss (Lunner, 2003; Shinn-Cunningham & Best, 2008; Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013; Mishra et al., 2014; Keidser et al., 2015) and have found both auditory and cognitive factors to be important for speech understanding (Humes, Kidd, & Lentz, 2013).

The present research has been designed based on the understanding gained from the CHABA and the more recent Framework for Understanding Effortful Listening (FUEL) model by Pichora-Fuller et al. (2016) which emphasizes the contribution of both auditory and cognitive skills for speech understanding, particularly in the presence of noise. These models suggest that difficulty listening in noise cannot be just an outcome of hearing loss, factors such as cognitive load or demand should also be considered in order to explore this issue. There are several other studies in the literature that support the evidence of auditory-cognitive interactions on listening in presence of noise (Bregman, 1990; McAdams & Bigand, 1993;

Neuhoff, 2004). The current project was, therefore, designed to explore the auditory-cognitive processes as the framework that underlies speech understanding in noise.

The CHABA and FUEL model talk about the importance of auditory and cognitive factors, however, the exact nature of the auditory or cognitive skills that tap into speech understanding skills is not well defined. For instance, auditory processing is an umbrella term that encompasses various subskills such as: localization, lateralization, auditory discrimination including spectral discrimination and resolution, temporal resolution, temporal integration, temporal discrimination, temporal ordering, and temporal masking (ASHA, 1996; ASHA, 2005; Henry et al., 2005). Similarly, cognitive processing is also an umbrella term and encompasses attention, working memory and other aspects such as cognitive spare capacity and statistical learning to name a few. Nevertheless, there is research that has highlighted individual subskills that are linked to speech understanding in noise (Pichora-fuller & Singh, 2006; Shinn-cunningham & Best, 2008; Conway et al., 2010; Mishra et al., 2014).

Routine clinical audiological evaluation involves pure tone audiometric testing which gives a measure of hearing sensitivity, along with speech audiometry, usually conducted in quiet as a single word recognition task (Carhart, 1946). Pure-tone testing gives an estimate of an individual’s hearing but does not directly address the auditory complaints that the individual may report. Similarly, speech tests conducted in quiet and with few contextual cues provided a poor test of functional performance in everyday listening conditions. When conducted in noise, speech audiometry gives an estimate of the signal to noise ratio at which an individual perceives the target signal 50% of the time, usually utilising a single noise source at the rear or side of the patient. Again, these tests do not replicate a real life experience of listening in noise where noise fields are diffuse and noise type and level may vary dramatically. Most speech tests, in clinics, involve the individual repeating words (recognition) presented in quiet and steady white noise, while in real life, we need to understand (comprehend) speech in a variety of noise types. In summary, the routine audiological evaluations are neither sufficient nor appropriate to address an individual's speech understanding difficulties in noise. Therefore, the present study has tried to incorporate auditory and cognitive tests that could possibly overcome the drawbacks of the tests used in regular clinical setting and give a better understanding to why the present cohort exhibit speech understanding in noise difficulty. The tests utilised were chosen based on their relevance to the auditory and cognitive aspects of speech understanding.

Auditory and cognitive processing measures and its relevance to speech understanding

Previous studies have reported the contribution of both spectral and temporal processing ability for understanding speech (Henry, Turner, & Behrens, 2005; Hopkins & Moore, 2010). Spectral processing refers to the ability to analyse the absolute and relative changes in a particular sound spectrum (Moore, 2003) while temporal processing refers to the ability to analyse the fluctuations in the sound spectrum across time (Moore, 1997). Some of the studies (Turner & Nelson, 1982; Hall & Wood, 1984; Abel, Krever, & Alberti, 1990; Grant, Summers, & Leek, 1998; Turner, Chi, & Flock, 1999; Leek & Summers, 2001; Henry et al., 2005; Won, Drennan, & Rubinstein, 2007; Feng, Yin, Kiefte, & Wang, 2010) have used tests such as frequency discrimination, iterated ripple noise test, spectral ripple noise test, and modulation detection thresholds. They have found that spectral and temporal processing skills are affected in individuals with hearing loss. In particular, sensorineural hearing loss not only results in reduced audibility but also results in supra-threshold deficits such as poor frequency selectivity and reduced temporal processing (see Moore, 2007 for a review) leading to lack of clarity in the perceived speech signal (Glasberg & Moore, 1988).

Reduced spectral and temporal resolutions are believed to adversely affect speech perception and understanding particularly in the presence of noise (Moore, 1985). For instance a review by Oxenham (2008) in individuals with hearing loss has suggested that temporal pitch processing is affected in individuals with hearing loss. Similarly, a study conducted by Leek and Summers (2001) showed poor rate-pitch processing abilities in individuals with hearing loss when tested using iterated ripple noise test. The ability to process pitch is considered an important cue to identify the speaker, especially in situations where there is competing noise (Shinn-Cunningham & Best, 2008). Therefore, in the present research we included a test measuring temporal pitch processing ability.

Another temporal processing ability that is important for speech perception is the use of temporal envelope cues (Gordon-salant & Fitzgibbons, 1993; Healy & Warren, 2003), in particular the amplitude envelope cues are the ones that provide information about manner, voicing, stress and intonation which is important for phoneme identification (Rosen, 1992). In order to decipher the given target speech it is important for one to adequately perceive the given speech signal. Considering that individuals with hearing loss have difficulty in resolving the spectral details of the signal, they are expected to rely more on the temporal cues to decipher the given signal (Healy & Warren, 2003; Hedrick & Younger, 2003). Therefore, in the present research a test assessing temporal envelope perception was included. Similarly, good spectral resolution is required for one to identify the target stimulus, especially when the spectral contrast is poor in the target speech, which can result, for example, from some of the existing compression based hearing aid processing algorithms. (Moore & Glasberg, 1986; Kates, 2010). Most often spectral processing ability is assessed by examining frequency and intensity resolution skills (Moore, 2003). Frequency resolution refers to one's ability to identify and discriminate the frequency components present in the auditory signal, commonly assessed using tests such as frequency discrimination and psychophysical tuning curves (Moore, 1995). Intensity resolution refers to one's ability to detect intensity related changes in the sound signal and it is commonly assessed using intensity discrimination tests. Spectral information provides important cues required for adequate identification of vowels (Turner & Henn 1989) and consonants (Thibodeau & Van Tasell 1987; Rosen 1992). Some of the studies conducted to evaluate spectral processing abilities in individuals with hearing loss using spectral ripple discrimination tests have shown significant correlation between spectral ripple discrimination and speech perception in quiet and noise (Henry et al., 2005; Won et al., 2007). Therefore, in the present study we have included a test of frequency discrimination and the spectral ripple discrimination test in order to evaluate spectral processing ability. To a certain extent these abilities have been evaluated in individuals with hearing loss, however, what is not known is whether these abilities contribute to the speech understanding in noise performance in those who self-report having speech in noise concerns.

To the author's knowledge, there are limited studies that have tried to investigate these auditory processing skills in individuals having clinically normal audiograms whilst also reporting speech understanding in noise concerns. Temporal processing skills have been found to be affected in older adults with clinically normal audiograms having speech understanding in noise issues, and these skills are believed to be contributing to their speech understanding concern (see Schneider & Pichora-Fuller, 2001 for a review). In older adults these changes in the temporal processing skills are believed to be an outcome of the ageing process. Researchers exploring listening in noise difficulties in individuals having clinically normal audiograms have found that these individuals have poor spectro-temporal processing skills (Stone, Moore, & Greenish, 2008; Kumar et al., 2012), however, the individuals involved were adults who were exposed to high levels of occupational noise on a daily basis. The cohort in the present study are young adults who were exposed to regular, day to day environmental noise. Therefore, the existing findings in the literature on individuals having clinically normal audiograms reporting a speech understanding in noise concern provide very limited insight to the problem that the present research cohort is reporting.

Tests of cognitive skills such as working memory, attention, cognitive spare capacity and statistical learning were selected based on their relevance to speech understanding abilities, particularly in complex scenarios such as the presence of noise (Pichora-fuller & Singh, 2006; Shinn-cunningham & Best, 2008; Conway et al., 2010; Mishra et al., 2014). Working memory capacity refers to the ability to simultaneously process and store task related information (Daneman & Carpenter, 1980; Baddeley, 1986). The role of working memory is believed to depend on the listening condition, for instance whether speech is perceived in the presence of background noise or in quiet (Rudner, Rönnberg, & Lunner, 2011). The ease of language understanding model describes the role of working of working memory capacity (Rönnberg, 2003; Rönnberg et al., 2008). When speech is presented in optimal conditions such as quiet, the input received is clear and intact and therefore the access to the mental lexicon is mostly automatic and implicit. However, in adverse conditions such as in the presence of noise the incoming signal is mostly distorted and therefore more explicit processing is required to match the given signal to the mental lexicon. Therefore, it is suggested that having a good working memory capacity would enable one to efficiently process under difficult listening conditions.

Working memory has been reported to be an important factor in perception of speech in the presence of noise, particularly in individuals with hearing loss (Rudner, Rönnberg, & Lunner, 2011). Studies conducted (Lunner, 2003; Ng et al., 2013) in individuals with hearing loss showed that individuals with higher working memory capacity were able to perform better than individuals with lower working memory capacity on speech in noise tasks. Therefore, the present research included a test of working memory to see if there were any differences in individuals self-reporting a speech in noise concern.

On a daily basis, an individual often encounters speech in the presence of multiple talkers. In such situations, an individual is required to selectively pay attention to the desired signal while ignoring the irrelevant signals (Alport, 1989; Posner, 1991). A review has highlighted the importance of selective attention for speech understanding in complex listening conditions, where individuals with hearing loss show a poor performance across selective attention tasks (Shinn-Cunningham & Best, 2008). Similarly, another type of attentional skill that is required for adequate perception of speech and understanding is attention switching (Shinn-Cunningham & Best, 2008). In a real life scenario, one may encounter situations where conversation occurs in the presence of multiple talkers, in such a scenario one needs to quickly switch attention when one topic and talker deviates to another. At least in one paper, individuals with hearing loss have been reported to have poor attention switching skills (Shinn-Cunningham & Best, 2008). In the current research, we hypothesized that individuals with reported difficulties in understanding speech in the presence of noise may have difficulty in selective attention and attention switching and therefore, the present research includes tests measuring both selective attention and attention switching.

One of the cognitive measures that is less explored in literature on speech in noise performance is the cognitive spare capacity test. Cognitive spare capacity can be defined as the residual capacity available for processing the information heard once listening has taken place successfully (Rudner et al., 2011). Some of the cognitive processing skills involved during the process of understanding speech are; 1) inhibition, which refers to the ability to inhibit irrelevant information, in this case, the other talkers (babble); 2) updating, which refers to the ability to update to the new incoming signal and; 3) shifting, which refers to the ability to select and switch to the required information (Miyake et al., 2000). Cognitive spare capacity tests aim to provide information on the remaining cognitive resources as listening task difficulty is varied (see Rudner & Lunner, 2013 for a review). Cognitive spare capacity in individuals with hearing loss has been shown to be reduced in comparison to individuals with normal hearing under a variety of listening conditions (Mishra et al., 2014; Keidser et al., 2015). The lower performance on cognitive spare capacity tests by individuals with hearing loss is believed to occur due to the need to allocate more of the available cognitive resources for the perception of the signal, allowing less cognitive capacity for other cognitive processing skills such as inhibition and updating. Therefore, we anticipated that the cohort in our study who complain of speech understanding in noise problems may have lower cognitive spare capacity scores, indicating that they are not able to use the required cognitive processing skills for higher level functions such as understanding speech in the presence of background noise.

Statistical learning is another cognitive measure that has recently gained prominence in studies exploring how understanding speech occurs in the presence of noise (Neger et al., 2014). Statistical learning may be defined as the ability to implicitly learn the regularities in the environment or language (Perruchet & Pacton, 2006). A recent study by Conway et al. (2010) found statistical learning correlated with word predictability. Predicting the incoming word is an important skill particularly when listening to speech in the presence of noise. Access to lexical information or contextual knowledge prior pre-lexical processing helps facilitate speech perception particularly in adverse conditions where speech is ambiguous (Elliott, 1995; McClelland et al., 2006). Therefore, it is not unreasonable to assume that individuals with speech understanding in noise difficulty may have poor statistical learning abilities. Statistical learning though, has not been much explored in adults with hearing loss or in adults with speech in noise difficulty. A study conducted by Conway et al. (2011) in deaf children with cochlear implants utilising implicit visual sequence learning revealed that that they had poor visual implicit sequence learning compared to their counterparts with normal hearing. Therfore in the present research we included a test of both auditory and visual statistical learning to evalute if adults with reported understanding speech in noise difficulty have any differences in these skills compared to individuals with no difficulty.

To date, there is some evidence exploring the impact of cognitive processing skills on speeh understanding ability in inivdiuals with hearing loss. Studies have also been conducted with a focus on either older adults with clinically normal hearing and speech understanding in noise concerns (see Schneider, Pichora-fuller, & Daneman, 2010 for a review) or those exposed to high levels of noise on a daily basis, with clinically normal hearing and understanding speech in noise difficulty (Kujala et al., 2004; Bressler, Goldberg, & Shinn-Cunningham, 2017) and have found deficits in either attention, working memory, or both. However, as mentioned earlier, the cohort in the present research are younger adults having an unremarkable environmental noise expsoure and therefore, the relevance of the findings in the existing literature can not necessarily be inferred to the present cohort. In addition, to date there are no studies that have used cognitive tests such as statistical learning and cognitive spare capacity to study individuals reporting understanding speech in noise difficulty with clinically normal audiograms. The present research therefore encompasses a cognitive test battery that includes most of the cognitive tests reported to have contributed to speech understanding particularly in noise.

Figure 1. shows the schematic representation of the interrelationship between speech understanding and the relevant auditory and cognitive measures that we have included in the research. We hypothesized that the cohort in the study who report difficulty understanding speech in the presence of noise will show deficits in the tests measuring the chosen auditory and cognitive skills.

Self-report of listening in noise concerns

The self-report of listening in noise concerns can be obtained in two ways; 1) interview: an interview would normally involve a face to face conversation between the researcher and the participant wherein details regarding the problem such as the onset, impact of the issue in daily life and many other details would be collected; 2) Questionnaire: the administration of a questionnaire would normally involve the participant either rating or describe the problem depending on the type of questionnaire used. An open-ended questionnaire would normally involve the participant describing the problem whereas a closed ended questionnaire would involve rating each question on a given scale. Even though the interview approach would give a deeper insight to the individual's problem it is time consuming and potentially difficult to analyse. Considering that the current research included a vast test battery comprising of various auditory and cognitive tests measured behaviourally and electrophysiologically, a closed questionnaire was chosen as a method to obtain information on the self-reported listening in noise concerns.

Some of the evidence on hearing aid outcomes such as satisfaction and speech tests show that routine speech tests are not sufficient to predict hearing aid satisfaction outcomes i.e. they may not be able to answer why the satisfaction with the hearing aid is high or low (see Taylor, 2007 for a review) and therefore the use of self-report measures is recommended. Furthermore, some studies conducted in adults with hearing loss have shown that performance on cognitive based tests were related to their self-reported hearing difficulties (Ng, Rudner, Lunner, & Rönnberg, 2013; Zekveld, George, Houtgast, & Kramer, 2013). As such in the present research a self-report of listening issues questionnaire was included to provide an insight into the problem the individual is facing in a more functional or real life scenario.

Behavioural and Physiological measures

In the current study, auditory and cognitive skills were evaluated using both behavioural and physiological measures. The physiological test battery included cortical evoked potentials (CAEPs). CAEPs have most commonly been used to detrmine the neurophysiological processing that underlie speech understanding and perception (Purdy et al., 2001; Tremblay, Piskosz, & Souza, 2003; Kutas & Federmeier, 2011). The main advantage of using CAEPs over other techniques such as auditory brainstem response is that it can be reliably evoked using consonant-vowels (such as /da/) (Tremblay, Friesen, Martin, & Wright, 2003) as well as sentences (Kutas & Federmeier, 2011), which provides a clear perspective on how speech is processed at the level of cortex. Cortical evoked potentials are classified into two types; 1) obligatory event related potentials and; 2) Cognitive event related potentials. An example of an obligatory event related potential would be the P1-N1-P2 complex whose latency and amplitude are driven by the acoustic parameters of the stimuli and an adequate auditory pathway. In contrast, cognitive event related potentials also known as endogenous event related potentials are the ones whose performance depends on the listener's attention and performance on the given task. For example, in the P300 response, a positive peak seen around 300 ms at Pz, is evoked when performing attention based tasks (see Cone-Wesson & Wunderlich, 2003 for a review). The neural generators for the obligatory potentials are believed to be sourced from the primary auditory cortex and the auditory association areas of the temporal lobe (Lütkenhöner & Steinsträter, 1998; Picton et al., 1999), while the cognitive or endogenous potentials are generated from the frontal lobe, hippocampus and primary auditory cortices (Picton, 1992).

Time locked and time frequency analyses carried out on the recorded CAEPs provide information on the underlying auditory and cognitive mechanisms that contribute to the task in question., For instance the P1-N1-P2 components of the cortical auditory evoked potentials (CAEPs) provides information on performance of the auditory areas for the given stimuli as they are believed to be generated from auditory thalamocortical, primary auditory cortex and various other association cortices (Näätänen & Picton, 1987; Ponton et al., 2002). Similarly, the information derived from alpha and beta oscillations are believed to be the outcome of cognitive mechanisms such as attention and memory retrieval (Klimesch, 2012; Sacchet et al., 2015). The P1-N1-P2 complex elicited by speech sounds has been used in various research domains for example, to understand the neural representation of speech cues, and to determine the speech discrimination skills in individuals with hearing loss post hearing aid fitting (Tremblay, Piskosz, & Souza, 2003; Durante et al., 2014). The auditory evoked potentials elicited using sentences, generally referred to as cognitive driven event related potentials (ERPs) are observed at a later latency of the waveform. The ERPs such as the N400 is observed at 300-600 ms, elicited at a cortical level indicating language processing by stimuli such as words and sentences (Kutas & Hillyard, 1980). The N400 is elicited only when presented with semantically inappropriate sentences, for example “the nanny fried the conflict on the stove” versus “the nanny fried the bacon in the stove”. The former sentence in this example is a semantically inappropriate sentence for which we would see a negative deflection occurring around 300-600 ms while the latter sentence is a semantically appropriate one for which we would not see the negative deflection. There are two theories explaining the occurrence of the N400. One is the integration view that believes the negative deflection occurs due to the time taken for semantically inappropriate sentences to integrate with already existing knowledge and the present context. Second, the lexical view believes the negative deflection occurs as an outcome of semantically inappropriate words taking a longer duration to access the given word from the long term memory when compared to semantically appropriate words which are relatively easily accessed (see Kutas & Federmeier, 2011 for a review). Both the P1-N1-P2 and N400 uses speech stimuli for eliciting the required response. Considering that the present cohort are individuals with speech understanding concerns, the chosen auditory evoked potential measures such as the P1-N1-P2 and N400 enable us to determine the underlying cortical processing when tasks such as speech perception and understanding are involved. To date, CAEPs have been most commonly used to study the auditory system development, threshold estimation, auditory discrimination abilities, and benefits from cochlear implantation, hearing aid amplification, and auditory training (see Cone-Wesson & Wunderlich, 2003 for a review). This is one of the first studies to use CAEPs as an exploratory measure to determine speech understanding abilities in individuals who report listening in noise concerns.

In addition to these advantages the use of physiological measures also helps to avoid the subject and experimenter bias which maybe encountered when using behavioural measures. However, the information obtained on the behavioural measures is as important as physiological measures and cannot be ignored. The behavioural measures are believed to provide information about an individuals' true hearing ability while physiological measures are believed to provide information on auditory functions (Folsom & Diefendorf, 1999). In a review study conducted by Billings (2013) on the uses and limitations of electrophysiological tests in hearing aid fitting in adults with hearing loss it was shown that physiological tests cannot be considered to be the perfect approach in the rehabilitative sector due to the vast variability present in the clinical population. Therefore, in the present study we have included both physiological and behavioural measures.

In summary

Overall, the existing literature investigating speech understanding in noise concerns in adults with and without hearing loss is still unclear. As reviewed, most studies conducted to determine speech understanding in noise difficulty in adults with clinically normal audiograms have been explored in populations comprised of either older adults (see Schneider, Pichora-fuller, & Daneman, 2010 for a review) or those adults exposed to occupation noise (Kujala et al., 2004; Bressler et al., 2017). In contrast, the present research encompasses adults (mean age: 40 years) with clinically normal audiograms exposed to generic daily life environmental noise. On the other hand, even though there is evidence to suggest compromised auditory and cognitive processing skills in individuals with hearing loss, understanding how all these auditory and cognitive processing skills contributes to speech understanding in noise performance is still lacking.

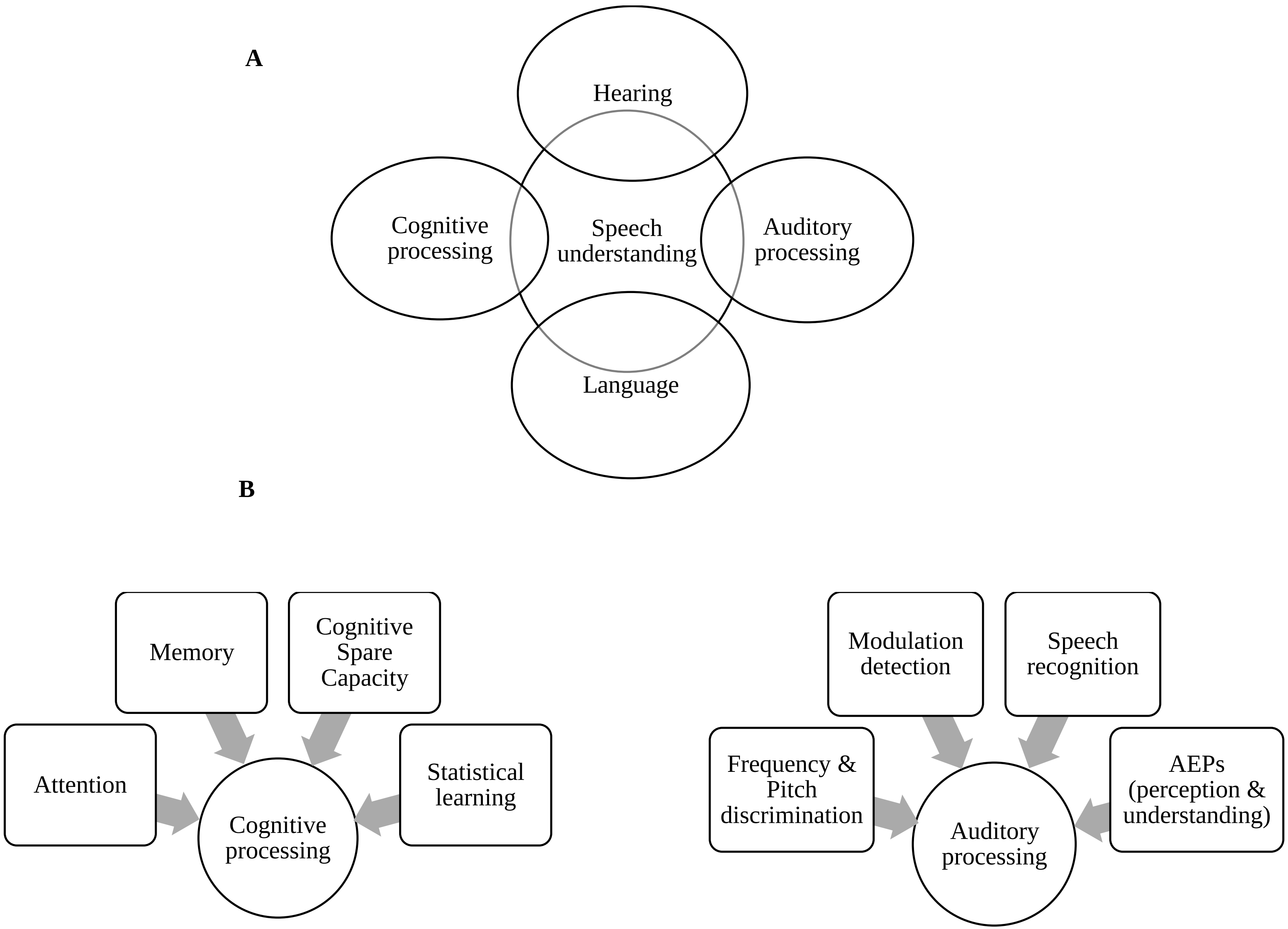
To date, there are limited studies that have been conducted on both adults with and without hearing loss *self-reporting* a listening in noise difficulty. The present research is one of the very few studies to have considered both auditory and cognitive factors and its impact on speech understanding abilities. To the author's knowledge, this is one of the first studies to have explored physiological measures such as the CAEPs to determine the underlying differences on speech perception and understanding in adults with and without hearing loss reporting of a speech understanding in noise issue.

The aims of the study are:

1) To identify the differences in performances on auditory, and cognitive skills amongst adults with and without hearing loss having listening in noise concerns in comparison to the control group having normal hearing sensitivity and no listening in noise concerns.

2) To determine the underlying differences in neural processing amongst adults with and without hearing loss having listening in noise concerns in comparison to the control group having normal hearing sensitivity and no listening in noise concerns.

Figure 1: Schematic diagram showing [A] the association between speech understanding and auditory and cognitive and language skills and [B] shows the tasks used in the current research for cognitive and auditory processing


A
Hearing
Cognitive processing
Speech understanding
Auditory processing
Language
B
Memory
Cognitive Spare Capacity
Attention
Statistical learning
Cognitive processing
Modulation detection
Speech recognition
Frequency & Pitch discrimination
AEPs (perception & understanding)
Auditory processing

Organization of Thesis

The thesis includes five chapters; an introduction, followed by three papers, and then an overall discussion. The referencing style for the first and fifth chapters was the recommended American Psychological Association (6th edition). The referencing style for the second, third and fourth chapters were based on the requirement of the specific journals.

Chapter 1

Chapter 1 gives an overall introduction to the thesis. It provides information on the main theme of the thesis, the methodology, the population, and the reason as to why the respective population was chosen for the study.

Chapter 2 and 3 are a part of study 1. In this chapter, we studied the auditory and cognitive performances of adults with reported listening in noise concerns having clinically normal audiograms using behavioural and physiological measures. The study group consisted of adults in the age range of 19-62 years. The mean age for the group with listening concerns in noise was 40 years while for the group with no concerns was 30 years.

Chapter 2

This is the first paper submitted to the journal Ear and Hearing. Adults with and without reported listening in noise concerns having clinically normal audiograms were tested on various auditory, cognitive and speech in noise tests. The tasks included in this study examined skills such as spectral and temporal processing skills, attention, working memory, statistical learning, cognitive spare capacity and speech in noise tests. The results indicated no significant differences between the two groups on any of the tasks. The results obtained may suggest that the individuals with listening concerns in noise are compensating for speech understanding difficulty using cognitive skills, their self-reports of difficulty therefore may reflect the fact that they are not able to use them in a real-life scenario. The chapter identifies some limitations that need to be considered in future studies.

Chapter 3

This chapter is the third paper and has been submitted to the journal Hearing Research. In this chapter, we aimed to evaluate the sentence-evoked N400 in adults with and without listening in noise concerns having clinically normal audiograms. N400 is an event related potential, a negative deflection obtained on presenting semantically incongruent sentences. The results obtained from the study showed significant N400 responses only for the group with no listening in noise concern. The N400 response is believed to be driven by linguistic-cognitive factors such as attention and word predictability. Word predictability refers to the ability to predict the incoming word using contextual cues. On evaluation of the onset response to the sentences, both the groups showed no difference implying that the percept of the sentences were similar for both groups. These findings suggest individuals with listening in noise problems may have difficulty with speech understanding but not with speech perception. This may explain why we see no difference on the onset response yet see an absent N400. In addition, time frequency analysis carried out on this data showed strong synchronised alpha oscillations for the group with no listening in noise concerns. These alpha oscillations were observed at the temporal region when presented with semantically congruent and incongruent sentences and from the frontal region on presenting semantically incongruent sentences. The presence of strong synchronised alpha oscillation only for the group with no listening in noise concerns may indicate these individuals to have better attention abilities which enables them to sustain their attention throughout the task.

Chapter 4

This chapter is the third paper and will be submitted to Clinical Neurophysiology. Chapter 4 is a part of study 2. In this study we aimed to determine the difference in performances on auditory, cognitive and speech in noise measures in individuals with hearing loss who report a speech understanding in noise difficulty. The results from the study indicated no significant differences in performance between the groups with hearing loss and the control group (no hearing loss and no reported listening concern) on all behavioural tests. On physiological measure, time frequency analysis revealed significant alpha oscillations only for the control group in the quiet condition. These alpha oscillations are an outcome of the differences underlying attention and inhibition abilities between the two groups.

Chapter 5

This is the overall discussion of the thesis that collates all the 3 study results, contribution to the field, limitations and future research, and conclusions and implications. The main highlight from all three studies conducted is that, physiological tests appear more sensitive than behavioural tests in the investigation of speech in noise concerns.

Authors' contributions

Shivali Appaiah and Mridula Sharma planned the concept for the research project. Shivali Appaiah with the help of Jessica J M Monaghan and Joaquin T Valderrama designed the auditory processing tests and N400. Shivali Appaiah with help of Mridula Sharma and Gitte Keidser decided on the auditory and cognitive tests to be applied in the current study. Shivali Appaiah recruited the participants and collected the data. The data analysis for study 1 (Chapter 2) was carried out by Shivali Appaiah with inputs from Mridula Sharma and Gitte Keidser. The data analysis for study 2 and 3 (Chapter 3 and 4) was carried out by Shivali Appaiah with inputs from Mridula Sharma, Joaquin T Valderrama, and Ronny Ibrahim. The manuscript for study 1 (Chapter 2) was mainly prepared by Shivali Appaiah with inputs from Mridula Sharma, Jessica J M Monaghan, Joaquin T Valderrama, Gitte Keidser, and John Newall. The manuscript for study 2 (Chapter 3) was mainly prepared by Shivali Appaiah with inputs from Mridula Sharma, Joaquin T Valderrama, Ronny Ibrahim and Jessica J M Monaghan. The manuscript for study 3 (Chapter 4) was mainly prepared by Shivali Appaiah with inputs from Mridula Sharma, Joaquin T Valderrama, Jessica J M Monaghan, Ronny Ibrahim and John Newall.

References

Baddeley, A. (1986). Working Memory. Cambridge: Oxford University Press.

Abel, S. M., Krever, E. M., & Alberti, P. W. (1990). Auditory detection, discrimination and speech processing in ageing, noise-sensitive and hearing-impaired listeners. *Scandinavian Audiology*, *19*(1), 43–54. http://doi.org/10.3109/01050399009070751

Alport, A. (1989). Foundations of cognitive science.

Alvord, L. S. (1983). Cochlear dysfunction in“ normal-hearing” patients with history of noise exposure. *Ear and Hearing*, *4*(5), 247–50. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6628849

ASHA. (1996). American Speech-Language-Hearing Association. *Current Status of Research and Implications for Clinical Practice.*

ASHA. (2005). American Speech-Language-Hearing Association. *(Central) Auditory Processing Disorders.*

Billings, C. J. (2013). Uses and limitations of electrophysiology with hearing aids. *In Seminars in Hearing*, *34*(4), 257.

Bregman, A. S. (1990). Auditory scene analysis. the perceptual organizarion of sound, (Cambridge: MIT press).

Bressler, S., Goldberg, H., & Shinn-Cunningham, B. (2017). Sensory coding and cognitive processing of sound in Veterans with blast exposure. *Hearing Research*, *349*, 98–110. http://doi.org/10.1016/j.heares.2016.10.018

Carhart, R. (1946). Selection of hearing aids. *Archives of Otolaryngology*, *44*(1), 1–18.

Committee on Hearing and Bioacoustics and Biomechanics (CHABA) (1988). Speech understanding and aging. *The Journal of the Acoustical Society of America*. *83*, 859–895.

Cone-Wesson, B. Wunderlich, J. (2003). Auditory evoked potentials from the cortex: audiology applications. *Current Opinion in Otolaryngology & Head and Neck Surgery*, *11*(5), 372–377.

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition*, *114*(3), 356–371. http://doi.org/10.1016/j.cognition.2009.10.009

Conway, C. M., Pisoni, D. B., Anaya, E. M., Karpicke, J., & Henning, S. C. (2011). Implicit sequence learning in deaf children with cochlear implants. *Developmental Science*, *14*(1), 69–82. http://doi.org/10.1111/j.1467-7687.2010.00960.x

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavio*, *19*(4), 450–466.

Dubno, J. R., & Ahlstrom, J. (1995a). Growth of low-pass masking of pure tones and speech for hearing-impaired and normal-hearing listeners. *The Journal of the Acoustical Society of America*, *98*(6), 3113–3124. http://doi.org/10.1121/1.413800

Dubno, J. R., & Ahlstrom, J. B. (1995b). Masked threshold and consonant recognition in low-pass maskers for hearing-impaired and normal-hearing listeners. *Journal of the Acoustical Society of America*, *97*(4), 2430–2441. http://doi.org/10.1121/1.411964

Dubno, J. R., Dirks, D. D., & Morgan, D. E. (1984). Effects of age and mild hearing loss on speech recognition in noise. *The Journal of the Acoustical Society of America*, *76*(1), 87–96. http://doi.org/10.1121/1.391011

Durante, A. S., Wieselberg, M. B., Carvalho, S., Costa, N., Pucci, B., Gudayol, N., & Almeida, K. de. (2014). Cortical Auditory Evoked Potential: evaluation of speech detection in adult hearing aid users. *CoDAS*, *26*(5), 367–373. http://doi.org/10.1590/2317-1782/20142013085

Elliott, L. L. (1995). Verbal Auditory Closure and the Speech Perception in Noise (SPIN) Test. *Journal of Speech and Hearing Research*, *38*(6), 1363–1376. http://doi.org/10.1044/jshr.3806.1363

Feng, Y., Yin, S., Kiefte, M., & Wang, J. (2010). Temporal Resolution in Regions of Normal Hearing and Speech Perception in Noise for Adults with Sloping High-Frequency Hearing Loss. *Ear & Hearing*, *31*(1), 115–125.

Folsom, R. C., & Diefendorf, A. O. (1999). Physiologic and behavioural approaches to pediatric hearing assessment. *Pediatric Clinics of North America*, *46*(1), 107–120.

Gatehouse, S., & Akeroyd, M. A. (2008). The effects of cueing temporal and spatial attention on word recognition in a complex listening task in hearing-impaired listeners. *Trends in Amplification*, *12*(2), 145–161.

Glasberg, B. R., & Moore, B. C. (1988). Psychoacoustic abilities of subjects with unilateral and bilateral cochlear hearing impairments and their relationship to the ability to understand speech. *Scandinavian Audiology*, 32, 1-25

Gordon-salant, S., & Fitzgibbons, P. J. (1993). Temporal Factors and Speech Recognition Performance in Young and Elderly Listeners. *Journal of Speech and Hearing Research*, *36*(6), 1276–1285.

Grant, K. W., Summers, V., & Leek, M. R. (1998). Modulation rate detection and discrimination by normal-hearing and hearing-impaired listeners. *The Journal of the*

Acoustical Society of America, *104*(2), 1051–1060. http://doi.org/10.1121/1.423323

Hall, J. W., & Wood, E. J. (1984). Stimulus duration and frequency discrimination for normal-hearing and hearing-impaired subjects. *Journal of Speech, Language, and Hearing Research*, *27*(2), 252–256.

Healy, E. W., & Warren, R. M. (2003). The role of contrasting temporal amplitude patterns in the perception of speech. *Journal of the Acoustical Society of America*, *113*(3), 1676–1688.

Hedrick, M. S., & Younger, M. S. (2003). Labeling of/s/and/ʃ/by listeners with normal and impaired hearing, revisited. *Journal of Speech, Language, and Hearing Research*, *46*(3), 636–648.

Henry, B. A., Turner, C. W., & Behrens, A. (2005). Spectral peak resolution and speech recognition in quiet: normal hearing, hearing impaired, and cochlear implant listeners. *The Journal of the Acoustical Society of America*, *118*(2), 1111–1121. http://doi.org/10.1121/1.1944567

Hind, S. E., Haines-Bazrafshan, R., Benton, C. L., Brassington, W., Towle, B., & Moore, D. R. (2011). Prevalence of clinical referrals having hearing thresholds within normal limits. *International Journal of Audiology*, *50*(10), 708–716. http://doi.org/10.3109/14992027.2011.582049

Hopkins, K., & Moore, B. C. (2010). The importance of temporal fine structure information in speech at different spectral regions for normal-hearing and hearing-impaired subjects. *The Journal of the Acoustical Society of America*, *127*(3), 1595–1608.

Humes, L. E., & Dubno, J. R. (2010). Factors affecting speech understanding in older adults. *In The Aging Auditory System*, 211–257.

Humes, L. E., Kidd, G. R., & Lentz, J. J. (2013). Auditory and cognitive factors underlying individual differences in aided speech-understanding among older adults. *Front Syst Neurosci*, *7*, 55. http://doi.org/10.3389/fnsys.2013.00055

Jerger, J., Jerger, S., & Pirozzolo, F. (1991). Correlational analtric scoreysis of speech audiomes, hearing loss, age, and cognitive abilities in the elderly. *Ear & Hearing*, *12*(2), 103–109.

Kates, J. M. (2010). Understanding compression: Modeling the effects of dynamic-range compression in hearing aids. *International journal of audiology*, *49*(6), 395-409.

Keidser, G., Best, V., Freeston, K., & Boyce, A. (2015). Cognitive spare capacity: Evaluation data and its association with comprehension of dynamic conversations. *Frontiers in Psychology*, *6*, 597. http://doi.org/10.3389/fpsyg.2015.00597

King, P. F. (1954). Psychogenic deafness. *The Journal of Laryngology & Otology*, *68*(9), 623–625.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. http://doi.org/10.1016/j.tics.2012.10.007

Kochkin. (2005). MarkeTrak VII: Customer satisfaction with hearing instruments in the digital age. *The Hearing Journal*, *58*(9), 30–32. http://doi.org/10.1097/01.HJ.0000286545.33961.e7

Kochkin, S. (2000). “MarkeTrak V:”Why my hearing aids are in the drawer" The consumers’ perspective. *The Hearing Journal*, *53*(2), 34–36.

Kujala, T., Shtyrov, Y., Winkler, I., Saher, M., Tervaniemi, M., Sallinen, M., … Näätänen, R. (2004). Long-term exposure to noise impairs cortical sound processing and attention control. *Psychophysiology*, *41*(6), 875–881. http://doi.org/10.1111/j.1469-8986.2004.00244.x

Kujawa, S. G., & Liberman, M. C. (2015). Synaptopathy in the noise-exposed and aging cochlea: Primary neural degeneration in acquired sensorineural hearing loss. *Hearing Research*, *330*, 191–199. http://doi.org/10.1016/j.heares.2015.02.009

Kumar, U. A., Ameenudin, S., & Sangamanatha, A. V. (2012). Temporal and speech processing skills in normal hearing individuals exposed to occupational noise. *Noise and Health*, *14*(58), 100–105.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*, *62*, 621–47. http://doi.org/10.1146/annurev.psych.093008.131123

Kutas, M., & Hillyard, S. A. (1980). Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biological Psychology*, *11*(2), 99–116. http://doi.org/10.1016/0301-0511(80)90046-0

Leek, M. R., & Summers, V. (2001). Pitch strength and pitch dominance of iterated rippled noises in hearing-impaired listeners. *The Journal of the Acoustical Society of America, 109*(6), 2944–2954. http://doi.org/10.1121/1.1371761

Liberman, M. C., Epstein, M. J., Cleveland, S. S., Wang, H., & Maison, S. F. (2016). Toward a differential diagnosis of hidden hearing loss in humans. *PLoS ONE*, *11*(9), e0162726. http://doi.org/10.1371/journal.pone.0162726

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

Lütkenhöner, B., & Steinsträter, O. (1998). High-precision neuromagnetic study of the functional organization of the human auditory cortex. *Audiology and Neurotology*, *3*(2–3), 191–213.

Mattys, S. L., Davis, M. H., Bradlow, A. R., & Scott, S. K. (2012). Speech recognition in adverse conditions : A review. *A Review. Language and Cognitive Processes*, *27*, 953–978. http://doi.org/10.1080/01690965.2012.705006

McAdams, S. E., & Bigand, E. E. (1993). *In Based on the Fourth Workshop in the Tutorial Workshop Series Organized by the Hearing Group of the French Acoustical Society*, (Clarendon Press/Oxford University Press).

McClelland, J. L., Mirman, D., & Holt, L. L. (2006). Are there interactive processes in speech perception? *Trends in Cognitive Sciences*, *10*(8), 363–369. http://doi.org/10.1016/j.tics.2006.06.007

Mishra, S., Stenfelt, S., Lunner, T., Rönnberg, J., & Rudner, M. (2014). Cognitive spare capacity in older adults with hearing loss. *Fronteirs in Aging Neuroscience*, *6*, 96. http://doi.org/10.3389/fnagi.2014.00096

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100.

Moore, B. C. J. (1985). Frequency selectivity and temporal resolution in normal and hearing-impaired listeners. *British Journal of Audiology*, *19*(3), 189–201.

Moore, B. C. J. (1995). Hearing, Academic Press.

Moore, B. C. J. (1997). An Introduction to the Psychology of Hearing. Academic Press. *San Diego*.

Moore, B. C. J. (2003). Coding of sounds in the auditory system and its relevance to signal processing and coding in cochlear implants. *Otology & Neurotology*, *24*(2), 243–254.

Moore, B. C. J. (2007). *Cochlear hearing loss: physiological, psychological and technical issues*. John Wiley & Sons.

Moore, B. C. J., & Glasberg, B. R. (1986). The role of frequency selectivity in the perception of loudness, pitch and time. *Frequency Selectivity in Hearing*, 251–308.

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology*, *24*(4), 375–425.

Neger, T. M., Rietveld, T., & Janse, E. (2014). Relationship between perceptual learning in speech and statistical learning in younger and older adults. *Frontiers in Human Neuroscience*, *8*, 628. http://doi.org/10.3389/fnhum.2014.00628

Neuhoff, J. G. (Ed.). (2004). *Ecological psychoacoustics. Amsterdam: Elsevier Academic Press.*

Ng, E. H. N., Rudner, M., Lunner, T., Pedersen, M. S., & Rönnberg, J. (2013). Effects of noise and working memory capacity on memory processing of speech for hearing-aid users. *International Journal of Audiology*, *52*(7), 433–441. http://doi.org/10.3109/14992027.2013.776181

Ng, E. H. N., Rudner, M., Lunner, T., & Rönnberg, J. (2013). Relationships between self-report and cognitive measures of hearing aid outcome Relationships between self-report and cognitive measures of hearing aid outcome. *Speech, Language and Hearing*, *16*(4), 197–207. http://doi.org/10.1179/205057113X13782848890774

Oxenham, A. J. (2008). Pitch perception and auditory stream segregation: implications for hearing loss and cochlear implants. *Trends in Amplification*, *12*(4), 316–331.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: one phenomenon, two approaches. *Trends in Cognitive Sciences*, *10*(5), 233–238. http://doi.org/10.1016/j.tics.2006.03.006

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., … Wingfield, A. (2016). Hearing Impairment and Cognitive Energy. *Ear and Hearing*, *37*, 5S–27S. http://doi.org/10.1097/AUD.0000000000000312

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. http://doi.org/10.1177/108471380601000103

Picton, T. W., Alain, C., Woods, D. L., John, M. S., Scherg, M., Valdes-Sosa, P., ... & Trujillo, N. J. (1999). Intracerebral sources of human auditory-evoked potentials. *Audiology and Neurotology*, *4*(2), 64–79.

Picton, T. W. (1992). The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology*, *9*(4), 456–479.

Plomp, R., & Duquesnoy, A. J. (1982). A model for the speech-reception threshold in noise without and with a hearing aid. *Scandinavian Audiology*, *15*, 95–111.

Ponton, C., Eggermont, J. J., Khosla, D., Kwong, B., & Don, M. (2002). Maturation of human central auditory system activity: separating auditory evoked potentials by dipole source modeling. *Clinical Neurophysiology*, *113*(3), 407–420.

Posner, M. I. (1991). Editor's note: attention as a cognitive neurosystem. *Journal of Cognitive Neuroscience*, *3*(4), 303–303.

Prendergast, G., Guest, H., Munro, K. J., Kluk, K., Léger, A., Hall, D. A., … Plack, C. J.

(2017). Effects of noise exposure on young adults with normal audiograms I: Electrophysiology. *Hearing Research*, *344*, 68–81. http://doi.org/10.1016/j.heares.2016.10.028

Purdy, S. C., Katsch, R. K., Storey, L. M., Dillon, H., & Ching, T. Y. (2001). Slow cortical auditory evoked potentials to tonal and speech stimuli in infants and adults. *In 17th International Evoked Response Audiometry Study Group Biennial Symposium, Vancouver, Canada.*

Rönnberg, J. (2003). Cognition in the hearing impaired and deaf as a bridge between signal and dialogue: a framework and a model. *International Journal of Audiology*, *42*(s1), 68–76. http://doi.org/10.3109/14992020309074626

Rönnberg, J., Rudner, M., Foo, C., & Lunner, T. (2008). Cognition counts: a working memory system for ease of language understanding (ELU). *International Journal of Audiology*, *47 Suppl 2*, S99–S105. http://doi.org/10.1080/14992020802301167

Rosen, S. (1992). Temporal information in speech: acoustic,auditory and linguistic aspects. *Philosophical Transactions: Biological Sciences*, *336*(1278), 367–373. http://doi.org/10.1098/rstb.1992.0070

Rudner, M., & Lunner, T. (2013). Cognitive spare capacity as a window on hearing aid benefit. *Seminars in Hearing*, *34*(4), 298–307. http://doi.org/10.1055/s-0033-1356642

Rudner, M., Ng, H. N., Rönnberg, N., Mishra, S., Rönnberg, J., Lunner, T., & Stenfelt, S. (2011). Cognitive spare capacity as a measure of listening effort. *Journal of Hearing Science*, *1*(2), 47–49.

Rudner, M., Rönnberg, J., & Lunner, T. (2011). Working memory supports listening in noise for persons with hearing impairment. *Journal of the American Academy of Audiology*, *22*(3), 156–167. http://doi.org/10.3766/jaaa.22.3.4

Sacchet, M. D., LaPlante, R. A., Wan, Q., Pritchett, D. L., Lee, A. K. C., Hamalainen, M., … Jones, S. R. (2015). Attention Drives Synchronization of Alpha and Beta Rhythms between Right Inferior Frontal and Primary Sensory Neocortex. *Journal of Neuroscience*, *35*(5), 2074–2082. http://doi.org/10.1523/JNEUROSCI.1292-14.2015

Saunders, G. H., & Haggard, M. P. (1989). The clinical assessment of obscure auditory dysfunction--1. Auditory and psychological factors. *Ear and Hearing*. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2744258

Schneider, B. A., Pichora-fuller, K., & Daneman, M. (2010). Effects of Senescent Changes in Audition and Cognition on Spoken Language Comprehension. *In The Aging Auditory System*, 167–210. http://doi.org/10.1007/978-1-4419-0993-0

Schneider, B. A., & Pichora-Fuller, M. K. (2001). Age-related changes in temporal processing: Implications for listening comprehension. *Seminars in Hearing*, *22*(3), 227–239.

Shinn-cunningham, B. G., & Best, V. (2008). Selective Attention in Normal and Impaired Hearing. *Trends in Amplification*, *12*(4), 1–17. http://doi.org/10.1177/1084713808325306

Shinn, J., Long, A., Rayle, C., Bush, M., Shinn, J., Long, A., … Bush, M. (2016). Primary auditory symptoms in patients with normal peripheral hearing sensitivity : Redefining hearing loss. *Hearing, Balance and Communication*, *14*(1), 44–49. http://doi.org/10.3109/21695717.2016.1095867

Smoorenburg, G. F., de Laat, J. A., & Plomp, R. (1982). The effect of noise-induced hearing loss on the intelligibility of speech in noise. *Scandinavian Audiology*.

Stone, M. A., Moore, B. C., & Greenish, H. (2008). Discrimination of envelope statistics reveals evidence of sub-clinical hearing damage in a noise-exposed population with “normal”hearing thresholds. *International Journal of Audiology*, *47*(12), 737–750.

Thibodeau, L. M., & Van Tasell, D. J. (1987). Tone detection and synthetic speech discrimination in band-reject noise by hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *82*(3), 864-873.

Tremblay, K. L., Friesen, L., Martin, B. A., & Wright, R. (2003a). Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. *Ear and Hearing*, *24*(3), 225–232. http://doi.org/10.1097/01.AUD.0000069229.84883.03

Tremblay, K. L., Friesen, L., Martin, B. A., & Wright, R. (2003b). Test-Retest Reliability of Cortical Evoked Potentials Using Naturally Produced Speech Sounds. *Ear and Hearing*, *24*(3), 225–232.

Tremblay, K. L., Piskosz, M., & Souza, P. (2003). Effects of age and age-related hearing loss on the neural representation of speech cues. *Clinical Neurophysiology*, *114*(7), 1332–1343. http://doi.org/10.1016/S1388-2457(03)00114-7

Turner, C. W., Chi, S. L., & Flock, S. (1999). Limiting spectral resolution in speech for listeners with sensorineural hearing loss. *Journal of Speech, Language, and Hearing Research*, *42*(4), 773–84. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10450899

Turner, C. W., & Henn, C. C. (1989). The relation between vowel recognition and measures of frequency resolution. *Journal of Speech, Language, and Hearing Research*, *32*(1), 49-58.

Turner, C. W., & Nelson, D. A. (1982). Frequency Discrimination Impaired in Regions of Normal and Impaired Sensitivity. *Journal of Speech and Hearing Research*, *25*(1), 34–41.

Van Rooij, J. C. G. M., & Plomp, R. (1990). Auditive and cognitive factors in speech perception by elderly listeners.II: Multivariate analyses. *Journal of the Acoustical Society of America*, *88*(6), 2611–2624. http://doi.org/10.3109/00016489109127275

Van Rooij, J. C. G. M., & Plomp, R. (1992). Auditive and cognitive factors in speech perception by elderly listeners.III. Additional data and final discussion. *Journal of the Acoustical Society of America*, *91*(2), 1028–1033. http://doi.org/10.1121/1.402628

Won, J. H., Drennan, W. R., & Rubinstein, J. T. (2007). Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *Journal of the Association for Research in Otolaryngology*, *8*(3), 384–392. http://doi.org/10.1007/s10162-007-0085-8

Yeend, I., Beach, E. F., Sharma, M., & Dillon, H. (2017). The effects of noise exposure and musical training on suprathreshold auditory processing and speech perception in noise. *Hearing Research*, *353*, 224–236. http://doi.org/10.1016/j.heares.2017.07.006

Zekveld, A. A., George, E. L. J., Houtgast, T., & Kramer, S. E. (2013). Cognitive Abilities Relate to Self-Reported Hearing Disability, *56*(5), 1364–1372. http://doi.org/10.1044/1092-4388(2013/12-0268)requirement

Chapter 2: Auditory processing, attention, memory and statistical learning in adults with listening in noise concerns in presence of normal audiogram

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ABSTRACT

Objectives: The aim of the study was to determine the auditory and cognitive processing skills in a group of normal-hearing listeners with and without listening concerns in the presence of noise.

Design: A between-group design study was conducted. Auditory processing ability was tested using a modulation detection threshold (MDT) task; iterated ripple noise detection threshold (IRN); spectral-temporally modulated ripple detection test (SMRT); and a frequency discrimination test (FD). Cognitive skills were measured using Digit Span Test, Test of Everyday Attention (TEA); National Acoustic Laboratories Dynamic Conversation Test (NAL-DCT); Cognitive Spare Capacity Test (CSCT); and a Statistical Learning (SL) task in both auditory and visual modalities. A Multivariate Analysis of Variance (MANOVA), using age as a co-variate, was used for the analysis.

Results: The results indicated no significant difference in performance between the two groups on any of the auditory or cognitive tests.

Conclusions: From the current results we can infer that either 1) the current test battery is not sensitive to real-life listening difficulties; or 2) personal biases and expectations are driving participants' listening concerns. Understanding speech in the presence of noise is a complex phenomenon that needs to be further explored using real-life assessment tasks to identify the factors that influence difficulty with speech understanding in noise and the subjective perception of these difficulties.

1. Introduction

Previous studies have found that some adults report significant difficulty understanding speech in the presence of noise, despite having normal peripheral hearing sensitivity (Schneider & Pichora-Fuller 2001; Pichora-Fuller & Souza 2003). In a UK prevalence study, it was reported that about 4% of 1025 adults between the ages of 17-60 attending for a hearing assessment with a complaint of listening concerns were found to have normal hearing (Hind et al. 2011). In a USA based study, the prevalence was reported to be 2.9% for adults with self-reported hearing difficulties, and presenting with a normal audiogram (Tremblay et al. 2015). The present study was designed to determine what auditory and/or cognitive skills may account for the reported listening in noise concerns in individuals whose hearing is within normal limits.

Various labels have been applied to this population, including: obscure auditory dysfunction (Saunders & Haggard 1989); King-Kopetzky syndrome (KKS; Hinchcliffe 1992); auditory processing disorder (APD; British Society of Audiology APD Special Interest Group 2011); cochlear synaptopathy (Kujawa & Liberman 2009); and more recently hidden hearing loss (Schaette & McAlpine 2011). These classifications *suggest* different origins for the listening problems encountered, spanning the auditory pathway from periphery to cortex.

Hidden hearing loss in humans is hypothesised to be related to cochlear synaptopathy observed in animals subjected to brief loud noise exposure. Following exposure to noise of 100 dB SPL for two hours, wave I of auditory brainstem response (ABR) is permanently reduced, and synapses of auditory nerve fibres with low- and medium- spontaneous firing rates (SR) impaired, despite absolute auditory thresholds remaining unchanged (Kujawa & Liberman 2009; Valero et al. 2017). These low and medium SR fibres are believed to encode acoustic information in the presence of background noise at medium to high levels (Young & Barta 1986). To this end, studies in humans (Alvord 1983; Kujala et al. 2004; Kumar et al. 2012; Hope et al. 2013) have attempted to relate noise exposure to listening difficulties in noise, with mixed results. Consistent with the findings in animals, some studies have shown a reduction in the ABR wave I amplitude despite normal clinical audiograms in those with self-reported noise exposure (Liberman et al. 2016; Pushpalatha & Konadath 2016; Bramhall et al. 2017; Valderrama et al. 2018). However, other studies found no such difference in adults with life-long/recreational noise exposure (Grinn et al. 2017; Prendergast et al. 2017b). These findings led to research studies investigating different domains of auditory processing, including extended high frequency audiometry in an attempt to determine the underlying cause of the difficulty understanding speech in the presence of noise in humans with normal clinical audiometric thresholds (Prendergast et al. 2017a, b; Yeend et al. 2017). One suggestion is that clinical audiometric thresholds across the range 250 Hz to 8 kHz is not sensitive to sub-clinical high-frequency hair cell loss (Don & Eggermont 1978).

Audiometric thresholds provide information on the sensitivity to sounds but cannot differentiate an outer hair cell or inner hair cell dysfunction. Therefore, individuals with listening in noise concerns may be found to have normal hearing sensitivity (for a review, see Zhao & Stephens 2007). Thus, it may be useful to assess the clinically evaluated audiometric frequencies (250 Hz to 8 kHz) as well as the extended frequency range (at least up to 12.5 kHz) especially when they are reported with listening in noise concerns.

Tests of auditory processing ability have been used in many studies as a potentially more sensitivity way of assessing supra-threshold hearing dysfunction, than simply thresholds alone. Auditory processing is an umbrella term that encompasses various subskills such as localization, lateralization, auditory discrimination including spectral discrimination and resolution, temporal resolution, temporal integration, temporal discrimination, temporal ordering, and temporal masking. Some of the earlier studies in the occupational noise-exposed group with normal audiograms have expanded their test battery to include additional auditory processing skills (Alvord 1983; Kujala et al. 2004; Kumar et al. 2012; Hope et al. 2013; Yeend et al. 2017). For instance, Kumar et al. (2012) evaluated deficits on gaps in noise detection, amplitude modulation detection at 60 Hz and 200 Hz, duration pattern test performance and speech recognition using sentences in background babble. Yeend et al. (2017) evaluated auditory processing skills such as temporal processing, spectral processing, speech in noise perception using amplitude modulation at 4 Hz and 90 Hz, a temporal fine structure task, threshold-equalizing noise test, listening in spatialized noise test, and speech in noise comprehension.

Similar to the ABR findings in humans, results investigating auditory processing skills are also not consistent (Kumar et al. 2012; Prendergast et al. 2017a; Yeend et al. 2017; Guest et al. 2018). For instance, Prendergast et al. (2017a) found no effect of lifetime exposure to noise on inter-aural phase difference discrimination, amplitude modulation detection, intensity difference limens, digit triplet test, frequency difference limens, localization task, and a speech in noise task. On the other hand, Kumar et al. (2012) found significantly poorer performance on amplitude modulation, duration pattern test, and speech recognition in noise task in train drivers potentially exposed to occupational noise about eight to ten hours a day for more than ten years. There is variability in the findings across studies.

In general, some studies (but not all) have found poor auditory processing skills in adults with speech in noise concerns with clinically normal audiograms. Notably, most of these studies have included individuals with high levels of exposure to lifelong occupational, and/or recreational noise (Yeend et al. 2017; Guest et al. 2018). In the present study, we aimed to investigate whether adults reporting listening concerns (with normal clinical audiogram) had poorer auditory processing and if their lifetime exposure to noise accounted for their reported listening concerns.

The psychoacoustic test battery employed in the present study included modulation detection threshold at 60 Hz, frequency discrimination, iterated ripple noise test, and spectral-temporally modulated ripple test (SMRT). Some of the tests, such as modulation detection threshold at 60 Hz, were chosen based on evidence from previous studies that performance in these tasks was affected in an occupational-noise exposed group (Kumar et al. 2012), with a few others chosen as they were found to be significantly poorer in individuals with hearing loss; such as frequency discrimination (Abel et al. 1990), iterated ripple noise test (Leek & Summers 2001), and spectral modulation detection (Won et al. 2007).

Speech understanding in noise relies on both auditory and cognitive systems (Wingfield et al. 2005; Pichora-Fuller & Singh 2006; Schneider et al. 2010). Rather than synaptopathy, some of the listening-concern group may suffer from difficulties with higher level processing, such as memory or attention. Alternatively, synaptopathy may disrupt higher level processing, particularly statistical learning (Bakay et al. 2018), compounding listening difficulties. Many studies have explored the relationship between cognitive skills and speech in noise performance in individuals with hearing loss (Lunner 2003; Ng et al. 2013; Mishra et al. 2014; Keidser et al. 2015). Some researchers have reported that older adults compensate for the hearing loss that accompanies aging by depending heavily on cognitive skills for understanding speech (Nahum et al. 2008; Shinn-Cunningham & Best 2008; Peelle et al. 2011).

A review article by Humes (2007) concluded that in hearing aid users, appropriate amplification as well as cognitive skills play a significant role in understanding speech in the presence of noise. Most of the studies on hearing-impaired people provide an insight to the possible cognitive skills that may also be impacted in the adults with self-reported listening concerns. To investigate this further, the present study aimed to determine if cognitive processing skills differ in adults with self-reported listening concerns as compared to control subjects.

Cognitive skills related to understanding speech in the presence of noise investigated to date include working memory (Lunner 2003; Ng et al. 2013) and attention (Yeend et al. 2017). Working memory, when explored in individuals with hearing loss, was reported to have significant correlations with speech recognition in noise (Lunner 2003; Ng et al. 2013), hence an assessment of working memory was included in the test battery. A positive correlation between attention (cumulative score of selective attention and attention switching) and speech understanding in noise has been as found in individuals with clinically normal audiograms (Yeend et al. 2017), therefore, a test of attention, including both selective attention and attention switching, was included in the present study.

A further aspect of interest when working with adults with listening concerns and hearing loss is cognitive spare capacity (CSC) (Mishra et al. 2014; Keidser et al. 2015). It has been suggested that in order to understand speech when listening in noise, there are at least three processes required. First, we need to ignore or inhibit the irrelevant sounds, second, we need to switch to or select the conversation of interest, and third update the new sounds and compare to stored lexicons to finally infer meaning. When the listening conditions are easy, more cognitive resources are available for inhibition, switching and updating (Keidser et al. 2015). In other words, CSC refers to this residual capacity available for processing a signal once the signal has been perceived (see Mishra et al. 2013 for more details on cognitive spare capacity). Conversely when the listening conditions are difficult, processing sound is cognitively expensive, and individuals have limited resources available. Appropriate amplification in those with hearing loss should then leave more CSC available for higher level speech processing (Mishra et al. 2014). In the present study, we were motivated to know whether adults in absence of hearing loss, struggled with listening in noise due to inadequate CSC.

Statistical learning (SL) is yet another factor that has been explored when trying to understand listening in noise (Neger et al. 2014). SL refers to the ability to identify regularities in language or environment implicitly (Perruchet & Pacton 2006). This ability has been investigated in studies exploring categorical perception in adults and how individuals adapt to novel environments and learn to listen in noise (Watkins 2005). For example, Conway et al. (2010) reported that participants were able to predict words when the context was known and that this skill correlates with SL. Therefore, in the present study, we wanted to determine if the difficulty of adults in listening in noise might in part be due to poor SL.

In summary, we were motivated to determine if adults who have no identified hearing loss and yet complain of listening concerns in noise had poor auditory and/or cognitive processing skills that contributed to their problem. We hypothesised that adults with self-reported listening in noise concerns would perform more poorly on tasks of auditory and cognitive processing as compared to those with no listening in noise concerns. We also hypothesised that the life-long exposure to noise would account for the difference in the listening in noise.

2. Materials and methods

2.1 Participants

Purposive sampling method was used to recruit participants with advertisements specifically inviting adults with and without listening in noise difficulties. The advertisements were posted in and around Macquarie University and audiology clinics in Sydney. Forty two adults between the ages of 19 to 62 years were recruited in to the study. Twenty adults self-reported listening concerns in noise (LC group) and remaining twenty two adults had no concerns listening in noise (control group, CG). Participants in both groups were asked to complete an online survey to define their listening concerns. The online survey consisted of two sections: one focussed on listening ability including the Speech, Spatial and Qualities of Hearing scale (SSQ12; Noble et al. 2013); and the second section identified noise exposure over their life span (Yeend et al. 2017). The questions in this second section were adapted from online surveys developed by Beach et al. (2013) and Williams et al. (2015). The noise exposure questionnaire provided a measure of lifetime noise exposure which was estimated using log Pa^2h*. The lifetime noise exposure calculation considers both leisure activity and workplace related noise exposure. Each participant was asked to list all the jobs where they were exposed to noise, duration of exposure in each of those environments and use of hearing protection. In addition, they were also asked to list around 12 high- noise leisure activities during each decade of life and the use of hearing protection devices during each of these activities (refer to, Yeend et al. 2017 for details). All the participants completed this section of the survey.

Section one of the online survey had 3 parts. Part 1 determined situations where the participants found understanding speech in the presence of noise to be difficult; part 2 included the psycho-social effects of listening in noise difficulty and part 3 included the SSQ12. The SSQ12 is a 11 point rating scale with 12 questions such that 0 indicated severe difficulty while 10 indicates no problems. The 12 questions were broadly categorized into three subcategories i.e. 5 questions on understanding speech, 3 questions on spatial separation, and 4 questions on sound quality. The LC group completed all three parts of the section one (Table 1). The CG did not complain of a listening in noise difficulty and therefore opted-out of the entire questionnaire.

The mean age of the LC group was 40 years and for CG was 29.9 years. There were 12 females in LC group and 15 in CG. This study was conducted at the Department of Linguistics, Australian Hearing Hub, Macquarie University (Sydney, Australia) with ethics approval from the Macquarie University Human Research Ethics Committee.

2.1 Inclusion criteria

All the participants were assessed on the Language Experience and Proficiency Questionnaire (LEAP-Q) to determine their English proficiency (Marian et al. 2007). All participants reported English as their first or second language and had a proficiency score ≥8 in speaking, reading and understanding (see table 2 for details). All participants were also evaluated on the Montreal Cognitive Assessment. All participants had a score of ≥26 on the MoCA, and therefore were included in the study (Table 2).

Participants underwent otoscopy to ensure that the ear canal and eardrum were unremarkable. Peripheral hearing status was evaluated using Pure-Tone Audiometry (PTA) for octave frequencies 250 to 8000 Hz, measured using an Interacoustics audiometer AC 40 (American National Standards Institute [ANSI] 1996), and acoustic reflex thresholds within 70-100 dB HL (Silman & Gelfand 1981), recorded using Interacoustics Titan IMP440 module. In addition, extended high frequency audiometry and DPOAE testing was also conducted using Interacoustics audiometer AC 40 and Interacoustics Titan DPOAE440 module. The extended high frequency audiometry and DPOAE testing was included to ensure the inner ear status of the individual. This was conducted to ensure whether the participant reporting of a speech understanding in noise issue was due to the presence of hearing loss at the extended frequency region or not. Table 3 provides the DPOAE details for both groups. Figure 1 provides the mean and standard deviation details for pure-tone audiometry.

2.2 Auditory measures

2.2.1 Common procedure for the auditory perception tests

The auditory processing tests used in the present study included measures of modulation detection threshold (MDT), iterated ripple noise (IRN) threshold, spectral-temporally modulated ripple test (SMRT), and frequency discrimination (FD). In all four tests, stimuli were presented through headphones that were calibrated to obtain a flat frequency response using a sound level meter (Brüel and Kjaer type 2250 G4) and an artificial ear (Brüel and Kjaer type 4153). The stimuli were created using a sampling rate of 44100 Hz.

All stimuli were computer generated through a sound card (Focusrite 219), and were presented through headphones (Sennheiser, HDA 300) at 70 dB SPL. In all tasks a two-up and one-down 3AFC (alternative-forced-choice) adaptive tracking method was used. The task was to indicate the variable stimuli. The threshold was calculated by taking the average of the last six reversals across the runs, and each task was repeated three times in order to ensure test-retest reliability. The presentation order of all the tests was varied for each participant.

MDT: Modulation detection thresholds were determined using The Maximum Likelihood Procedure (MLP; Grassi & Soranzo 2009) toolbox which uses a staircase procedure. A 500 ms Gaussian noise was amplitude-modulated at 60 Hz. The noise stimuli had two 10-ms raised cosine-ramps at onset and offset. This was used to reduce the loudness cue. Two of the three presented stimuli consisted of the reference stimuli with zero modulation while the third consisted of the modulated stimuli. On obtaining a correct response, the modulation depth (in dB) was reduced.

IRN: Stimuli were created using Matlab (R2015a). A delay and add algorithm was used (Leek & Summer 2001; Peter et al. 2014). The delayed noise was added to the original noise. A delay of 10 ms and 8 iterations were used to construct the stimuli. The pitch strength of the IRN in the variable stimuli was controlled by varying the gain, that is, the degree to which the delayed repetition was attenuated relative to the original noise. The gain ranged from 0.32 to 0.01. The noise had a duration of 1000 ms and a bandwidth of 1 to 4 kHz. Two of the three presented stimuli consisted of the reference stimuli with zero iterations while the third consisted of the IRN stimuli.

SMRT: Stimuli were also created using Matlab (R2015a). In an adaptive procedure the ripple density of the variable stimuli was modified until the listener was unable to distinguish between the variable and reference stimuli 50% of the time. The SMRT stimuli was generated using a non-harmonic complex that consisted of 202 equal amplitude pure-tone frequency components that spaced every 1/33.3 of an octave between 100 to 6400 Hz (Aronoff & Landsberger 2013). The duration for each stimulus was 500 ms with 10-ms linear onset and offset ramps. Two of the stimuli contain the reference stimuli that had 20 ripples per octave and the third variable stimuli consisted of 2 ripples per octave at the start. A correct response resulted in the ripple density being increased in the variable stimuli.

FD**:** The task was adapted from the MLP tool box. The duration of each stimuli was 250 ms with 10-ms onset and offset ramps. A 1000 Hz tone was used for discrimination. The starting level between the reference and the varied stimuli was set at a difference of 100 Hz. A correct response resulted in the decrease in frequency difference between the stimuli.

2.3 Cognitive measures

The cognitive measures included the Digit Span Test, Elevator task with distraction and reversal subtests of Test of Everyday Attention (TEA), the NAL Dynamic Conversation Test (NAL-DCT), Cognitive Spare Capacity Test (CSCT), and a test of Statistical Learning (SL) in both the auditory and visual modality. The presentation order for the tests was varied for each participant.

Digit Span Test: This was taken from the Wechsler Adult Intelligence Scale IV (Wechsler 2008). All participants repeated a set of verbally presented (live voice) numbers in the required order (forward/reverse/sequence) at a rate of digit/second. Correct responses were given a score of 1. The complexity of the task increased based on the number of correct responses. The test was terminated when two incorrect responses were obtained consecutively.

Elevator task with distraction and reversal (Robertson et al. 1994): These two subtests are taken from the Test of Everyday Attention (Version A) and measures the selective attention and attention switching (Robertson et al. 1994). In the elevator counting task with distraction, the individual was given low pitch tones in the presence of a high pitch tones. The task required the participant to count the low pitch tones while ignoring the high pitch tones. In the elevator counting task with reversal, the participants were given three different pitch tones. The participants needed to count only the number of medium pitch tones and not the high pitch or the low pitch tones. When a low pitch tone was heard, the order of counting had to be reversed. In both elevator counting tasks correct responses were given a score of 1. The stimuli used in the subtests were presented through headphones (Sennheiser, HDA 300) at 70dB SPL.

NAL-DCT: In NAL-DCT, each participant heard 3 short passages that consisted of two-talker conversations. These conversations were presented in simulated cafeteria noise composed of seven two-talker conversations. The passages were taken from the Listening Comprehension subtest of the International English Language Testing System (Jakeman & McDowell 1995 in Keidser et al. 2015).

Before undertaking the passage task, an adaptive sentence in noise test was conducted using Beautifully Efficient Speech Test (BEST) (Best et al. 2014) to obtain the SRT for each participant. The target level was adapted to track 50% correct sentence recall using custom software. Each individual had to complete two runs of this adaptive sentence in noise test. Each run comprised a maximum of thirty-two sentences and the background noise was kept constant at 65dB SPL (see Keidser et al. 2013 for further details). The individual was asked to repeat as much of the sentence or word as possible from the given sentence and was encouraged to guess if unsure. Every morpheme accurately identified was scored. The values obtained from 2 adaptive tracks were averaged to obtain a single Speech Recognition Threshold (SRT), used to derive the Signal to Noise Ratio (SNR) at which the NAL-DCT passages were presented.

During the NAL-DCT task, the participants were given the questions on paper and asked to respond as they heard the dialogue. There were 10 questions for each of the passages. Each passage took around 2-4 minutes to be completed. The answers varied from multiple-choice questions requiring a tick, circling the correct answer or writing a word. A gap of 30 seconds was given between passages. Each correct response was given a score of 1.

The test was conducted in an anechoic chamber, with stimuli presented through an array of 41 equalized Tannoy V8 loudspeakers. The loudspeakers were distributed in a three-dimensional, spherical array within 1.8 m radius (Keidser et al. 2015). Three speakers placed at -67°, +67° and 0° azimuth were used to present the target stimuli with the background noise presented at the remaining locations (refer Keidser et al. 2015 for further details). Each passage was presented using one of the three combinations i.e., -67°0°, +67°0°, -67°+67°.

Cognitive Spare Capacity Test (CSCT): The English version of the Cognitive Spare Capacity test was adapted from Keidser et al. (2015) and presented within the same anechoic chamber set up as the NAL-DCT. The target stimuli were presented at 0° azimuth and background noise was presented from different locations (please refer to Keidser et al. 2015 for more details on the equipment and stimuli presentation). Similar to NAL-DCT, SNR required to present the CSCT stimuli was derived using the SRT determined from BEST. However, for CSCT the SRT from BEST was adapted to obtain 80% correct sentence recall using custom software. Once the SNR level was obtained the participants were presented with a list of numbers and were asked to repeat them in order to ensure that the participants were able to perceive the signal 90% of the time. If the participants had a score lower than 90%, the level of the signal was increased until a score of 90% of the numbers correct was achieved. Once the level was established, the main test commenced. Each participant was presented with 6 lists of numbers, each list had thirteen numbers. The participants were asked to recall either the two highest numbers or two lowest numbers from the given list. Correct responses were given a score of 1.

Visual and auditory statistical learning (aSL and vSL): The visual stimuli were adapted from Fiser and Aslin (2001) (vSL). The visual stimuli consisted of twelve black and white odd-shaped pictures. These pictures had no definable shape and therefore provided no statistical advantage in learning (Siegelman et al. 2017). The 12 pictures were grouped together to create a set of four triplets. Their dimensions were set to be 200*200 mm.

The aSL paradigm was adapted from (Saffran et al. 1999; Vasuki et al. 2016). The tones were referenced to the musical octave with A=440Hz. The tones were combined in a way that the triplets could be co-identified with the image triplets, i.e., four triplets with the auditory tones. The tones were created on Matlab (R2016a) with a sampling rate of 44100 Hz. Each tone was 550 ms long with 25-ms onset and offset ramps.

Each auditory triplet was created such that no recognisable/familiar melody or rhythm was formed as this would lead to easier and hence biased learning of items (Saffran et al. 1999). A repeated-measures ANOVA was conducted to observe whether any significant differences existed within the semitone transitions between the embedded triplets. Results showed that there was no significant difference ($p > 0.05$) in the semitones within triplets. Furthermore, the semitones across triplets were also analysed to ensure that no auditory triplet was easier to learn than another.

Both in aSL and vSL, there were two tasks: 1) familiarization; and 2) behavioural task. In the *familiarization task* the participants were exposed to a set of pictures appearing on the computer screen/auditory tones presented through loudspeakers. These pictures/tones appeared simultaneously one after the other. In addition, they were given a *cover task* in which the participants were asked to press the space bar when they saw a picture/tone occurring twice consecutively. This was applied to ensure that the participant maintained their attention during the presentation of the stream of stimuli. The pictures appeared at the centre of the screen for a duration of 800 ms whilst the auditory tones were presented for 550 ms. The interstimulus interval was set to 50 ms for both paradigms. This was done to ensure that the familiarization phase was neither too long nor taxing for the participants (Vasuki et al. 2016). The familiarization phase lasted in total 8.5 minutes for the visual task and 7.5 minutes for the auditory task. The familiarization task included each triplet being presented 240 times. The triplets, pictures/tones were presented sequentially. These 240 sequences were randomized using Matlab (R2016b) such that no two triplets occurred consecutively. The cover task consisted of the second picture/tone of each triplet repeating itself (e.g. ABBC, DEEF, GHHI, JKKL). Forty such repetitions were randomly placed among the 240 presentation items, bringing the overall number of stimuli to 280 (Vasuki et al.

2016). The Transitional probabilities (TPs) calculated for these 280 stimuli ranged from 0.216 to 0.333 (mean = 0.276).

After the completion of the familiarization task, a surprise *behavioural test* was carried out. It was imperative that the participants were not aware that there was to be a behavioural test to avoid any overt or covert learning. The behavioural task included 32 trials of a 2AFC task. During this task, the participants were given two set of pictures/tones, one triplet from the familiarization test, and one novel triplet as it had never been viewed before. The participants had to choose the set of pictures/tones (triplets) that was more familiar to them to evaluate their implicit learning (see Fig. 2). The pictures appeared at the centre of the screen for 800ms (Turk-Browne et al. 2005; Arciuli & Simpson 2011). Each tone of a triplet was presented for 550ms. There was an interval of one second between the two triplets during this task. The percentage of pictures/tones identified correctly (i.e., the triplet is familiar) during the behavioural test, estimated the visual/auditory statistical learning ability of the participant.

2.4 Data analysis

There were two analyses undertaken to determine if there were any group differences and subsequently to determine if there were any within-group effects. Multivariate analysis of variance (MANOVA), with age as a co-variate, was used to analyse the data to identify if there were differences across groups. Age was used as a co-variate to compensate for the differences that existed between the two groups. To examine within-group effects, standard scores were used to analyse individual LC group data. For this analysis, standard scores or *z*-scores were calculated by subtracting the population mean (in this case performance on tasks by the CG) from the individual score and thereafter dividing the difference by the population standard deviation.

3. Results

3.1 Demographics: Age, Hearing, Language, Cognitive screening

Across group differences observed for age, left and right ear pure-tone average (3 frequency pure-tone average), MoCA and LEAP-Q using MANOVA are given in Table 2. The results on extended high frequency revealed no significant group effects for either right [$F (4, 36) = 1.4$, $p = 0.2$, partial $\eta^2 = 0.1$] or left ear [$F (4, 36) = 1.0$, $p = 0.4$, partial $\eta^2 = 0.1$]. Similarly, there were no difference between the two groups on DPOAE for both right [$F (7, 33) = 1.3$, $p = 0.2$, partial $\eta^2 = 0.2$] and left ear [$F (7, 33) = 1.1$, $p = 0.3$, partial $\eta^2 = 0.1$].

LEAP-Q was evaluated to determine if there were any significant differences between monolinguals and bilinguals in rating their proficiency on English on speaking, understanding and reading. There were thirteen bilingual (English as their second language) and nine monolingual participants in the CG. All the bilinguals rated their proficiency in speaking, understanding, and reading to be ≥8 out of 10. Bilingual and monolingual participants did not vary on their English language proficiency in speaking [$F (1, 19) = 1.5$, $p = 0.2$, partial $\eta^2 = 0.07$], understanding [$F (1, 19) = 0.6$, $p = 0.4$, partial $\eta^2 = 0.03$], or reading [$F (1, 19) = 0.5$, $p = 0.4$, partial $\eta^2 = 0.02$].

3.2 Listening in noise

Self-reported listening in noise difficulty obtained from the online survey (section 1, part one and two): 90% of the LC participants reported face to face conversation in the presence of background noise to be hard, 81% found face to face conversation in the presence of background music to be hard, and 68% found understanding speech to be difficult in rooms with poor acoustics, understanding actors speech in background noise, and whilst having a conversation in a moving car/train. The different psychosocial effects associated with the reported listening difficulty included embarrassment (40%); anxiousness (31%); and low self-confidence in personal life (27%). The results obtained on SSQ12 from each participant is shown in Table 1. Overall, most participants in the LC group showed difficulty on at least one of the categories i.e., speech understanding in noise, spatial separation or sound quality except six participants. For these six participants when individual rating was examined for each of the questions within the speech understanding category, 4 of them had rated low (below 7) in just one of the questions that related to a dual task situation while 2 others rated low (below 7) on situations with multi-talker conversations.

Comparison between the SSQ12 information obtained from the present study cohort and data obtained from young normal hearing 18-25 year old adults on Speech Spatial and Qualities 49 (SSQ 49) (from Demeester et al. 2012 in Bressler et al. 2017) is provided in supplementary table. SSQ 12 is the shorter version of the SSQ 49 and those questions included in SSQ 12 are also present in SSQ 49. Inclusion of this would help us gain an understanding of the performance of the current cohort on SSQ 12 who report speech understanding in noise difficulty versus those individuals who do not have listening in noise concern. On comparison of the rating on each of these 12 questions, it does show that the cohort in the current study have poorer rating on the SSQ 12. However, it should be noted that the norms are taken from younger normal hearing 18-25 years old adults compared to the participants in the current study.

3.3 Noise exposure measure

The average lifetime noise exposure for the CG was 3463.6 Pa^2h and for the LC group was 4621.5 Pa^2h. An independent samples test showed that there was no significant difference in the measured noise exposure between the groups [t (40) = -0.6, p=0.5)].

3.4 Auditory processing tests

Mean, median, and standard deviation for the two groups for MDT, IRN, SMRT, and FD are shown in Table 4. MANOVA did not reveal a significant group difference for MDT [$F(1, 39) = 0.06$, $p= 0.7$, partial $\eta^2 =0.002$], IRN [$F(1, 39) = 1.0$, $p= 0.3$, partial $\eta^2 =0.02$], SMRT [$F(1, 39) = 3.3$, $p= 0.07$, partial $\eta^2 =0.07$] or FD [$F(1, 39) = 0.8$, $p= 0.3$, partial $\eta^2 =0.02$].

3.5 Cognitive processing tests

Table 5 shows the mean and standard deviation of the digit span tests, attention tasks (elevator counting with distraction and reversal), NAL-DCT, CSCT, vSL, and aSL for the LC group and CG. MANOVA with age as co-variate was used to analyse short-term and working memory, attention tasks, NAL-DCT, and CSCT to identify if there was a difference across groups. MANOVA did not reveal a significant group difference for digit span forward scores [$F (1, 39) = 0.49$, $p= 0.48$, partial $\eta^2 =0.07$], digit span backward scores [$F (1, 39) = 0.02$, $p= 0.8$, partial $\eta^2 =0.01$], digit span sequence scores [$F (1, 39) = 1.6$, $p= 0.2$, partial $\eta^2 =0.03$], digit span scaled scores [$F (1, 39) = 0.01$, $p= 0.9$, partial $\eta^2 =0.00$], elevator counting with distraction [$F (1, 39) = 0.47$, $p= 0.49$, partial $\eta^2 =0.01$] elevator counting with reversal [$F (1, 39) = 0.2$, $p= 0.6$, partial $\eta^2 =0.005$], NAL-DCT [$F (1, 39) = 0.2$, $p= 0.6$, partial $\eta^2 =0.07$], or CSCT [$F(1, 39) = 0.2$, $p= 0.6$, partial $\eta^2 =0.07$].

For SL, data obtained from the cover tasks were inspected to identify the number of repeated stimuli correctly identified by the participant. Only participants who performed above 50% on the cover tasks were considered, to remove any chance performers. This criterion was set in order to rule out participants who may not have attended to the familiarization stream (Arciuli & Simpson 2012). There were 5 participants in CG and 6 participants in LC group who performed below 50% on the aSL cover tasks and therefore these participants were excluded from the analysis.

A one sample t-test was carried out to determine whether participants performed above chance level during the test phase (percentage of triplets identified correctly). Results indicated above chance level performance for all participants on vSL and aSL for both LC group [t(19) = 16.8, p<0.001)], [t(13) = 11.8, p<0.001)] and the CG [t (21) = 14.4, p<0.001)], [t(16) = 28.1, p<0.001)] respectively.

The data was further explored to see if there was a group difference. MANOVA with age as co-variate was used to analyze aSL and vSL. MANOVA did not reveal a significant group difference for either vSL [F (1, 39) = 1.1, p= 0.2, partial η^2 =0.02] or aSL [F (1, 28) = 0.3, p= 0.5, partial η^2 =0.01].

3.6 Individual data analysis (Within group effects)

Most of the individuals in the LC group performed within ±2 standard deviation which in-turn shows that the LC group performed similar to the CG on all the tests. The results obtained are given in the supplementary figures.

4. Discussion

The main aim of the study was to examine the cognitive and auditory skills in individuals with normal hearing thresholds, but who report listening concerns in the presence of noise (LC group). The hypothesis was that the LC group would show poorer performance on auditory and cognitive processing skills as compared to the CG and that LC group would also have higher lifetime exposure to noise.

The second aim was to determine if the lifetime noise exposure would explain the listening in noise concerns. The results on the lifetime exposure to noise in the CG group (3463.6 Pa^2h) was not significantly different to the LC group (4621.5 Pa^2h), therefore the lifetime noise exposure could not account for the complaints of the current research participants, a result which is consistent with previous findings such as Prendergast et al. (2017a). This may imply three things: 1) this population may be different to those in previous studies that reported higher reported noise exposure (occupational and/or recreational) for the LC group; 2) the self-report measures we used to evaluate their lifetime noise exposure were not sensitive enough to separate the two groups; or 3) noise exposure history has no relation to the reported listening difficulties in the current study research participants.

In the current study, contrary to the hypothesis, no differences were noted on any of the auditory or cognitive skills in the current cohort. There could be several factors that may have contributed to the findings of no differences noted in LC group as compared to the CG.

4.1 Clinically measured thresholds versus extended audiogram thresholds

A recent study performed by Yeend et al. (2017) found extended high-frequency hearing loss to be related to speech understanding in noise performance. Bearing this in mind, in the present study both the groups were tested on audiometric frequencies up to 12.5 kHz. While there are limited studies with norms available, LC group had similar thresholds to CG from 9 kHz to 12.5 on the right ear (21.5 dB HL) and the left ear (22 dB HL) except for 2 participants. One LC participant showed a shift of about 45-65 dB in the extended frequency region (9-12.5 kHz) for only the right ear, while the left was about 10dB better and within the age-expected norms (Rodríguez et al. 2014).

Another participant in the LC group had a noise notch at 4 kHz bilaterally while extended high frequencies were no different to the CG group (refer fig.1). However, both these individuals performed similarly to the CG on all the cognitive and auditory processing tasks. Even on their SSQ12, these participants did not rate their concerns any more than other LC participants. These results indicate listening in noise concerns in humans is a complex phenomenon and listening in noise issues can be present in both the presence and absence of elevated extended high frequency thresholds.

4.2 Cognitive skills and speech understanding in noise

The ability to understand speech in the presence of noise may involve both sensory and cognitive factors (Pichora-Fuller et al. 1995). The role of cognition is evident in individuals with peripheral hearing loss, where cognitive skills are used to supplement the degraded auditory signal (Wingfield et al. 2005; Humes 2007; Shinn-Cunningham & Best 2008). For instance Ng et al. (2013) investigated the effects of noise reduction algorithm on speech understanding performance, the negative effects of noise was reduced only for those with greater working memory capacity. Similar findings were observed by Lunner (2003), where working memory positively associated with aided speech perception performance. Individuals with good cognitive abilities were reported to perform better in speech recognition task than those with poorer cognitive abilities (Lunner 2003). In the present study there was no difference observed in performance between the two groups on the working memory task. It may be that the LC group is using this skill to compensate for their difficulties and therefore they performed well on the speech understanding task. If so, this may result in listening in noise being more effortful for the LC group, which may be the basis for their complaints. Measuring listening effort in noise for this group may be a more sensitive way of elucidating their listening in noise difficulties.

There are limited studies that have investigated the role of attention on speech understanding in noise in adults with listening concerns having normal audiogram. However, only one study found that attention is an important predictor to understand speech in the presence of noise (Yeend et al. 2017). Similarly, in another study, it was reported that attention played an important role in speech understanding in the presence of noise (Bressler et al. 2017). However, it is important to note that this study was conducted on soldiers exposed to blast sounds and their inclusion criteria relating to audiogram thresholds were quite broad (i.e., up to 25dB HL at 500 Hz, 1 kHz and 2 kHz and up to 45dB HL at 4 kHz). In this case it is hard to differentiate whether the attention problems found were due to this slight loss of peripheral sensitivity, or to other factor related to blast exposure. However, in the present study, we found no differences in performance in attention tasks between the LC group and CG even when balanced for hearing thresholds. These findings may imply two things 1) the tests used to identify selective attention and attention switching may not be sensitive enough; or 2) difficulties in selective attention and attention switching may not be the source of speech understanding in noise concerns for this group.

At least two studies have shown that individuals with hearing loss have lower CSC (Mishra et al. 2014; Keidser et al. 2015). In the present study, no differences were observed and that may well be because 1) our population had no hearing loss, and 2) was a relatively young cohort (20-62 years). Humes (2007) suggested cognitive function to be an important predictor for speech understanding in noise in older adults when reduced audibility was controlled for. A few aspects to note are that each behavioural task was no more than 15-20 minutes long, the tasks were varied to keep them engaged and all tests were undertaken in a sound-treated booth with minimal visual distraction. Consequently, while performing these tests there is a high possibility that the individuals in our LC group would have been able to give their best performance. In future, studies of real-life noise including reverberation and monitoring of performance over time (rather than average performance) should be utilised.

There are no studies to this date that have reported SL (auditory or visual) in a LC group. Conway et al. (2010) reported that SL is associated with word predictability, which, as noted earlier, is an important factor during speech understanding in the presence of noise. The results indicated no such difference in performance on aSL and vSL between the two groups. Paraskevopoulos et al. (2012) when comparing musicians to non-musicians on aSL showed a significant difference in musicians only on MEG results and not behavioural testing. Although direct comparison cannot be made to the present study, it could be that the behavioural SL measures are not sensitive enough to capture the differences between the groups.

4.3 Language Proficiency and speech understanding in noise

Another aspect that could possibly contribute to speech understanding in noise is proficiency of language. In the present study we did not include a direct measure of language proficiency, rather we included a questionnaire LEAP-Q in which the participants self-evaluated their language skills. Based on LEAP-Q, bilingual and monolingual participants did not vary on their English language proficiency in speaking, understanding, or reading. There were five participants in the LC group who reported English as their second language. However, these five participants' individual performances were similar to the monolinguals within the same group. We did not see any difference in performance on any auditory or cognitive tasks within the group, implying that at least in the current population, language proficiency is not the cause for their listening concerns (results in supplementary figures).

4.4 Are the chosen tasks appropriate or enough?

Another possible reason for the finding of no differences between the two groups could be that we have not chosen tests that are sensitive enough to identify the problem of speech understanding difficulties in adults with normal audiograms. A study from Oxenham (2016) employing signal detection theory demonstrated that even if a substantial amount of cochlear synaptopathy/hidden hearing loss occurs it might be hard to measure its effects on perception. This study demonstrated that 50% loss of synapses could decrease d-prime by a factor of $\sqrt{2}$ on psychophysical tasks. This would be well within the variability range across individuals having normal audiograms. Therefore, the effects may not be evident on the tests of perception such as the ones we employed.

4.5 Subjective interpretation of the questionnaire

It could be that the LC group overestimated their listening in noise problems when filling in the questionnaire. Personal expectation or intrinsic motivation may be driving the listening concerns and may account for differences in the self-report. This may be one of the reasons why there was no significant difference on NAL-DCT and SRT between the two groups.

5. Conclusion

In summary, the present study investigated the auditory and cognitive profile of individuals who report listening in noise concerns but normal audiograms. From the results obtained, the present study did not find any significant differences between the groups. The present study suggests that listening in noise concerns in those with normal hearing thresholds remain unexplained, and that ‘real’ life assessments need to be explored to better understand the causes of the listening concerns.

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6. References

Abel, S. M., Krever, E. M., & Alberti, P. W. (1990). Auditory detection, discrimination and speech processing in ageing, noise-sensitive and hearing-impaired listeners. *Scandinavian Audiology*, *19*, 43–54.

Alvord, L. S. (1983). Cochlear dysfunction in“ normal-hearing” patients with history of noise exposure. *Ear and Hearing*, *4*, 247–50.

American National Standards Institute. (1996). Specifications for Audiometers (ANSI S3.6-1996). *New York: American National Standards Institute.*

Arciuli, J., & Simpson, I. C. (2011). Statistical learning in typically developing children: The role of age and speed of stimulus presentation. *Developmental Science*, *14*, 464–473.

Arciuli, J., & Simpson, I. C. (2012). Statistical Learning Is Related to Reading Ability in Children and Adults. *Cognitive Science*, *36*, 286–304.

Aronoff, J. M., & Landsberger, D. M. (2013). The development of a modified spectral ripple test. *The Journal of the Acoustical Society of America*, *134*, EL217-EL222.

Bakay, W. M. H., Anderson, L. A., Garcia-Lazaro, J. A., et al. (2018). Hidden hearing loss selectively impairs neural adaptation to loud sound environments. *Nature Communications*, *9*, 4298.

Beach, E.F., Gilliver, M., Williams, W., (2013). Sound Check Australia: a citizen science approach to noise & hearing conservation research. In: Paper Presented at the National Hearing Conservation Association Conference.

Best, V., M. McLelland, & H. Dillon. (2014). The BEST (Beautifully Efficient Speech Test) for

Evaluating Speech Intelligibility in Noise. World Congress of Audiology. Brisbane, Australia.

Bramhall, N. F., Konrad-Martin, D., McMillan, G. P., et al. (2017). Auditory Brainstem Response Altered in Humans with Noise Exposure Despite Normal Outer Hair Cell Function. *Ear Hear*, *38*, e1.

Bressler, S., Goldberg, H., & Shinn-Cunningham, B. (2017). Sensory coding and cognitive processing of sound in Veterans with blast exposure. *Hearing Research*, *349*, 98–110.

British Society of Audiology. (2011). What's in a name? APD by any other name would not smell so sweet. *International Journal of Audiology, 50*, 496.

Conway, C. M., Bauernschmidt, A., Huang, S. S., et al. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition*, *114*, 356-371.

Demeester, K., Topsakal, V., Hendrickx, J. J., Fransen, E., Van Laer, L., Van Camp, G., ... & van Wieringen, A. (2012). Hearing disability measured by the Speech, Spatial, and Qualities of Hearing Scale in clinically normal-hearing and hearing-impaired middle-aged persons, and disability screening by means of a reduced SSQ (the SSQ5). *Ear and hearing*, *33*, 615-616.

Don, M., & Eggermont, J. J. (1978). Analysis of the click-evoked brainstem potentials in man using high-pass noise masking. *The Journal of the Acoustical Society of America*, *63*, 1084–1092.

Fiser, J., & Aslin, R. N. (2001). Unsupervised statistical learning of higher-order spatial structures from visual scenes. *Psychological Science*, *12*, 499–504.

Grassi, M., & Soranzo, A. (2009). MLP: A MATLAB toolbox for rapid and reliable auditory threshold estimation. *Behavior Research Methods*, *41*, 20–28.

Grinn, S. K., Wiseman, K. B., Baker, J. A., et al. (2017). Hidden hearing loss? No effect of common recreational noise exposure on cochlear nerve response amplitude in humans. *Frontiers in Neuroscience*, *11,* 465.

Guest, H., Munro, K. J., Prendergast, G., et al. (2018). Impaired speech perception in noise with a normal audiogram: No evidence for cochlear synaptopathy and no relation to lifetime noise exposure. *Hearing research, 364,* 142-151.

Hinchcliffe, R. (1992). King-Kopetzky syndrome: An auditory stress disorder? Audiological Medicine, 1, 89–98.

Hind, S. E., Haines-Bazrafshan, R., Benton, C. L., et al. (2011). Prevalence of clinical referrals having hearing thresholds within normal limits. *International Journal of Audiology*, *50*, 708–716.

Hope, A. J., Luxon, L. M., & Bamiou, D. E. (2013). Effects of chronic noise exposure on speech-in-noise perception in the presence of normal audiometry. *Journal of Laryngology and Otology*, *127*, 233–238.

Humes, L. E. (2007). The Contributions of Audibility and Cognitive Factors to the Benefit Provided by Amplified Speech to Older Adults. *Journal of the American Academy of Audiology*, *18,* 590–603.

Keidser, G., Best, V., Freeston, K., et al. (2015). Cognitive spare capacity: Evaluation data and its association with comprehension of dynamic conversations. *Frontiers in Psychology*, *6*, 597.

Keidser, G., Dillon, H., Mejia, J., et al. (2013). An algorithm that administer adaptive speech-in-noise testing to a specified reliability at selectable points on the psychometric function. *International Journal of Audiology*, 52, 795–800.

Kujala, T., Shtyrov, Y., Winkler, I., et al. (2004). Long-term exposure to noise impairs cortical sound processing and attention control. *Psychophysiology*, *41*, 875–881.

Kujawa, S. G., & Liberman, M. C. (2009). Adding Insult to Injury: Cochlear Nerve Degeneration after "Temporary" Noise-Induced Hearing Loss. *Journal of Neuroscience*, *29*, 14077–14085.

Kumar, U. A., Ameenudin, S., & Sangamanatha, A. V. (2012). Temporal and speech processing skills in normal hearing individuals exposed to occupational noise. *Noise and Health*, *14*, 100.

Leek, M. R., & Summers, V. (2001). Pitch strength and pitch dominance of iterated rippled noises in hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *109*, 2944–2954.

Liberman, M. C., Epstein, M. J., Cleveland, S. S., et al. (2016). Toward a differential diagnosis of hidden hearing loss in humans. *PLoS ONE*, *11*, 1–15.

Lunner, T. (2003). Cognitive function in relation to hearing aid use. *International Journal of Audiology*, *42*, 49–58.

Marian, V., Blumfield, H., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing Language Profiles in Bilinguals and

Multilinguals Viorica. *Hearing Research*, *50*, 940–967.

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

Mishra, S., Stenfelt, S., Lunner, T., et al. (2014). Cognitive spare capacity in older adults with hearing loss. *Fronteirs in Aging Neuroscience*, *6*, 96.

Nahum, M., Nelken, I., & Ahissar, M. (2008). Low-level information and high-level perception: The case of speech in noise. *PLoS Biology*, *6*, 0978–0991.

Neger, T. M., Rietveld, T., & Janse, E. (2014). Relationship between perceptual learning in speech and statistical learning in younger and older adults. *Frontiers in Human Neuroscience*, *8*, 628.

Ng, E. H. N., Rudner, M., Lunner, T., et al. (2013). Effects of noise and working memory capacity on memory processing of speech for hearing-aid users. *International Journal of Audiology*, *52*, 433–441.

Noble, W., Jensen, N. S., Naylor, G., Bhullar, N., & Akeroyd, M. A. (2013). A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: The SSQ12. *International Journal of Audiology*, *52*, 409–412

Oxenham, A. J. (2016). Predicting the Perceptual Consequences of Hidden Hearing Loss. *Trends in Hearing*, *20*, 1–6.

Paraskevopoulos, E., Kuchenbuch, A., Herholz, S. C., et al. (2012). Statistical learning effects in musicians and non-musicians: An MEG study. *Neuropsychologia*, *50*, 341–349.

Peelle, J. E., Troiani, V., Grossman, M., et al. (2011). Hearing loss in older adults affects neural systems supporting speech comprehension. *The Journal of Neuroscience, 31*, 12638–12643.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: one phenomenon, two approaches. *Trends in Cognitive Sciences, 10*, 233–238.

Peter, V., Wong, K., Narne, V. K., et al. (2014). Assessing Spectral and Temporal Processing in Children and Adults Using Temporal Modulation Transfer Function (TMTF), Iterated Ripple Noise (IRN) Perception, and Spectral Ripple Discrimination (SRD). *Journal of the American Academy of Audiology, 25*, 210–218.

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *The Journal of the Acoustical Society of America*, *97*, 593–608.

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*, 29–59.

Pichora-Fuller, M. K., & Souza, P. E. (2003). Effects of aging on auditory processing of speech. *International Journal of Audiology*, *42*, 11–16.

Prendergast, G., Millman, R. E., Guest, H., et al. (2017a). Effects of noise exposure on young adults with normal audiograms II: Behavioural measures. *Hearing Research, 356*, 74–86.

Prendergast, G., Guest, H., Munro, K. J., et al. (2017b). Effects of noise exposure on young adults with normal audiograms I: Electrophysiology. *Hearing Research*, *344*, 68–81.

Pushpalatha, Z., & Konadath, S. (2016). Auditory brainstem responses for click and CE-chirp stimuli in individuals with and without occupational noise exposure. *Noise and Health*, *18*, 260.

Robertson, I.H., Ward, T., Ridgeway, V., et al. (1994). The Test of Everyday Attention Manual.

Rodríguez Valiente, A., Trinidad, A., García Berrocal, J. R., et al. (2014). Extended high-frequency (9-20 kHz) audiometry reference thresholds in 645 healthy subjects. *International Journal of Audiology*, *53*, 531–545.

Saffran, J. R., Johnson, E. K., Aslin, R. N., et al. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*, *70*, 27–52.

Saunders, G. H., & Haggard, M. P. (1989). The clinical assessment of obscure auditory dysfunction--1. Auditory and psychological factors. *Ear Hear*, *10*, 200-208.

Schaette, R., & McAlpine, D. (2011). Tinnitus with a Normal Audiogram: Physiological Evidence for Hidden Hearing Loss and Computational Model. *Journal of Neuroscience, 31*, 13452–13457.

Schneider, B. A., Pichora-fuller, K., & Daneman, M. (2010). Effects of Senescent Changes in Audition and Cognition on Spoken Language Comprehension. *In The Aging Auditory System*, 167–210.

Schneider, B. A., & Pichora-Fuller, M. K. (2001). Age-related changes in temporal processing: Implications for listening comprehension. *Seminars in Hearing*, *22*, 227–239.

Shinn-Cunningham, B. G., & Best, V. (2008). Selective attention in normal and impaired hearing. *Trends in Amplification*, *12*, 283–299.

Siegelman, N., Bogaerts, L., & Frost, R. (2017). Measuring individual differences in statistical learning: Current pitfalls and possible solutions. *Behavior Research Methods*, *49*, 418–432.

Silman, S., & Gelfand, S. A. (1981). The relationship between magnitude of hearing loss and acoustic reflex threshold levels. *The Journal of Speech and Hearing Disorders*, *46*, 312–316.

Tremblay, K. L., Pinto, A., Fischer, M. E., et al. (2015). Self-Reported Hearing Difficulties Among Adults With Normal Audiograms : The Beaver Dam Offspring Study. *Ear Hear*, *36*, e290.

Turk-Browne, N. B., Jungé, J., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology. General*, *134*, 552.

Valderrama, J. T., Beach, E. F., Yeend, I., et al. (2018). Effects of lifetime noise exposure on the middle-age human auditory brainstem response, tinnitus and speech-in-noise intelligibility. *Hearing Research*.

Valero, M. D., Burton, J. A., Hauser, S. N., et al. (2017). Noise-induced cochlear synaptopathy in rhesus monkeys (Macaca mulatta). *Hearing Research*, *353*, 213–223.

Vasuki, P. R. M., Sharma, M., Demuth, K., et al. (2016). Musicians' edge: A comparison of auditory processing, cognitive abilities and statistical learning. *Hearing Research*, *342*, 112–123.

Watkins, A. J. (2005). Perceptual compensation for effects of reverberation on speech identification. *The Journal of the Acoustical Society of America*, *118*, 249–262.

Wechsler, D. (2008). Wechsler Adult Intelligence Scale–Fourth Edition (WAIS–IV). San Antonio, TX: The Psychological Corporation.

Williams, W., Carter, L., Seeto, M. (2015). Pure tone hearing thresholds and leisure noise: is there a relationship? *Noise Health*, 17, 358.

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*, *14*, 144–148.

Won, J. H., Drennan, W. R., & Rubinstein, J. T. (2007). Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *Journal of the Association for Research in Otolaryngology*. *8*, 384–392.

Yeend, I., Beach, E. F., Sharma, M., et al. (2017). The effect of noise exposure and musical training on supra threshold auditory processing and speech perception in noise. *Hearing Research*, *353*, 224–236.

Young, E. D., & Barta, P. E. (1986). Rate responses of auditory nerve fibers to tones in noise near masked threshold. *The Journal of the Acoustical Society of America*, *79*, 426–442.

Zhao, F., & Stephens, D. (2007). A critical review of King-Kopetzky syndrome: Hearing difficulties, but normal hearing? *Audiological Medicine*, *5*, 119–124.

7. Tables

Table 1: Shows the self-reported rating on SSQ-12 for the participants in the LC group. SSQ-12 is a 11 point rating scale with 12 questions, 0 indicating severe difficulty.

Participants	Understanding speech					Spatial separation			Sound Quality			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
LC 1	8	2	8	8	8	6	7	6.5	5	6	7	2
LC 2	6	4	5	7	6	8	5	9	6	8	9	3
LC 3	6	3	5	5	4.5	9.5	7	9.5	6	6.5	9	3.5
LC4	4	0	4	0	0	8	9	9	2	6	3	5
LC5	9.5	9.5	8	7	7	8	7.5	9	9	9	9.5	8.5
LC6	9	0.5	0.5	6	9	5	5	9.5	0	4	6	5
LC7	6	5	7	5	6	7	7	7	5	7	8	7
LC8	7.5	6.5	6.5	6.5	4	8.5	7	8	8	10	9.5	8
LC9	9	6	9	8	8	8	8	7	10	6	10	7
LC10	8	7	8	8	9	9	9	9	7.5	7	10	10
LC 11	2	1	4	3	2	2	3	3	2	2	10	1
LC 12	3	2	3	3	3	3	7	0	0	8	0	4
LC 13	10	8	10	8	8	10	10	10	9	10	10	8
LC14	7	4	3	3	3	9	9	9	9	7	8	4
LC15	9	3	5	2	7	4	5	4	2	5	8	5
LC16	4	0.5	2.5	6	9	4	7	8	8	8	10	8
LC17	10	6	8.5	8	10	9	9	8	10	9	10	10
LC18	5	6	3	3	3	9	8	8	5	7	9	9
LC19	5	6	3	3	3	9	8	8	5	7	9	9
LC20	9	2	8	7.5	9	9	9	9	9	9	9	8.5

Note: LC: Listening Concern group

TABLE 2: Mean and standard deviations (in brackets) of the age, LEAP-Q, MoCA and Pure Tone Audiometry (PTA 3-frequency average) thresholds for the control (CG) and listening concern (LC) groups are provided. The MANOVA column provides the difference statistics across the two groups.

VARIABLES	CG (N=22)	LC (N=20)	MANOVA
AGE	29.9(7.6)	40.0(14.2)	[F (1, 40) = 7.7, $p < 0.008$, partial η^2=0.1]
LEAP-Q (SPEAKING)	8.7(1.0)	9.2(0.8)	[F (1, 40) = 1.0, p= 0.3, partial η^2 = 0.02]
LEAP-Q (UNDERSTANDING)	9.2(0.8)	9.3(0.8)	[F (1, 40) = 0.2, p= 0.6, partial η^2=0.005]
LEAP-Q (READING)	9.2(0.9)	9.4(0.5)	[F (1, 40) = 0.5, p= 0.4, partial η^2 = 0.01]
MOCA	27.2(1.2)	27.4(1.0)	[F (1, 40) = 0.1, p= 0.7, partial η^2=0.03]
PTA (RE)	8.7(0.5)	8.4(3.9)	[F (1, 40) = 0.1, p= 0.7, partial η^2 = 0.004]
PTA (LE)	9.2(1.0)	7.9(2.6)	[F (1, 40) = 3.1, p= 0.08, partial η^2=0.7]

Note: LE = left ear; RE = right ear; PTA = pure-tone 3-frequency average: mean of thresholds at 500, 1000 and 2000 Hz; SD = standard deviation; MoCA = Montreal Cognitive Examination; Language Experience and Proficiency Questionnaire (LEAP-Q)

TABLE 3: Mean and standard deviations of Distortion Product Oto-acoustic emissions (OAE's) for both groups. There were no significant effects across the groups.

		1kHz	**1.5 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
CG N=22	RE	4.4(6.1)	8.0(6.3)	6.7(4.6)	5.0(5.8)	10.3(4.5)	6.9(7.4)	0.7(9.5)
	LE	4.1(6.2)	7.2(6.0)	6.2(5.9)	5.4(5.1)	10.3(4.5)	7.0(6.0)	2.4(7.1)
LC N=20	RE	1.2(10.4)	5.3(8.2)	2.4(6.9)	1.0(9.6)	0.0(13.0)	-5.7(11.6)	-8.4(8.4)
	LE	1.8(7.3)	2.4(6.6)	-0.4(8.5)	-0.4(7.6)	2.8(10.5)	-1.4(10.4)	-4.8(14.1)

Note: CG: Control Group; LC: Listening Concern group

TABLE 4: Mean, median and standard deviations (in brackets) of IRN, FD, MDT and SRN for both groups (LC=20 and CG, N=22). There were no significant effects across the groups.

TEST	GROUP	MEAN (STDEV)	MEDIAN
MDT 60Hz (in dB)	CG	-14.0(2.2)	-14.6
	LC	-13.9(2.6)	-14.7
FD (in log)	CG	1.1(0.4)	1.0
	LC	1.0(0.4)	0.8
IRN (in dB)	CG	13.5(2.0)	13.9
	LC	13.9(1.8)	14.2
SRN (ripples per octave)	CG	7.5(1.6)	7.8
	LC	7.6(1.8)	6.9

Note: CG: Control Group; LC: Listening Concern group
IRN: Iterated Ripple Noise; FD: Frequency Discrimination
MDT: Modulation Detection Threshold; SRN: Spectral Ripple Noise

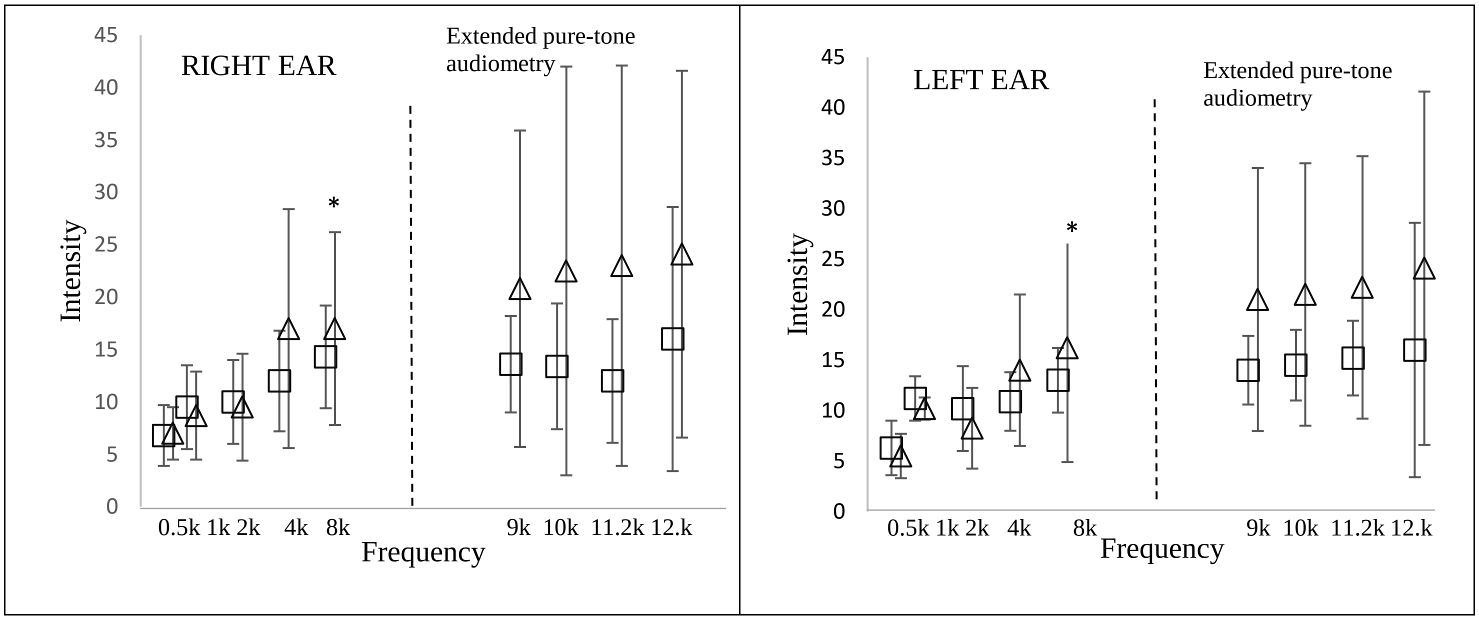
TABLE 5: Mean, median and standard deviations (in brackets) of digit span tests, TEA, CSCT, DCT, aSL, vSL for both groups. (LC=20 and CG, N=22 each). There were no significant effects across the groups.

TEST	**GROUP**	**MEAN (STDEV)**	**MEDIAN**
Digit span forward	CG	12.0(1.8)	11.0
	LC	11.6(2.3)	12.0
Digit span backward	CG	9.8(1.7)	9.0
	LC	9.5(2.2)	9.5
Digit span sequence	CG	8.8(1.2)	9.0
	LC	9.0(1.9)	8.5
Digit span scaled score	CG	11.1(1.9)	11.0
	LC	11.0(2.6)	11.0
TEA: distractor (scaled score)	CG	10.3(2.3)	10.0
	LC	9.7(2.4)	10.0
TEA: reversal (scaled score)	CG	10.0(3.6)	11.5
	LC	9.9(2.8)	10.0
NAL-DCT (raw score)	CG	20.5(5.4)	21.5
	LC	20.6(4.4)	20.2
CSCT (raw score)	CG	8.3(1.4)	8.0
	LC	8.1(1.5)	8.5
vSL (accuracy%)	CG	53.3(13.8)	50.0
	LC	58.0 (8.5)	56.2
aSL (accuracy%)	CG	61.6(9.0)	60.0
	LC	59.6(22.0)	64.0

Note: CG: Control Group; LC: Listening Concern group
TEA: Test of Everyday Attention; CSCT: Cognitive Spare Capacity Test
NAL-DCT: National Acoustics Laboratories Dynamic Conversation Test; aSL: auditory Statistical Learning; vSL: visual Statistical Learning.

8. Figures

FIGURE 1: Pure-tone audiometry thresholds (in dB HL) including extended high frequencies and standard deviations (error bars) for control group (CG, in square) and listening concern group (LC, in triangle) for both right and left ear (LC =20 and CG=22)



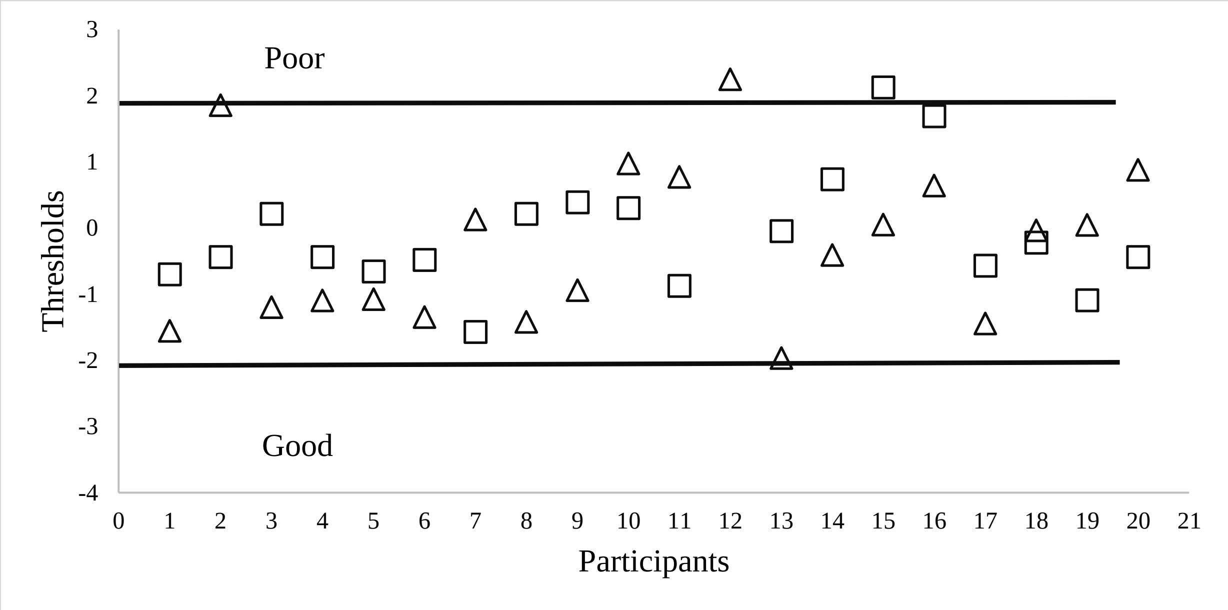
Note: * One participant showed a noise induced notch at 4 kHz, hence the wide standard deviation dispersion.

FIGURE 2: Triplets presented for aSL and vSL tasks. Visual stimuli were adapted from (Fiser & Aslin 2001) and the aSL paradigm was adapted from (Saffran et al. 1999; Vasuki et al. 2016)

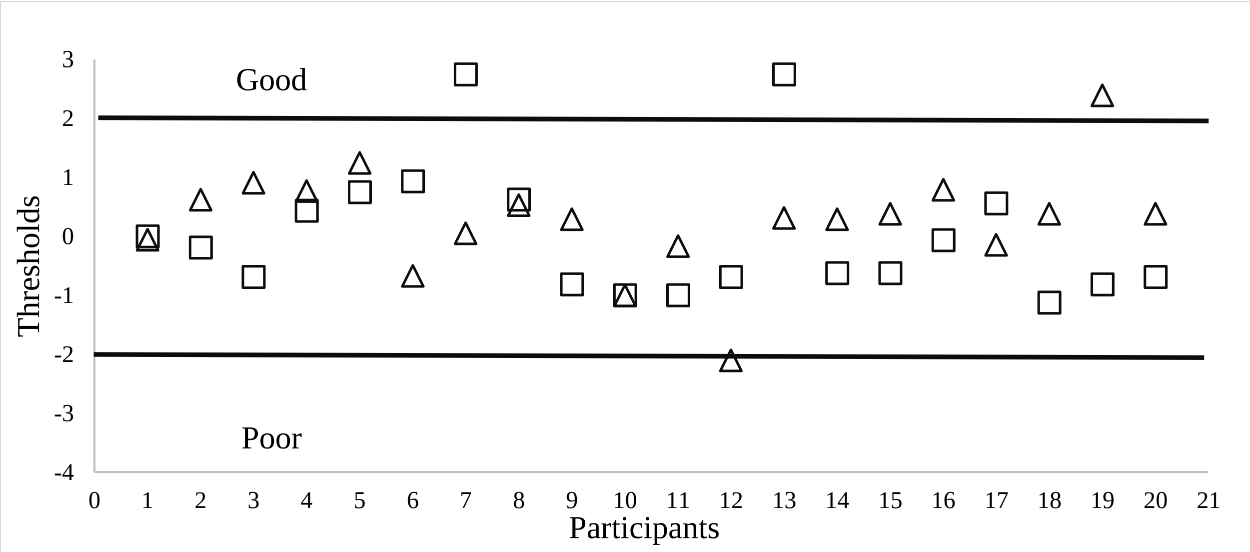
Triplet	aSL	vSL
Triplet 1	**FCF#**	
Triplet 2	**D#AG**	
Triplet 3	**A#DE**	
Triplet 4	**C#BG#**	
Novel triplet 1	**ACA#**	
Novel triplet 2	**D#FG#**	
Novel triplet 3	**C#EG**	
Novel triplet 4	**BDF#**	

9. Supplementary figures

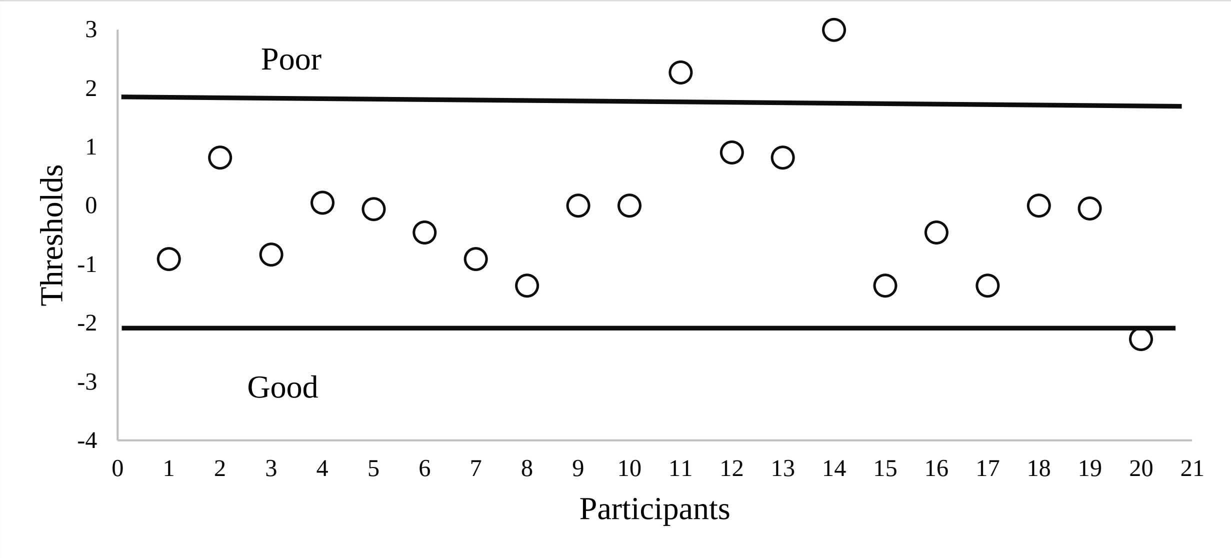
1) Individual Performance of the LC group on MDT in square and FD in triangle (LC =20). Performance below zero indicates very good performance. Zero is the mean performance of the CG group.



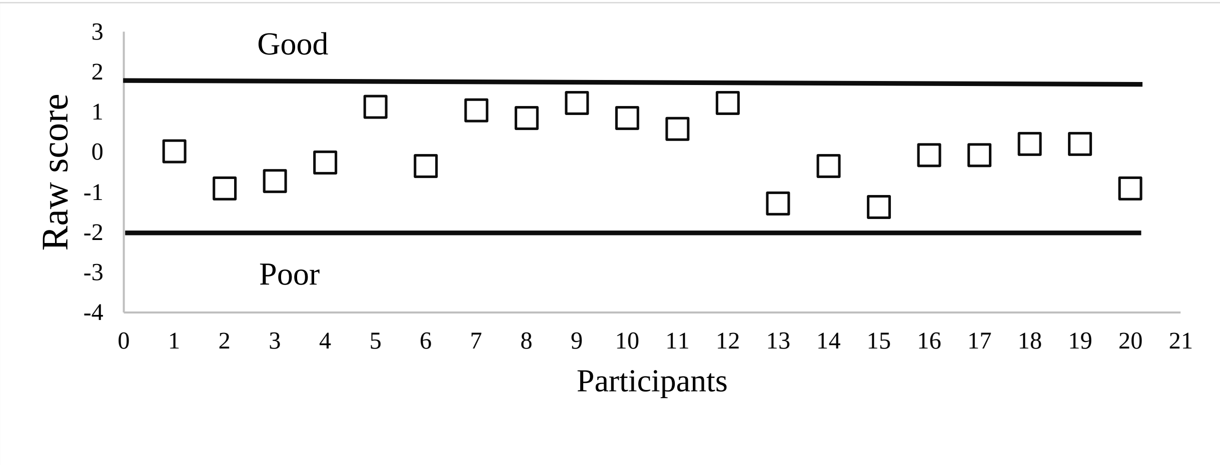
2) Individual Performance of the LC group on SRN in square and IRN in triangle (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



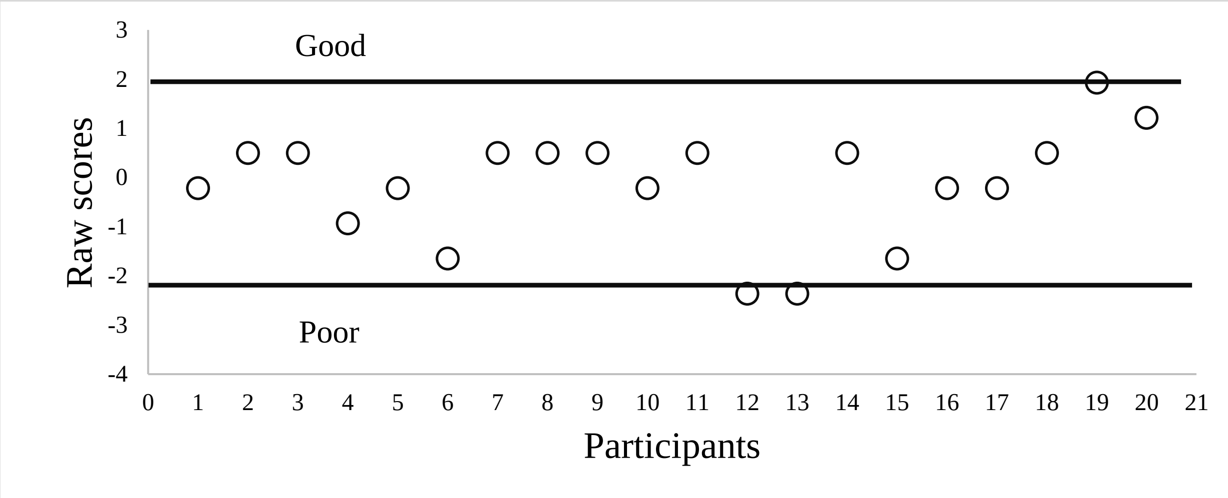
3) Individual Performance of the LC group on SRT (LC =20). Performance below zero indicates very good performance. Zero is the mean performance of the CG group.



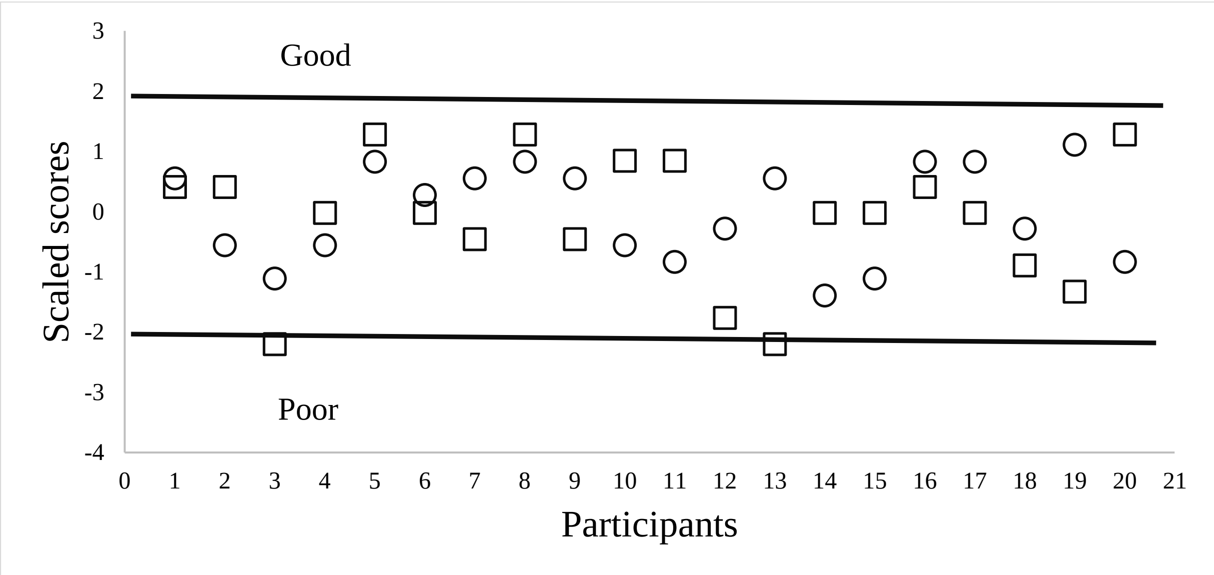
4) Individual Performance of the LC group on NAL-DCT (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



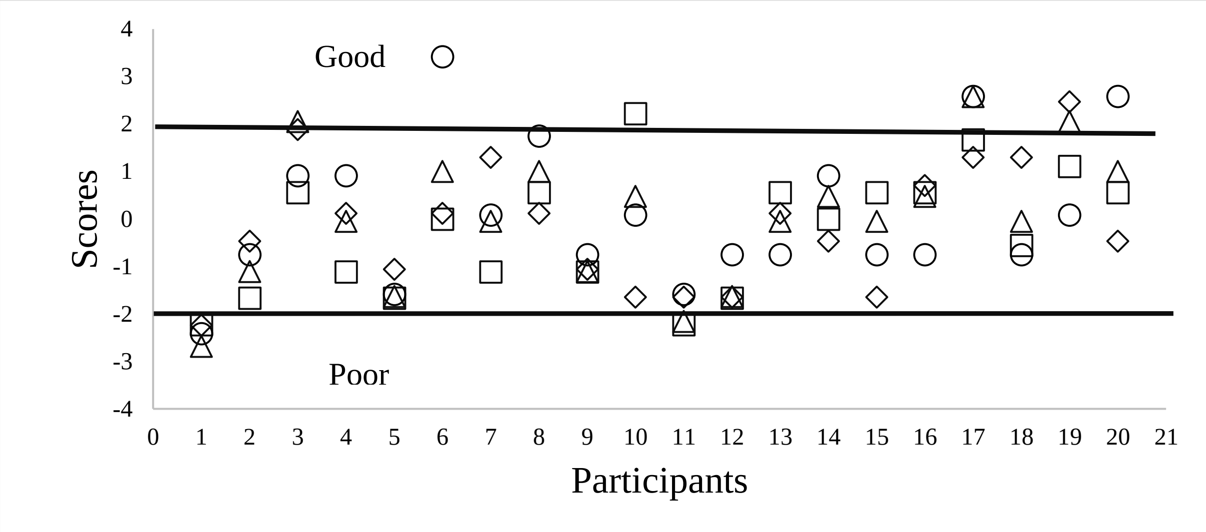
5) Individual Performance of the LC group on CSCT (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



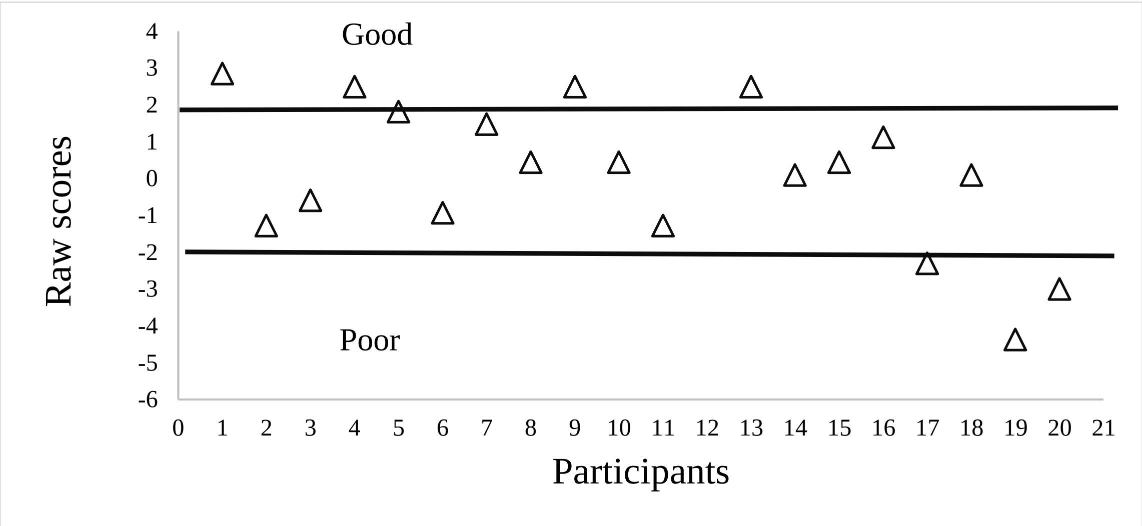
6) Individual Performance of the LC group on elevator task with distraction in square and elevator task with reversal in circle (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



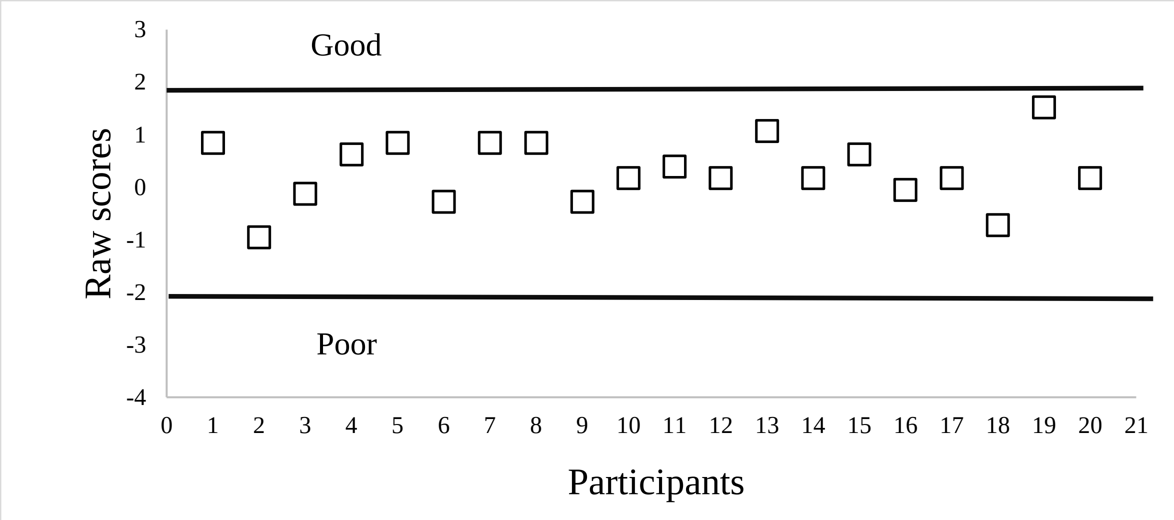
7) Individual Performance of the LC group on digit span task, digit span forward scores in square, digit span backward score in diamond, digit span sequence scores in circle, digit span scaled score in triangle (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



8) Individual Performance of the LC group on aSL (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



9) Individual Performance of the LC group on vSL (LC =20). Performance above zero indicates very good performance. Zero is the mean performance of the CG group.



10. Supplementary table

Table 1: Shows the mean and standard deviation of each participant in the LC group on the SSQ12. The 12 questions were categorized as per the SSQ 49 index as the normal hearing control subjects were tested on SSQ 49. The 12 questions from the SSQ 12 were listed under four categories i.e. selective attention, divided attention, spatial and quality. The shaded column shows the expected mean and standard deviation from young (18-25 years old) normal hearing adults. The norms are captured from Demeester et al. (2012) in Bressler et al. (2017).

SSQ 49 category	**SSQ 12 questions**	**LC group (n=20) mean (SD)**	Normal Hearing (n=103)* mean (SD)
Selective Attention	Q1: Speech in noise	6.8(2.4)	9.5(0.7)
	Q3: Speech in speech	4.1(2.7)	9.2(1.1)
	Q4: Speech in noise	5.5(2.6)	8.8(1.2)
	Q5: Multiple speech streams	5.3(2.4)	9.4(1.2)
	Q9: Segregation	5.9(2.9)	9.1(1.3)
Divided Attention	Q2: Multiple speech streams	7.2(2.3)	6.2(2.7)
Spatial	Q7: Distance and movement	7.3(1.7)	8.1(1.4)
	Q8: Distance and movement	7.5(2.5)	9.2(1.2)
	Q6: Localization	5.8(3.2)	8.7(1.9)
Quality	Q11: Quality and naturalness	7.0(1.9)	9.6(1.4
	Q12: Listening effort	8.2(2.5)	8.5(2.3)
	Q10: Identification of sound	6.2(2.7)	7.5(2.4)

Chapter 3: Objective measure of speech Understanding in Noise: an N400 study

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Key words: Event-related potentials, semantically congruent and incongruent sentence, listening in noise

ABSTRACT

Objective: The aim of this study was to evaluate the speech understanding using event related potentials specifically N400 response in adults with clinically normal hearing and reported listening in noise concerns.

Method: Twenty two adults with normal hearing, control group, (*19-50 years, 7 males*) and twenty with reported listening in noise concerns, listening concern group (*21-62 years, 8 males*). Sixty-four channel electroencephalography (EEG) was carried out on all the participants using semantically congruent and incongruent sentences. Onset responses, P1-N1-P2 were identified for both congruent and incongruent sentences within the first 200ms at the start of the sentence. N400 magnitude was estimated as the area under the curve on the difference waveform (between incongruent and congruent response waveform) in the time frame [0.4-0.8] seconds following the onset of the critical word. Time frequency analysis was also carried out for the recorded EEG.

Results: Analysis of variance of the onset of the sentence and area under the curve for N400 showed no significant difference across the groups. There were, however, significant differences between evoked responses elicited to incongruent versus congruent sentences for the control group but not for the group with listening concerns. Significant clusters in the frontal electrodes were observed in the control group when comparing incongruent and congruent sentences. These results possibly highlight the differences in the information processing ability of the control group. The fact that there were no differences on the onset responses across groups may indicate that both groups perform similarly on simple perception tasks. In contrast, N400 elicitation, along with auditory perception requires additional cognitive skills. Cognitive skills include the ability to pay attention and predict the occurrence of the incoming sentences. The presence of clusters obtained only for the control group on evaluating the difference in waveform from the target word of the

congruent and incongruent sentences may suggest the control group may have differences in auditory and cognitive processing skills particularly while performing complex tasks such as speech understanding. Time frequency analysis revealed stronger synchronised alpha oscillations for the control than the group with listening concerns. Alpha oscillations were present at left temporal region for semantically congruent and incongruent sentences and at left frontal region for semantically incongruent sentences. Presence of strong alpha oscillations in the control group may indicate that these individuals are able to maintain their attention throughout the task which is why they are able to perform better than the group with listening concern on the N400.

Significance: N400 may be a potentially useful tool in identifying speech understanding in noise issues. However, this area needs to be further explored before incorporating N400 into clinical use.

1. Introduction

"I find it hard to follow speech in the presence of noise." This reported concern is a common complaint reported by older adults mostly above fifty five years of age despite having clinically normal hearing thresholds (Pichora-Fuller and Souza, 2003; Golding et al., 2004). The reported problem of listening in noise is, however, not just observed in older adults. Survey studies conducted in US and in the UK showed 2.9 to 4% adults attending hearing evaluation between the ages of 21 to 65 and 17-60 years respectively have normal hearing sensitivity and report listening in noise concerns (Hind et al., 2011; Tremblay et al., 2015). Similarly, a recent retrospective study examined 498 clients who visited an otolaryngology practice centre with auditory complaints. Even though, majority of the clients complained of hearing loss (48%) there were 13% of the population having clinically normal hearing who were identified as having auditory processing difficulties (Shinn et al., 2016).

The aim of the present study was to explore neural processing involved in speech understanding task using electroencephalography (EEG) in individuals who report of speech understanding difficulty particularly in the presence of noise. EEG involves recording of the spontaneous electrical activity at the level of cortex over a period of time (Niedermeyer & da Silva, 2005). The EEG comprises information on both Event Related Potentials (ERPs) which are time and phase locked (Luck, 2005) and also the spectral content which are the neural oscillatory activities that are non-phase locked in the time-frequency domain (Makeig et al., 2004).

Cortical auditory evoked potentials (CAEPs) are time locked responses that are most commonly used physiological measure to determine how sounds are perceived at the level of the auditory cortex. To date, the N1 component of the CAEP and mismatch negativity (MMN) have been most commonly used in audiological assessments but these evaluate speech at sound or syllable level (Stapells, 2002; Martin et al., 2008). In order to assess sentence recognition, a later response must be measured. The N400 is a form of Event Related Potentials (ERPs) waveform elicited at the cortical level in response to the semantically inappropriate words (Kutas and Hillyard, 1980). N400 is a late negative wave obtained about 300-600 ms post the presentation of the stimulus (Kutas and Hillyard, 1980). The N400 amplitude is believed to be inversely related to the expectancy of a given word at the end of the sentence (Sur and Sinha, 2009). For instance, the sentence “the girl ate the <u>chocolates</u>” elicits a smaller N400 amplitude at 300-600 ms as this is expected than “the girl ate the <u>aeroplane</u>” which is not predictable”(Kutas and Hillyard, 1980, Rugg, 1985).

The neural oscillatory activities or the spectral component are derived from the synchronous and rhythmic of the neuronal populations generated from a given task (auditory/visual) (refer Roach and Mathalon, 2008 for an overview). This spectral component of the EEG is commonly measured using a technique referred to as time frequency analysis (refer Roach and Mathalon, 2008 for an overview). Time frequency analysis involves extraction of magnitude and phase information for each frequency present in the EEG signal. This process may also be called as spectral decomposition. Information obtained from each of the frequency band are believed to represent the oscillatory component reflecting specific auditory or visual mechanism, for instance, frequency band between 8-12 Hz known as the alpha band is believed to be an outcome of cognitive processing skills such as attention and memory retrieval (Senkowski et al., 2008; Gilley and Sharma 2010; Klimesch, 2012).

In the current study, N400 was selected as a CAEP measure to determine the differences in neural processing underlying speech understanding task in individuals who report difficulty understanding speech in noise in the presence of noise. Both time locked and time frequency analysis were carried out to evaluate these differences.

N400

There are two views in literature describing the underlying mechanism for the N400 effects: 1) integration view and, 2) lexical view. The integration view describes N400 to be an outcome of semantic integration of the critical word with the context or the prior world knowledge while the lexical view describes N400 to be elicited by the critical words by accessing the long term memory (Lau et al., 2008). The integration view believes sentences that are semantically incongruent requires more time for integration with the already existing world knowledge and that results in larger N400 responses while the lexical view believes the words that are semantically appropriate are easily accessible from the long term memory and therefore we do not observe a large N400 responses for such words. However, irrespective of the theories, the N400 response is elicited as a consequence of adequate perception and comprehension of a given sentence, to appreciate the context and therefore predict the keyword. Considering, the individuals in the present cohort reported speech understanding concerns, N400 was selected as the physiological measure to investigate the underlying differences during the process of speech understanding. N400 has been commonly used in research studies to understand the underlying mechanisms of language processing when given auditory and visual stimulus (refer Kutas and Federmeier, 2011 for a review).

The N400 can be recorded to various modalities such as visual, auditory stimulus, sign languages, environmental sounds and smell (Kutas and Hillyard, 1980; Meade et al., 2018). Although as discussed earlier, the generation of N400 is mainly based on the type of the stimulus (Van Petten and Kutas, 1991) i.e. greater N400 for semantically inappropriate stimulus and smaller for semantically appropriate stimulus (Kutas and Federmeier, 2011). In addition, the N400 response can be elicited in both active and passive conditions, active condition refers to the state where the participant pays attention to the stimuli and task while passive condition refers to the state where the task does not require one to pay attention (Perrin and Garcıa-Larrea, 2003). However, there is evidence showing greater N400 effect for the stimulus that requires one to pay attention (Okita and Jibu, 1998). Therefore, in the present study, the N400 response to sentences that were semantically congruent and incongruent were measured while requiring the individual to pay attention to the sentences.

We hypothesized that individuals who report speech understanding difficulty particularly in the presence of noise may have difficulty in two aspects; 1) Paying attention to the ongoing sentences; and/or 2) Predict the key word based on the perceived context.

To date, N400 has been used among patients with pathologies such as developmental disorders, neurological disorders, psychiatric disorders and also on patients with strokes to evaluate the semantic language comprehension (Duncan et al., 2009). To the authors' knowledge, no study to date has explored the N400 response in individuals who report a speech understanding in noise problem. Therefore, the aim of the present study was to identify the differences in N400 responses in individuals with a normal audiogram reporting speech understanding in noise concerns compared to individuals with a normal audiogram having no concerns.

2. Method

2.1 Participants

Forty two participants between the ages of 19 to 62 were recruited for study. Purposive sampling method was used to recruit participants. The advertisements were designed particularly to recruit adults with and without speech understanding in noise concerns. Twenty two participants with no such concerns (CG group) and twenty participants with self-reported speech understanding in noise problems participated in the study (LC group). The former group comprised of twelve females with a mean age of 30 years (standard deviation: 7.6) and the later comprised of 15 females with mean age of 40 years (standard deviation: 14.2). This study was conducted at the Department of Linguistics, Australian Hearing Hub, Macquarie University (Sydney, Australia) with ethics approval from the Macquarie University Human Research Ethics Committee.

2.2 Inclusion criteria

All the participants were evaluated for their English language proficiency using the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007). All the participants required to have their rating on understanding, speaking and reading English to be ≥7. After which, cognitive screening was carried out using Montreal Cognitive Assessment (MoCA,Nasreddine et al., 2005). They had to obtain a score of ≥26 on the MoCA, in order to be included in the study. Scores below 26 would be an indicative of mild-cognitive issue (Nasreddine et al., 2005).

All participants who passed the cognitive screening later underwent few hearing screening tests. Initially, otoscopy was carried out to ensure the ear canal and eardrum were unremarkable. Pure-Tone Audiometry (PTA) for octave frequencies 250 to 8000 Hz, measured using an Interacoustics audiometer AC 40 (Interacoustics, Denmark) (American National Standards Institute [ANSI] 1996) was carried out to evaluate the peripheral hearing status. All participants had to have their thresholds with 15 dB HL for pure-tone frequencies between 250 Hz to 8 kHz. In addition, extended high frequency audiometry for frequencies between 9 kHz to 12.5 kHz was also evaluated using Interacoustics audiometer AC 40. All participants had to have their acoustic reflex thresholds within 70-100 dB HL (Silman and Gelfand, 1981). The acoustic thresholds were recorded using Interacoustics Titan IMP440 module (Interacoustics, Denmark). Distortion Product

Oto-Acoustic Emissions (DPOAE's) were also carried out for both groups using Interacoustics Titan DPOAE440 module. Table 1 provides the mean and standard deviation details for pure-tone audiometry. This population has been previously described (refer Appaiah et al., 2018, under review, Ear and Hearing for more details). Demographic details comprising age, language proficiency, MoCA, three frequency pure-tone average for both right and left ear are given in table 2 while table 3 comprises DPOAE details for both groups.

2.3 Self-report on listening ability

All participants who self-reported to have a listening-in-noise concern were asked to complete the Speech Spatial and Qualities Hearing Scale (SSQ-12). The SSQ12 is a 11 point rating scale with 12 questions with 0 indicating severe difficulty and 10 indicating no problems. The 12 questions were broadly categorized into three subcategories, consisting of 5 questions on understanding speech, 3 questions on spatial separation, and 4 questions on sound quality (refer table 4). The SSQ was reported similar to the way reported by (Bressler et al., 2017). SSQ-12 was completed only by the LC group, CG did not complain of a listening in noise difficulty and therefore opted out of the questionnaire.

2.4 N400 measure

This test requires the individual's attention in making judgments whether the given sentences are semantically correct or incorrect. All sentences for measuring N400 followed the same pattern of "the + [2 syllables substantive] + [monosyllable verb] + the + [keyword: 2 syllables substantive starting with occlusive consonant, e.g. /d/ /t/ /p/ /k/ + [3 syllables ending]. An example of the sentence structure would be "the driver puts the petrol in the car" (refer, appendix III for the sentence list). In-addition to semantically congruent and incongruent sentences, all participants were given catch trials that included answering questions and filler sentences. The addition of 24 questions organized in between the congruent and incongruent sentences was to ensure attention was maintained during the testing. The participants were asked simple questions related to the preceding sentence. For example: if the sentence presented was “the driver puts the petrol in the car” the filler question would be “where does the driver put the petrol”?

In addition, there were 14 fillers included which consisted of sentences that followed a different structure to the test stimuli such as “she is not sure if the table is made of plastic or wood”. The purpose of the filler sentences was to ensure reduction in the effect of predictability of occurrence of sentences. Both fillers and sentences were presented in a pseudorandomized order to ensure no two fillers or questions occur consecutively. The response to each question was monitored through a talk-back microphone, ensuring the participant is paying attention to the given stimuli and remains alert during the testing.

2.4.1 Stimuli

The test stimuli were constructed using 640 sentences with a reasonable amount of complexity, homogeneity and sentence length. The sentences used for the test were chosen based on a survey that was given to native English speakers. Each sentence was rated based on a scale of 1 to 6 where 1 indicated completely meaningful sentence (congruent) and 6 indicated meaningless sentence (incongruent). Out of these sentences 160 congruent and incongruent sentences was chosen based on the rating. Each sentence followed the same pattern similar to “the writer reads the story to the class”, for congruent sentences and “the barman drinks the story after work”, for incongruent sentences. Those sentences that obtained a score of 1 to 2 by minimum 5 people were chosen as congruent and those with rating of 5 to 6 were chosen as incongruent sentences.

The final 160 congruent and incongruent sentences were digitally recorded in a sound treated room and normalized to ensure similar gain was provided to the whole sentences and then across all sentences. Following this, the clarity check of the recording was carried out. This was followed by setting up the triggers for both congruent and incongruent sentences using Praat software. Triggers were set at the onset of the target word. 160 sentences were randomly presented during the testing. The sentences were not repeated and therefore there was no familiarization. The sampling frequency was set to 48,000 Hz using Matlab (The Mathworks Inc., Natick, MA).

The stimuli were delivered diotically at 65 dB sound pressure level (SPL) through Etymotic ER-3A insert earphones (Etymotic Research, Inc., Elk Grove Village, IL). Calibration was done using a hand-held sound level meter Brüel and Kjær type 2250 G4, connected to a 2 cc coupler. The 2cc acoustic coupler was connected to type 4122 pressure microphone which in turn was connected to a type 2636 measuring amplifier through type 2639 preamplifier cable (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark).

2.4.2 ERP recordings and test procedure

The electroencephalograms were recorded in an electrically and acoustically shielded room. All participants were made to sit 1 meter away from a computer screen where the individuals were asked to focus on a particular point to avoid artifacts that arise due to eye movements. EEGs were recorded using the Neuroscan ® Acquire 4.5 (Compumedics, Germany) 64 channel EEG system i.e., at 1000 Hz sampling rate. The electrodes were placed on an elastic easy cap (EASYCAP, Germany) using the International 10/20 EEG system. The horizontal movements were recorded using electrodes placed on the outer canthus of the right and left eye and vertical eye movements from the electrodes placed above and below the right eye. The electrode placed on the left mastoid was used as the reference electrode. The electrode and inter-electrode impedances were kept below 5 kΩ. Techniques such as combing the scalp was used to enhance good conduction (Mahajan &

McArthur, 2010). Individuals were asked to focus on the sentences presented and respond to only the questions asked in between the test.

2.5 Data analysis

The recorded EEG data was analysed using customized scripts developed in Matlab to obtain two types of auditory evoked potentials i.e. the onset response and N400. The first step was to re-reference the data. The EEG data was re-referenced to the average of combined mastoids (left & right). The artefacts obtained due to eye blinks were removed using a technique called iterative template matching and suppression [ITMS: (Valderrama et al., 2018)]. As a first step, this technique applies ITMS to a single channel that is situated at FP1, i.e. an electrode placed close to the left eye. Once the eye blinks were detected on that channel, a simplified version of the ITMS was applied to the remaining channels consisting of the processes: blink-artifact template estimate, amplitudes estimate, blink-artifact model estimate, and model suppression (refer Valderrama et al., 2018 for more details). The clean EEG signals were epoched with a range of -100 to 300 for the onset response analysis and -300 to 800 ms for N400 analysis. To emphasize low frequency neural activity, an offline digital filtering between 0.1 to 30 Hz a Butterworth filter was used. The accepted trials were then averaged to obtain the ERP waveform.

The N400 magnitude was determined by the area under the curve, which was defined as the area between the ERP associated to the incongruent sentence and the ERP associated with the congruent sentence in the time range [0.4 to 0.8] s. The area had to be greater than zero with statistical significance level at 0.05 on two sample t-test to be considered as an N400 response.

For both the N400 and the onset response, cluster permutation analysis was carried out to determine across and within group differences. Non-parametric randomization procedure was used to overcome the problem that arises due to multiple comparisons over a large number of electrodes (Maris, 2004, Maris and Oostenveld, 2007). The outcome from the statistical analysis comprised cluster of electrodes, sum of t-statistics in the cluster and the Monte Carlo estimates of the p value. Cluster of electrodes identified were corrected for multiple comparisons and among all clusters, only those clusters that had cluster values greater that 95% derived by random permutation of data, were considered.

The Global field power (GFP) was carried out only for the onset responses for both groups. GFP was determined for every individual in each group. GFP gives a single reference-independent measure of the response strength by quantifying the neural activity across the entire scalp as a function of time (Murray et al., 2008). GFP provides an advantage of comparing the results derived from the entire scalp rather than an single electrode (Hamburger and vd Burgt, 1991). This is done by calculating the standard deviation of all the waveforms from each electrode location and participant (Lehmann and Skrandies, 1980). For the GFP values obtained, an independent samples t-test was carried out in order to determine between group differences.

Lastly, an offline time frequency analysis was carried out using Matlab fieldtrip (Oostenveld et al. 2011). The continuous EEG data were re-referenced to the common average reference (CMR) by excluding noisy electrode channels. An independent component analysis (ICA) was then used to correct for ocular artefacts which includes the horizontal and vertical eye movements as proposed by (Jung, 2011). The ocular corrected EEG were segmented into trials which had 2000 ms prior to the stimulus onset and 4000 ms post stimulus onset. Noisy trials rejection was then performed by excluding all trials which had an absolute amplitude greater than 150 μV^2. The remaining trials were then analysed in time and frequency by decomposing each of the trials using the wavelet transform. The mortlett wavelet with a filter tap of 5 cycles was used.

The resulting time-frequency spectra were then converted to a relative power measure known as the event related spectral perturbation (ERSP). This was done by normalising each of the trails as proposed in (Grandchamp and Delorme, 2011). The ERSP denotes the changes in brain oscillatory activities. Furthermore, to determine if there were any differences in the time frequency analysis between the two groups across the two conditions, Monte-Carlo cluster permutation analysis slope t-test was performed.

3. Results

3.1 Extended pure-tone audiometry and DPOAE

For both extended pure-tone audiometry and DPOAE no significant differences were observed for both right [F (4, 36) = 1.4, p= 0.2, partial $ŋ^2$ = 0.1], [F (7, 33) = 1.3, p= 0.2, partial $ŋ^2$ = 0.2] and left ears [F (4, 36) = 1.0, p= 0.4, partial $ŋ^2$ = 0.1], [F (7, 33) = 1.1, p= 0.3, partial $ŋ^2$ = 0.1] between the two groups.

3.2 Onset Reponses

The onset responses were analysed for both congruent and incongruent sentences. Figure 1 shows the grand-average waveform of the onset response of both the LC and CG group for the congruent sentences and incongruent sentences. GFP calculated across the two groups for both congruent [t (40) = -0.8, p=0.4)] and incongruent sentence onset responses [t (40) = 0.5, p=0.6)] at 100-150ms showed no differences across the 2 groups (see figure 2). Similarly, cluster permutation analysis using independent t test showed no differences between the two groups for onset responses for congruent or incongruent sentences (p>0.05).

3.3 N400 response

The N400 responses were analysed for both groups. Figure 3 shows the grand average waveform obtained for congruent sentences and incongruent sentences of both LC and CG group for the Cz electrode.

The N400 responses were examined for within group and across group. As a first step we examined if there was an N400 response observed within the two groups when presented with semantically congruent and incongruent sentences. For this, first the incongruent sentence response waveforms were subtracted from the congruent sentence responses and one-sample t test was applied to the difference waveforms. The results revealed the presence of N400 responses only for the CG but not for the LC group on most of the fronto-central electrodes except for Cz where the N400 responses were seen in both groups (refer table 5). In the present study we chose to analyse the frontal and central electrodes because, while we did the grand-average across all the channels, as previous literature has recommended that N400 responses are most prominent in the frontal and central electrodes(Kutas and Federmeier, 2011; Jamison et al., 2016). Cluster permutation analysis showed differences in neural processing on the central and frontal electrodes only for the CG but not the LC group, (figure 3).

After completing the within group analysis, using two-sample t test we evaluated if there were any differences on N400 across the two groups on the frontal and central electrodes. The results indicated no significant differences between the two groups on two-sample t test ($p>0.05$). Similar results were also observed on cluster permutation analysis using independent t test ($p>0.05$).

Lastly, on the time frequency analysis, both CG and LC group showed synchronised alpha oscillations however, the CG had stronger synchronised alpha oscillations for both congruent 800-1060 ms (p-val = 0.014) and incongruent 800-1060ms (p-val = 0.014) sentences. The effect was observed in the left temporal regions for the congruent sentences and on left frontal and temporal regions for the incongruent sentences, shown in figure 4. In addition, linear mixed model effects test was carried out to see if the observed strong synchronised alpha oscillations in the CG were due to the influence of age. Despite being within the same age range, the median of the CG and LC group were 10 years apart. Therefore, the question was if the listening in noise reports were due to age differences. The results indicate that after controlling for age, the observed difference for both congruent [estimate=-0.0, SE=0.0, t=-1.3, p=0.2] and incongruent sentences [estimate=-0.0, SE=0.0, t=-1.1, p=0.2] were significant indicating that the groups are different but not because of the age. .

4. Discussion

The main aim of the study was to examine the differences in N400 in individuals reporting speech understanding in noise problems. We predicted individuals with listening in noise concerns will show differences in neural processing compared to adults with normal hearing on their N400.

Are the individuals in the LC group different from CG?

The answer to this question would be yes. In the current study, only the CG had measurable N400 when compared to the LC group. The significant N400 effect was observed in the fronto-central electrodes. Additionally, on time frequency analysis the CG showed relatively stronger alpha oscillations than the LC group. The alpha activations were observed at different cortical areas for semantically congruent and incongruent sentences and these were not due to age differences. There are reports of adults with listening concerns in the absence of the hearing loss in previous population based studies (Hind et al., 2011; Tremblay et al., 2015). The profile of these populations is still not clear, but the current results support the presence of a group of adults with listening concerns.

What could be the reasons for the observed differences in neural processing across the two groups?

Davis and Johnsrude (2007) suggested pragmatic knowledge to be an important factor for decoding speech particularly in a degraded situation such as noise. This may be applicable even in the processing of sentences that are semantically congruent and incongruent. Pragmatic knowledge encompasses the probabilistic relationships between the words in the spoken language, allowing a speaker to fill in the content that is missing by predicting what is likely to occur (Conway et al., 2010). The ability to predict the likelihood of the forthcoming word is deemed important for speech understanding (DeLong et al., 2005). In the N400 task, one needs to use the given context in-order to gauge the forthcoming word. This is particularly important while listening to semantically incongruent sentence. For example, if the presented sentence is odd or incongruent, there is a difference between the expected versus presented sentence. It may be that the LC group have difficulty in predicting the preceding context and therefore N400 is not elicited in the LC group as clearly as the CG. Another important aspect to note is that there were no differences between the groups on evaluating the onset response. This implies that the percept of the sentence is not different between the groups.

Another important factor while performing the N400 task would be the ability to maintain attention throughout the task. In order to judge whether the given sentence is semantically congruent or incongruent, primarily, the individual must pay attention to the given task. Bentin et al. (1995) studied the semantic priming effects on N400 to attended and unattended words. They found the semantic priming effects on N400 amplitude to only those words that were attended.

They found reduced N400 amplitude to the semantically primed attended words. Similar effects of attention was also observed in a study conducted by Okita and Jibu (1998) in which the participants were asked to either attend or not attend to the given words. They wanted to observe the effects of repetition on N400 to words attended in comparison to words when unattended. Similar to Bentin et al. (1995) Okita and Jibu (1998) noticed N400 amplitudes to be attenuated due to the effects of repetition of words and this was *only* observed for the words that were attended. Some of this evidence highlights the role of attention on N400 response.

The results obtained from the time frequency analysis show stronger synchronised alpha oscillations around the fronto-temporal regions when presented with semantically incongruent sentences in the CG. Some of the previous literature have shown synchronised alpha oscillations being observed in tasks where in one needs to pay attention to the given stimuli and remember them even while they are not responding to them (Tuladhar et al., 2007; Scheeringa et al., 2009). In the N400 task, the individual had to pay attention to the given stimuli in order to judge if they were semantically congruent or incongruent sentences. The time frequency analysis results indicate that the individuals in the LC group had difficulty maintaining their attention on the task which may explain the differences in the synchronised alpha oscillations.

4.2 Sensory versus cortical neural processing

Studies done on individuals who are exposed to occupational/recreational noise, reporting a speech understanding in noise problems and having clinically normal audiograms (Prendergast et al., 2017; Grinn et al., 2017) showed no difference on their auditory brainstem response. From the results gathered from the present study and evidence from previous literature, it may indicate individuals who complain of a speech understanding in noise problem have differences in processing information at the level of cortex rather than at brainstem level. These results may suggest N400 to be a potentially important tool and may be used clinically to identify listening in issues. However, test efficacy needs to be further explored before using it as a clinical tool.

5. Conclusion

In summary, we hypothesised that individuals who report of a speech understanding in noise problem having clinically normal audiograms would show differences in their cortical neural processing abilities. From the results obtained, there are differences in neural processing in the CG group when compared to the LC group in processing of semantically congruent versus incongruent sentences. These underlying differences in cortical processing could be the reason why adults with clinically normal hearing report of understanding speech in noise to be difficult.

6. Limitation

In future, conducting the N400 measure on a cohort with similar profile at different signal to noise ratio could provide additional information on the cortical processing ability when speech signal is processed at varying levels of complexity.

7. References

American National Standards Institute. (1996). Specifications for Audiometers (ANSI S3.6-1996). New York: American National Standards Institute.

Appaiah, S.K., Sharma, M., Monaghan, J.J.M., Keidser, G., & Newall, J. Auditory processing, attention, memory and statistical learning in adults with listening in noise concerns in presence of normal audiogram. Ear and Hearing 2018: Under review.

Bentin, S., Kutas, M., & Hillyard, S. A. Semantic processing and memory for attended and unattended words in dichotic listening: Behavioural and electrophysiological evidence. Journal of Experimental Psychology: Human Perception and Performance 1995;21:54.

Bressler, S., Goldberg, H., & Shinn-Cunningham, B. Sensory coding and cognitive processing of sound in Veterans with blast exposure. Hearing Research 2017;349:98–110.

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. Implicit statistical learning in language processing: Word predictability is the key. Cognition 2010;114:356–371.

Davis, M. H., & Johnsrude, I. S. Hearing speech sounds: top-down influences on the interface between audition and speech perception. Hearing Research 2007;229:132–147.

DeLong, K. a, Urbach, T. P., & Kutas, M. Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. Nature Neuroscience 2005;8:1117.

Duncan, C. C., Barry, R. J., Connolly, J. F., Fischer, C., Michie, P. T., Näätänen, R, et al. Event-related potentials in clinical research: guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400. Clinical Neurophysiology 2009; 120:1883–1908.

Gilley, P. M., & Sharma, A. Functional brain dynamics of evoked and event-related potentials from the central auditory system. Perspectives on Hearing and Hearing Disorders: Research and Diagnostics 2010;14:12-20.

Golding, M., Carter, N., Mitchell, P., & Hood, L. J. Prevalence of Central Auditory Processing (CAP) Abnormality in an Older Australian Population: The Blue Mountains Hearing Study. Journal of American Academy of Audiology 2004;15:633–642.

Grandchamp, R., & Delorme, A. Single-trial normalization for event-related spectral decomposition reduces sensitivity to noisy trials. Frontiers in Psychology 2011;2:236.

Grinn, S. K., Wiseman, K. B., Baker, J. A., & Le Prell, C. G. Hidden hearing loss? No effect of common recreational noise exposure on cochlear nerve response amplitude in humans. Frontiers in Neuroscience 2017;11:465.

Hamburger, H. L., & vd Burgt, M. a. Global field power measurement versus classical method in the determination of the latency of evoked potential components. Brain Topography 1991;3:391–396.

Hind, S. E., Haines-Bazrafshan, R., Benton, C. L., Brassington, W., Towle, B., & Moore, D. R. Prevalence of clinical referrals having hearing thresholds within normal limits. International Journal of Audiology 2011;50:708–716.

Jamison, C., Steve J. Aiken, Kiefte, M., Newman, A. J., Bance, M., & Sculthorpe-Petley, L. (2016). Preliminary Investigation of the Passively Evoked N400 as a Tool for Estimating Speech-in-Noise Thresholds. American Journal of Speech-Language Pathology 2016;25:44–358.

Jung, T. P., Makeig, S., McKeown, M. J., Bell, A. J., Lee, T. W., & Sejnowski, T. J. (2001). Imaging brain dynamics using independent component analysis. Proceedings of the IEEE 2001; *89*:1107-1122.

Klimesch, W. Alpha-band oscillations, attention, and controlled access to stored information. Trends in cognitive sciences 2012;16:606-617.

Kutas, M., & Federmeier, K. D. Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). Annual Review of Psychology 2011;62:621–47.

Kutas, M., & Hillyard, S. A. Reading senseless sentences: brain potentials reflect semantic incongruity. Science 1980.

Lau, E. F., Phillips, C., & Poeppel, D. A cortical network for semantics: (de)constructing the N400. Nature Reviews Neuroscience 2008;9:920.

Lehmann, D., & Skrandies, W. Reference-free identification of components of checkerboard-evoked multichannel potential fields. Electroencephalography and Clinical Neurophysiology 1980;48:609–621.

Luck, S. J. An introduction to the event-related potential technique.2005;1.

Mahajan, Y., & McArthur, G. Does combing the scalp reduce scalp electrode impedances? Journal of Neuroscience Methods 2010;188:287–289.

Makeig, S., Debener, S., Onton, J., & Delorme, A. Mining event-related brain dynamics. Trends in cognitive sciences, 2004;8:204-210.

Marian, V., Blumfield, H., & Kaushanskaya, M. The Language Experience and Proficiency

Questionnaire (LEAP-Q): Assessing Language Profiles in Bilinguals and Multilinguals Viorica. Hearing Research 2007;50:940–967.

Maris, E. Randomization tests for ERP topographies and whole spatiotemporal data matrices. Psychophysiology 2004;41:142–151.

Maris, E., & Oostenveld, R. Nonparametric statistical testing of EEG-and MEG-data. Journal of Neuroscience Methods 2007;164:177–190.

Martin, B. A., Tremblay, K. L., & Korczak, P. Speech evoked potentials: from the laboratory to the clinic. Ear & Hearing 2008;29:285–313.

McCarthy, G., & Nobre, A. Modulation of semantic processing by spatial selective attention. Electroencephalography and Clinical Neurophysiology 1993;88:210–219.

Meade, G., Lee, B., Midgley, K. J., Holcomb, P. J., & Emmorey, K. Phonological and semantic priming in American Sign Language: N300 and N400 effects. Language, Cognition and Neuroscience 2018:1–15.

Murray, M. M., Brunet, D., & Michel, C. M. Topographic ERP analyses: A step-by-step tutorial review. Brain Topography 2008;20:249–264.

Nasreddine, Z., Phillips, N., Bédirian, V., Charbonneau, S., Whitehead, V., Colllin, I, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. Journal of the American Geriatrics Society 2005;53:695–699

Niedermeyer, E., & da Silva, F. L. (Eds.). Electroencephalography: basic principles, clinical applications, and related fields. Lippincott Williams & Wilkins 2005.

Okita, T., & Jibu, T. Selective attention and N400 attenuation with spoken word repetition.

Psychophysiology 1998;35:260–271.

Perrin, F., & Garcıa-Larrea, L. Modulation of the N400 potential during auditory phonological/semantic interaction. Cognitive Brain Research 2003;17:36–47.

Pichora-Fuller, M. K., & Souza, P. E. Effects of aging on auditory processing of speech. International Journal of Audiology 2003;42:11–16.

Prendergast, G., Guest, H., Munro, K. J., Kluk, K., Léger, A., Hall, D. A, et al. Effects of noise exposure on young adults with normal audiograms I: Electrophysiology. Hearing Research 2017;344:68–81.

Roach, B. J., & Mathalon, D. H. Event-related EEG time-frequency analysis: an overview of measures and an analysis of early gamma band phase locking in schizophrenia. Schizophrenia bulletin 2008;34:907-926.

Rugg, M. D. The effects of semantic priming and word repetition on event-related potentials. Psychophysiology 1985;22:642–647.

Scheeringa, R., Petersson, K. M., Oostenveld, R., Norris, D. G., Hagoort, P., &, & Bastiaansen, M. C. Trial-by-trial coupling between EEG and BOLD identifies networks related to alpha and theta EEG power increases during working memory maintenance. Neuroimage 2009;44:1224–1238.

Senkowski, D., Schneider, T. R., Foxe, J. J., & Engel, A. K. Crossmodal binding through neural coherence: implications for multisensory processing. Trends in neurosciences 2008;31:401-409.

Shinn, J., Long, A., Rayle, C., Bush, M., Shinn, J., Long, A, et al. Primary auditory symptoms in patients with normal peripheral hearing sensitivity : Redefining hearing loss. Hearing, Balance and Communication 2016;14:44–49.

Silman, S., & Gelfand, S. A. The relationship between magnitude of hearing loss and acoustic reflex threshold levels. The Journal of Speech and Hearing Disorders 1981;46:312–316.

Stapells, D. R. Cortical event-related potentials to auditory stimuli. Handbook of Clinical Audiology 2002;5:378–406.

Sur, S., & Sinha, V. K. Event-related potential: An overview. Industrial Psychiatry Journal 2009;18:70.

Tuladhar, A. M., Huurne, N. T., Schoffelen, J. M., Maris, E., Oostenveld, R., & Jensen, O. Parieto-occipital sources account for the increase in alpha activity with working memory load. Human Brain Mapping 2007;28:785–792.

Tremblay, K. L., Pinto, A., Fischer, M. E., Klein, B. E. K., Klein, R., Levy, S, et al. Self-Reported Hearing Difficulties Among Adults With Normal Audiograms : The Beaver Dam Offspring Study. *Ear and Hearing 2015*;*36*:e290.

Valderrama, J. T., de la Torre, A., & Van Dun, B. An automatic algorithm for blink-artifact suppression based on iterative template matching: Application to single channel recording of cortical auditory evoked potentials. Journal of Neural Engineering 2018; 15:016008.

Van Petten, C., & Kutas, M. Influences of semantic and syntactic context on open-and closed-class words. Memory & Cognition 1991;19:95–112.

8. Tables

TABLE 1: Shows the pure-tone audiometry thresholds (in dB HL) including extended high frequencies of both the groups for both right and left ear with mean and standard deviations (in brackets).

FREQUENCIES	CG (N=22)		LC (N=20)	
	RE	**LE**	**RE**	**LE**
500 Hz	6.8(2.9)	6.3(2.7)	7.0(2.5)	5.5(2.2)
1 kHz	9.5(4.0)	11.1(2.2)	8.7(4.2)	10.2(1.1)
2 kHz	10.0(4.0)	10.2(4.2)	9.5(5.1)	8.2(4.0)
4 kHz	12.7(4.8)	10.9(2.9)	17.0(11.4)	14.0(7.5)
8 kHz	14.3(4.9)	13.1(3.2)	17.0(9.2)	16.2(11.3)
9 kHz	13.6(4.6)	14.0(3.3)	19.7(14.7)	21.0(13.0)
10 kHz	13.4(6.0)	14.5(3.4)	21.2(18.9)	21.5(13.5)
11.2 kHz	12.7(5.9)	15.2(3.6)	22.2(18.3)	22.2(13.9)
12.5 kHz	16.1(12.6)	15.2(3.)	22.7(17.1)	23.5(13.3)

Note: CG: Control Group; LC: Listening Concern group; LE = left ear; RE = right ear

TABLE 2: Shows the age, LEAP-Q, MoCA and Pure Tone Audiometry (PTA 3-frequency average) thresholds for the control (CG) and listening concern (LC) groups. It provides the mean and standard deviations (in brackets) and the difference statistics across the two groups are given in the MANOVA row.

	VARIABLES						
	Age	**LEAP-Q (speaking)**	**LEAP-Q (understanding)**	**LEAP-Q (reading)**	**MoCA**	**PTA (RE)**	**PTA (LE)**
CG (N=22)	29.9(7.6)	8.7(1.0)	9.2(0.8)	9.2(0.9)	27.2(1.2)	8.7(0.5)	9.2(1.0)
LC (N=20)	40.0(14.2)	9.2(0.8)	9.3(0.8)	9.4(0.5)	27.4(1.0)	8.4(3.9)	7.9(2.6)
MANOVA	[$F(1, 40) = 7.7$, $p < 0.008$, partial $\eta^2=0.1$]	[$F(1, 40) = 1.0$, $p = 0.3$, partial $\eta^2 = 0.02$]	[$F(1, 40) = 0.2$, $p = 0.6$, partial $\eta^2=0.005$]	[$F(1, 40) = 0.5$, $p = 0.4$, partial $\eta^2 = 0.01$]	[$F(1, 40) = 0.1$, $p = 0.7$, partial $\eta^2=0.03$]	[$F(1, 40) = 0.1$, $p = 0.7$, partial $\eta^2 = 0.004$]	[$F(1, 40) = 3.1$, $p = 0.08$, partial $\eta^2=0.7$]

Note: LE = left ear; RE = right ear; PTA = pure-tone 3-frequency average: mean of thresholds at 500, 1000 and 2000 Hz; SD = standard deviation; MoCA = Montreal Cognitive Examination; Language Experience and Proficiency Questionnaire (LEAP-Q)

TABLE 3: Shows the Distortion Product Oto-acoustic emissions (OAE's) for both groups with the mean and standard deviations (in brackets). There were no significant effects observed across the two groups.

FREQUENCIES	**CG**		**LC**	
	RE	LE	RE	LE
1 kHz	4.4(6.1)	4.1(6.2)	1.2(10.4)	1.8(7.3)
1.5 kHz	8.0(6.3)	7.2(6.0)	5.3(8.2)	2.4(6.6)
2 kHz	6.7(4.6)	6.2(5.9)	2.4(6.9)	-0.4(8.5)
3 kHz	5.0(5.8)	5.4(5.1)	1.0(9.6)	-0.4(7.6)
4 kHz	10.3(4.5)	10.3(4.5)	0.0(13.0)	2.8(10.5)
6 kHz	6.9(7.4)	7.0(6.0)	-5.7(11.6)	-1.4(10.4)
8 kHz	0.7(9.5)	2.4(7.1)	-8.4(8.4)	-4.8(14.1)

Note: CG: Control Group; LC: Listening Concern group; LE = left ear; RE = right ear

TABLE 4: Shows the total ratings of the LC group for each participant on the SSQ 12 where 0 indicates severe difficulty per question. The 12 questions on the SSQ 12 were broadly categorized into three groups i.e. understanding speech, spatial separation, and sound quality. The sum scores for each participant under each category and the combined sum scores from all three categories are shown in the table.

	PARTICIPANTS									
	LC1	**LC2**	**LC3**	**LC4**	**LC5**	**LC6**	**LC7**	**LC8**	**LC9**	**LC10**
UNDERSTANDING SPEECH (RR: 0-50)	34.0	28.0	23.5	8.0	41.0	25.0	29.0	31.0	40.0	40.0
SPATIAL SEPARATION (RR: 0-30)	19.5	22.0	26.0	26.0	24.5	19.5	21.0	23.5	23.0	27.0
SOUND QUALITY (RR:0 – 40)	20.0	26.0	25.0	16.0	36.0	15.0	27.0	35.5	33.0	34.5
SOUND QUALITY (RR:0 – 120)	73.5	76.0	74.0	50.0	101.0	59.5	77.0	90.0	96.0	101.0
	LC11	**LC12**	**LC13**	**LC14**	**LC15**	**LC16**	**LC17**	**LC18**	**LC19**	**LC20**
UNDERSTANDING SPEECH (RR: 0-50)	12.0	14.0	44.0	20.0	26.0	22.0	42.5	20.0	20.0	32.5
SPATIAL SEPARATION (RR: 0-30)	8.0	10.0	30.0	27.0	13.0	19.0	26.0	25.0	25.0	27.0
SOUND QUALITY (RR:0 – 40)	15.0	12.0	37.0	28.0	20.0	34.0	39.0	30.0	30.0	35.0
SOUND QUALITY (RR:0 – 120)	35.0	36.0	111.0	75.0	59.0	75.0	107.0	75.0	75.0	98.0

Note: LC: Listening Concern group; RR: Rating range

Table 5: Shows mean, median, standard deviation and two sample t test values of CG and LC group for N400.

ELECTRODE	ELECTRODE	MEAN (MIN, MAX)	MEDIAN	STDEV	TWO-SAMPLE T TEST
CG	Fcz	0.41(1.4; -0.4)	0.3	0.4	t(21) = 3.9978, p = 0.0007
LC		0.28(2.1; 0.7)	0.3	0.6	t(19) = 1.8549, p = 0.0792
CG	Fz	0.44(1.7; 0.5)	0.4	0.6	t(21) = 3.2534, p = 0.0038
LC		0.3(3.8; -1.1)	0.3	1.0	t(19) = 1.4212, p = 0.1715
CG	Cz	0.4(1.1; -0.5)	0.4	0.4	t(21) = 4.5090, p = 0.0002
LC		0.2(1.8; -0.5)	0.2	0.5	t(19) = 2.3289, p = 0.0311
CG	Cpz	0.3(1.2; -0.6)	0.4	0.4	t(21) = 3.6401, p = 0.0015
LC		0.1(1.5; -0.9)	0.2	0.6	t(19) = 1.2303, p = 0.2336

9. Figures

FIGURE 1: Shows the grandaverage waveform onset response with the standard error of the LC and CG group for the congruent and incongruent sentences (Cz electrode). Blue line shows the response of CG and the green line shows the response of the LC group.

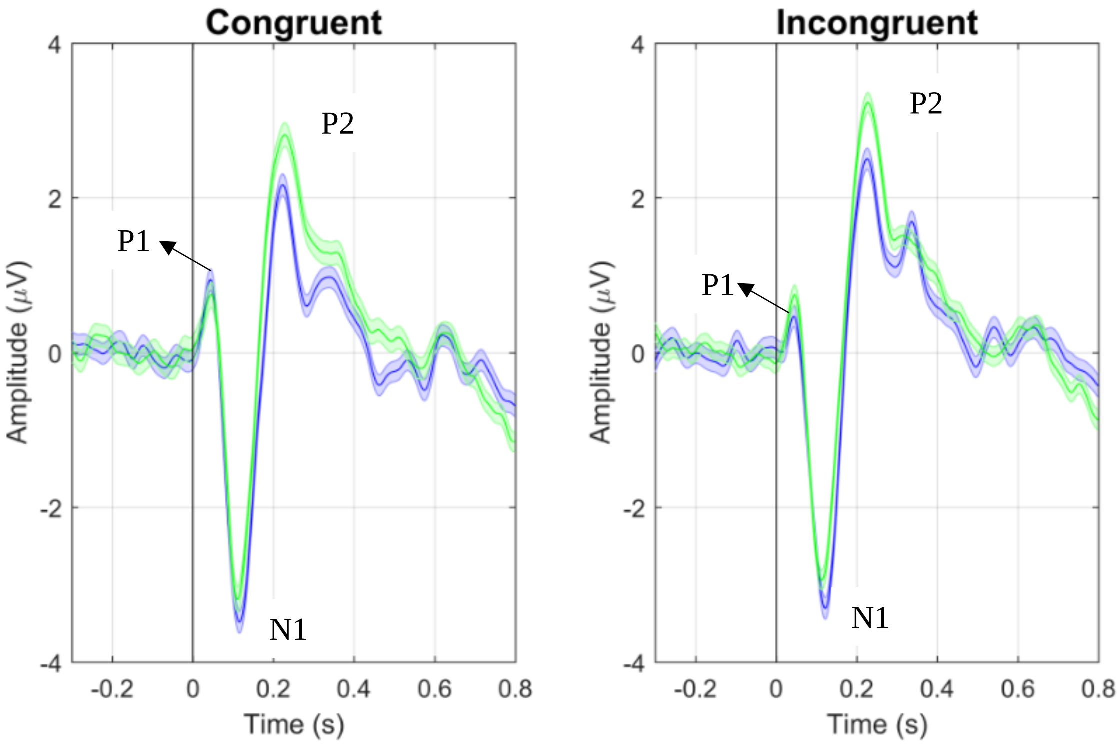


FIGURE 2: Shows the GFP of the onset response of the LC and CG group for the congruent and incongruent sentences. Blue line shows the response of CG and the green line shows the response of the LC group.

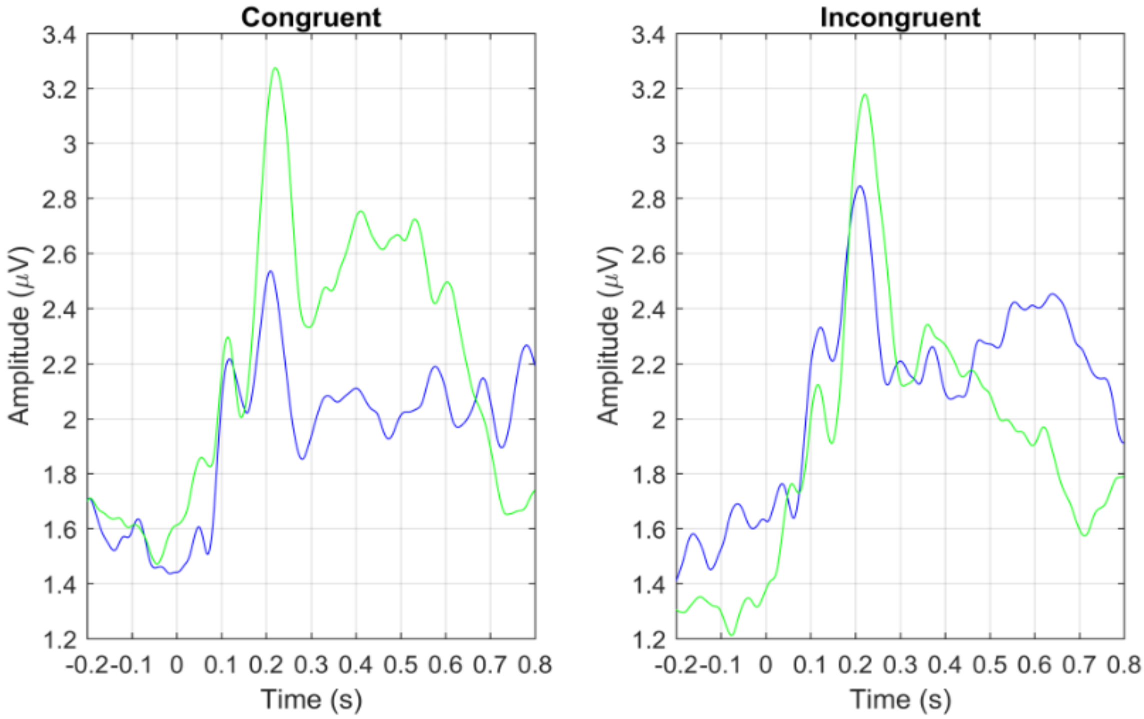


FIGURE 3: shows the grand average waveform obtained for congruent sentences and incongruent sentences with the standard error of both LC and CG group for the Cz electrode. Blue line shows the response for congruent sentences and the green line shows the response for incongruent sentences. The right column shows the clusters obtained for the CG and LC group on cluster permutation analysis. The clusters were present only for the CG group on the centro-frontal electrodes.

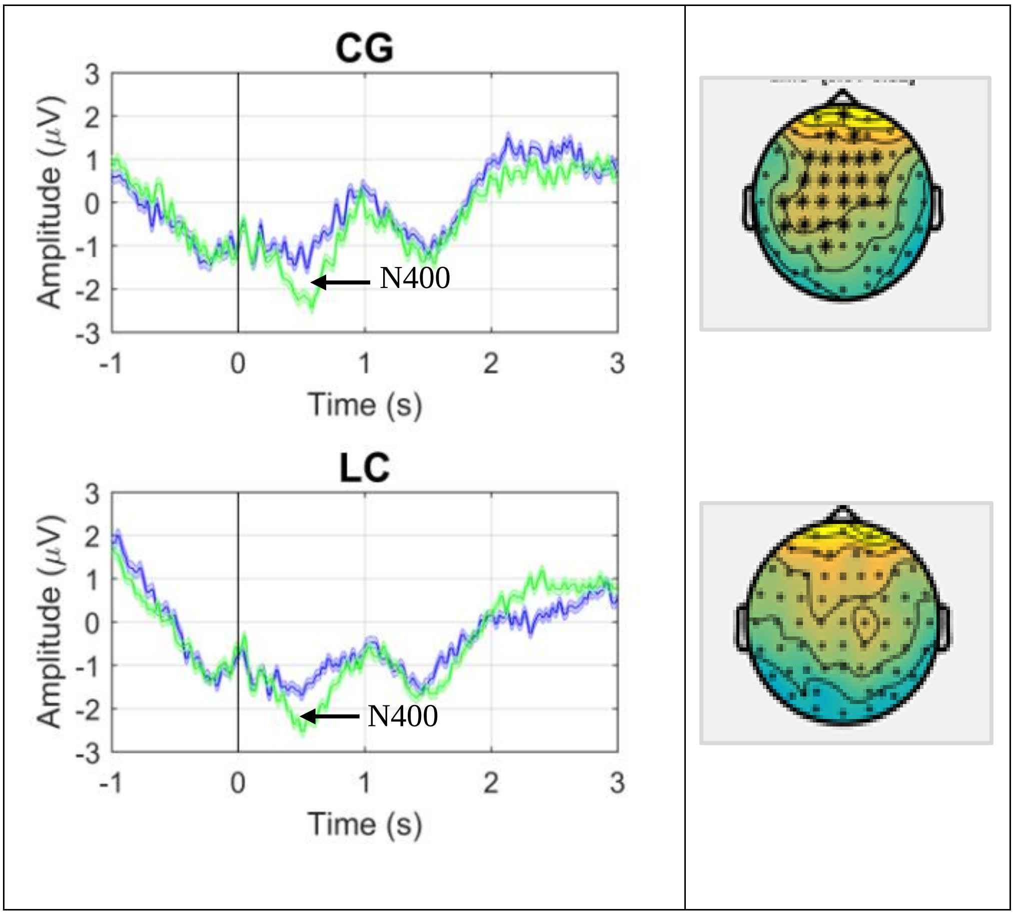
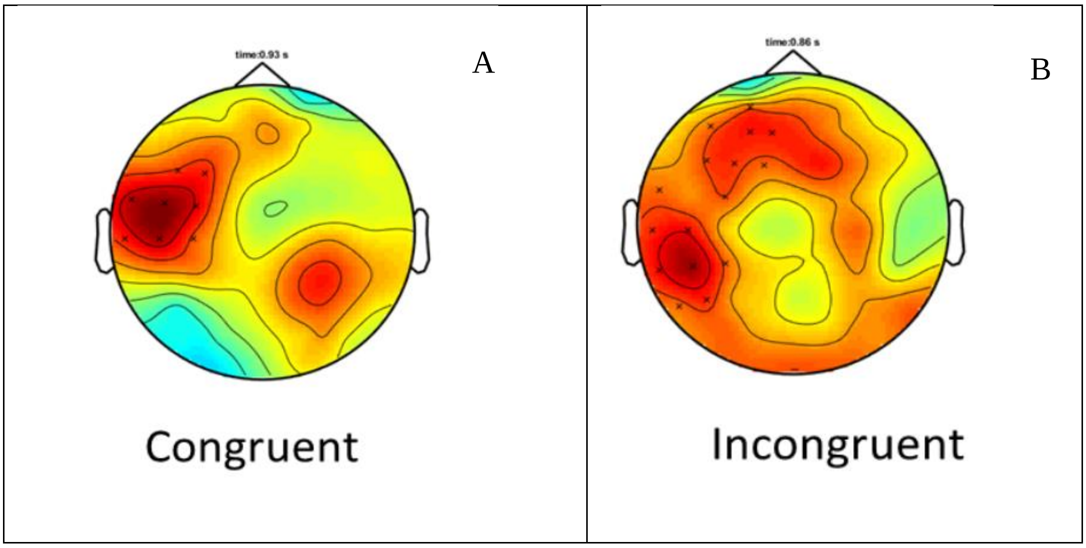


FIGURE 4: A shows the cortical activation when presented with semantically congruent sentences and B shows the cortical activation when presented with semantically incongruent sentences between the LC and CG group



Chapter 4: Auditory and cognitive processing skills in individuals with and without hearing loss who report speech understanding in noise difficulty

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ABSTRACT

People with hearing loss (HL) often report difficulty in understanding speech in the presence of noise despite adequate amplification. The present study aims to determine differences in auditory and cognitive processing skills in individuals with hearing loss who report speech understanding difficulties in situations with substantial background noise compared to a control group. Ten participants (19-62 years, mean ± std = 35.7 ± 14.0 years) with bilateral, symmetric, mild-moderate to moderately-severe sensori neural hearing loss and ten individuals with clinically normal hearing (21-67 years, mean ± std = 40.6 ±19.6 years) participated in the present study. Behavioural auditory and cognitive tests included: pitch discrimination, spectral resolution, amplitude modulation, speech in noise, short-term memory, working memory, attention, cognitive spare capacity, and statistical learning tasks. The physiological test comprised of cortical auditory evoked potentials (CAEPs) to /da/ measured in quiet at 65 dB SPL and 8 dB SNR (8 talker babble noise). For the group with hearing loss, all the auditory stimuli were amplified using filters based on the National Acoustics Laboratories-Revised Profound (NAL-RP) prescription formula to ensure adequate audibility.

Behavioural test results revealed no significant differences on any of the auditory and cognitive tasks. Physiological results showed similar amplitudes and latencies for P1-N1-P2 to /da/ in quiet and noise across the two groups. Further time frequency analysis of electroencephalography revealed significantly higher alpha (8-12Hz) synchronisation at the centro-frontal electrodes in quiet in the normally hearing group.

The summarised findings are: 1) the significant synchronized alpha oscillations in individuals with normal hearing in quiet condition may be indicative of the normal hearing group's ability to attend to the relevant stimulus /da/ as well as inhibit non-task related cortical

regions from responding; and 2) adults with hearing loss performed as well as the normal hearing group on the speech comprehension task despite reported listening difficulties. One reason may be that they are able to use their language and cognitive skills to draw contextual information during the speech understanding task.

In conclusion, the physiological tests are relatively more sensitive than behavioral measures to difficulties with the speech recognition in noise reported by individuals with hearing loss. At least for the current cohort, it appears that relatively poorer attention on the task is contributing to their inability to recognition and potentially understand speech.

1. Introduction

Speech in noise perception has always been a challenge for individuals with hearing loss (Plomp and Duquesnoy, 1982; Smoorenburg et al., 1982) despite a relatively good speech perception in quiet (Dubno et al., 1984). The self-evaluation of aided individuals with hearing loss shows satisfaction in quiet situations but not in noise (Kochkin, 2000; Kochkin, 2005).

Previous research has reported that hearing thresholds, especially in the mid-to-high frequencies (i.e., 1000, 2000 and 4000 Hz) have the largest contribution to the individual speech perception ability (Van Rooij and Plomp, 1990; Van Rooij and Plomp, 1992; Dubno, J. R., and Dirks, 1992; Dubno and Ahlstrom, 1995a;1995b). In the presence of a hearing loss, these affected frequencies are compensated by most amplification devices (Edwards, 2007). It might be expected, therefore, that providing amplification at these frequencies should result in speech perception more closely aligned with normal hearing listeners. However, this is not always the case. In a study, it was reported that 91% of the individuals wearing hearing aids, described understanding speech as difficult, particularly in the presence of noise (Kochkin, 2010).

There is a correlation between hearing thresholds and speech in noise performance. However, only a modest amount of the variation in speech in noise performance can be attributed to hearing threshold (Souza et al. 2007; Killion and Niquette, 2015), indeed many studies now report cases of speech in noise difficulty in those with clinically normal audiograms (Yeend et al., 2017; Prendergast et al., 2017). Hearing loss or reduced hearing thresholds are thus not sufficient to explain performance in noise, and compensating for lack of audibility, although important (Humes, 2002), is not sufficient to overcome these difficulties (Humes et al., 2006; Akeroyd, 2008; Hee Lee and Humes, 2012).

The Framework for Understanding Effortful Listening (FUEL) model by Pichora-Fuller et al. (2016) has provided a more holistic approach to understanding listening in the presence of noise. The FUEL model suggests that, apart from hearing loss it is important to consider effects of cognitive demands and motivation. This model provides a framework for audiologists to gain a better understanding of the effort applied while listening in everyday life particularly in challenging situations such as in the presence of noise. There is a growing body of literature that has emphasized the importance of auditory-cognitive interactions on listening performance, (Bregman, 1990; McAdams and Bigand, 1993; Neuhoff, 2004) particularly in the presence of noise (CHABA, Committee on Hearing, Bioacoustics and Biomechanics, 1988; Humes et al., 2006; Akeroyd, 2008).

A study conducted by Humes, Kidd, and Lentz (2013) examined the factors that contribute to individual variance in speech understanding in adults. The results showed cognitive skills contribute to 11.4% of the total variance while hearing loss only about 8.8%. Most participants in Humes et al. (2013) study were not hearing aid users despite having a hearing loss, although audibility was reportedly restored for conduct of the tests. In the present study we were interested to examine how bilaterally aided individuals with hearing loss who report issues with speech understanding in noise performed on various auditory and cognitive processing tasks in comparison to individuals with normal hearing having no speech understanding in noise issues.

The auditory and cognitive test battery of this study was selected based on two aspects: (i) Evidence from earlier studies on performance by individuals with hearing loss on each of these tests; and (ii) their contribution to speech perception in noise.

A number of studies have shown that individuals with hearing loss have poorer performance on a range of different auditory and cognitive processing tasks compared to individuals with normal hearing: (i) modulation detection threshold (MDT) Grant et al., 1998; Feng et al., 2010), (ii) frequency discrimination (FD) (Turner and Nelson, 1982; Hall and Wood, 1984; Abel et al., 1990); (iii) iterated ripple noise test (IRN) (Leek and Summers, 2001); (iv) spectral-temporally modulated ripple test (SMRT) (Turner et al.,1999; Henry et al., 2005; Won et al., 2007); (v) digit span test assessing short-term and working memory (Lunner, 2003; Ng et al., 2013), (vi) attention (see Shinn-Cunningham and Best, 2008 for review); (vii) cognitive spare capacity (CSC) (Mishra et al., 2014; Keidser et al., 2015); and (viii) statistical learning (SL) (Conway et al., 2011).

The influence of temporal processing on speech perception may be attributed either in the form of temporal envelope or temporal fine structure information (Hopkins and Moore, 2010). Adequate spectral processing with sufficient spectral resolution is also essential for accurate perception of speech (Henry et al., 2005). Therefore, one may predict these skills to be important especially for speech perception in the presence of noise. Consequently, in the present study, we have included auditory tests that assess both temporal and spectral information.

One of the cognitive measures tested, working memory, refers to the neural processes in which information is encoded and processed into meaningful units (Baddeley, 1992). Cognitive spare capacity, refers to the residual capacity existing when all the cognitive resources have been utilized for processing a signal, most often when the signal is degraded in the presence of noise (see Mishra et al., 2013 for more details on cognitive spare capacity). Similarly, selective attention and attention switching are also important cognitive measures (Shinn-Cunningham and Best, 2008). These attentional measures test the ability to pay attention to the required source and ignore unwanted distractors. These cognitive measures have been reported to potentially contribute to speech understanding in noise performance in individuals with hearing loss (Lunner, 2003; Shinn-Cunningham and Best, 2008; Ng et al., 2013; Mishra et al., 2014; Keidser et al., 2015).

Another cognitive factor that has not been explored much in individuals with hearing loss is statistical learning, which is the capacity to recognize the regularities in the environment or language implicitly (Perruchet and Pacton, 2006). Behavioural studies conducted show that humans have the ability to learn statistical regularities when stimulus is presented both in auditory (Pena et al., 2002; Seidenberg et al., 2002) and visual domain (Fiser and Aslin, 2002; Kirkham et al., 2002). Statistical learning has also been found to account for certain language acquisition skills such as word segmentation (Swingley, 2005), phonological learning (Maye et al., 2002) and syntactic learning (Thompson and Newport, 2007). Furthermore, in a study conducted by Conway et al. (2010), it was found that statistical learning correlated with word predictability, which is reportedly contributes to understanding speech in the presence of noise (Elliott, 1995; McClelland et al., 2006). Considering the evidence, the role statistical learning potentially plays towards understanding speech in the presence of noise, current study included a test of statistical learning in both auditory and visual modality.

In addition to these behavioural measures assessing auditory and cognitive processing skills, the present study also included the recording of cortical auditory evoked potentials (CAEPs) in background noise as a physiological correlate of auditory perception in adverse listening scenarios such as multitalker babble. CAEPs are the electrical activity of the cortex measured using electrodes placed on the scalp. They are recorded around 50 to 250 ms from the onset of the stimuli and are believed to represent the neural activity of the thalamocortical circuits (Näätänen and Picton, 1987; Eggermont, 2007). CAEPs may help determine neurophysiological processes underlying speech perception (Purdy et al., 2001; Tremblay et al., 2003). CAEPs have also been studied for evaluating speech recognition in individuals with hearing impairment (Chang et al., 2012; Durante et al., 2014).

The recorded EEGs at auditory cortex, encompass time-locked responses and are the result of underlying neural oscillations that stem from the synchronous and rhythmic activity of neuronal populations elicited (refer Roach and Mathalon, 2008 for an overview). Time locked EEG at cortical level are related for instance, to an auditory task that interact at each trial with the background neural oscillations in some sort of systematic manner to elicit CAEPs. When CAEPs are acquired, the EEG can be analysed in time and frequency to evaluate both time-locked activity and the neural oscillations.

The frequencies in EEG signals are commonly grouped in specific bins such as delta (0-4Hz), theta (4-8Hz), alpha (8-12Hz), beta (13-30Hz), and gamma (>30Hz) and may be the basis of the sensory and cognitive processes (Yordanova et al., 1998). For instance, neural oscillations obtained between the frequency range of 30-80 Hz referred to as gamma band, is believed to contribute towards the early feature detection which is modulated by attention (Gilley and Sharma, 2010; Mesgarani and Chang, 2012). Similarly, there are other frequency bands obtained on time frequency analysis i.e., beta (12-20 Hz) (Hong and Buchanan, 2008), alpha (8-12 Hz) (Klimesch, 2012) and theta (4-8 Hz) (Lakatos et al. 2005) that reflects processes such as sensory gating and attention. Therefore, the current study included EEG neural oscillations analyses in order to gain a better understanding of the contribution of sensory and cognitive processes in speech perception abilities in individuals with hearing loss.

To the best of our knowledge, there are only a few studies that have explored auditory and cognitive skills behaviourally and physiologically in individuals with hearing loss who report of speech understanding in noise difficulty. Therefore, the present study aims to investigate the underlying differences in their auditory and cognitive skills that could attribute to their speech understanding in noise ability using behavioural and physiological measures in comparison to individuals with normal hearing and no reported concerns.

2. Methods

2.1 Participants

Participants consisted of ten normal hearing (NH) individuals (8 female, [19-62] years, mean ± std = 35.7 ± 14.0 years); and ten individuals with acquired bilateral symmetric mild-moderate to moderately-severe sensorineural HL, reporting difficulties in understanding speech in noise (7 female, [21-67] years, mean ± std = 40.6 ±19.6 years). All hearing impaired participants were bilateral hearing aid users with regular use for at least five years. As reported, all participants wore digital hearing aids fitted to NAL-NL2 prescription targets (Keidser et al., 2011). The age, duration of hearing aid use, age at which hearing aid was given and the type of hearing aid used by the HL group is shown in Table 1. Both NH and HL participants were recruited using flyers posted around the Macquarie University campus (Sydney, Australia).

2.2 Screening information

All the participants underwent a number of screening tests to ensure they met the requirements for the current study. The screening tests included otoscopy, tympanometry/ acoustic reflex thresholds (recorded using Interacoustics Titan Suite) and the Montreal Cognitive Assessment (MoCA, Nasreddine et al., 2005). Otoscopy and tympanometry were carried out to ensure that the ear canal and ear drum status were normal. MoCA was conducted to screen for cognitive impairment. The inclusion criteria consisted of presenting (i) an “A” type tympanogram, (ii) acoustic reflex thresholds within 70-100 dB HL (Silman and Gelfand, 1981), and (iii) a MoCA score ≥26. Any score below 26 would be an indicative of cognitive issue (MoCA, Nasreddine et al., 2005)

2.3 Language Proficiency

The Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007) was used to ensure that all participants had an advanced level of speaking, reading and writing English. The LEAP-Q consists of a 10-point rating scale with questions for speaking, reading and writing. Each participant needed to rate themselves on how well they read, speak and understand English on a regular basis. All participants reported that their level of English was ≥7 in the three categories.

2.4 Self-reported listening in noise report

Speech, Spatial and Qualities of Hearing scale (SSQ12; Noble et al., 2013) was used to evaluate the self-reported listening ability in challenging environments. The HL group completed the questionnaire while the NH stated that they had no concerns listening in noise and therefore did not attempt the questionnaire. The SSQ12 consists of an eleven point rating scale, zero indicating severe difficulty. The 12 questions were categorized into 3 subcategories i.e. understanding speech, spatial separation, and sound quality. There were 5 questions under the category understanding speech, 3 questions under spatial separation and 4 questions on sound quality.

2.5 Hearing thresholds

Pure-tone audiometry was carried out using Interacoustics audiometer AC 40 (Interacoustics, Denmark) for octave frequencies between 250 Hz to 8 kHz. All the participants in the NH group had their thresholds within 20 dB HL (American National Standards Institute [ANSI], 1996).

2.6 Amplification

For all tests conducted under head phones, filters which approximated the NAL-RP (NAL-Revised Profound) prescription formula were implemented within the test utilising Matlab

(The Mathworks Inc., Natick, MA) to ensure adequate audibility. Whilst for speech in noise measures which required the presentation of the stimuli through loudspeakers and for the two cognitive measures, one which required the presentation of the stimuli verbally and the other through loudspeaker a standard hearing aid (from a well-known hearing aid manufacturing company) was used to provide the NAL-RP gain. The NAL-RP prescription formula was chosen for the current study for the following reasons: (i) It is a standard approach that has been widely used in other research studies(Korczak et al., 2005; Glyde et al., 2013), and therefore it may facilitate comparison between studies; (ii) the formula has been systematically assessed to ensure adequate performance (Byrne and Cotton, 1988); and (iii) it has similar gain at moderate inputs similar to other hearing aid prescriptions such as NAl-NL1 or NAL-NL2 (Byrne et al., 2001).

For the participants who had hearing loss, a standard hearing aid was fitted to ensure uniformity across all participants. The gain was determined based on the hearing loss and with each participant real ear measurement was undertaken to ensure that the hearing aid provided the required gain. The following steps were undertaken: (i) measurement of the real-ear aided response; (ii) measurement of the unaided response; and (iii) calculation of the real ear insertion gain, i.e. the difference between real ear aided and unaided response.

2.7 Behavioural tests

The tests included behavioural auditory/cognitive processing measures, and speech understanding in noise. Auditory processing tests included MDT, IRN, SMRT, and FD. Cognitive processing tests included Digit Span Test, Elevator task with distraction and reversal, Cognitive Spare Capacity Test (CSCT), and SL in both auditory and visual modality. Speech understanding in noise was measured using the NAL Dynamic Conversation Test (NAL-DCT).

The auditory and cognitive tests such as the MDT, IRN, SMRT, FD, Elevator task with distraction and reversal were programmed to be delivered through Matlab and were calibrated using a sound level meter (Brüel and Kjaer type 2250 G4) and an artificial ear (Brüel and Kjaer type 4153).

All the auditory stimuli were created using custom made scripts in Matlab and presented through a Focusrite 219 sound card (Focusrite, England) to HDA 300 Sennheiser headphones (Senheiser, Germany) using a sampling rate of 44100 Hz. For all the auditory tests three alternative-forced-choice (AFC) adaptive tracking was used. The threshold was calculated by taking the average of the last six reversals. Each test had three runs of the same to ensure that they had a good test-retest reliability. Detailed description for each auditory and cognitive processing test is given in tables 2 and 3.

The speech understanding in noise test (NAL-DCT; Keidser et al., 2015) was conducted in an anechoic chamber using loudspeakers placed at -67°, +67° and 0°. 0° refers to the location of the speaker placed in the front, relative to the individual's head position while, -67°, +67° refers to the right and left side respectively. Before, starting with the NAL-DCT task, an adaptive sentence in noise test was carried out using Beautifully Efficient Speech Test (BEST) (Best et al. 2014) in the presence of simulated cafeteria noise comprising seven two-talker conversations at 65 dB SPL (see Keidser et al., 2013 for further details) to obtain the SRT for each participant. In BEST the target level was adapted using custom software in order to track 50 % correct sentence recall. Each individual had to mandatorily complete two sets of this adaptive sentence in noise test. Each set consisted of 32 sentences and were presented with a background noise of 65 dB SPL. The background noise was kept constant for the entire test. The scores obtained from the two sets were averaged to obtain a single Speech Recognition Threshold (SRT). This individual SRT was used to derive the Signal to Noise Ratio at which the NAL-DCT was carried out.

For the NAL-DCT task, there were three short passages presented to each participant. The task was to listen to the passage and simultaneously provide a written answer to a number of questions. The passages were presented through loudspeakers placed at -67°, +67° and 0° and noise from the other speakers located at different directions. For each passage three combinations of the loudspeaker array were used: [-67°,0°], [+67°,0°], [-67°,+67°]. The presentation order was randomized. A total of ten questions were presented in each passage, the duration of which varied from 2 to 4 minutes. Each correct response was given a score of 1.

2.8 Physiological measure

The CAEP for a speech recognition task was measured in quiet and in background noise at a signal-to-noise ratio (SNR) of 8 dB. A 79 ms duration /da/ was used as the speech stimulus due to its sharp onset, thus providing a synchronous activation of the cortical auditory pathway. The number of stimulus repetitions was 150 and the inter-stimulus interval varied randomly between 950 and 1100 ms. The stimulus was presented at 65 dB SPL. The task of the individual was to stay alert and attend to the stimuli.

Calibration of the stimuli was done using Bruel and Kjaer type 2250 G4 (Brüel and Kjær Sound and Vibration Measurement A/S, Nærum, Denmark) Sound Level Meter (SLM). First, the SLM was calibrated using a pistonphone which produced a sound of 94 and 114 dB SPL. Once the correction factor for the SLM was noted down, stimuli calibration began. To calibrate a short stimulus such as /da/ an oscilloscope was used to mark the boundaries of the stimulus within which the voltage was measured. This voltage was then used as the V_1 and the voltage measured for the pistonphone output of 94 dB was taken as the V_0. The voltage was then converted into dB ppeSPL using the formula: $dB = 20 \log (V_1/V_0) + 94$.

To measure the pistonphone output, the SLM was connected to the oscilloscope (ADS7102CA) using a cable. The SLM was then connected to the Pistonphone using a 2 cc coupler. Once the SLM calibration was complete, and the reference voltage was noted, the SLM was connected to the insert earphones through which the /da/ stimulus was presented. For the /da/ stimulus in quiet, only the peak to peak voltage at the burst of the /da/ was measured. For the /da/ stimulus in noise, the peak to peak voltage of the noise within which the /da/ was embedded was also determined to derive 8 dB SNR. The voltage of the /da/ and the noise was converted into dB using the formula stated above to ensure that an 8 dB SNR was maintained. The NAL-RP filters were applied to provide necessary amplification while testing individuals with hearing loss.

The CAEP recording was carried out in an acoustically and electromagnetically shielded room. All participants were seated on a comfortable chair and requested to stay still as much as possible during the testing. 64 channel electroencephalography (EEG) recording was carried out using Neuroscan^{R} Acquire 4.5 (Compumedics, Germany). The electrodes were placed on an elastic easy cap (EASYCAP, Germany) which was chosen based on individual needs, using the International 10/20 EEG system. The left mastoid electrode was used as the reference electrode (M1). Online filtering of 0.01-100 Hz was used. The horizontal and vertical movements of the eye were measured using electrodes placed on outer canthus of the eye for horizontal movements, above and below the eye for vertical movements. The electrode impedances were all kept below 5 kΩ.

2.9 Data analysis

2.9.1 Analysis of behavioural tests

The analysis of the behavioural data obtained comprised two methods: (i) A multivariate analysis of variance (MANOVA) using age as a co-variate. The behavioural data of 10 individuals in the HL group was compared to the 10 individuals from NH group; and (ii) Individual analysis to see the performance of each participant in the HL and NH using standardization or z score. In-order to observe and compare the individual performance of individuals in both these groups we tested another set of 14 controls with the same inclusion criteria as that of the NH group. The 14 new controls were tested *only* for the behavioural measures. This was done in order to get a clearer understanding on the differences between the HL and NH groups. While comparing the HL to the NH group is considered optimal, it would just show the performance of the HL group in comparison to the NH group but not the performance of the individuals in the NH group. Thus, the inclusion of the 14 new controls would enable us to simultaneously evaluate the performance of each individual in both these groups.

Furthermore, to ensure the 14 new controls used for standardization had similar performance on the various tasks as the 10 age matched individuals in the NH group, a statistical test was carried out. On MANOVA, using age a co-variate both these groups showed no significant difference on any of the auditory and cognitive tests ($p>0.05$). The mean and standard deviation obtained on all the auditory and cognitive tests are provided in tables 5 and 6.

2.9.2 Analysis of physiological measures

All the CAEP recordings were analysed offline using custom made scripts using the Fieldtrip toolbox (Oostenveld et al., 2011) in Matlab. The continuous EEG signal was first re-referenced to the common average reference (CMR) by excluding noisy electrode channels from the CMR calculation. The re-referenced data was then epoched between -100 to 500 ms range relative to the onset of the stimulus, and baseline corrected considering the time range -100 to 0 ms. Artefacts originating from eye movements were removed using Independent Component analysis (ICA) which uses blind source separation approach (Jung et al., 2000). The ICA identifies the components with maximal temporal statistical independency. The signal was then subjected to digital band-pass filter between 0.1 to 30 Hz. Variance rejection criterion was applied to identify noisy trials. All trials with variances above 80 μV^2 between -100 ms to 500 ms were not included in the averaging process. The remaining trials were then averaged to obtain a CAEP waveform.

The global field power (GFP) was calculated for the two groups across both the conditions. GFP helps to quantify the variability of the neural activity across the scalp as a function of time, thus constituting a single reference-independent measure of the response strength (Murray et al., 2008). GFP is measured as the standard deviation of all the waveforms derived for all the recorded scalp locations for both the conditions and each participant (Lehmann and Skrandies, 1980). It gives the advantage of comparing the results obtained from the whole scalp (all the recorded locations) rather than one single electrode location (Hamburger and vd Burgt, 1991).

The P1-N1-P2 complex of the CAEP was compared between the two groups of subjects in the two SNR conditions. A non-parametric randomization procedure was used to overcome multiple electrode comparison effects (Maris, 2004; Maris and Oostenveld, 2007). An independent t-test was used as the statistical test to measure the differences. The output from the statistical test consisted of a cluster electrodes, the p-values were estimated according to Monte Carlo simulations. Only the clusters that comprised of cluster values greater than 95 % among all the clusters derived from random permutation of data were considered.

Lastly, time frequency analysis was carried out offline using Matlab fieldtrip (Oostenveld et al. 2011). The continuous EEG data was re-referenced to the average of combined mastoids (M1 and M2). The EEG trials were then epoched 600 ms prior to the auditory stimulus onset and 1400 ms post the auditory stimulus onset. ICA was then applied to remove ocular artefacts (horizontal and vertical eye movements) for each subject. All the trials that had variance above 80 μV^2 were considered noisy and therefore eliminated from further analysis. A wavelet transform function was then used to convert the accepted trials to the time-frequency domain. The wavelet transform function utilizes the Mortlet wavelet with a filter tap of five cycles in-order to ensure a good time-frequency resolution. Following this, these time frequency spectra were then converted to a relative power measure known as event related spectral perturbation (ERSP) by normalising each of the trials as proposed in (Grandchamp and Delorme, 2011). The ERSP represents the change in brain oscillatory activities. Monte-Carlo cluster permutation analysis slope t-test was performed across and within the groups to determine if there were any differences.

Ethics

This study was conducted at the Department of Linguistics, Australian Hearing Hub, Macquarie University with ethics approval from the Macquarie University Human Research Ethics Committee (5201600438). All the participants were informed about the study before the start of the test and gave written consent to participate.

3. Results

3.1 Audiometry

Figure 1 presents the audiometric thresholds for the HL group. This figure shows that the participants from the HL group presented a bilateral mild-moderate to moderately severe sensorineural hearing loss.

All participants in the NH group had audiometric thresholds below 20 dB HL in all tested frequencies except for one participant with audiometric threshold of 25 dB HL at 8 kHz.

3.2 Language proficiency on LEAP-Q

Both NH and HL reported English as their first or second language. There were no significant differences on independent samples t-test in the self-reported competency in English for speaking [$t (18) = 0.4$, $p=0.6$)], reading [$t (18) = -0.1$, $p=0.9$)] or understanding [$t (18) = -0.2$, $p=0.8$)] across the groups. In general, all participants had English as their first language with a few exceptions. Three individuals in both groups rated English to be their second language. In the NH group, two participants reported that they learnt English from 10 years of age and another participant reportedly learnt English at the age of five. Two participants in the HL group reportedly were exposed to English from their birth along with their first language and another participant reported to have learnt English from the age of nine.

3.3 SSQ12: Self-reported listening in noise report

Table 4 presents the SSQ-12 score for the group of participants with hearing loss. The SSQ12 comprises of twelve questions. Individual rating for each question is given in table 4. The table also includes the sum scores from the 12 questions for each participant. From the SSQ12 results, we noticed that there was one participant with a relatively high score compared to the rest of the participants. On examining rating given for each question on SSQ 12, this participant noted problem in just one question focussing on a dual task situation while there was no much difficulty on the other questions.

Supplementary table provides comparison of the SSQ 12 rating by individuals in the HL group versus data from young 18-25 year old adults with normal hearing on Speech Spatial and Qualities 49 (SSQ 49) (from Demeester et al., 2012 in Bressler et al., 2017). The SSQ 49 is a longer version which also comprises the twelve questions included in the SSQ12. Comparison between these data would enable us to get a better understanding of the performance of the HL group who report of speech understanding in noise difficulty on SSQ 12. Overall, the comparison table indicates that the HL group does have poorer rating on the SSQ 12 when compared to those individuals with normal hearing and no listening in noise concerns. It is important to note that the adults with normal hearing were younger adults compared to the current participating cohort.

3.4 Auditory processing tests

Table 5 shows the mean, median and standard deviation for the HL and NH group respectively. MANOVA showed no difference in performance across groups (see table 5).

3.5 Cognitive processing tests

Table 6 shows the mean and standard deviation for the HL and NH group for the cognitive tests. MANOVA showed no significant difference between the two groups on any of the cognitive tests.

For both the aSL and vSl tasks, firstly the cover tasks were evaluated to check the number of repeated stimuli that was correctly identified by the participant. Only those who got the cover task right 50 % of the time were considered. This procedure was carried out to rule those who performed at or below chance level potentially due to lack of attention to the familiarization stream (Arciuli and Simpson, 2012). There was one participant in NH group who scored below 50% in the auditory cover task and therefore was excluded from the analysis. Following this a one sample t-test was performed on both NH and HL groups (within group analysis) to identify if all the participants have performed above chance during the test phase, i.e., whether there was a significant difference in the percentage of triplets correctly identified by all participants within the two groups. Results showed above chance performance for all the participants on vSL and aSL for both NH group [$t(9) = 12.6$, $p<0.001$)], [$t(8) = 23.2$, $p<0.001$)] and the HL group [$t(9) = 12.5$, $p<0.001$)], [$t(9) = 14.9$, $p<0.001$)] respectively. There were no differences across groups on aSL or vSL (table 6).

3.6 Onset CAEPs and EEG time-frequency analysis

The physiological test results were analysed on 9 NH and 10 HL. One of the participants in the NH group did not complete the physiological test as the participant did not appreciate the idea of having the gel applied on the scalp for the testing. Figure 2 shows the grand average waveforms obtained for both the groups at Cz electrode comparing da-evoked P1N1P2 responses in quiet and in noise.

GFP and cluster permutation statistical analysis was carried out between NH in quiet versus HL in quiet and NH in noise versus HL in noise. GFP measures the amplitude distribution of the scalp at the time frame where N1 is observed on both conditions (quiet and noise). On independent t test there was no significant difference between the two groups when compared NH in quiet versus HL in quiet [$t(17) = 1.0$, $p = 0.3$] and NH in noise versus HL in noise [$t(17) = -0.3$, $p = 0.7$], shown in figure 3. Similarly, on cluster permutation statistical analysis the two groups did not show any significant difference in neural processing on both quiet and noise conditions on using independent t test ($p>0.05$).

On time frequency analysis, the NH group showed increased synchronised alpha oscillations (8-12 Hz) in the quiet condition. Significant synchronised alpha oscillations were observed on centro-frontal electrodes on cluster permutation analysis, using dependent samples t-test ($p<0.05$) (see figures 4 and 5). Furthermore, other frequencies were also tested, and no significant differences were observed. Similarly, there were no significant differences were observed ($p>0.05$) when groups were compared across for the two conditions.

4. Discussion

The current study aimed to identify the underlying differences in auditory and cognitive processing ability in individuals with hearing loss who report speech understanding in noise concerns versus adults with clinically normal audiograms having no speech understanding in noise concerns. To analyse these differences both physiological and behavioural tests were used. In the current study we had hypothesized that our group with HL would show poor performance on the auditory and cognitive tests when compared to the NH group.

4.1 Physiological test

On the physiological test analysed using time frequency analysis, within group analysis across the two conditions showed significant alpha oscillations in the centro-frontal electrodes *only* for the NH group in the quiet condition, while there were no differences observed for the HL group. Previous literature has suggested that cognitive factors such as attention and inhibition drive synchronised alpha oscillations (Klimesch et al., 2007). Synchronised alpha oscillations were reported to be observed during the tasks that requires one to pay attention to the given stimuli and remember them, while not responding to them (Jensen et al., 2002; Tuladhar et al., 2007; Scheeringa et al., 2009). In addition, alpha synchronizations were also observed as an inhibitory response by the different areas of the cortical regions that are not task relevant (Klimesch, 2012). For instance, large alpha power was observed over the visual cortical areas while the task required one to pay attention to the auditory stimuli (Foxe et al., 1998). The present task did not require participants to remember or react to the stimuli as it was a repetitive presentation of /da/ at fixed ISI. However, the participants were required to listen to the stimuli. Based on the previous literature, it would appear that the presence of alpha synchronisations in the NH group indicates that they are able to pay attention to the stimuli and inhibit the irrelevant distractors (Foxe et al., 1998; Jensen et al., 2002). The implications of the current findings maybe that the HL group is not able to attend to the stimuli and/or inhibit distractions as well as the NH group does. Therefore, HL group experiences more difficulties in understanding speech in adverse listening conditions such as the presence of noise.

Across group analysis on both conditions showed no differences in both quiet and noise. This could be due to the small sample size and variance in performance across the individuals. It is also important to note that, the alpha oscillations were not very well observed in the noise condition even for the NH group. One way to analyse this difference in noise would be to evaluate the recognition of /da/ at different SNRs not just at 8 dB SNR. A study by Wong et al., (2009) on cortical mechanisms underlying word perception in noise, observed no difference in the behavioural performance of individuals when tested for speech perception in quiet and 20 dB SNR. However, using a physiological measure (functional magnetic resonance imaging), differences in cortical processing were observed at 20 dB SNRs. Another suggestion for future studies could be to use ecologically valid stimuli such as words/sentences instead of a simple stimuli such as CV (/da/ in the current study) and to apply variable noise including reverberation. However, in order to provide a better understanding of oscillatory brain patterns, it is essential to have brain-behaviour correlations and we need to use ecological valid stimuli for both behaviour and physiological methods to determine the individuals’ performance across both methodologies.

4.2 Behavioural tests

On quantitative measures, the results indicated no significant differences between the two groups on any of the behavioural tests. Some of the factors that could have impacted the behavioural test results obtained in the current study are discussed below.

4.2.1 Amplification, auditory tests and speech understanding

In the present study, we anticipated that the individuals with hearing loss who complain of speech understanding in noise may show deficits on the tests assessing auditory temporal and spectral information. However, the results obtained did not show significant differences on any of tests.

In the current study, the stimuli to the HL group were presented using NAL RP filters to ensure appropriate audibility. It could be that if stimulus is presented at the required level, individuals with hearing loss are able to perform similar to the group with NH. This, however, does not explain why they continue to experience difficulties understanding speech in noise. It may be important to note that, on examining the amplification provided by the personal hearing aids used by the participants, the hearing aid was not always set to the prescribed required target (NAL-NL2) in participants except one (see supplementary figures 1 and 2). For the remaining nine participants the provided amplification was either below or above the required target. It could be that fitting the hearing aids to the exact target level (as done in the current study) may help to address reported difficulties in understanding speech in noise. However, it is important to note that the SSQ 12 rating for the participants with the best fit hearing aid (HL9, refer table 4) did not have any less reported difficulties than the rest of the HL participants, and similarly the participant who rated themselves with least difficulties on SSQ 12 (HL5, refer table 4) did not have their hearing aid set to the prescribed target. This suggests that having the exact target amplification is not a significant factor in explaining their reported listening difficulties.

4.2.2 Cognitive measures and Speech understanding

Speech understanding particularly in the presence of noise relies on interaction between auditory and cognitive processing abilities (CHABA, 1988; Pichora-Fuller et al., 1995; Humes, 2007). Previous studies have reported that individuals with hearing loss compensate for a degraded auditory signal by utilizing attention and working memory (Wingfield et al., 2005; Humes, 2007; Shinn-Cunningham and Best, 2008). In the present study, the results indicated no difference in performance between the two groups on any of the cognitive tests. We also found comparable performance on speech understanding task (NAL DCT) between the two groups in presence of differences at the speech recognition level (50% SRT). These findings suggest that despite ensuring appropriate audibility, the presence of adequate cognitive skills, perhaps enabled the current participants to complete speech understanding task.

A previous study by Ng et al., (2013) with individuals with hearing loss showed that individuals with good working memory capacity were the ones who performed well on speech understanding compared to the group with low working memory capacity. Given that all our participants in the HL group performed as well as the NH on all the cognitive tests, it could be that they were using all their working memory and attentional skills to compensate for the speech understanding task. Therefore, it may be that the cognitive load on the HL group was higher to match the performance on speech understanding in noise task to the normal hearing group. In the current study, we did not monitor the cognitive load during the speech understanding task and should be a consideration in the future studies.

Another potential reason for the participants in HL group to perform well on the speech understanding task could be the availability of the contextual cues in the task. A study conducted by Humes et al. (2013) on individuals with a high frequency sloping hearing loss showed no difference on most of the speech understanding measures when compared to the control except for a time-compressed speech-in-noise test, which lacked contextual cues. This suggests that the cohort in our study were able to make use of the contextual cues present in speech understanding measures to supplement the loss of information attributed due to the presence of hearing loss. Therefore, we were not able to see a difference in performance between the HL group and NH on the NAL-DCT. However, their responses to the SSQ 12 show they are not able to use the skills in the real-life listening situations. Given that all our participants in the HL group performed as well as the NH on all the cognitive tests including working memory as well as speech understanding in noise, it is difficult to explain why there are reported concerns. Perhaps the real life SNRs for each participant is worse than the current study applied and therefore harder for them to compensate with their cognitive skills or that the cognitive effort is high and difficult to sustain.

4.2.3 Self-report of listening in noise difficulty

One of the aspects that we have not considered in the research is personal expectation. Studies have shown that individuals with hearing loss where the questionnaire information on listening scenarios in hearing aid users have correlated with their cognitive test performance i.e. individuals with better cognitive capacity tend to report more hearing difficulties (Zekveld et al., 2013; Ng et al., 2013). This could be one of the reasons why the HL group in the present study showed no difference in any of the cognitive and auditory tests despite reported listening difficulty.

4.2.4 Motivation and listening effort

Motivation and listening effort could also be the reason to observe attention related differences only on the physiological measures but not on the behavioural measures. The behavioural tasks are more engaging, and the task performance is monitored on a face to face scenario while the physiological tasks are more self-driven even as the researcher is seated in a control room and the responses are monitored distantly and therefore, the chances for staying motivated is greater on the behavioural measures. Similarly, for the tasks that are monitored closely, the individual might put greater effort consciously in order to perform well. The lack of motivation on the task and increased listening effort in the current cohort was not evaluated but may have contributed to the results on physiological measures (refer Peele, 2008 for a review).

4.2.5 Test sensitivity

Another question that arises, is the difficulty reported by the HL group equivalent to speech understanding in noise tests? Also, are the tests sensitive enough to capture the reported difficulty? In a regular research test scenario the individual volunteers to participant and is aware of the tests being conducted and consequently is likely to allocate all their resources in the test situation. Even though their performance is within "normal" expectations, the effort applied may be greater than that required by the normal hearing group. Therefore, it is important to develop more tests that can tap into real life scenarios.

5. Limitations

There are three limitations in the current study. First, there was no measure of self-expectation to determine the impact of motivation on the test performance. Two, the control group consists of adults with normal hearing. Even though there are no differences in performance between HL group with speech understanding in noise concern and NH group, it may be useful to compare a control group with HL with no speech understanding in noise concerns. Three, the present study population was a small sample of ten.

6. Conclusion

In summary, the present study investigated the differences underlying auditory and cognitive performances in individuals with and without hearing loss reporting difficulty understanding speech in the presence of noise. The results obtained suggests physiological tests are more sensitive to the reported speech understanding in noise at least in this cohort of adults. It would appear that the adults with no hearing or listening concerns, have better cognitive processes such as attention and inhibition during a task. This may be the reason why understanding speech is difficult even in quiet.

7. References

Abel, S. M., Krever, E. M., & Alberti, P. W. (1990). Auditory detection, discrimination and speech processing in ageing, noise-sensitive and hearing-impaired listeners. *Scandinavian Audiology*. *19*, 43–54. http://doi.org/10.3109/01050399009070751

Akeroyd, M. A. (2008). Are individual differences in speech reception related to individual differences in cognitive ability? A survey of twenty experimental studies with normal and hearing-impaired adults. *International Journal of Audiology*. *47*, 53–71. http://doi.org/10.1080/14992020802301142

American National Standards Institute. (1996). Specifications for Audiometers (ANSI S3.6-1996). *New York: American National Standards Institute.*

Arciuli, J., & Simpson, I. C. (2012). Statistical Learning Is Related to Reading Ability in Children and Adults. *Cognitive Science*. *36*, 286–304. http://doi.org/10.1111/j.1551-6709.2011.01200.x

Aronoff, J. M., & Landsberger, D. M. (2013). The development of a modified spectral ripple test. *The Journal of the Acoustical Society of America*. *134*, EL217-22. http://doi.org/10.1121/1.4813802

Bacon, S. P., & Gleitman, R. M. (1992). Modulation detection in subjects with relatively flat hearing losses. *Journal of Speech and Hearing Research*. *35*, 642–653. http://doi.org/10.1044/jshr.3503.642

Baddeley, A. (1992). Working memory. *Science*. *255*, 556–559.

Best, V., M. McLelland, & H. Dillon (2014). The BEST (Beautifully Efficient Speech Test) for Evaluating Speech Intelligibility in Noise World Congress of Audiology. Brisbane, Australia.

Bregman, A. S. (1990). Auditory scene analysis. the perceptual organizarion of sound, (Cambridge: MIT press).

Bressler, S., Goldberg, H., & Shinn-Cunningham, B. (2017). Sensory coding and cognitive processing of sound in Veterans with blast exposure. *Hearing Research*. *349*, 98–110. http://doi.org/10.1016/j.heares.2016.10.018

Buss, E., Hall, J. W., & Grose, J. H. (2004). Temporal fine-structure cues to speech and pure tone modulation in observers with sensorineural hearing loss. *Ear and Hearing*. *25*, 242–250. http://doi.org/10.1097/01.AUD.0000130796.73809.09

Byrne, D., & Cotton, S. (1988). Evaluation of the National Acoustic Laboratories' new hearing aid selection procedure. *Journal of Speech & Hearing Disorders*. *31*, 178–186. http://doi.org/10.1044/jshr.3102.178

Byrne, D., Dillon, H., Ching, T., Katsch, R., & Keidser, G. (2001). NAL-NL1 procedure for fitting nonlinear hearing aids: characteristics and comparisons with other procedures. *Journal of the American Academy of Audiology*. *12*, 37–51.

Committee on Hearing and Bioacoustics and Biomechanics (CHABA) (1988). Speech understanding and aging. *The Journal of the Acoustical Society of America*. *83*, 859–895.

Chang, H. W., Dillon, H., Carter, L., Van Dun, B., & Young, S. T. (2012). The relationship between cortical auditory evoked potential (CAEP) detection and estimated audibility in infants with sensorineural hearing loss. *International Journal of Audiology*. *51*, 663–670. http://doi.org/10.3109/14992027.2012.690076

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition*. *114*, 356–

371. http://doi.org/10.1016/j.cognition.2009.10.009

Conway, C. M., Pisoni, D. B., Anaya, E. M., Karpicke, J., & Henning, S. C. (2011). Implicit sequence learning in deaf children with cochlear implants. *Developmental Science*. *14*, 69–82. http://doi.org/10.1111/j.1467-7687.2010.00960.x

Dubno, J. R., & Dirks, D. D. (1992). Factors Affecting Performance of Psychoacoustic and Speech-Recognition Tasks in the Presence of Hearing Loss. *Acoustical Factors Affecting Hearing Aid Performance*.

Dubno, J. R., & Ahlstrom, J. (1995a). Growth of low-pass masking of pure tones and speech for hearing-impaired and normal-hearing listeners. *The Journal of the Acoustical Society of America*. *98*, 3113–3124. http://doi.org/10.1121/1.413800

Dubno, J. R., & Ahlstrom, J. B. (1995b). Masked threshold and consonant recognition in low-pass maskers for hearing-impaired and normal-hearing listeners. *Journal of the Acoustical Society of America*. *97*, 2430–2441. http://doi.org/10.1121/1.411964

Dubno, J. R., Dirks, D. D., & Morgan, D. E. (1984). Effects of age and mild hearing loss on speech recognition in noise. *The Journal of the Acoustical Society of America*. *76*, 87–96. http://doi.org/10.1121/1.391011

Durante, A. S., Wieselberg, M. B., Carvalho, S., Costa, N., Pucci, B., Gudayol, N., & Almeida, K. de. (2014). Cortical Auditory Evoked Potential: evaluation of speech detection in adult hearing aid users. *CoDAS*. *26*, 367–373. http://doi.org/10.1590/2317-1782/20142013085

Edwards, B. (2007). The Future of Hearing Aid Technology. *Trends in Amplification*. *11*, 31–45. http://doi.org/10.1177/1084713806298004

Eggermont, J. (2007). Electric and magnetic fields of synchronous neural activity-peripheral and central origins of auditory evoked potentials. *Auditory Evoked Potentials: Basic Principles and Clinical Application.*

Elliott, L. L. (1995). Verbal Auditory Closure and the Speech Perception in Noise (SPIN) Test. *Journal of Speech and Hearing Research*. *38*, 1363–1376. http://doi.org/10.1044/jshr.3806.1363

Ernst, S. M., & Moore, B. C. (2012). The role of time and place cues in the detection of frequency modulation by hearing-impaired listeners. *The Journal of the Acoustical Society of America*. *131*, 4722–4731.

Feng, Y., Yin, S., Kiefte, M., & Wang, J. (2010). Temporal Resolution in Regions of Normal Hearing and Speech Perception in Noise for Adults with Sloping High-Frequency Hearing Loss. *Ear & Hearing*. *31*, 115–125.

Fiser, J., & Aslin, R. N. (2001). Unsupervised statistical learning of higher-order spatial structures from visual scenes. *Psychological Science*. *12*, 499–504.

Fiser, J., & Aslin, R. N. (2002). Statistical learning of higher-order temporal structure from visual shape sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 458.

Foxe, J. J., Simpson, G. V., & Ahlfors, S. P. (1998). Parieto-occipital∼ 1 0Hz activity reflects anticipatory state of visual attention mechanisms. *Neuroreport*. *9*, 3929–3933.

Gelfand, S. A., Piper, N., & Silman, S. (1985). Consonant recognition in quiet and in noise with aging among normal hearing listeners. *The Journal of the Acoustical Society of America*. *78*, 1198–1206. http://doi.org/10.1121/1.394323

Gilley, P. M., & Sharma, A. (2010). Functional brain dynamics of evoked and event-related potentials from the central auditory system. *Perspectives on Hearing and Hearing Disorders: Research and Diagnostics*, *14*, 12-20.

Glasberg, B. R., & Moore, B. C. J. (1986). Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. *The Journal of the Acoustical Society of America. 79*, 1020–1033. http://doi.org/10.1121/1.393374

Glyde, H., Cameron, S., Dillon, H., Hickson, L., & Seeto, M. (2013). The effects of hearing impairment and aging on spatial processing. *Ear and Hearing*. *34*, 15–28. http://doi.org/10.1097/AUD.0b013e3182617f94

Grandchamp, R., & Delorme, A. (2011). Single-trial normalization for event-related spectral decomposition reduces sensitivity to noisy trials. *Frontiers in Psychology*. *2*, 236.

Grant, K. W., Summers, V., & Leek, M. R. (1998). Modulation rate detection and discrimination by normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*. *104*, 1051–1060. http://doi.org/10.1121/1.423323

Grassi, M., & Soranzo, A. (2009). MLP: A MATLAB toolbox for rapid and reliable auditory threshold estimation. *Behavior Research Methods*. *41,* 20–28. http://doi.org/10.3758/BRM.41.1.20

Hall, J. W., & Wood, E. J. (1984). Stimulus duration and frequency discrimination for normal-hearing and hearing-impaired subjects. *Journal of Speech, Language, and Hearing Research*. *27*, 252–256.

Hamburger, H. L., & vd Burgt, M. A. (1991). Global field power measurement versus classical method in the determination of the latency of evoked potential components. *Brain Topography*. *3*, 391–396. http://doi.org/10.1007/BF01129642

Hee Lee, J., & Humes, L. E. (2012). Effect of fundamental-frequency and sentence-onset differences on speech-identification performance of young and older adults in a competing-talker background. *The Journal of the Acoustical Society of America*. *132*, 1700–1717. http://doi.org/10.1121/1.4740482

Henry, B. A., Turner, C. W., & Behrens, A. (2005). Spectral peak resolution and speech recognition in quiet: normal hearing, hearing impaired, and cochlear implant listeners. *The Journal of the Acoustical Society of America*. *118*, 1111–1121. http://doi.org/10.1121/1.1944567

Hong, L. E., Buchanan, R. W., Thaker, G. K., Shepard, P. D., & Summerfelt, A. (2008). Beta (~ 16 Hz) frequency neural oscillations mediate auditory sensory gating in humans. *Psychophysiology*, *45*, 197-204.

Hopkins, K., & Moore, B. C. (2010). Development of a fast method for measuring sensitivity to temporal fine structure information at low frequencies. *International Journal of Audiology*. *49*, 940–946.

Hopkins, K., & Moore, B. C. J. (2011). The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *The Journal of the Acoustical Society of America*. *130*, 334–349. http://doi.org/10.1121/1.3585848

Humes, L. E. (2002). Factors underlying the speech-recognition performance of elderly hearing-aid wearers. *The Journal of the Acoustical Society of America*. *112*, 1112–1132. http://doi.org/10.1121/1.1499132

Humes, L. E. (2007). The Contributions of Audibility and Cognitive Factors to the Benefit Provided by Amplified Speech to Older Adults. *Journal of the American Academy of Audiology*. *18*, 590–603. http://doi.org/10.3766/jaaa.18.7.6

Humes, L. E., Kidd, G. R., & Lentz, J. J. (2013). Auditory and cognitive factors underlying individual differences in aided speech-understanding among older adults. *Front Syst Neurosci*. *7,* 55. http://doi.org/10.3389/fnsys.2013.00055

Humes, L. E., Lee, J. H., & Coughlin, M. P. (2006). Auditory measures of selective and divided attention in young and older adults using single-talker competition. *The Journal of the Acoustical Society of America*. *120*, 2926–2937. http://doi.org/10.1121/1.2354070

Jensen, O., Gelfand, J., Kounios, J., & Lisman, J. E. (2002). Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. *Cerebral Cortex*. *12*, 877–882.

Jung, T., Makeig, S., Humphries, C., Lee, T., McKeown, M. J., Iragui, I., & Sejnowski, T. J. (2000). Removing Electroencephalographic aretfacts by blind source seperation. *Psychophysiology*. *37,* 163–178. http://doi.org/10.1111/1469-8986.3720163

Keidser, G., Best, V., Freeston, K., & Boyce, A. (2015). Cognitive spare capacity: Evaluation data and its association with comprehension of dynamic conversations. *Frontiers in Psychology*. *6,* 597. http://doi.org/10.3389/fpsyg.2015.00597

Keidser, G., Dillon, H., Mejia, J., & Nguyen, C. V. (2013). An algorithm that administers adaptive speech-in-noise testing to a specified reliability at selectable points on the psychometric function. *International Journal of Audiology*. *52,* 795–800.

Keidser, G., Dillon, H. R., Flax, M., Ching, T., & Brewer, S. (2011). The NAL-NL2 prescription procedure. *Audiology Research*. *1*. http://doi.org/10.4081/audiores.2011.e24

Killion, M. C., & Niquette, P. A. (2015). What can the pure-tone audiogram tell us about a patient's SNR loss. *Hear J*. *53,* 46–53. Retrieved from http://statistics.gov.rw/publications/rwanda-poverty-profile-report-results-eicv-4

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition*, *83*, B35-B42.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*. *16*, 606–617. http://doi.org/10.1016/j.tics.2012.10.007

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews*. *53*, 63–88. http://doi.org/10.1016/j.brainresrev.2006.06.003

Kochkin. (2005). MarkeTrak VII: Customer satisfaction with hearing instruments in the digital age. *The Hearing Journal*. *58*, 30–32. http://doi.org/10.1097/01.HJ.0000286545.33961.e7

Kochkin, S. (2000). “MarkeTrak V:”Why my hearing aids are in the drawer" The consumers’ perspective. *The Hearing Journal*. *53*, 34–36.

Kochkin, S. (2010). MarkeTrak VIII : Consumer satisfaction. *The Hearing Journal*. *63*, 19–20.

Korczak, P. A., Kurtzberg, D., & Stapells, D. R. (2005). Effects of sensorineural hearing loss and personal hearing aids on cortical event-related potential and behavioural measures of speech-sound processing. *Ear and Hearing*. *26*, 165–185. http://doi.org/10.1097/00003446-200504000-00005

Lakatos, P., Shah, A. S., Knuth, K. H., Ulbert, I., Karmos, G., & Schroeder, C. E. (2005). An oscillatory hierarchy controlling neuronal excitability and stimulus processing in the auditory cortex. *Journal of neurophysiology*, *94*, 1904-1911.

Leek, M. R., & Summers, V. (2001). Pitch strength and pitch dominance of iterated rippled noises in hearing-impaired listeners. *The Journal of the Acoustical Society of America*. *109*, 2944–2954. http://doi.org/10.1121/1.1371761

Lehmann, D., & Skrandies, W. (1980). Reference-free identification of components of checkerboard-evoked multichannel potential fields. *Electroencephalography and Clinical Neurophysiology*. *48*, 609–621. http://doi.org/10.1016/0013-4694(80)90419-8

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

Marian, V., Blumfield, H., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing Language Profiles in Bilinguals and Multilinguals Viorica. *Hearing Research*. *50*, 940–967. http://doi.org/10.1044/1092-4388(2007/067)

Maris, E. (2004). Randomization tests for ERP topographies and whole spatiotemporal data matrices. *Psychophysiology*. *41*, 142–151.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG-and MEG-data. *Journal of Neuroscience Methods*. *164*, 177–190.

Maye, J., Werker, J. F., & Gerken, L. (2002). Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition, 82*, B101-B111.

McAdams, S. E., & Bigand, E. E. (1993). *In Based on the Fourth Workshop in the Tutorial Workshop Series Organized by the Hearing Group of the French Acoustical Society*, (Clarendon Press/Oxford University Press).

McClelland, J. L., Mirman, D., & Holt, L. L. (2006). Are there interactive processes in speech perception? *Trends in Cognitive Sciences*. *10,* 363–369. http://doi.org/10.1016/j.tics.2006.06.007

Mesgarani, N., & Chang, E. F. (2012). Selective cortical representation of attended speaker in multi-talker speech perception. *Nature*, *485*, 233.

Mishra, S., Lunner, T., Stenfelt, S., Rönnberg, J., & Rudner, M. (2013). Visual information can hinder working memory processing of speech. *Journal of Speech Language and Hearing Research*. *56*, 1120–1132. http://doi.org/10.1044/1092-4388(2012/12-0033)a

Mishra, S., Stenfelt, S., Lunner, T., Rönnberg, J., & Rudner, M. (2014). Cognitive spare capacity in older adults with hearing loss. *Fronteirs in Aging Neuroscience*. *6*, 96. http://doi.org/10.3389/fnagi.2014.00096

Murray, M. M., Brunet, D., & Michel, C. M. (2008). Topographic ERP analyses: A step-by-step tutorial review. *Brain Topography*. *20*, 249–264. http://doi.org/10.1007/s10548-008-0054-5

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology*. *24*, 375–425.

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

Nelson, D. A., & Freyman, R. L. (1986). Psychometric functions for frequency discrimination from listeners with sensorineural hearing loss. *The Journal of the Acoustical Society of America*. *79*, 799–805. http://doi.org/10.1121/1.393470

Neuhoff, J. G. (Ed). (2004). *Ecological psychoacoustics. Amsterdam: Elsevier Academic Press.*

Ng, E. H. N., Rudner, M., Lunner, T., Pedersen, M. S., & Rönnberg, J. (2013). Effects of noise and working memory capacity on memory processing of speech for hearing-aid users. *International Journal of Audiology*. *52*, 433–441. http://doi.org/10.3109/14992027.2013.776181

Ng, E. H. N., Rudner, M., Lunner, T., & Rönnberg, J. (2013). Relationships between self-report and cognitive measures of hearing aid outcome Relationships between self-report and cognitive measures of hearing aid outcome. *Speech, Language and Hearing*. *16*, 197–207. http://doi.org/10.1179/205057113X13782848890774

Niedermeyer, E. (1999). "The normal EEG of the walking adult," in *Electroencephalography: Basic Principles, Clinical Applications and Related Fields*, eds E. Niedermeyer and F. Lopes da Silva (Baltimore: Lippincott Williams and Wilkins), 149–173

Noble, W., Jensen, N. S., Naylor, G., Bhullar, N., & Akeroyd, M. A. (2013). A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: The SSQ12. *International Journal of Audiology*. *52*, 409–412.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*. *1*, 1–9. http://doi.org/10.1155/2011/156869

Peelle, J. E. (2018). Listening effort: How the cognitive consequences of acoustic challenge are reflected in brain and behavior. *Ear and Hearing*, *39*, 204.

Peña, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech processing. *Science*, *298*, 604-607.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: one phenomenon, two approaches. *Trends in Cognitive Sciences*. *10*, 233–238. http://doi.org/10.1016/j.tics.2006.03.006

Peter, V., Wong, K., Narne, V. K., Sharma, M., Purdy, S. C., & McMahon, C. (2014). Assessing Spectral and Temporal Processing in Children and Adults Using Temporal Modulation Transfer Function (TMTF), Iterated Ripple Noise (IRN) Perception, and Spectral Ripple Discrimination (SRD). *Journal of the American Academy of Audiology*. *25*, 210–218. http://doi.org/10.3766/jaaa.25.2.9

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., … Wingfield, A. (2016). Hearing Impairment and Cognitive Energy. *Ear and Hearing*. *37*, 5S–27S. http://doi.org/10.1097/AUD.0000000000000312

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *The Journal of the Acoustical Society of America*. *97*, 593–608. http://doi.org/10.1121/1.412282

Plomp, R., & Duquesnoy, A. J. (1982). A model for the speech-reception threshold in noise without and with a hearing aid. *Scandinavian Audiology*. *15*, 95–111.

Prendergast, G., Millman, R. E., Guest, H., Munro, K. J., Kluk, K., Dewey, R. S., … Plack, C. J. (2017). Effects of noise exposure on young adults with normal audiograms II: Behavioural measures. *Hearing Research*. *356*, 74–86. http://doi.org/10.1016/j.heares.2017.10.007

Purdy, S. C., Katsch, R. K., Storey, L. M., Dillon, H., & Ching, T. Y. (2001). Slow cortical auditory evoked potentials to tonal and speech stimuli in infants and adults. *In 17th International Evoked Response Audiometry Study Group Biennial Symposium, Vancouver, Canada.*

Roach, B. J., & Mathalon, D. H. (2008). Event-related EEG time-frequency analysis: an overview of measures and an analysis of early gamma band phase locking in schizophrenia. *Schizophrenia bulletin*, *34*, 907-926.

Robertson, I.H., Ward, T., Ridgeway, V., et al. (1994). The Test of Everyday Attention Manual.

Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*. *70*, 27–52. http://doi.org/10.1016/S0010-0277(98)00075-4

Scheeringa, R., Petersson, K. M., Oostenveld, R., Norris, D. G., Hagoort, P., &, & Bastiaansen, M. C. (2009). Trial-by-trial coupling between EEG and BOLD identifies networks related to alpha and theta EEG power increases during working memory maintenance. *Neuroimage*. *44*, 1224–1238.

Schoof, T., & Rosen, S. (2014). The role of auditory and cognitive factors in understanding speech in noise by normal-hearing older listeners. *Frontiers in Aging Neuroscience*. *6*, 307. http://doi.org/10.3389/fnagi.2014.00307

Seidenberg, M. S., MacDonald, M. C., & Saffran, J. R. (2002). Does grammar start where statistics stop?. *Science*, *298*, 553-554.

Sek, A., Baer, T., Crinnion, W., Springgay, A., & Moore, B. C. (2015). Modulation masking within and across carriers for subjects with normal and impaired hearing. *The Journal of the Acoustical Society of America*. *138*, 1143–1153.

Shinn-Cunningham, B. G., & Best, V. (2008). Selective attention in normal and impaired hearing. *Trends in Amplification*. *12*, 283–299. http://doi.org/10.1177/1084713808325306

Silman, S., & Gelfand, S. A. (1981). The relationship between magnitude of hearing loss and acoustic reflex threshold levels. *The Journal of Speech and Hearing Disorders*. *46*, 312–316. http://doi.org/10.1044/jshd.4603.312

Simon, H. J., & Yund, E. W. (1993). Frequency discrimination in listeners with sensorineural hearing loss. *Ear and Hearing*. *14*, 190–201. http://doi.org/10.1097/00003446-199306000-00006

Smoorenburg, G. F., de Laat, J. A., & Plomp, R. (1982). The effect of noise-induced hearing loss on the intelligibility of speech in noise. *Scandinavian Audiology*.

Souza, P. E., Boike, K. T., Witherell, K., & Tremblay, K. (2007). Prediction of Speech Recognition from Audibility in Older Listeners with Hearing Loss: Effects of Age, Amplification, and Background Noise. *Journal of the American Academy of Audiology*. *18*, 54–65. http://doi.org/10.3766/jaaa.18.1.5

Swingley, D. (2005). Statistical clustering and the contents of the infant vocabulary. *Cognitive psychology*, *50*, 86-132.

Tandetnik, S., Garnier, S., & Lorenzi, C. (2001). Measurement of first- and second-order modulation detection thresholds in listeners with cochlear hearing loss. *British Journal of Audiology*. *35*, 355–364. http://doi.org/10.1080/00305364.2001.11745253

Thompson, S. P., & Newport, E. L. (2007). Statistical learning of syntax: The role of transitional probability. *Language learning and development*, *3*, 1-42.

Tremblay, K. L., Friesen, L., Martin, B. A., & Wright, R. (2003). Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. *Ear and Hearing*. *24*, 225–232. http://doi.org/10.1097/01.AUD.0000069229.84883.03

Tuladhar, A. M., Huurne, N. T., Schoffelen, J. M., Maris, E., Oostenveld, R., & Jensen, O. (2007). Parieto-occipital sources account for the increase in alpha activity with working memory load. *Human Brain Mapping. 28*, 785–792.

Turner, C. W., Chi, S. L., & Flock, S. (1999). Limiting spectral resolution in speech for listeners with sensorineural hearing loss. *Journal of Speech, Language, and Hearing Research*. *42*, 773–84. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10450899

Turner, C. W., & Nelson, D. A. (1982). Frequency Discrimination Impaired in Regions of Normal and Impaired Sensitivity. *Journal of Speech and Hearing Research*. *25*, 34–41.

Van Rooij, J. C. G. M., & Plomp, R. (1990). Auditive and cognitive factors in speech perception by elderly listeners.II: Multivariate analyses. *The Journal of the Acoustical Society of America. 88*, 2611–2624. http://doi.org/10.3109/00016489109127275

Van Rooij, J. C. G. M., & Plomp, R. (1992). Auditive and cognitive factors in speech perception by elderly listeners.III. Additional data and final discussion. *Journal of the Acoustical Society of America*. *91*, 1028–1033. http://doi.org/10.1121/1.402628

Vasuki, P. R. M., Sharma, M., Demuth, K., & Arciuli, J. (2016). Musicians' edge: A comparison of auditory processing, cognitive abilities and statistical learning. *Hearing Research*. *342*, 112–123. http://doi.org/10.1016/j.heares.2016.10.00

Wechsler, D. (2008). Wechsler Adult Intelligence Scale–Fourth Edition (WAIS–IV). San Antonio, TX: The Psychological Corporation.

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*. *14*, 144–148.

Won, J. H., Drennan, W. R., & Rubinstein, J. T. (2007). Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *Journal of the Association for Research in Otolaryngology*. *8*, 384–392. http://doi.org/10.1007/s10162-007-0085-8

Wong, P. C. M., Jin, J. X., Gunasekera, G. M., Abel, R., Lee, E. R., & Dhar, S. (2009). Aging and cortical mechanisms of speech perception in noise. *Neuropsychologia*. *47*, 693–703. http://doi.org/10.1016/j.neuropsychologia.2008.11.032

Yeend, I., Beach, E. F., Sharma, M., & Dillon, H. (2017). The effects of noise exposure and musical training on suprathreshold auditory processing and speech perception in noise. *Hearing Research*. *353*, 224–236. http://doi.org/10.1016/j.heares.2017.07.006

Yordanova, J. Y., Kolev, V. N., & Başar, E. (1998). EEG theta and frontal alpha oscillations during auditory processing change with aging. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *108*, 497-505.

Zekveld, A. A., George, E. L. J., Houtgast, T., & Kramer, S. E. (2013). Cognitive Abilities Relate to Self-Reported Hearing Disability. *56*, 1364–1372. http://doi.org/10.1044/1092-4388(2013/12-0268)requirement

8. Tables

TABLE 1: Group of participants with hearing loss, detailing age, duration of hearing aid use, age at which hearing aid was given and type of hearing aid.

Participant	Age	Hearing loss noticed (in years)	Age hearing aid was received (in years)	Duration of hearing aid use (in years)	Type of hearing aid in both ears
HL1	21.5	4	16	5	RIC
HL2	29.6	14	19	10	RIC
HL3	67.11	32	42	25	RIC
HL4	25.4	10	10	15	RIC
HL5	68.4	21	56	12	IC
HL6	22.8	5	14	8	RIC
HL7	39.4	23	29	10	RIC
HL8	66	56	56	10	RIC
HL9	22.6	4	4	18	RIC
HL10	44.1	20	29	15	RIC

Note: RIC= Receiver In the Canal; IC= In the Canal

TABLE 2: Detailed test description and objective of all the auditory tests

Test	Stimuli	Description	Test objective
MDT: Conducted using The Maximum Likelihood Procedure (MLP; Grassi and Soranzo, 2009) toolbox	Gaussian noise of 500 ms, amplitude modulated at 60 Hz	Three alternative-forced-choice (AFC) adaptive tracking was used. Two of the stimuli presented were the reference stimuli having zero modulation and third one was the variable stimuli having the modulated signal. The threshold was calculated by taking the average of the last six reversals. Each test had three runs of the same to ensure that we had a good test-retest reliability. The task was to identify the variable stimuli.	Measure temporal envelope
IRN: Delay and add algorithm adapted (Leek and Summers, 2001; Peter et al. 2014).	Delayed noise of 10 ms with eight iterations was added to the original noise. The duration of noise was around 1000 ms with a bandwidth of 1 to 4 kHz. Pitch strength was determined varying the gain (0.32 to 0.01)	Three alternative-forced-choice (AFC) adaptive tracking was used. Two stimuli presented were reference stimuli having iterations and third one was the variable stimuli having the IRN stimuli. The threshold was calculated by taking the average of the last six reversals. Each test had three runs of the same to ensure that we had a good test-retest reliability. The task was to identify the variable stimuli.	Measure temporal pitch processing ability
SMRT (Aronoff and Landsberger, 2013)	Stimuli was created using a non-harmonic complex that consisted of 202 equal amplitude pure-tone frequency components that spaced every 1/33.3 of an octave between 100 to 6400 Hz. The duration of each stimulus was	Three alternative-forced-choice (AFC) adaptive tracking was used. Two stimuli presented were reference stimuli having 20 ripples per octave and third one was the variable stimuli having 2 ripples per octave. The threshold was calculated by taking the average of the last six reversals. Each test had three runs of the same to ensure that we had a good test-retest reliability. The task was to identify the variable stimuli.	Measure spectral resolution

	500 ms with 10-ms linear onset and offset ramps		
FD: Conducted using The Maximum Likelihood Procedure (MLP; Grassi & Soranzo, 2009) toolbox	1000 Hz tone with a duration of 250 ms with 10-ms onset and offset ramps was used for discrimination task	Three alternative-forced-choice (AFC) adaptive tracking was used. A difference of 100 Hz was set initially for discrimination between the reference and the variable stimuli. The threshold was calculated by taking the average of the last six reversals. Each test had three runs of the same to ensure that we had a good test-retest reliability. The task was to identify the variable stimuli.	Measure spectral resolution

TABLE 3: Detailed test description and objective of all the cognitive tests

Test	Stimuli Description & procedure	Test objective
Digit Span Test (forward/reverse/sequence): Subtest of Wechsler Adult Intelligence Scale IV (Wechsler, 2008)	The stimuli was presented verbally. The task of the participant was to repeat the given numbers in any of the given order such as forward/reverse/sequence. Each accurate response is given a score of 1. The test complexity increases as the number of correct response given increase.	Measure short-term and working memory
Elevator task with distraction and reversal: Subtest of Test of Everyday Attention (Robertson et al. 1994)	Elevator task with distraction: The stimulus was presented at 70 dB SPL through headphones (Sennheiser, HDA 300). The task of the participant was to count low pitch tones and ignore the high pitch tones. Correct response is given a score of 1 Elevator task with reversal: Presentation level and mode: 70 dB SPL through headphones (Sennheiser, HDA 300) Task: To count medium pitch tones and ignore the high and low pitch tones. Score: correct response is given a score of 1	Measure selective attention and attention switching
CSCT: English version of the Cognitive Spare Capacity test, adapted from Keidser et al. (2015)	The stimuli was presented at a SNR level that was derived from speech recognition threshold test conducted at 80 % using Beautifully Efficient Speech Test (BEST) (Best et al. 2014 with a simulated cafeteria noise comprising seven two-talker conversations at 65 dB SPL through loudspeakers (see Keidser et al. 2013 for further details). The SNR was set at a level such that the individual could identify the signal given with 90% accuracy. The target signal	Measure cognitive load

	was given from the loudspeaker located at 0° azimuth and noise from the other speakers located at different directions. The task of the participant was to remember the two numbers from a given set of numbers (For example: highest and the lowest number from the given set of numbers. Each set comprised of thirteen numbers. The participants had to complete six such sets. correct response is given a score of 1	
Statistical learning: auditory and visual (aSL and vSL)	vSL: Twelve black and white odd-shaped pictures were used, adapted from Fiser and Aslin (2001). Four triplets were created using these twelve pictures each having 200 x 200 mm dimension. aSL: This paradigm was adapted from (Saffran et al., 1999; Vasuki et al., 2016). Tones from A=440 Hz were generated on MATLAB and organised into four triplets at a sampling rate of 44100 Hz. For both aSL and vSL the triplets were created such that they could not easily form a recognisable melody or well defined shape which could facilitate statistical learning advantage (Saffran et al. 1999) The aSL and vSL consisted of two tasks familiarization and behavioural task. The aSl was presented at the comfortable level. Familiarization task: All the triplets (vSL & aSL) were presented around 240 times. The pictures/tones were presented through computer screens/ loudspeakers. The pictures/tones were presented simultaneously. Each picture appeared for 800 ms at the center of the screen and each auditory tone appeared for 550 ms. Inter-stimulus interval was 50 ms for both paradigms. The familiarization phase was 8.5 minutes for vSL and 7.5 minutes for the aSL. In-	Measure the ability to identify statistical regularities implicitly in both auditory and visual domain

	addition a cover task was included in the familiarization phase to ensure that the participant is paying attention to all the tones/pictures presented. The task given was to press the space bar when a picture/ tone was repeated consecutively. The second tone/picture of the triplet was repeated consecutively (e.g. ABBC, DEEF, GHHI, JKKL). There were 280 stimuli in the familiarization task including the cover task. The Transitional probabilities (TPs) for these 280 stimuli ranged from 0.216 to 0.333 (mean = 0.276). Behavioural task: There were 32 trials. It comprised of a two alternative force choice method (2AFC). The participant was given two triplets, a novel triplet and an original triplet (shown during familiarization task). The task of the participant was to identify the triplet (vSL/aSL) that is familiar. Correctly identified triplet was given a score of 1. Each picture in vSL appeared for 800 ms and each tone in aSl appeared for 550 ms.

TABLE 4: Shows the self-reported rating on SSQ-12 for individuals in the HL group. SSQ-12 is a 11 point rating scale with 12 questions, 0 indicating severe difficulty.

Participants	Understanding speech					Spatial separation				Sound Quality		
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
HL 1	0	3	3	3	3	9	10	8	10	8	9	8
HL 2	1	0	3	1	0	1	0	1	0	4	1	10
HL 3	3	3	5	6	5	4	0	4	9	4	5	5
HL4	5	2	5	3	5	4	0	5	8	6	6	8
HL5	10	5	10	10	10	10	10	10	10	10	10	10
HL6	8	4	4	6	7	6	6	9	8	10	9	9
HL7	9	7	7	3	3	8	5	3	5	5	7	5
HL8	6	7	8	6	9	9	9	9	0	9	4	7
HL9	7	5	4	3	3	9	8	7	1	8	8	6
HL10	7	7	8	2	2	2	8	10	9	10	9	2

*Note:** indicates participant with the highest SSQ12 score; HL: Hearing loss group

TABLE 5: Mean, median and standard deviations (in brackets) on auditory processing tasks of IRN, FD, MDT and SRN for the three groups (HL=10, NH =10, Controls=14). The MANOVA results show the differences in performance between the NH and HL group

Test	NH		HL		Controls		MANOVA
	MEAN	STDEV; MEDIAN	MEAN	STDEV; MEDIAN	MEAN	STDEV; MEDIAN	
MDT 60Hz (in dB)	-13.6	1.6;-13.6	-16.1	1.8;-15.9	-14.4	2.3;-14.9	[F(1, 17) = 8.4, p= 0.01 partial $ŋ^2$ =0.3]
IRN (in dB)	13.1	2.0;13.2	11.6	1.1;11.7	13.7	1.9;14.2	[F(1, 17) = 3.6, p= 0.07, partial $ŋ^2$ =0.1]
SRN (ripples per octave)	7.0	1.3;7.5	7.0	1.8;7.8	7.7	1.6;8.2	[F(1, 17) = 0.0, p= 0.9, partial $ŋ^2$ =0.0]
FD (in log)	1.0	0.4;0.9	0.9	0.2;1.0	1.2	0.3;1.2	[F(1, 17) = 0.3, p= 0.5, partial $ŋ^2$ =0.01]

Note: NH: Normal hearing group; HL: Hearing loss group

IRN: Iterated Rippled Noise; FD: frequency discrimination; MDT: Modulation Detection Thresholds; SRN: Spectral Rippled Noise

TABLE 6: Mean, median and standard deviations (in brackets) of cognition tasks including digit span tests, TEA, CSCT, DCT and SL for the three groups (HL=10, NH =10, Controls=14). The MANOVA results show the differences in performance between the NH and HL group

Test	NH		HL		Controls		MANOVA
	MEAN	STDEV; MEDIAN	MEAN	STDEV; MEDIAN	MEAN	STDEV; MEDIAN	
Digit span forward (raw score)	10.6	1.4;10.5	12.0	2.1;11.5	12.7	1.5;13.5	[F (1, 17) = 2.6, p= 0.1, partial η^2 =0.1]
Digit span backward (raw score)	9.3	1.8;9.0	8.7	2.2;8.0	10	1.6;9.5	[F (1, 17) = 0.4, p= 0.4, partial η^2 =0.02],
Digit span sequence (raw score)	8.7	2.2;8.0	8.0	1.0;8.0	9	1.4;10	[F (1, 17) = 2.1, p= 0.1, partial η^2 =0.1]
Digit span (scaled score)	10.3	1.9;10.0	10.7	2.2;10.0	11.6	1.8;12	[F (1, 17) = 0.04, p= 0.8, partial η^2 =0.0]
TEA: distractor (scaled score)	11.7	1.7;12.5	9.9	2.2;10.2	9.5	2.1;10	[F(1, 17) = 3.3, p= 0.08, partial η^2 =0.1]
TEA: reversal (scaled score)	9.9	3.7;10.5	11.1	2.6;11.5	10	3.4;11	[F(1, 17) = 0.8, p= 0.3, partial η^2 =0.04]
CSCT (raw score)	8.3	1.7;8.5	8.6	1.5;9.0	8.5	1.2;8.5	[F(1, 17) = 0.2, p= 0.6, partial η^2 =0.01]
DCT (raw score)	21.6	5.4;22.7	17	18.3;18.25	20.2	5.2;20.5	[F(1, 17) = 2.3, p= 0.1, partial η^2 =0.1]

vSL (accuracy %, raw scores)	49.6	12.3;48.4	47.4	11.2;48.4	54.6	13.9;51.5	[F(1, 17) = 0.4, p= 0.5, partial η^2 =0.02].
aSL (accuracy %, raw scores)	64.9	8.3;65.6	67.1	13.6;67.1	61.1	8.4;59.3	[F (1, 16) = 0.1, p= 0.6, partial η^2 =0.01]

Note: NH: control group; HL: Bilateral sensori-neural hearing loss group

TEA: test of everyday attention; CSCT: cognitive spare capacity test

DCT: dynamic conversation test; SL: statistical learning

9. Figures

FIGURE 1: Pure-tone audiometric thresholds for octave frequencies between 250 Hz to 8 kHz for each participant in the HL group. Each colour belongs to a different participant. The left column shows the left ear and the right column shows the right ear.

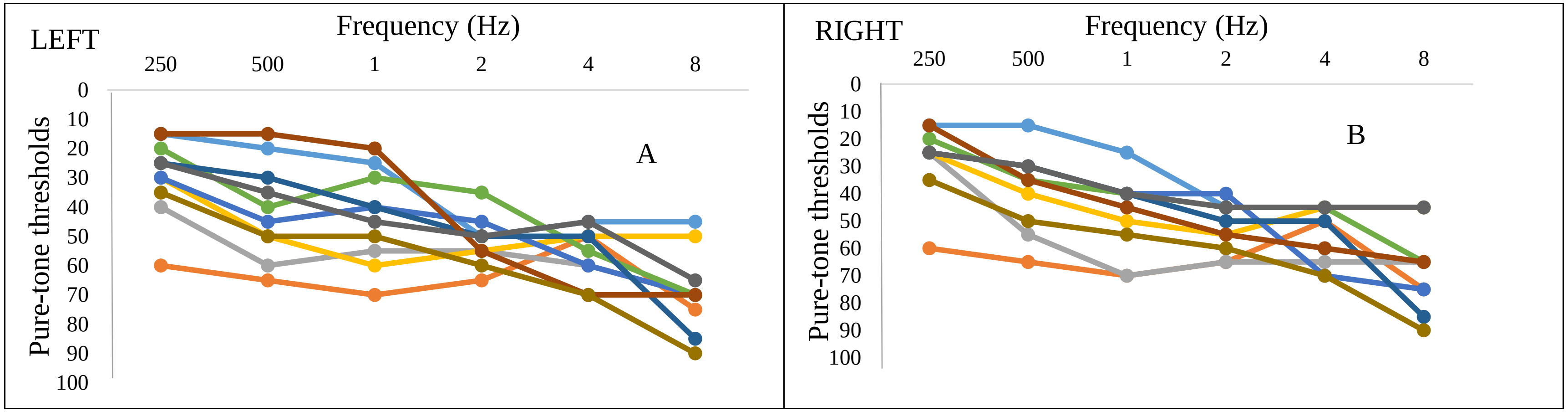


FIGURE 2: Shows the grand average CAEP waveforms to /da/ of NH (blue) and HL (green) group obtained for the (A) quiet and (B) 8-talker babble noise conditions. The y-axis shows the amplitude in microV and x-axis shows time in seconds.

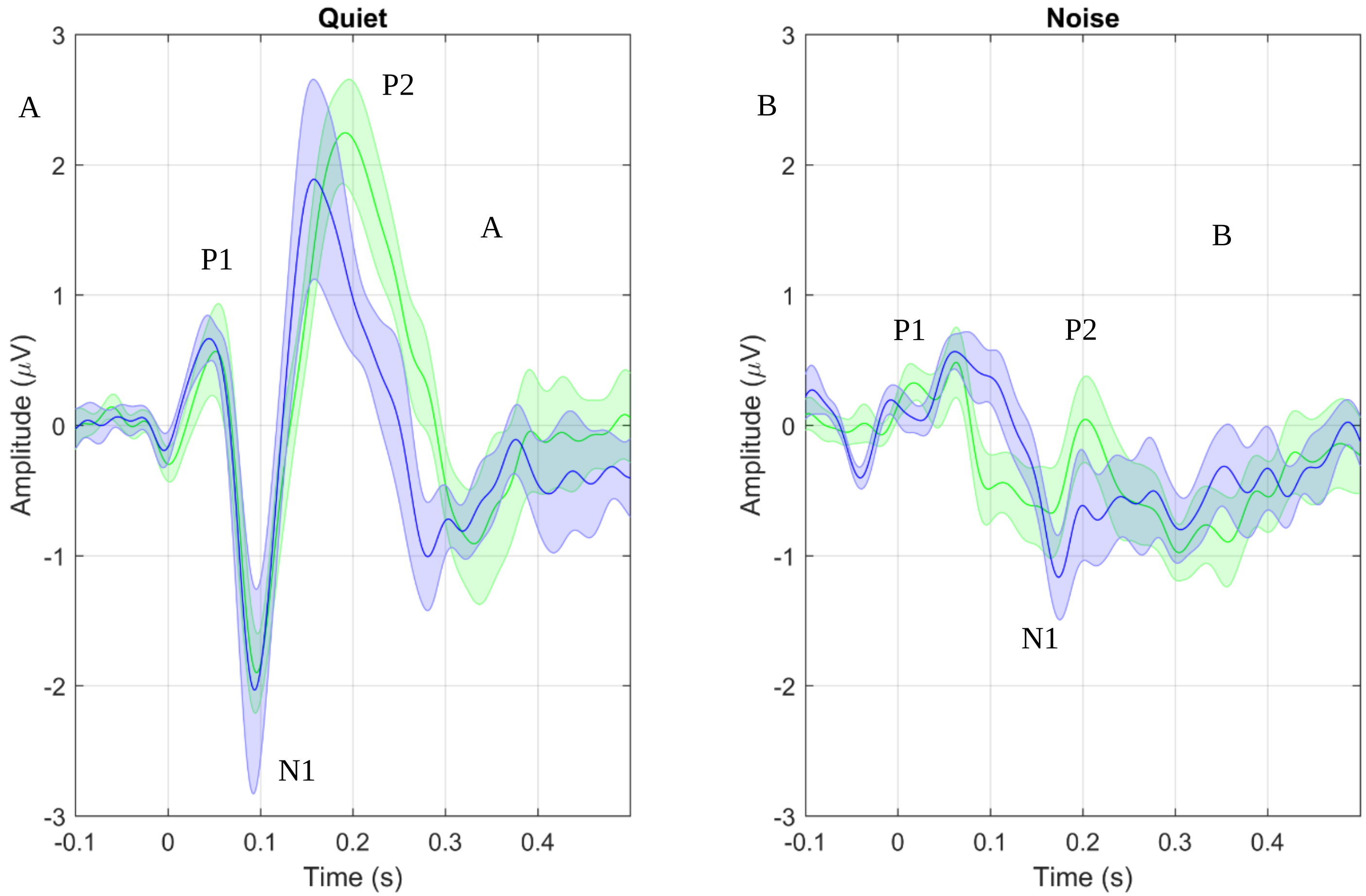


FIGURE 3: Shows the GFP analysis waveforms to /da/ of NH (blue) and HL (green) group obtained for the (A) quiet and (B) 8-talker babble noise conditions. The y-axis shows the amplitude in microV and x-axis shows time in second.

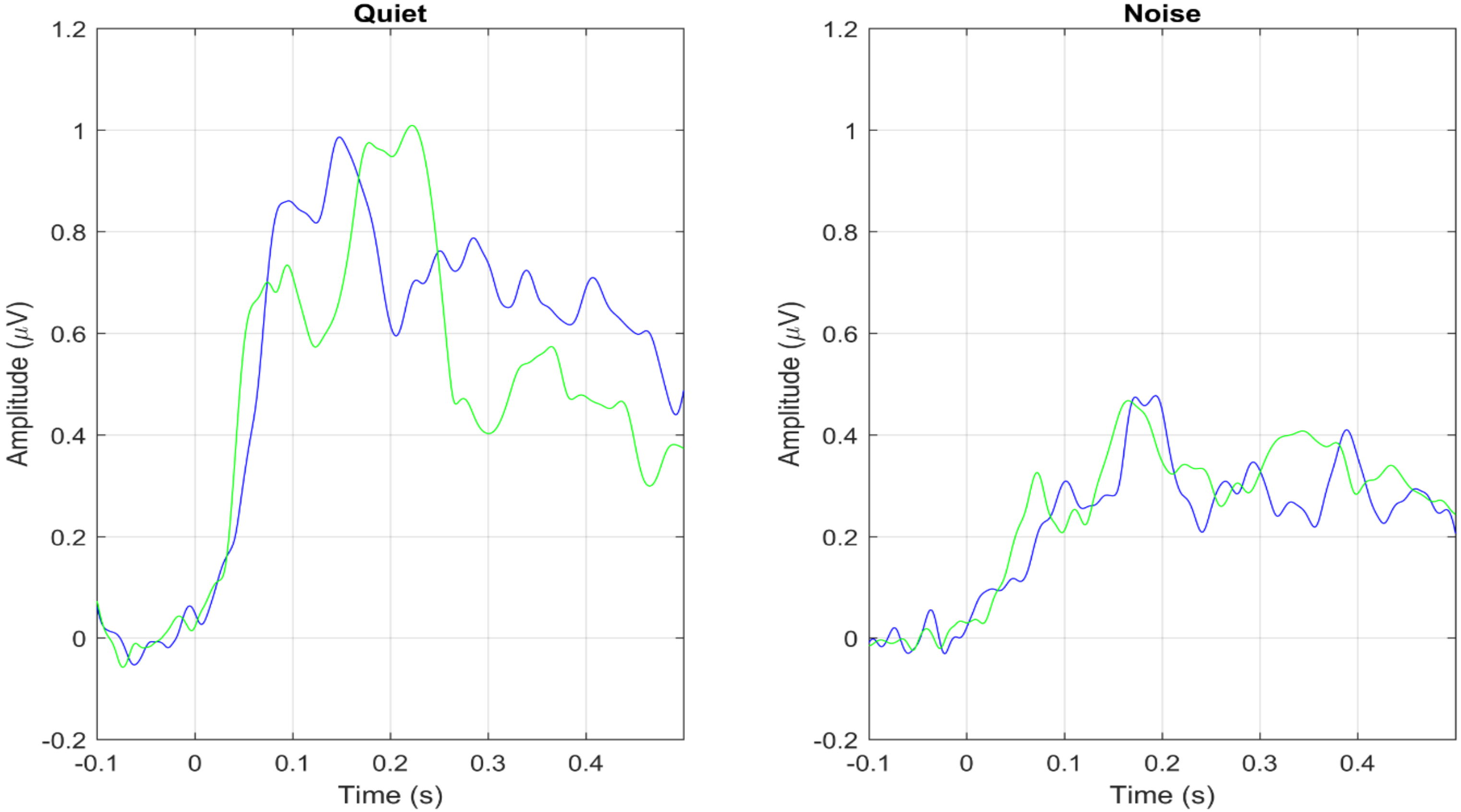


FIGURE 4: Alpha oscillations (8-12 Hz) for the NH and HL group for quiet and noise conditions for centro-frontal electrodes. The synchronised alpha oscillations are stronger for the NH group in quiet condition.

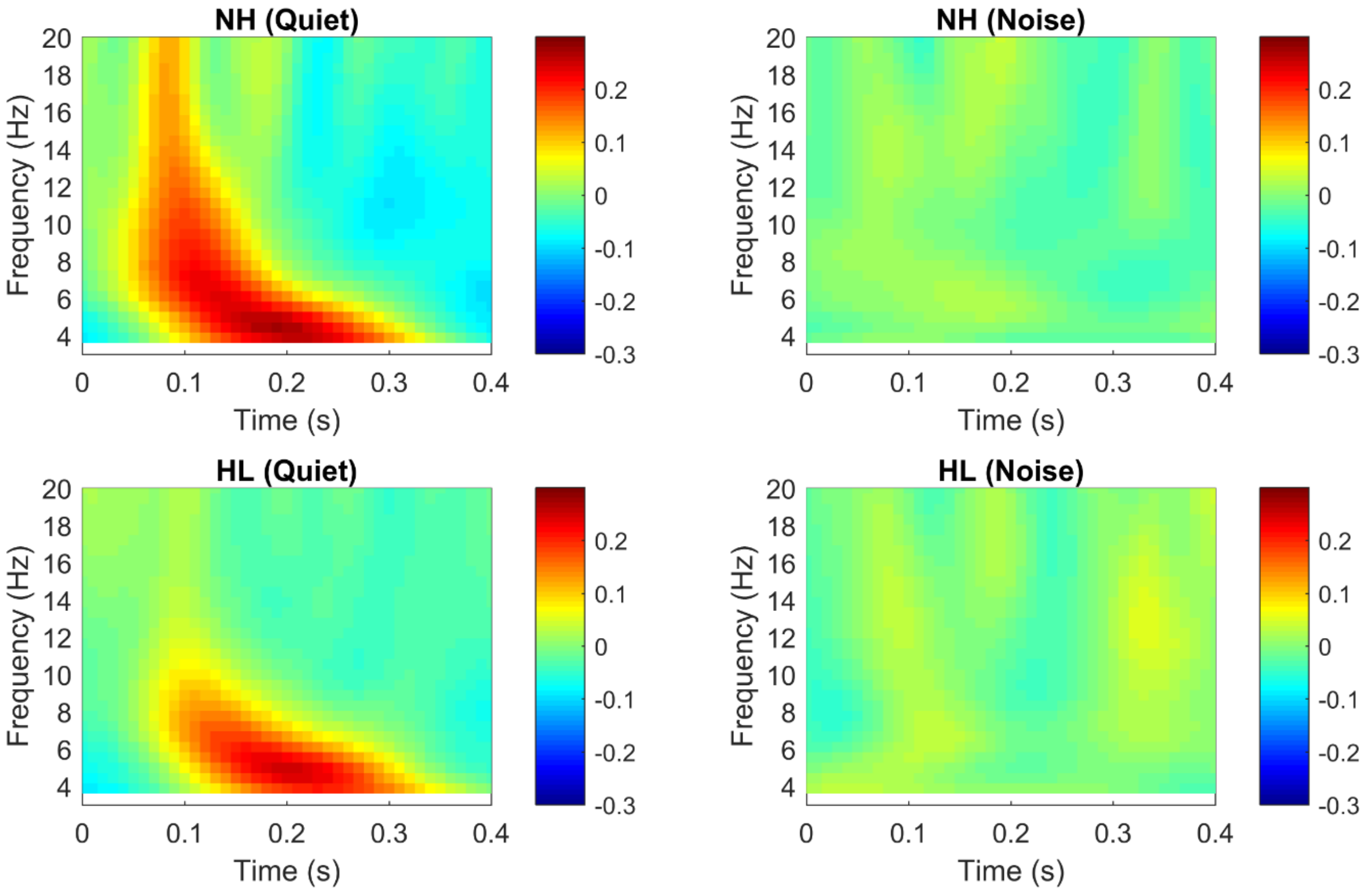
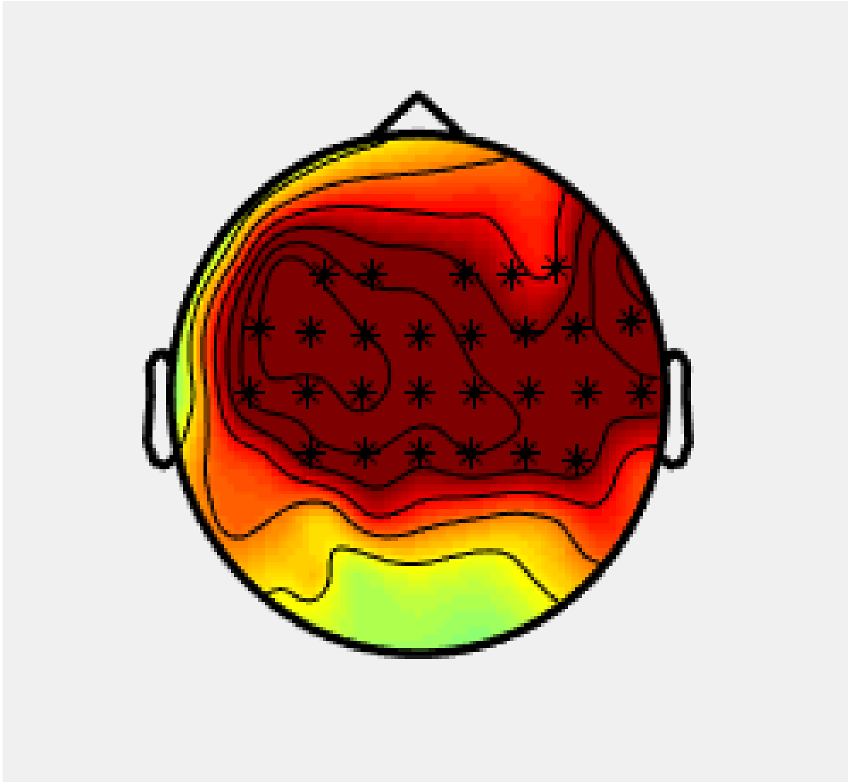


FIGURE 5: Within group cluster permutation analysis carried out in quiet versus noise conditions. The figure shows significant clusters for the control group in quiet condition. Significant clusters were noted for alpha oscillations in the centro-frontal electrodes. The clusters were seen between 0.07 to 0.14 sec. There were no significant clusters in noise condition.

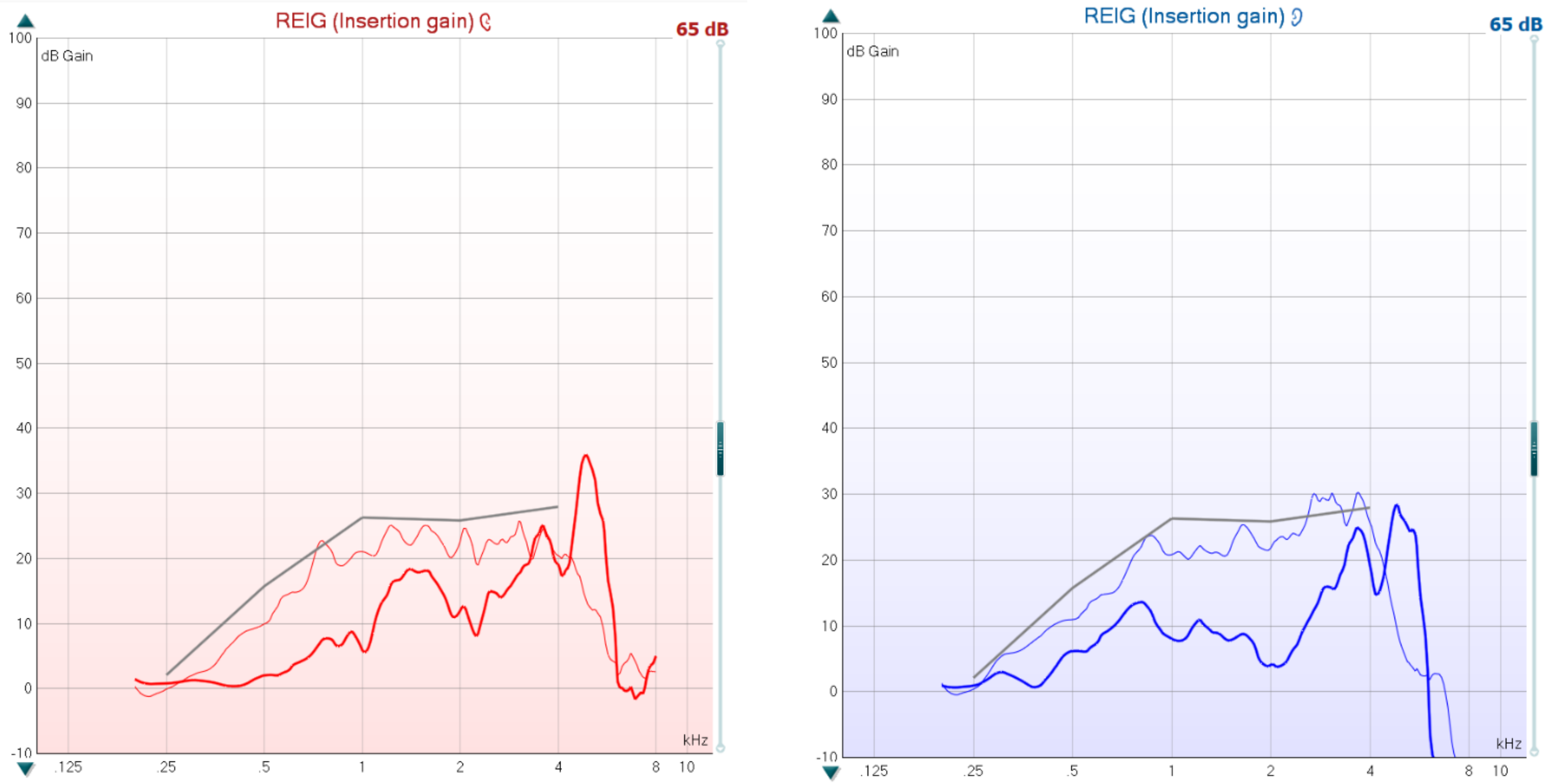


10. Supplementary Figures

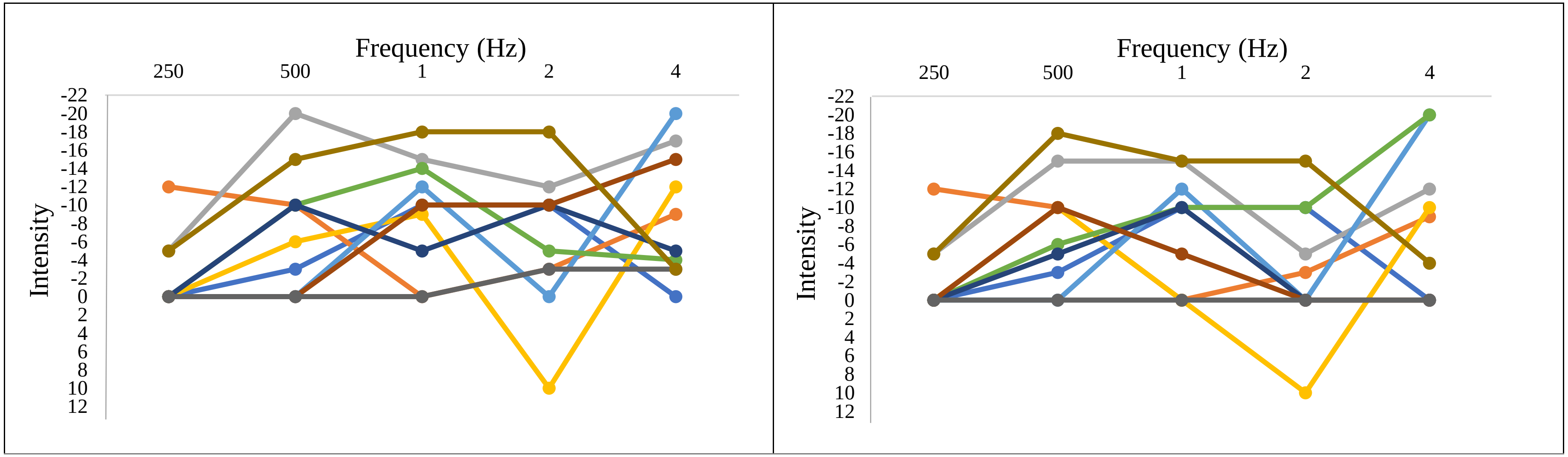
1) Real measurement of two participants (of 10) with their personal hearing aids. A represents the participant with the best fit for right (red) and left ear (blue). B represents the participant with relatively poor fit for both ears. The thick lines show the amount of gain given by personal hearing aid of the participant, thin lines show the amount of gain given by hearing aid programmed for the current study and the grey line represents the required target. The y-axis represents frequency (in kHz) and x-axis represents intensity.

A

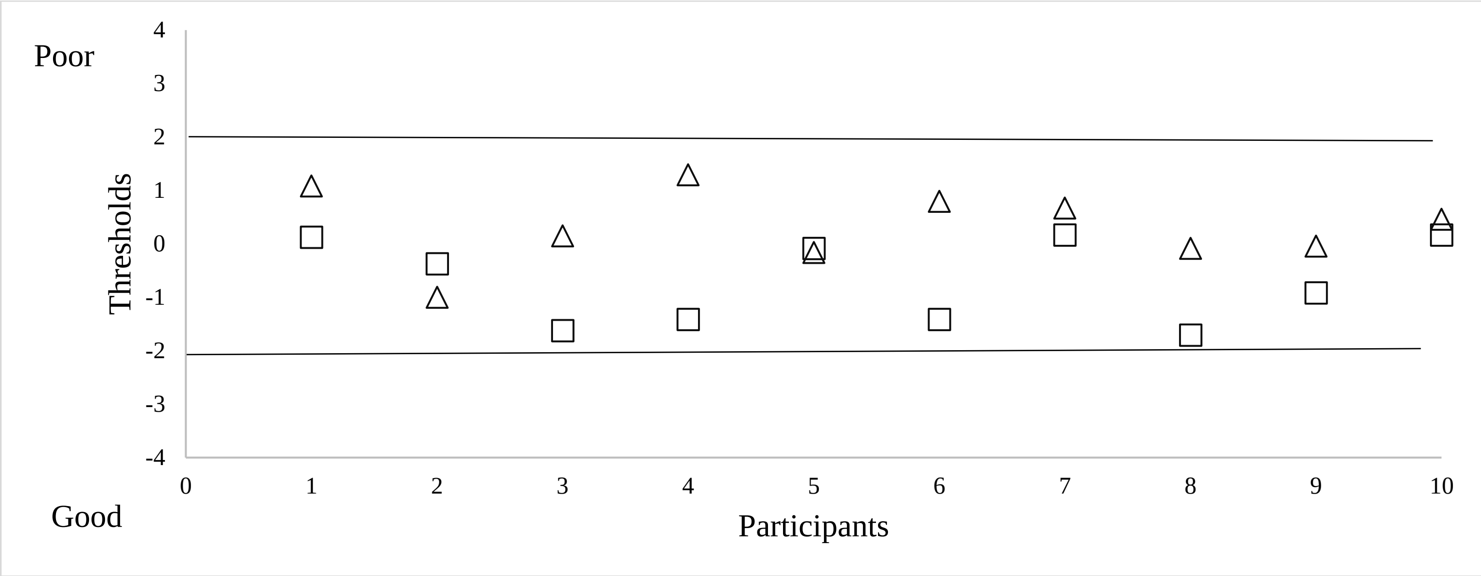
B


REIG (Insertion gain)
65 dB
dB Gain
100
90
80
70
60
50
40
30
20
10
0
-10
.125
.25
.5
1
2
4
8
10
kHz
REIG (Insertion gain)
65 dB
dB Gain
100
90
80
70
60
50
40
30
20
10
0
-10
.125
.25
.5
1
2
4
8
10
kHz

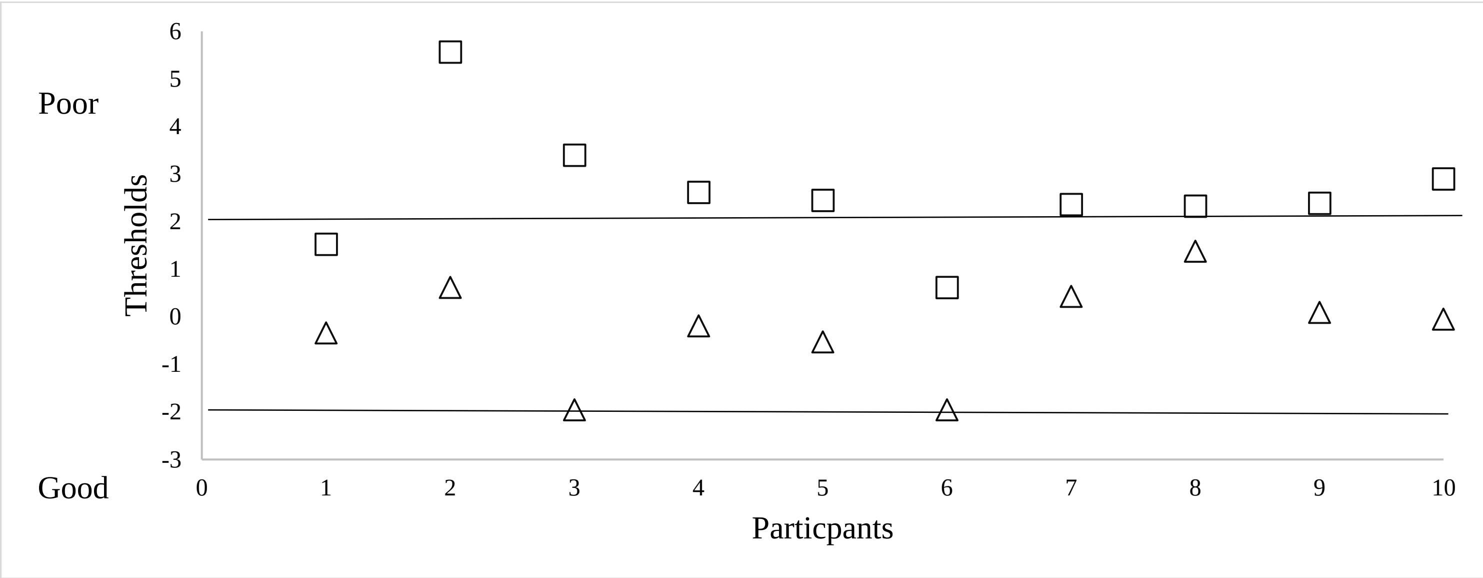
2) Overview of the amplification provided by the personal hearing aids of each participant, 0 (y-axis) represents the required target. Each colour belongs to a different participant. The left column shows the left ear and the right column shows the right ear.



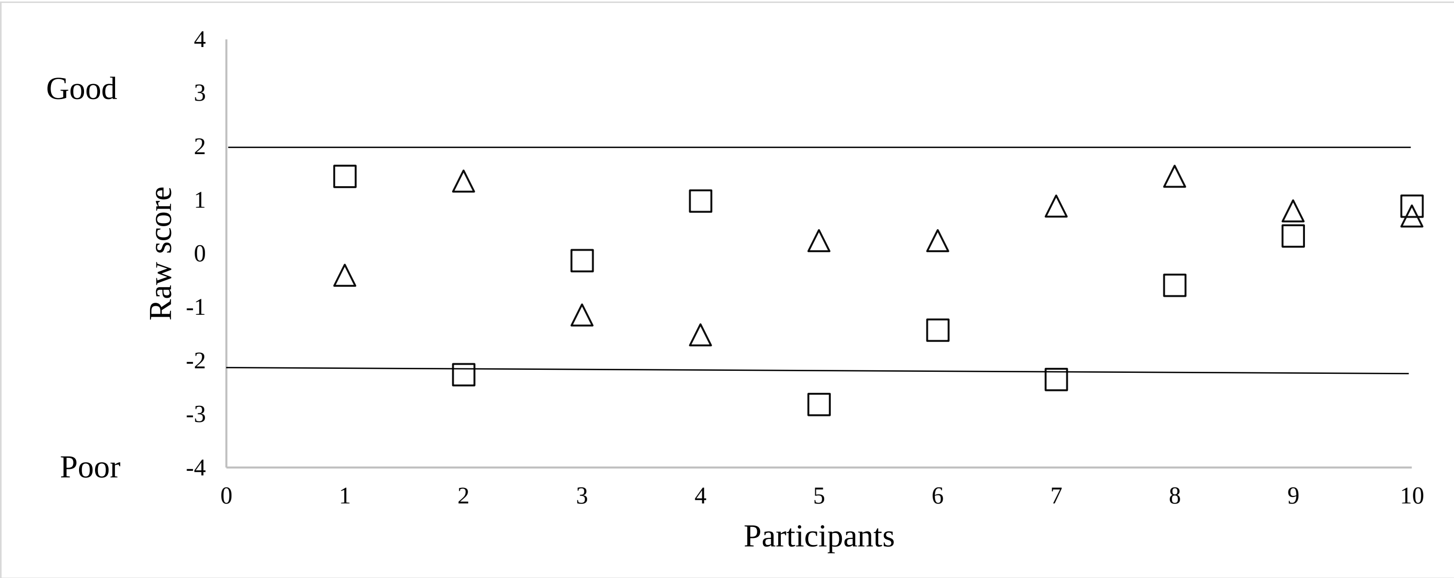
3) Individual Performance of the HL group on MDT in square and NH in triangle (HL & NH =10). Performance below zero indicates very good performance. Zero is the mean performance of the 14 controls.



4) Individual Performance of the HL group on SRT in square and NH in triangle (HL & NH =10). Performance below zero indicates very good performance. Zero is the mean performance of the 14 controls.



5) Individual Performance of the HL group on NAL-DCT in square and NH in triangle (HL & NH =10). Performance above zero indicates very good performance. Zero is the mean performance of the 14 controls.



11. Supplementary table

Table 1: Shows the mean and standard deviation of each participant in the HL group on the SSQ12. The 12 questions were categorized as per the SSQ 49 index as the normal hearing control subjects were tested on SSQ 49. The 12 questions from the SSQ12 were listed under four categories i.e. selective attention, divided attention, spatial and quality. The shaded column shows the expected mean and standard deviation from young (18-25 years old) normal hearing adults. The norms are captured from Demeester et al. (2012) in Bressler et al. (2017).

SSQ 49 category	**SSQ 12 questions**	**HL group (n=10) mean (SD)**	Normal Hearing (n=103)* mean (SD)
Selective Attention	Q1: Speech in noise	5.6(3.3)	9.5(0.7)
	Q3: Speech in speech	5.7(2.4)	9.2(1.1)
	Q4: Speech in noise	4.3(2.6)	8.8(1.2)
	Q5: Multiple speech streams	4.7(3.1)	9.4(1.2)
	Q9: Segregation	6.0(4.1)	9.1(1.3)
Divided Attention	Q2: Multiple speech streams	4.3(2.3)	6.2(2.7)
Spatial	Q7: Distance and movement	5.6(4.1)	8.1(1.4)
	Q8: Distance and movement	6.6(3.1)	9.2(1.2)
	Q6: Localization	6.2(3.2)	8.7(1.9)
Quality	Q11: Quality and naturalness	6.8(2.8)	9.6(1.4
	Q12: Listening effort	7.0(2.5)	8.5(2.3)
	Q10: Identification of sound	7.4(2.4)	7.5(2.4)

Chapter 5: Overall discussion and conclusion

The present research has examined the auditory and cognitive differences in adults with and without clinically normal audiograms reporting speech understanding in noise difficulty on a similar test battery. Speech perception has been evaluated using both subjective and objective measures. Study 1 and study 2 focussed on the underlying differences in auditory and cognitive processing skills in adults with clinically normal audiograms with reported speech understanding in noise concerns in comparison to adults with no reported concerns. Study 3 focussed on individuals with hearing loss reporting speech understanding in noise difficulty. This study examined the underlying differences in auditory and cognitive processing between individuals with hearing loss reporting speech understanding in noise concerns versus those individuals with normal hearing and no difficulties understanding speech in noise. The results obtained from the current research provide a wider insight and understanding to the existing problem.

The overall findings from the research are:

1) Adults with and without hearing loss reporting speech understanding in noise concerns performed similar to the group with clinically normal hearing having no reported concerns on well-known clinical tests of attention and memory. Considering we found no difference on tests measuring speech understanding ability in the presence of noise, may be both adults with and without hearing loss are using these cognitive skills to assist during the speech understanding in noise tasks. Congruent findings were observed in studies conducted by Lunner (2003) and Ng et al. (2013), where individuals with good working memory capacity performed better on speech understanding in noise tasks than individuals with hearing loss and poor working memory capacity. Adults reporting difficulty understanding speech in noise may be using their cognitive skills to overcome the problem possibly leading to effortful listening.

It may be this effortful listening which is the crux of the problem, and indeed this increased listening effort could be what the adults are actually defining as difficulty understanding speech in noise. Therefore, measurement of listening effort should be the future direction of research in this cohort of adults with listening in noise concerns.

2) Adults with and without hearing loss reporting speech understanding in noise concerns in the current project have shown no differences on any of the selected behavioural auditory and cognitive tests. One explanation may be that the participants were using all or some of their cognitive and auditory skills in the laboratory testing to compensate for the listening in noise difficulty. This again leads to listening effort that in future studies needs to be measured. It is possible that these adults reporting speech understanding in noise concerns are unable to compensate in a real-life leading to the reported speech in noise difficulties. Consequently, future studies need to include real life challenging listening scenarios. It may be important to develop more realistic measures or ecological valid tasks to evaluate these concerns. The results from the present research may not be able to provide an answer to why the individuals with and without hearing loss complain of speech understanding in noise issues but it provides impetus for the need to develop research utilising more real life-based assessments.

3) Behavioural tests in general provided limited insight into those with self-reported problems processing speech in noise. Physiological tests seem more sensitive to the reported speech in noise difficulties. Cortical auditory evoked potentials conducted using both sentences and syllables were found to be impacted in both adults with and without hearing loss reporting of difficulty understanding speech in the presence of noise. These differences in cortical processing observed on CAEPs may be driven by cognitive factors. For instance, the elicitation of N400 using sentences may require the ability to predict the key word using contextual cues (Conway et al. 2010). Similarly, the synchronised alpha oscillations found while measuring CAEPs using syllables and sentences are believed to be driven by the ability to pay attention

to the given task (Scheeringa et al., 2009; Klimesch, 2012). These differences were observed in quiet and thus may not completely explain why both adults with and without hearing loss report difficulty understanding speech in the presence of noise. It could be that those with speech in noise concerns have problems listening in all situations quiet and noise but are more sensitive or aware of their difficulties in noisy environments. Better questionnaires with more open-ended questions may be required to determine the exact nature of the reported concern.

The SSQ provides specific scenarios with a ranking and therefore limits determining the nature of the difficulty. Even though, all the participants reported speech understanding in noise difficulty, there were a few individuals who did not appear to exhibit a difficulty on SSQ12. One reason for this could be that the questionnaire did not directly target the problem that the individual was reporting. For instance, in the present study it was observed individuals with listening in noise concerns had poorer performance in the physiological tests in quiet condition. However, the SSQ12 does not include questions regarding speech understanding in quiet. SSQ 12 shows variability for different scenarios across all participants with listening concerns. For instance, only 5 cited difficulties in most scenarios of SSQ while most others have difficulty in one or two scenarios within one section. In future studies it would be recommended that rather than using pre-set questionnaires such as SSQ 12, interviews are conducted. The advantage of interviews are that individuals can state their concern more specifically.

4) In the present research, speech understanding was considered as resulting from the contribution of various independent auditory and cognitive factors in a linear fashion. The current hypothesis was that the individual factors feed into speech understanding skills. Results from the present research suggest that speech understanding is a complex phenomenon that is driven by the interaction between various factors. For instance, the interaction between auditory and cognitive factors were observed in the physiological data in both the groups. In

the current project, we have explored syllables in quiet and noise and sentences in quiet. Future studies should include syllables, words and sentences at different signal to noise ratios involving behavioural and electrophysiological analysis as well as time frequency analysis.

Conclusion:

The reported speech understanding in noise concerns in adults with and without hearing loss are more sensitive to physiological measures than the behavioural measures. The results obtained from the current research suggest that the differences underlying cognitive rather than auditory processing skills are largely driving the reported speech understanding in noise concerns.

Conclusions and implications

The three studies reported here investigate and highlight the concerns of adults with and without hearing loss who report that listening to speech in noise is a challenge. The test battery used in a regular clinical setting appears insufficient to identify and investigate the reported concerns. On the other hand, this research suggests that a physiological test battery may be effective in identifying differences in speech processing abilities.

Both studies including individuals with and without hearing loss having listening in noise concerns have highlighted the involvement of strong synchronised alpha oscillations only for the individuals with clinically normal audiogram, appear to highlight the influence of attention driving these responses (Klimesch et al., 2007). Previously literature has reported synchronised alpha oscillations to be observed in tasks where one requires to pay attention to the given stimuli and remember them even while not responding to them (Tuladhar et al., 2007; Scheeringa et al., 2009). This ability to maintain good attention may be particularly important during tasks that requires one to ignore the irrelevant signals and focus on the required signal, for example, during a speech understanding task in the presence of noise, one may have to ignore the noise in order to focus on the required signal and this is possible only if one can pay attention to the given task.

Similarly, on the N400 task, only the group with clinically normal audiograms with no speech understanding in noise concerns exhibited an N400, while it was absent for the group with clinically normal audiograms with reported concerns. N400 is a test that requires one to understand the given sentence and is believed to be driven by factors such as attention and word predictability (Kutas & Federmeier, 2011; Okita & Jibu, 1998). Absence of the N400 in the group with reported speech understanding in noise concerns may indicate that these individuals may have difficulty with word predictability skills and therefore find understanding speech particularly in the presence of noise to be difficult. The main advantage of using physiological tests are that they provide an insight to the neural processing during the speech processing task at a cortical level (see Cone-Wesson & Wunderlich, 2003 for a review). Physiological techniques also avoid subject and experimenter bias during testing. The physiological tests used in the present research are non-invasive and therefore could be relatively easily applied in a regular clinical set up to identify the reported speech understanding in noise concern. However, future studies need to be conducted to evaluate the test efficacy before applying it in a clinical set up.

Limitations and future research

1) In the current study, physiological measures such as sentence evoked CAEPs was applied only on adults with clinically normal audiograms reporting speech understanding in noise concern while the syllable evoked CAEPs were applied only on adults with hearing loss reporting difficulty understanding speech in the presence of noise. Future research should investigate both sentence and syllable evoked CAEPs on both adults with and without hearing loss reporting of understanding speech in noise concern. This would enable us to determine if we are able to see similar synchronised alpha oscillations in both these groups even while the stimulus type is different which would provide a better understanding of the reported issue.

2) The current research used only a limited number of SNR ratios. Future research should conduct both physiological measures; sentence evoked, and syllable evoked cortical responses at different signal to noise ratios such as 20 dB SNR along with worse signal to noise ratios. This would determine if low level of noise is also difficult for the adults with reported concerns compared to those who have no concerns.

3) The sample size for the group with hearing loss reporting a speech understanding in noise difficulty in the current study was small. Power analysis carried out showed the group should comprise around 49 participants. Future research needs to be conducted on a larger group to confirm the current findings. On that note, however, it is quite unlikely that we may see any difference on the behavioural measures considering all the participants in the HL group performed within 2 SD on most of the tests (refer, supplementary figures chapter 3).

4) In the current study, the performance on various auditory and cognitive tests was compared between adults with hearing loss reporting a speech understanding in noise concern and a control group with normal hearing with no reported concern. Future research should consider incorporating a group with hearing loss and no reported speech in noise concerns when comparing physiological measures.

References

Bentin, S., Kutas, M., & Hillyard, S. A. (1995). Semantic processing and memory for attended and unattended words in dichotic listening: Behavioural and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 54.

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition*, *114*(3), 356–371. http://doi.org/10.1016/j.cognition.2009.10.009

Glasberg, B. R., & Moore, B. C. J. (1986). Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. *The Journal of the Acoustical Society of America*, *79*(4), 1020–1033. http://doi.org/10.1121/1.393374

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews*. *53,* 63–88. http://doi.org/10.1016/j.brainresrev.2006.06.003

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. http://doi.org/10.1016/j.tics.2012.10.007

Moore, B. C. J., & Street, D. (1993). Effects of spectral smearing on the intelligibility ofof Sentences in Noise. *The Journal of the Acoustical Society of America*, *94*(3), 1229–1241.

Ng, E. H. N., Rudner, M., Lunner, T., Pedersen, M. S., & Rönnberg, J. (2013). Effects of noise and working memory capacity on memory processing of speech for hearing-aid users. *International Journal of Audiology*, *52*(7), 433–441.

http://doi.org/10.3109/14992027.2013.776181

Scheeringa, R., Petersson, K. M., Oostenveld, R., Norris, D. G., Hagoort, P., &, & Bastiaansen, M. C. (2009). Trial-by-trial coupling between EEG and BOLD identifies networks related to alpha and theta EEG power increases during working memory maintenance. *Neuroimage*, *44*(3), 1224–1238.

Shinn-Cunningham, B. G., & Best, V. (2008). Selective attention in normal and impaired hearing. *Trends in Amplification*, *12*(4), 283–299. http://doi.org/10.1177/1084713808325306

Tuladhar, A. M., Huurne, N. T., Schoffelen, J. M., Maris, E., Oostenveld, R., & Jensen, O. (2007). Parieto-occipital sources account for the increase in alpha activity with working memory load. *Human Brain Mapping. 28*, 785–792.

Appendix I: Ethics Approval

Office of the Deputy Vice-Chancellor
(Research)

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Macquarie University
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http://www.research.mq.edu.au/
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19 July 2016

Dear Associate Professor Sharma

Reference No: 5201600438

Title: *Efficacy of auditory training in adults with hearing loss and auditory processing disorders*

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:

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

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.

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.

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*.

Details of this approval are as follows:

Approval Date: 18 July 2016

The following documentation has been reviewed and approved by the HREC (Medical Sciences):

Documents reviewed	Version no.	Date
Macquarie University Ethics Application Form		Received 08/06/2016

Correspondence responding to the issues raised by the HREC (Medical Sciences)		Received 15/07/2016
MQ Participant Information and Consent Form (PICF)	2	15/07/2016
Advertisement	1	15/07/2016

***If the document has no version date listed one will be created for you. Please ensure the footer of these documents are updated to include this version date to ensure ongoing version control.**

Appendix II: Research information and consent form

Dept. of Linguistics, Faculty of Human Sciences
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<u>Information Statement and Consent Form</u>

Efficacy of auditory training in adults with hearing loss and auditory processing disorders

<u>The research team</u>

Associate Professor Mridula Sharma (The chief investigator – MU)
Dr. John Newall (Co-Investigator – MU)
Dr. Jessica Monaghan (Co-Investigator – MU)
Dr. Gitte Keidser (Co-Investigator – National Acoustics Laboratories)
Dr Elizabeth Beach (Adviser- National Acoustics Laboratories)
Ms. Shivali Appaiah Konganda (Associate Investigator – MU)

The project: Understanding Speech in the presence of noise is of prime concern for adults. One of the primary causes for this issue may be the presence of hearing loss. However, there are individuals who have difficulty listening in noise despite having normal hearing sensitivity. Researchers from various sectors such as hearing and cognitive science have tried to determine the cause and to determine an appropriate treatment program. Currently, hearing aids and auditory training are two intervention strategies to assist with hearing related difficulties. While there is a literature available on auditory training, the potential benefits of auditory training still remains uncertain.

Considering the findings and challenges from literature, our study aims to investigate the efficacy of a tonal- based auditory discrimination training program on 2 groups of adult population i.e. with hearing loss and on those with listening difficulties due to noise exposure (without hearing loss). There is a dearth of tests designed to identify hearing related difficulties in adults especially in the presence of noise. In-order to ensure that the tasks selected provides similar results to what has been reported in literature, we require a group of young adults with normal hearing to participate in our study.

Testing will take place at the Macquarie Speech and Hearing Clinic, Macquarie University.

Who should participate: 1) Adults aged between 18 -70yrs with hearing related complaints such as hearing loss and/or difficulty in speech understanding in the presence of noise 2) Young adults aged between 18-69 years with normal hearing.

What would you do: If you decide to participate in this study, we will email you with details of an online questionnaire and a unique ID. When filling the questionnaire, please make sure that you enter the unique ID. The questionnaire asks about your exposure to noise, music experience and general life style. The questions are in two sets and will take approximately 30 minutes to complete.

Following this, we will request you to come in at Macquarie University. We will administer a case history where general information regarding your hearing status and medical condition will be obtained. Following this, you will undergo screening tests which include a basic hearing screening comprising 1) otoscopy: to ensure ear canal, ear drum are normal 2) immittance audiometry: a plug will be placed in your ear and you will hear a few tones, results obtained will help us determine if the middle and inner ear pathways are within normal limits 3) pure-tone audiometry: In this test you will be presented with few tones at different levels and you will be asked to respond as you hear these tones. This test will help us evaluate your hearing sensitivity. These screening tests would approximately take around 30 minutes.

Once the screening tasks are completed, you will undergo further tests which will be carried out in two sessions, each of which would approximately take around 150 minutes.

First session: This will comprise a set of behavioural measures which would include an initial administration of a questionnaire assessing hearing rehabilitation benefits and drawbacks followed by measures which includes a test of attention and memory. Furthermore, tests assessing the listening, listening effort, sounds in words, and learning abilities will also be undertaken.

Second session: The second half will include an objective measure assessing brain response to sounds. In our study we will be using auditory stimuli and the responses obtained will be recorded and evaluated. This test will be carried out by placing a cap on your head that has multiple areas for electrode placement. It is noninvasive and might take around 150 minutes for the entire completion of the test.

Note: Tests included in session 1 and session 2 will be conducted 3 times. The first round of testing will be carried out on the day of arrival where in the 1st session will be carried out on the same day and 2nd session on the next day. Similarly, second round of testing will be carried out after 4 weeks interval. Before the third round of testing you will be enrolled in a training program for 4 weeks after which the third round of testing will be carried out. The training program will require spending 30 minutes for 5 days over 4 weeks on a game which is either sound based or visual based. If you are interested in trialing both, you will be given access to the second training at the end of the research. We have included two baseline measures before the actual training mainly to avoid any kind of learning effects from the first round of testing to the second and also to ensure that the improvements seen is mainly from the contribution of auditory training program that has been used.

Benefits: You will be reimbursed for your travels with gift vouchers of up to $20 for each session.

Risks or Discomforts: There are no risks associated with this research. As mentioned earlier, the brain responses are non-invasive and are used in clinics for testing hearing abilities in babies. However, there is a slight possibility of you experiencing a temporary irritation to the surgical tape or gel used on the sensors on the cap used for CAEP. This will clear in a day. In case you are uncomfortable with the tape, gel or the cap that is being used, please let the investigator know, so that the assessment will be stopped right away.

Confidentiality: The information obtained in this study will be strictly confidential. The data obtained will be accessed only by the investigators and co-investigators. To avoid any kind of identity that could personally identify you we will be giving you a code number, no personal details will be mentioned in any of our reports.
Decision to participate and the right to quit at any time If you decide to participate, you are free to withdraw from further participation in the research at any time without having to give a reason and without consequence. Should you have any questions about the study, do not hesitate to contact the Principal Investigator (Dr Mridula Sharma, ph 02 9850 4863) or myself (Shivali Appaiah 0469794272).

Should you have any inquiries regarding the study, please contact the following personnel for assistance.

Shivali Appaiah Konganda	Associate Professor Mridula Sharma
Dept of Linguistics	Dept of Linguistics
Macquarie University	Macquarie University

Participant's Consent Form

I, ________________________(your first and last name) have read and understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

Participant's Signature: ______________________________Date:
Investigator's name (please print) Shivali Appaiah________________________

Investigator's signature____

Date_________________

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics (telephone [02] 9850 7854, fax [02] 9850 8799, email: ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

(INVESTIGATOR'S [OR PARTICIPANT'S] COPY)

Appendix III: N400 sentences

ID	Var1	Var2	Var3	Var4	Var5	Var6
XXXa	Congruent sentence.					
XXXb	Incongruent sentence. This sentence has the same ending as the congruent.					
XXXc	Congruent sentence used to record the incongruent sentence. It has the same start.					
1a	The	driver	puts	the	petrol	in the car
1b	The	mother	breaks	the	petrol	on the shelf
1c	The	mother	breaks	the	glasses	on the shelf
f1a	Where does the driver put the petrol? [In the car]					
f1b	Where does the mother break the petrol? [On the shelf]					
2a	The	artist	paints	the	body	carefully
2b	The	students	fail	the	body	on the test
2c	The	students	fail	the	questions	on the test
f2a	Who paints the body carefully? [The artist]					
f2b	What do the students fail on the test? [The body]					
3a	The	soldier	knew	the	conflict	would be tough
3b	The	nanny	fried	the	conflict	on the stove
3c	The	nanny	fried	the	bacon	on the stove
f3a	Who knew the conflict would be tough? [The soldier]					
f3b	What did the nanny fry on the stove? [The conflict]					
4a	The	pilots	judge	the	distance	from the map
4b	The	couple	helped	the	distance	cross the road
4c	The	couple	helped	the	children	cross the road
f4a	Who judged the distance from the map? [The pilots]					
f4b	Who helped the distance cross the road? [The couple]					
5a	The	teacher	taught	the	students	all she knew
5b	The	father	plants	the	students	in July
5c	The	father	plants	the	cabbage	in July
f5a	What did the teacher teach the students? [All she knew]					
f5b	What does the father plant in July? [The students]					
6a	The	doctors	stopped	the	treatment	for three weeks
6b	The	cousin	wakes	the	treatment	on Sunday
6c	The	cousin	wakes	the	children	on Sunday
f6a	For how long did the doctors stop the treatment? [For three weeks]					
f6b	Who wakes the treatment on Sunday? [The cousin]					
7a	The	brothers	broke	the	trophy	on the shelf
7b	The	sister	phoned	the	trophy	yesterday
7c	The	sister	phoned	the	council	yesterday
f7a	What did the brothers break on the shelf? [The trophy]					
f7b	When did the sister phone the trophy? [Yesterday]					

8a	The	sister	ate	the	sandwich	from the fridge
8b	The	actor	wakes	the	sandwich	in her bed
8c	The	actor	wakes	the	sister	in her bed
f8a	Who ate the sandwich from the fridge? [The sister]					
f8b	Where does the actor wake the sandwich? [In her bed]					
9a	The	captain	made	the	changes	yesterday
9b	The	neighbour	swam	the	changes	very fast
9c	The	neighbour	swam	the	distance	very fast
f9a	Did the captain make the changes yesterday? [Yes]					
f9b	Who swam the changes very fast? [The neighbour]					
10a	The	barman	stirred	the	cocktails	all night long
10b	The	builder	climbs	the	cocktails	with his tools
10c	The	builder	climbs	the	staircase	with his tools
f10a	What did the barman stir all night long? [The cocktails]					
f10b	With what does the builder climb the cocktails? [With his tools]					
11a	The	caller	phoned	the	council	yesterday
11b	The	boyfriend	spreads	the	council	carefully
11c	The	boyfriend	spreads	the	butter	carefully
f11a	When did the caller phone the council? [Yesterday]					
f11b	How does the boyfriend spread the council? [Carefully]					
12a	The	runner	wins	the	trophy	for the race
12b	The	fighter	warned	the	trophy	on Monday
12c	The	fighter	warned	the	princess	on Monday
f12a	What does the runner win for the race? [The trophy]					
f12b	When did the fighter warn the trophy? [On Monday]					
13a	The	golfer	reads	the	paper	at breakfast
13b	The	woman	drank	the	paper	at the bar
13c	The	woman	drank	the	cocktail	at the bar
f13a	Who reads the paper at breakfast? [The golfer]					
f13b	Who drank the paper at the bar? [The woman]					
14a	The	mother	cooks	the	salmon	for dinner
14b	The	brother	asks	the	salmon	all the time
14c	The	brother	asks	the	question	all the time
f14a	Who cooks the salmon for dinner? [The mother]					
f14b	When does the brother ask the salmon? [All the time]					
15a	The	father	killed	the	spider	on the wall
15b	The	Frenchman	cleaned	the	spider	that morning
15c	The	Frenchman	cleaned	the	bedroom	that morning
f15a	Did the mother kill the spider on the wall? [No]					
f15b	Who cleaned the spider that morning? [The Frenchman]					

16a	The	husband	bought	the	glasses	for his wife
16b	The	soldiers	learnt	the	glasses	in winter
16c	The	soldiers	learnt	the	tactics	in winter
f16a	What did the husband buy for his wife? [The glasses]					
f16b	When did the soldiers learn the glasses? [In winter]					
17a	The	daughter	asked	the	question	of her dad
17b	The	nanny	cleans	the	question	every day
17c	The	nanny	cleans	the	bathroom	every day
f17a	Who asked the question of her dad? [The daughter]					
f17b	Who cleans the question every day? [The nanny]					
18a	The	athlete	swam	the	distance	easily
18b	The	hunter	hunts	the	distance	cautiously
18c	The	hunter	hunts	the	tiger	cautiously
f18a	Did the athlete swim the distance easily? [Yes]					
f18b	Who hunts the distance cautiously? [The hunter]					
19a	The	guidedog	led	the	person	through the street
19b	The	mother	poured	the	person	of water
19c	The	mother	poured	the	glasses	of water
f19a	Where did the guidedog lead the person? [Through the street]					
f19b	Who poured the person of water? [The mother]					
20a	The	children	saw	the	tiger	in the zoo
20b	The	uncle	spills	the	tiger	from the mug
20c	The	uncle	spills	the	coffee	from the mug
f20a	What did the children see in the zoo? [The tiger]					
f20b	Who spills the tiger from the mug? [The uncle]					
21a	The	children	fear	the	darkness	in the room
21b	The	sailor	caught	the	darkness	on Tuesday
21c	The	sailor	caught	the	tuna	on Tuesday
f21a	What do the children fear in the room? [The darkness]					
f21b	When did the sailor catch the darkness? [On Tuesday]					
22a	The	fighter	wins	the	battle	on his own
22b	The	neighbour	grilled	the	battle	this morning
22c	The	neighbour	grilled	the	tuna	this morning
f22a	What did the fighter win on his own? [The battle]					
f22b	When did the neighbour grill the battle? [This morning]					
23a	The	actor	sews	the	costume	for the play
23b	The	lion	chased	the	costume	on the grass
23c	The	lion	chased	the	tiger	on the grass

f23a What does the actor sew for the play? [The costume]
f23b Who chased the costume on the grass? [The lion]

24a	The	parrot	eats	the	cherry	in the tree
24b	The	neighbour	fought	the	cherry	in his house
24c	The	neighbour	fought	the	burglar	in his house

f24a Where does the parrot eat the cherry? [In the tree]
f24b Who fought the cherry in his house? [The neighbour]

25a	The	neighbour	found	the	glasses	on the desk
25b	The	hiker	climbed	the	glasses	very fast
25c	The	hiker	climbed	the	tower	very fast

f25a Where did the neighbour find the glasses? [On the desk]
f25b Did the hiker climb the glasses slowly? [No]

26a	The	butcher	cuts	the	bacon	on the bench
26b	The	patient	phoned	the	bacon	this morning
26c	The	patient	phoned	the	doctor	this morning

f26a What does the butcher cut on the bench? [The bacon]
f26b Who phoned the bacon this morning? [The patient]

27a	The	waitress	brought	the	glasses	of water
27b	The	tourguide	guides	the	glasses	in Sydney
27c	The	tourguide	guides	the	tourists	in Sydney

f27a What did the waitress bring? [The glasses of water]
f27b Does the tourguide guide the glasses in Paris? [No]

28a	The	nanny	washed	the	dishes	in the sink
28b	The	father	trimmed	the	dishes	of the tree
28c	The	father	trimmed	the	branches	of the tree

f28a Where did the nanny wash the dishes? [In the sink]
f28b What did the father trim? [The dishes (of the tree)]

29a	The	postman	placed	the	package	in his bag
29b	The	lawyer	told	the	package	what to do
29c	The	lawyer	told	the	client	what to do

f29a Where did the postman place the package? [In his bag]
f29b What did the lawyer tell the package? [What to do]

30a	The	worker	packed	the	boxes	full of fruit
30b	The	DJ	plays	the	boxes	constantly
30c	The	DJ	plays	the	playlist	constantly

f30a Who packed the boxes full of fruit? [The worker]
f30b Does the DJ play the boxes constantly? [Yes]

31a	The	puppy	chased	the	cricket	on the grass
31b	The	waitress	filled	the	cricket	with water

31c	The	waitress	filled	the	glasses	with water
f31a	who chased the cricket on the grass? [The puppy]					
f31b	What did the waitress fill with water? [The cricket]					
32a	The	college	wins	the	title	every year
32b	The	cheetah	feeds	the	title	once a day
32c	The	cheetah	feeds	the	puppy	once a day
f32a	Does the college lose the title every year? [No]					
f32b	What does the cheetah feed once a day? [The title]					
33a	The	banker	checked	the	figures	carefully
33b	The	student	failed	the	figures	every time
33c	The	student	failed	the	questions	every time
f33a	Who checked the figures carefully? [The banker]					
f33b	Who failed the figures every time? [The student]					
34a	The	father	trimmed	the	branches	of the tree
34b	The	classmate	reads	the	branches	to the class
34c	The	classmate	reads	the	paper	to the class
f34a	What did the father trim? [The branches (of the tree)]					
f34b	What does the classmate read to the class? [The branches]					
35a	The	shepherd	saw	the	tower	in the mist
35b	The	gambler	dealt	the	tower	all the cards
35c	The	gambler	dealt	the	players	all the cards
f35a	What did the shepherd see in the mist? [The tower]					
f35b	What did the gambler deal the tower? [All the cards]					
36a	The	waitress	sets	the	banquet	in the hall
36b	The	farmer	plants	the	banquet	with his hands
36c	The	farmer	plants	the	palmtree	with his hands
f36a	Where does the waitress set the banquet? [In the hall]					
f36b	Who plants the banquet with his hands? [The farmer]					
37a	The	farmer	grew	the	ginger	in the yard
37b	The	father	sewed	the	ginger	on his shirt
37c	The	father	sewed	the	button	on his shirt
f37a	Who grew the ginger in the yard? [The farmer]					
f37b	What did the father sew on his shirt? [The ginger]					
38a	The	husband	bought	the	painting	for his wife
38b	The	dentist	called	the	painting	this morning
38c	The	dentist	called	the	client	this morning
f38a	What did the husband buy for his wife? [The painting]					
f38b	Who did the dentist call this morning? [The painting]					
39a	The	uncle	made	the	basket	last weekend

39b	The	singer	sang	the	basket	with her friends
39c	The	singer	sang	the	polka	with her friends
f39a	What did the uncle make last weekend? [The basket]					
f39b	What did the singer sing with her friends? [The basket]					
40a	The	beagle	sniffed	the	boxes	on the floor
40b	The	cheetah	feeds	the	boxes	in the woods
40c	The	cheetah	feeds	the	puppies	in the woods
f40a	Who sniffed the boxes on the floor? [The beagle]					
f40b	What does the cheetah feed in the woods? [The boxes]					
41a	The	client	paid	the	butcher	for the meat
41b	The	children	pick	the	butcher	in July
41c	The	children	pick	the	cherries	in July
f41a	Who did the client pay for the meat? [The butcher]					
f41b	When do the children pick the butcher? [In July]					
42a	The	wizard	found	the	chamber	down the stairs
42b	The	schoolboy	hung	the	chamber	on the wall
42c	The	schoolboy	hung	the	painting	on the wall
f42a	Where did the wizard find the chamber? [Down the stairs]					
f42b	Where did the schoolboy hang the chamber? [On the wall]					
43a	The	princess	bought	the	castle	this morning
43b	The	people	caught	the	castle	on Tuesday
43c	The	people	caught	the	tuna	on Tuesday
f43a	Who bought the castle this morning? [The princess]					
f43b	When did the people catch the castle? [On Tuesday]					
44a	The	salesman	showed	the	photos	of the house
44b	The	hunter	killed	the	photos	last Monday
44c	The	hunter	killed	the	tiger	last Monday
f44a	What did the salesman show? [The photos (of the house)]					
f44b	What did the hunter kill last Monday? [The photos]					
45a	The	artist	drew	the	background	in colour
45b	The	client	eats	the	background	every day
45c	The	client	eats	the	pudding	every day
f45a	Who drew the background in colour? [The artist]					
f45b	Who eats the background every day? [The client]					
46a	The	DJ	hosts	the	party	at the club
46b	The	servant	knocked	the	party	on the desk
46c	The	servant	knocked	the	glasses	on the desk
f46a	Where does the DJ host the party? [At the club]					
f46b	What did the servant knock on the desk? [The party]					

47a	The	grocer	filled	the	barrel	with peaches
47b	The	puppy	wakes	the	barrel	every night
47c	The	puppy	wakes	the	children	every night
f47a	With what did the grocer fill the barrel? [With peaches]					
f47b	Who wakes the barrel every night? [The puppy]					
48a	The	people	brought	the	flowers	to the house
48b	The	tourist	asked	the	flowers	all the time
48c	The	tourist	asked	the	questions	all the time
f48a	Where did the people bring the flowers? [To the house]					
f48b	Who asked the flowers all the time? [The tourist]					
49a	The	gambler	found	the	ticket	on the ground
49b	The	hotel	phoned	the	ticket	yesterday
49c	The	hotel	phoned	the	postman	yesterday
f49a	Who found the ticket on the ground? [The gambler]					
f49b	Who did the hotel phone yesterday? [The ticket]					
50a	The	gambler	lost	the	ticket	at the track
50b	The	dentist	told	the	ticket	to come back
50c	The	dentist	told	the	client	to come back
f50a	Where did the gambler lose the ticket? [At the track]					
f50b	What did the dentist tell the ticket? [To come back]					
51a	The	drummer	banged	the	platform	like a drum
51b	The	agent	risked	the	platform	once again
51c	The	agent	risked	the	business	once again
f51a	Who banged the platform like a drum? [The drummer]					
f51b	Who risked the platform once again? [The agent]					
52a	The	pilot	felt	the	pressure	drop down fast
52b	The	uncle	baked	the	pressure	carefully
52c	The	uncle	baked	the	biscuits	carefully
f52a	Did the pilot feel the pressure drop down fast? [Yes]					
f52b	Who baked the pressure carefully? [The uncle]					
53a	The	waiter	served	the	dinner	to the staff
53b	The	nanny	sewed	the	dinner	on the shirt
53c	The	nanny	sewed	the	button	on the shirt
f53a	To whom did the waiter serve the dinner? [To the staff]					
f53b	Where did the nanny sew the dinner? [On the shirt]					
54a	The	agent	booked	the	singer	for the show
54b	The	peasant	filled	the	singer	with water
54c	The	peasant	filled	the	bottle	with water
f54a	Who did the agent book for the show? [The singer]					
f54b	What did the peasant fill with water? [The singer]					

55a	The	woman	bought	the	biscuits	yesterday
55b	The	master	taught	the	biscuits	yesterday
55c	The	master	taught	the	people	yesterday
f55a	What did the woman buy yesterday? [The biscuits]					
f55b	What did the master teach yesterday? [The biscuits]					
56a	The	sister	helped	the	children	cross the road
56b	The	dentist	wore	the	children	after work
56c	The	dentist	wore	the	jacket	after work
f56a	Who helped the children cross the road? [The sister]					
f56b	When did the dentist wear the children? [After work]					
57a	The	neighbour	fried	the	bacon	on the stove
57b	The	plumber	fixed	the	bacon	this morning
57c	The	plumber	fixed	the	drainage	this morning
f57a	Where did the neighbour fry the bacon? [On the stove]					
f57b	Who fixed the bacon this morning? [The plumber]					
58a	The	builder	found	the	buyers	hard to please
58b	The	nephew	eats	the	buyers	every day
58c	The	nephew	eats	the	doughnut	every day
f58a	Who found the buyers hard to please? [The builder]					
f58b	What does the nephew eat every day? [The buyers]					
59a	The	trainer	told	the	people	what to do
59b	The	husband	bakes	the	people	every day
59c	The	husband	bakes	the	doughnut	every day
f59a	Who told the trainer what to do? [The people]					
f59b	When does the husband bake the people? [Every day]					
60a	The	doctor	helped	the	patient	up the stairs
60b	The	swimmer	swam	the	patient	easily
60c	The	swimmer	swam	the	distance	easily
f60a	Who did the doctor help up the stairs? [The patient]					
f60b	Who swam the patient easily? [The swimmer]					
61a	The	dragon	won	the	contest	with the knight
61b	The	daughter	pats	the	contest	with her friend
61c	The	daughter	pats	the	puppy	with her friend
f61a	Who won the contest with the knight? [The dragon]					
f61b	What does the daughter pat with her friend? [The contest]					
62a	The	baker	rolled	the	pastry	for the pie
62b	The	poacher	kills	the	pastry	in the field
62c	The	poacher	kills	the	tiger	in the field
f62a	Who rolled the pastry for the pie? [The baker]					

f62b Who kills the pastry in the field? [The poacher]

63a	The	lady	found	the	bargain	at the shop
63b	The	sailor	docks	the	bargain	at the wharf
63c	The	sailor	docks	the	cruiser	at the wharf

f63a Where did the lady find the bargain? [At the shop]
f63b Where does the sailor dock the bargain? [At the wharf]

64a	The	teacher	showed	the	pattern	to the class
64b	The	woman	spiced	the	pattern	with pepper
64c	The	woman	spiced	the	carrots	with pepper

f64a Who showed the pattern to the class? [The teacher]
f64b Did the woman spice the pattern with oil? [No]

65a	The	pirate	shot	the	cannon	from the ship
65b	The	students	doubt	the	cannon	in the test
65c	The	students	doubt	the	questions	in the test

f65a Who shot the cannon from the ship? [The pirate]
f65b Who doubts the cannon in the test? [The students]

66a	The	father	did	the	banking	on Tuesday
66b	The	donkey	licks	the	banking	on the ground
66c	The	donkey	licks	the	bacon	on the ground

f66a When did the father do the banking? [On Tuesday]
f66b Who licks the banking on the ground? [The donkey]

67a	The	children	filled	the	barrel	with some sweets
67b	The	learner	fails	the	barrel	on the test
67c	The	learner	fails	the	questions	on the test

f67a Who filled the barrel with some sweets? [The children]
f67b Who fails the barrel on the test? [The learner]

68a	The	lady	found	the	surname	hard to say
68b	The	children	blew	the	surname	on the cake
68c	The	children	blew	the	candles	on the cake

f68a Who found the surname hard to say? [The lady]
f68b What did the children blow on the cake? [The surname]

69a	The	cheetah	stopped	the	tiger	in its tracks
69b	The	couple	solved	the	tiger	in one day
69c	The	couple	solved	the	puzzle	in one day

f69a Did the cheetah stop the tiger in its tracks? [Yes]
f69b What did the couple solve in one day? [The tiger]

70a	The	lizard	found	the	sunshine	nice and hot
70b	The	daughter	cleans	the	sunshine	on Sundays
70c	The	daughter	cleans	the	bedroom	on Sundays

f70a	What did the lizard find nice and hot? [The sunshine]					
f70b	Who cleans the sunshine on Sundays? [The daughter]					
71a	The	seamstress	sewed	the	button	on the shirt
71b	The	farmer	milks	the	button	on the farm
71c	The	farmer	milks	the	cattle	on the farm
f71a	What did the seamstress sew on the shirt? [The button]					
f71b	Where does the farmer milk the button? [On the farm]					
72a	The	possum	climbs	the	fences	every night
72b	The	couple	told	the	fences	to be fair
72c	The	couple	told	the	colleagues	to be fair
f72a	Who climbs the fences every night? [The possum]					
f72b	who told the colleagues to be fair? [The couple]					
73a	The	lawyer	kept	the	papers	on his desk
73b	The	artist	met	the	papers	last Monday
73c	The	artist	met	the	client	last Monday
f73a	What did the lawyer keep on his desk? [The papers]					
f73b	Who did the artist meet last Monday? [The papers]					
74a	The	magpie	stole	the	pennies	from the desk
74b	The	cyclist	rode	the	pennies	very fast
74c	The	cyclist	rode	the	corner	very fast
f74a	Who stole the pennies from the desk? [The magpie]					
f74b	What did the cyclist ride very fast? [The pennies]					
75a	The	toddler	ate	the	custard	in the pram
75b	The	cowboy	asked	the	custard	in the bar
75c	The	cowboy	asked	the	question	in the bar
f75a	What did the toddler eat in the pram? [The custard]					
f75b	Where did the cowboy ask the custard? [In the bar]					
76a	The	jockey	rode	the	corner	way too fast
76b	The	daughter	stirred	the	corner	with one hand
76c	The	daughter	stirred	the	carrots	with one hand
f76a	What did the jockey ride way too fast? [The corner]					
f76b	What did the daughter stir with one hand? [The corner]					
77a	The	banker	hid	the	papers	from his boss
77b	The	housemate	phoned	the	papers	last Monday
77c	The	housemate	phoned	the	daughter	last Monday
f77a	Who hid the papers from his boss? [The banker]					
f77b	Who phoned the papers last Monday? [The housemate]					
78a	The	robber	stole	the	dollars	from the bank
78b	The	captain	docked	the	dollars	yesterday

78c	The	captain	docked	the	cruiser	yesterday
f78a	What did the robber steal from the bank? [The dollars]					
f78b	When did the captain dock the dollars? [Yesterday]					
79a	The	lion	tears	the	chicken	into bits
79b	The	girlfriend	sang	the	chicken	cheerfully
79c	The	girlfriend	sang	the	poem	cheerfully
f79a	Who tears the chicken into bits? [The lion]					
f79b	Who sang the chicken cheerfully? [The girlfriend]					
80a	The	tiger	stalked	the	village	every night
80b	The	lady	pats	the	village	all day long
80c	The	lady	pats	the	puppy	all day long
f80a	Who stalked the village every night? [The tiger]					
f80b	When does the lady pat the village? [All day long]					
81a	The	cheetah	chased	the	chicken	round the yard
81b	The	artist	billed	the	chicken	by email
81c	The	artist	billed	the	client	by email
f81a	What did the cheetah chase round the yard? [The chicken]					
f81b	Who billed the chicken by email? [The artist]					
82a	The	writer	reads	the	story	to the class
82b	The	barman	drinks	the	story	after work
82c	The	barman	drinks	the	cocktail	after work
f82a	Who reads the story to the class? [The writer]					
f82b	What does the barman drink after work? [The story]					
83a	The	author	signed	the	paper	for her fans
83b	The	colleague	met	the	paper	of his friend
83c	The	colleague	met	the	parents	of his friend
f83a	What did the author sign for her fans? [The paper]					
f83b	Who met the paper of his friend? [The colleague]					
84a	The	bridegroom	kissed	the	parents	of the bride
84b	The	DJ	filled	the	parents	with CDs
84c	The	DJ	filled	the	boxes	with CDs
f84a	Who kissed the parents of the bride? [The bridegroom]					
f84b	Who filled the parents with CDs? [The DJ]					
85a	The	boyfriend	gave	the	flowers	to his girl
85b	The	player	beats	the	flowers	in poker
85c	The	player	beats	the	dealer	in poker
f85a	What did the boyfriend give to his girl? [The flowers]					
f85b	Who beats the flowers in poker? [The player]					
86a	The	girlfriend	drank	the	cocktail	in the bar

86b	The	lawyer	told	the	cocktail	to his friend
86c	The	lawyer	told	the	background	to his friend

f86a What did the girlfriend drink in the bar? [The cocktail]
f86b To whom did the lawyer tell the cocktail? [To his friend]

87a	The	people	bought	the	clothing	from the shop
87b	The	barman	shuts	the	clothing	at seven
87c	The	barman	shuts	the	business	at seven

f87a What did the people buy from the shop? [The clothing]
f87b At what time does the barman shut the clothing? [At seven]

89a	The	couple	thought	the	future	would be bright
89b	The	father	cleans	the	future	frequently
89c	The	father	cleans	the	kitchen	frequently

f89a Who thought the future would be bright? [The couple]
f89b Does the father clean the future frequently? [Yes]

90a	The	children	loved	the	flavour	of the sweets
90b	The	soldier	faced	the	flavour	with courage
90c	The	soldier	faced	the	battle	with courage

f90a What did the children love? [The flavour (of the sweets)]
f90b How did the soldier face the flavour? [With courage]

91a	The	person	found	the	city	on the map
91b	The	lifeguard	swam	the	city	in August
91c	The	lifeguard	swam	the	Tasman	in August

f91a Who found the city on the map? [The person]
f91b What did the lifeguard swim in August? [The Tasman]

92a	The	horses	lick	the	sugar	from her hand
92b	The	parents	trimmed	the	sugar	of the tree
92c	The	parents	trimmed	the	branches	of the tree

f92a What do the horses lick from her hand? [The sugar]
f92b Who trimmed the sugar of the tree? [The parents]

93a	The	woman	made	the	coffee	for her friend
93b	The	expert	told	the	coffee	of the risks
93c	The	expert	told	the	council	of the risks

f93a For whom did the woman make the coffee? [For her friend]
f93b What did the expert tell the coffee? [The risks]

94a	The	women	met	the	challenge	on their own
94b	The	aunty	cooked	the	challenge	at the feast
94c	The	aunty	cooked	the	turkey	at the feast

f94a Who met the challenge on their own? [The women]
f94b Who cooked the challenge at the feast? [The aunty]

95a	The	parents	watched	the	program	on TV
95b	The	helpers	taste	the	program	for the chef
95c	The	helpers	taste	the	cooking	for the chef

f95a Who watched the program on TV? [The parents]
f95b What do the helpers taste for the chef? [The program]

96a	The	owner	hung	the	painting	on the wall
96b	The	actress	drank	the	painting	at seven
96c	The	actress	drank	the	cocktail	at seven

f96a Where did the owner hang the painting? [On the wall]
f96b Who drank the painting at seven? [The actress]

97a	The	children	ate	the	breakfast	on the porch
97b	The	gambler	turned	the	breakfast	very fast
97c	The	gambler	turned	the	corner	very fast

f97a Where did the children eat the breakfast? [On the porch]
f97b What did the gambler turn very fast? [The breakfast]

98a	The	artist	kept	the	flowers	in the vase
98b	The	driver	guides	the	flowers	in Sydney
98c	The	driver	guides	the	tourists	in Sydney

f98a Where did the artist keep the flowers? [In the vase]
f98b What does the driver guide in Sydney? [The flowers]

99a	The	partner	saw	the	paper	on the desk
99b	The	agent	trained	the	paper	last Monday
99c	The	agent	trained	the	banker	last Monday

f99a Who saw the paper on the desk? [The partner]
f99b Who trained the paper last Monday? [The agent]

100a	The	student	found	the	subject	way too hard
100b	The	sailor	sank	the	subject	in the sea
100c	The	sailor	sank	the	boxes	in the sea

f100a What did the student find way too hard? [The subject]
f100b Where did the sailor sink the subject? [In the sea]

101a	The	husband	cleans	the	kitchen	every day
101b	The	tourist	sent	the	kitchen	in July
101c	The	tourist	sent	the	postcard	in July

f101a What does the husband clean every day? [The kitchen]
f101b Who sent the kitchen in July? [The tourist]

102a	The	members	choose	the	chairman	every year
102b	The	sailor	sank	the	chairman	in April
102c	The	sailor	sank	the	cruiser	in April

f102a Who chose the chairman every year? [The members]
f102b When did the sailor sink the chairman? [In April]

103a	The	artist	drew	the	background	first of all
103b	The	cyclist	rides	the	background	on Sundays
103c	The	cyclist	rides	the	tandem	on Sundays
f103a	What did the artist draw first of all? [The background]					
f103b	Who rides the background on Sundays? [The cyclist]					
104a	The	cowboy	knew	the	country	very well
104b	The	sheriff	jailed	the	country	last Monday
104c	The	sheriff	jailed	the	killer	last Monday
f104a	Who knew the country very well? [The cowboy]					
f104b	Who jailed the country last Monday? [The sheriff]					
105a	The	viewers	watched	the	program	on Sunday
105b	The	mother	drained	the	program	at seven
105c	The	mother	drained	the	bathtub	at seven
f105a	Who watched the program on Sunday? [The viewers]					
f105b	Who drained the program at seven? [The mother]					
106a	The	tourist	made	the	transfer	just in time
106b	The	witness	told	the	transfer	to his friend
106c	The	witness	told	the	background	to his friend
f106a	Who made the transfer just in time? [The tourist]					
f106b	What did the witness tell to his friend? [The transfer]					
107a	The	farmer	grew	the	cotton	in his fields
107b	The	soldier	joined	the	cotton	in August
107c	The	soldier	joined	the	peacecorps	in August
f107a	Where did the farmer grow the cotton? [In his fields]					
f107b	Who joined the cotton in August? [The soldier]					
108a	The	owner	set	the	prices	very high
108b	The	servant	helps	the	prices	to get dressed
108c	The	servant	helps	the	princess	to get dressed
f108a	What did the owner set very high? [The prices]					
f108b	Who helped the prices to get dressed? [The servant]					
109a	The	miner	found	the	copper	in the ground
109b	The	actor	ate	the	copper	for breakfast
109c	The	actor	ate	the	porridge	for breakfast
f109a	Where did the miner find the copper? [In the ground]					
f109b	Who ate the copper for breakfast? [The actor]					
110a	The	children	heard	the	singer	at the show
110b	The	sister	skips	the	singer	once a week
110c	The	sister	skips	the	diet	once a week
f110a	Where did the children hear the singer? [At the show]					

f110b How often does the sister skip the singer? [Once a week]

111a	The	soldier	guards	the	platform	every night
111b	The	sisters	nurse	the	platform	every day
111c	The	sisters	nurse	the	baby	every day

f111a What does the soldier guard every night? [The platform]
f111b Who nurses the platform every day? [The sisters]

112a	The	children	took	the	pictures	to the school
112b	The	Frenchman	cooks	the	pictures	for dinner
112c	The	Frenchman	cooks	the	chicken	for dinner

f112a Where did the children take the pictures? [To the school]
f112b What does the Frenchman cook for dinner? [The pictures]

113a	The	children	got	the	presents	at Christmas
113b	The	farmer	grew	the	presents	in the ground
113c	The	farmer	grew	the	cabbage	in the ground

f113a What did the children get at Christmas? [The presents]
f113b Who grew the presents in the ground? [The farmer]

114a	The	seller	knew	the	buyer	in advance
114b	The	athlete	swam	the	buyer	easily
114c	The	athlete	swam	the	distance	easily

f114a Who did the seller know in advance? [The buyer]
f114b What did the athlete swim easily? [The buyer]

115a	The	mother	found	the	curry	much too hot
115b	The	actress	danced	the	curry	in the show
115c	The	actress	danced	the	polka	in the show

f115a How did the mother find the curry? [Much too hot]
f115b What did the actress dance in the show? [The curry]

116a	The	dealer	dealt	the	players	all the cards
116b	The	baker	toasts	the	players	on the stove
116c	The	baker	toasts	the	biscuits	on the stove

f116a What did the dealer deal the players? [All the cards]
f116b What does the baker toast on the stove? [The players]

117a	The	mother	took	the	children	to the show
117b	The	teacher	read	the	children	in the park
117c	The	teacher	read	the	paper	in the park

f117a Who took the children to the show? [The mother]
f117b Who read the children in the park? [The teacher]

118a	The	teacher	writes	the	paper	every day
118b	The	walker	climbed	the	paper	of the mount
118c	The	walker	climbed	the	summit	of the mount

f118a When does the teacher write the paper? [Every day]
f118b Who climbed the paper of the mount? [The walker]

119a	The	brother	cleans	the	bathroom	every day
119b	The	sister	rides	the	bathroom	all day long
119c	The	sister	rides	the	pony	all day long

f119a When does the brother clean the bathroom? [Every day]
f119b When does the sister ride the bathroom? [All day long]

120a	The	children	ate	the	pizza	last Sunday
120b	The	daughter	rode	the	pizza	to get home
120c	The	daughter	rode	the	tandem	to get home

f120a What did the children eat last Sunday? [The pizza]
f120b What did the daughter ride to get home? [The pizza]

121a	The	lizard	bites	the	fingers	forcefully
121b	The	neighbour	paid	the	fingers	on Sunday
121c	The	neighbour	paid	the	baker	on Sunday

f121a Who bites the fingers forcefully? [The lizard]
f121b Who paid the fingers on Sunday? [The neighbour]

122a	The	writer	wore	the	glasses	on the bus
122b	The	authors	read	the	glasses	on Sunday
122c	The	authors	read	the	paper	on Sunday

f122a Where did the writer wear the glasses? [On the bus]
f122b When do the authors read the glasses? [On Sunday]

123a	The	waiter	chills	the	cocktail	with ice cubes
123b	The	neighbour	trimmed	the	cocktail	of the tree
123c	The	neighbour	trimmed	the	branches	of the tree

f123a Who chills the cocktails with ice cubes? [The waiter]
f123b Who trimmed the cocktail of the tree? [The neighbour]

124a	The	singer	signs	the	picture	for the child
124b	The	hunter	hunts	the	picture	in winter
124c	The	hunter	hunts	the	panther	in winter

f124a Who signs the picture for the child? [The singer]
f124b Who hunts the picture in winter? [The hunter]

125a	The	brother	pushed	the	cycle	near the bush
125b	The	carer	feeds	the	cycle	on the floor
125c	The	carer	feeds	the	puppy	on the floor

f125a Who pushed the cycle near the bush? [The brother]
f125b Who feeds the cycle on the floor? [The carer]

126a	The	hiker	takes	the	picture	in the park
126b	The	magpie	hears	the	picture	in the park

126c The magpie hears the puppy in the park
f126a What does the hiker take in the park? [The picture]
f126b Who hears the picture in the park? [The magpie]

127a The uncle met the children last Monday
127b The parents weed the children in summer
127c The parents weed the garden in summer
f127a Who did the uncle meet last Monday? [The children]
f127b What do the parents weed in summer? [The children]

128a The farmer milks the cattle every day
128b The workers paint the cattle in two years
128c The workers paint the castle in two years
f128a Who milks the cattle every day? [The farmer]
f128b What do the workers paint in two years? [The cattle]

129a The plumber billed the father on Friday
129b The artist wears the father at the show
129c The artist wears the jacket at the show
f129a When did the plumber bill the father? [On Friday]
f129b What does the artist wear at the show? [The father]

130a The waiter ate the biscuits on Sunday
130b The trainer taught the biscuits how to play
130c The trainer taught the players how to play
f130a Who ate the biscuits on Sunday? [The waiter]
f130b Who taught the biscuits how to play? [The trainer]

131a The speaker faced the tourists this morning
131b The student learned the tourists this morning
131c The student learned the tactics this morning
f131a When did the speaker face the tourists? [This morning]
f131b What did the student learn this morning? [The tourists]

132a The teacher reads the questions in the class
132b The player lifts the questions cheerfully
132c The player lifts the trophy cheerfully
f132a Where does the teacher read the questions? [In the class]
f132b What does the player lift cheerfully? [The questions]

133a The captain drives the ferry every day
133b The rabbit eats the ferry with pleasure
133c The rabbit eats the carrot with pleasure
f133a Who drives the ferry every day? [The captain]
f133b What does the rabbit eat with pleasure? [The ferry]

134a The farmer sold the carrots on Monday

134b	The	doctor	leads	the	carrots	on Monday
134c	The	doctor	leads	the	discourse	on Monday

f134a When did the farmer sell the carrots? [On Monday]

f134b When does the doctor lead the carrots? [On Monday]

135a	The	husband	sends	the	basket	to his wife
135b	The	children	blow	the	basket	on the cake
135c	The	children	blow	the	candles	on the cake

f135a What does the husband send to his wife? [The basket]

f135b Who blows the basket on the cake? [The children]

136a	The	brother	eats	the	pudding	every day
136b	The	nephew	built	the	pudding	by the lake
136c	The	nephew	built	the	cottage	by the lake

f136a What does the brother eat every day? [The pudding]

f136b Where did the nephew build the pudding? [By the lake]

137a	The	actress	pays	the	teacher	every time
137b	The	cleaner	closed	the	teacher	on Monday
137c	The	cleaner	closed	the	passage	on Monday

f137a Who pays the teacher every time? [The actress]

f137b Who closed the teacher on Monday? [The cleaner]

138a	The	patient	phoned	the	doctor	this morning
138b	The	worker	fixed	the	doctor	of the car
138c	The	worker	fixed	the	panels	of the car

f138a Who phoned the doctor this morning? [The patient]

f138b Who fixed the doctor of the car? [The worker]

139a	The	mother	called	the	teacher	this morning
139b	The	driver	parks	the	teacher	on the road
139c	The	driver	parks	the	taxi	on the road

f139a Who did the mother call this morning? [The teacher]

f139b Where does the driver park the teacher? [On the road]

140a	The	actress	books	the	table	for supper
140b	The	agent	called	the	table	this morning
140c	The	agent	called	the	builder	this morning

f140a Who books the table for supper? [The actress]

f140b When did the agent call the table? [This morning]

141a	The	parents	met	the	teacher	of their child
141b	The	farmer	drank	the	teacher	of water
141c	The	farmer	drank	the	bottle	of water

f141a Who did the parents meet? [The teacher (of their child)]

f141b who drank the teacher of water? [The farmer]

142a	The	pilot	does	the	training	for his job
142b	The	children	dyed	the	training	bright yellow
142c	The	children	dyed	the	T-shirt	bright yellow
f142a	Who does the training for his job? [The pilot]					
f142b	Did the children dye the training bright yellow? [Yes]					

143a	The	mother	bakes	the	pudding	for her son
143b	The	client	asks	the	pudding	a question
143c	The	client	asks	the	barman	a question
f143a	Who bakes the pudding for her son? [The mother]					
f143b	What does the client ask the pudding? [A question]					

144a	The	women	grilled	the	salmon	for dinner
144b	The	helper	asked	the	salmon	where to go
144c	The	helper	asked	the	tourists	where to go
f144a	Who grilled the salmon for dinner? [The women]					
f144b	What did the helper ask the salmon? [Where to go]					

145a	The	nephew	solved	the	problems	without help
145b	The	hiker	walked	the	problems	yesterday
145c	The	hiker	walked	the	pathway	yesterday
f145a	Did the nephew solve the problems with help? [No]					
f145b	When did the hiker walk the problems? [Yesterday]					

146a	The	student	asked	the	questions	in the class
146b	The	athlete	swims	the	questions	every day
146c	The	athlete	swims	the	distance	every day
f146a	Who asked the questions in the class? [The student]					
f146b	When does the athlete swim the questions? [Every day]					

147a	The	aunty	bought	the	cushion	last Sunday
147b	The	couple	ate	the	cushion	at lunch time
147c	The	couple	ate	the	pizza	at lunch time
f147a	When did the aunty buy the cushion? [Last Sunday]					
f147b	Who ate the cushion at lunch time? [The couple]					

148a	The	granny	ate	the	pastry	with some tea
148b	The	children	pat	the	pastry	in their house
148c	The	children	pat	the	puppy	in their house
f148a	What did the granny eat with some tea? [The pastry]					
f148b	Where did the children pat the pastry? [In their house]					

149a	The	author	wrote	the	story	in one day
149b	The	cowboy	touched	the	story	on the back
149c	The	cowboy	touched	the	pony	on the back
f149a	What did the author write in one day? [The story]					
f149b	Where did the cowboy touch the story? [On the back]					

150a	The	people	fill	the	boxes	with rubbish
150b	The	student	heard	the	boxes	in the class
150c	The	student	heard	the	teacher	in the class
f150a	What do the people fill with rubbish? [The boxes]					
f150b	Who heard the boxes in the class? [The student]					
151a	The	grandpa	buys	the	paper	every day
151b	The	nurses	calmed	the	paper	easily
151c	The	nurses	calmed	the	babies	easily
f151a	Who buys the paper every day? [The grandpa]					
f151b	What did the nurses calm easily? [The paper]					
152a	The	tutor	calls	the	student	from the school
152b	The	worker	sealed	the	student	on Monday
152c	The	worker	sealed	the	pipeline	on Monday
f152a	Who does the tutor call from the school? [The student]					
f152b	What did the worker seal on Monday? [The student]					
153a	The	children	hold	the	party	in the park
153b	The	farmer	strokes	the	party	on the back
153c	The	farmer	strokes	the	donkey	on the back
f153a	Where did the children hold the party? [In the park]					
f153b	Who strokes the party on the back? [The farmer]					
154a	The	daughter	knocks	the	picture	off the wall
154b	The	waiter	spilled	the	picture	on her head
154c	The	waiter	spilled	the	coffee	on her head
f154a	What does the daughter knock off the wall? [The picture]					
f154b	Where did the waiter spill the picture? [On her head]					
155a	The	barman	mocks	the	clients	on purpose
155b	The	workers	fix	the	clients	securely
155c	The	workers	fix	the	pipeline	securely
f155a	Who mocks the clients on purpose? [The barman]					
f155b	What do the workers fix securely? [The clients]					
156a	The	woman	cleans	the	bathroom	every week
156b	The	expert	files	the	bathroom	on the shelf
156c	The	expert	files	the	papers	on the shelf
f156a	Who cleans the bathroom every week? [The woman]					
f156b	What does the expert file on the shelf? [The bathroom]					
157a	The	toddler	wakes	the	father	every night
157b	The	cleaner	scrapes	the	father	at his work
157c	The	cleaner	scrapes	the	barrel	at his work
f157a	When does the toddler wake the father? [Every night]					

f157b What does the cleaner scrape at his work? [The father]

158a	The	butcher	carves	the	turkey	in the shop
158b	The	classmate	browsed	the	turkey	of the trip
158c	The	classmate	browsed	the	pictures	of the trip

f158a What does the butcher carve in the shop? [The turkey]
f158b What did the classmate browse? [The turkey (of the trip)]

159a	The	baby	licks	the	sugar	off the cake
159b	The	driver	crashed	the	sugar	last Monday
159c	The	driver	crashed	the	buggy	last Monday

f159a Who licks the sugar off the cake? [The baby]
f159b What did the driver crash last Monday? [The sugar]

160a	The	foxes	eat	the	chicken	at night time
160b	The	master	spent	the	chicken	at the market
160c	The	master	spent	the	dollars	at the market

f160a Who eat the chicken at night time? [The foxes]
f160b Who spent the chicken at the market? [The master]

161a	The	lizard	caught	the	spider	yesterday
161b	The	waiter	cleans	the	spider	thoroughly
161c	The	waiter	cleans	the	table	thoroughly

f161a When did the lizard catch the spider? [Yesterday]
f161b What does the waiter clean thoroughly? [The spider]

162a	The	mother	asks	the	question	all the time
162b	The	father	drains	the	question	in the sink
162c	The	father	drains	the	pasta	in the sink

f162a Who asks the question all the time? [The mother]
f162b What does the father drain in the sink? [The question]

163a	The	brother	reads	the	title	of the book
163b	The	person	froze	the	title	in a bag
163c	The	person	froze	the	chicken	in a bag

f163a Who reads the title of the book? [The brother]
f163b What did the person freeze in a bag? [The title]

164a	The	player	kicks	the	football	in the field
164b	The	trainer	feeds	the	football	some chicken
164c	The	trainer	feeds	the	tiger	some chicken

f164a Who kicks the football in the field? [The player]
f164b What does the trainer feed some chicken? [The football]

165a	The	donkey	likes	the	carrots	every day
165b	The	person	closed	the	carrots	of water
165c	The	person	closed	the	bottle	of water

f165a What does the donkey like every day? [The carrots]
f165b Who closed the carrots of water? [The person]

166a	The	mother	spiced	the	curry	yesterday
166b	The	daughter	rides	the	curry	with her friend
166c	The	daughter	rides	the	tandem	with her friend

f166a What did the mother spice yesterday? [The curry]
f166b Who rides the curry with her friend? [The daughter]

167a	The	couple	likes	the	circus	very much
167b	The	father	hangs	the	circus	on the wall
167c	The	father	hangs	the	picture	on the wall

f167a Does the couple like the circus? [Yes, very much]
f167b What does the father hang on the wall? [The circus]

168a	The	children	try	the	samples	at the shop
168b	The	grandchild	nursed	the	samples	back to health
168c	The	grandchild	nursed	the	kitten	back to health

f168a Where do the children try the samples? [At the shop]
f168b Who nursed the samples back to health? [The grandchild]

169a	The	mother	rocks	the	baby	off to sleep
169b	The	aunty	spreads	the	baby	on the toast
169c	The	aunty	spreads	the	butter	on the toast

f169a Who does the mother rock off to sleep? [The baby]
f169b What does the aunty spread on the toast? [The baby]

170a	The	daughter	kicked	the	football	in the park
170b	The	mother	woke	the	football	from his nap
170c	The	mother	woke	the	baby	from his nap

f170a Where did the daughter kick the football? [In the park]
f170b What did the mother wake from his nap? [The football]

171a	The	uncle	eats	the	dinner	happily
171b	The	tailor	sewed	the	dinner	on the shirt
171c	The	tailor	sewed	the	button	on the shirt

f171a How does the uncle eat the dinner? [Happily]
f171b What did the tailor sew on the shirt? [The dinner]

172a	The	puppy	chews	the	football	every day
172b	The	waiter	fills	the	football	with water
172c	The	waiter	fills	the	glasses	with water

f172a Who chews the football every day? [The puppy]
f172b What does the waiter fill with water? [The football]

173a	The	children	solved	the	problem	on their own
173b	The	kitten	scratched	the	problem	with its claws

173c	The	kitten	scratched	the	table	with its claws
f173a	Who solved the problem on their own? [The children]					
f173b	How did the kitten scratch the problem? [With its claws]					
174a	The	artist	paints	the	painting	in her room
174b	The	mother	calmed	the	painting	in his crib
174c	The	mother	calmed	the	baby	in his crib
f174a	Who paints the painting in her room? [The artist]					
f174b	Where did the mother calm the painting? [In his crib]					
175a	The	lawyer	plans	the	cases	thoroughly
175b	The	neighbour	combs	the	cases	every week
175c	The	neighbour	combs	the	doggy	every week
f175a	How does the lawyer plan the cases? [Thoroughly]					
f175b	What does the neighbour comb every week? [The cases]					
176a	The	student	missed	the	classes	last Monday
176b	The	waiter	cooks	the	classes	on the stove
176c	The	waiter	cooks	the	turkey	on the stove
f176a	Who missed the classes last Monday? [The student]					
f176b	Who cooks the classes on the stove? [The waiter]					
177a	The	woman	kills	the	spider	with the shoe
177b	The	sailor	sang	the	spider	on the ship
177c	The	sailor	sang	the	ballad	on the ship
f177a	What does the woman kill with the shoe? [The spider]					
f177b	Who sang the spider of the ship? [The sailor]					
178a	The	hunter	watched	the	tigers	in the swamp
178b	The	workers	blow	the	tigers	in the fire
178c	The	workers	blow	the	glasses	in the fire
f178a	What did the hunter watch in the swamp? [The tigers]					
f178b	Where do the workers blow the tigers? [In the fire]					
179a	The	youngster	likes	the	bubbles	in the bath
179b	The	captain	burned	the	bubbles	by mistake
179c	The	captain	burned	the	table	by mistake
f179a	Who likes the bubbles in the bath? [The youngster]					
f179b	Who burned the bubbles by mistake? [The captain]					
180a	The	teacher	tells	the	story	quietly
180b	The	bottle	leaks	the	story	everywhere
180c	The	bottle	leaks	the	tonic	everywhere
f180a	How does the teacher tell the story? [Quietly]					
f180b	Who leaks the story everywhere? [The bottle]					
181a	The	tanker	takes	the	petrol	to the town

181b	The	builder	cuts	the	petrol	in two parts
181c	The	builder	cuts	the	timber	in two parts

f181a What does the tanker take to the town? [The petrol]
f181b Who cuts the petrol in two parts? [The builder]

182a	The	brother	gives	the	pizza	to his friend
182b	The	hiker	climbed	the	pizza	to the top
182c	The	hiker	climbed	the	pathway	to the top

f182a To whom does the brother give the pizza? [To his friend]
f182b Who climbed the pizza to the top? [The hiker]

183a	The	toddler	rolled	the	football	down the hill
183b	The	daughter	eats	the	football	off the plate
183c	The	daughter	eats	the	chicken	off the plate

f183a Who rolled the football down the hill? [The toddler]
f183b Who eats the football off the plate? [The daughter]

184a	The	brother	makes	the	breakfast	every day
184b	The	father	asked	the	breakfast	for its name
184c	The	father	asked	the	parrot	for its name

f184a Who makes the breakfast every day? [The brother]
f184b Who did the father ask for its name? [The breakfast]

185a	The	painter	used	the	colour	everywhere
185b	The	husband	cuts	the	colour	for dinner
185c	The	husband	cuts	the	carrots	for dinner

f185a Who used the colour everywhere? [The painter]
f185b What does the husband cut for dinner? [The colour]

186a	The	tourist	takes	the	pictures	of the beach
186b	The	swimmers	stretch	the	pictures	on the sand
186c	The	swimmers	stretch	the	towels	on the sand

f186a Who takes the pictures of the beach? [The tourist]
f186b What do the swimmers stretch on the sand? [The pictures]

187a	The	children	change	the	picture	all the time
187b	The	toddler	fed	the	picture	in the zoo
187c	The	toddler	fed	the	dolphin	in the zoo

f187a Who changes the picture all the time? [The children]
f187b What did the toddler feed in the zoo? [The picture]

188a	The	city	has	the	palace	on the hill
188b	The	youngster	feeds	the	palace	at the farm
188c	The	youngster	feeds	the	cattle	at the farm

f188a Where is the palace? [On the hill]
f188b What does the youngster feed at the farm? [The palace]

189a	The	painter	makes	the	picture	colourful
189b	The	woman	drank	the	picture	too quickly
189c	The	woman	drank	the	cocktail	too quickly

f189a Who makes the picture colourful? [The painter]
f189b Who drank the picture too quickly? [The woman]

190a	The	woman	sews	the	button	on the dress
190b	The	lawyer	eats	the	button	for breakfast
190c	The	lawyer	eats	the	kiwi	for breakfast

f190a What does the woman sew on the dress? [The button]
f190b What does the lawyer eat for breakfast? [The button]

191a	The	worker	broke	the	pieces	of metal
191b	The	uncle	rides	the	pieces	with his friend
191c	The	uncle	rides	the	tandem	with his friend

f191a What did the worker break? [The pieces (of metal)]
f191b With whom does the uncle ride the pieces? [With his friend]

192a	The	children	like	the	picture	of the car
192b	The	artist	played	the	picture	at the show
192c	The	artist	played	the	trumpet	at the show

f192a What do the children like? [The picture (of the car)]
f192b Who played the picture at the show? [The artist]

193a	The	convict	burnt	the	boxes	on purpose
193b	The	father	dressed	the	boxes	with pepper
193c	The	father	dressed	the	salad	with pepper

f193a Who burnt the boxes on purpose? [The convict]
f193b Who dressed the boxes with pepper? [The father]

194a	The	parents	stopped	the	party	in the park
194b	The	women	wore	the	party	to the ball
194c	The	women	wore	the	perfume	to the ball

f194a What did the parents stop? [The party in the park]
f194b Who wore the party to the ball? [The women]

195a	The	mother	likes	the	glasses	at the shop
195b	The	students	told	the	glasses	where they went
195c	The	students	told	the	teacher	where they went

f195a Who likes the glasses at the shop? [The mother]
f195b Who told the glasses where they went? [The students]

196a	The	biscuits	had	the	sugar	on the top
196b	The	insect	stung	the	sugar	on her foot
196c	The	insect	stung	the	daughter	on her foot

f196a What was on top of the biscuits? [The sugar]
f196b Where did the insect sting the sugar? [On her foot]

197a	The	pirate	found	the	treasure	at the beach
197b	The	farmer	shears	the	treasure	in summer
197c	The	farmer	shears	the	sheep	in summer

f197a What did the pirate find at the beach? [The treasure]
f197b Who shears the treasure in summer? [The farmer]

198a	The	hiker	saw	the	tower	on the hill
198b	The	players	ate	the	tower	too quickly
198c	The	players	ate	the	dinner	too quickly

f198a What did the hiker see on the hill? [The tower]
f198b How did the players eat the tower? [Too quickly]

199a	The	husband	trims	the	garden	all day long
199b	The	lady	taught	the	garden	many tricks
199c	The	lady	taught	the	puppy	many tricks

f199a Who trims the garden all day long? [The husband]
f199b Who taught the garden many tricks? [The lady]

200a	The	mother	bought	the	cushion	at the shop
200b	The	expert	writes	the	cushion	at his desk
200c	The	expert	writes	the	program	at his desk

f200a What did the mother buy at the shop? [The cushion]
f200b Who writes the cushion at his desk? [The expert]

201a	The	painter	draws	the	picture	of the car
201b	The	boyfriend	licked	the	picture	at his house
201c	The	boyfriend	licked	the	spoon	at his house

f201a What does the painter draw? [The picture (of the car)]
f201b Who licked the picture at his house? [The boyfriend]

202a	The	children	make	the	sculpture	in art class
202b	The	waiter	serves	the	sculpture	at lunch time
202c	The	waiter	serves	the	salad	at lunch time

f202a Where do the children make the sculpture? [In art class]
f202b What does the waiter serve at lunch time? [The sculpture]

203a	The	women	saw	the	dresses	in the shop
203b	The	actress	cooks	the	dresses	for herself
203c	The	actress	cooks	the	porkchop	for herself

f203a What did the women see in the shop? [The dresses]
f203b Who cooks the dresses for herself? [The actress]

204a	The	builder	cuts	the	cable	at his work
204b	The	buyer	pleased	the	cable	at the shop
204c	The	buyer	pleased	the	plumber	at the shop

f204a Where does the builder cut the cable? [At his work] f204b Who pleased the cable at the shop? [The buyer]

205a The daughter tore the dresses by mistake
205b The learner writes the dresses in his house
205c The learner writes the program in his house
f205a who tore the dresses by mistake? [The daughter]
f205b Where does the learner write the dresses? [In his house]

206a The dragon flew the children to safety
206b The writers type the children for the news
206c The writers type the stories for the news
f206a Who did the dragon fly to safety? [The children]
f206b What did the writers type for the news? [The children]

207a The boxes hold the pictures of the boy
207b The spider bites the pictures on her foot
207c The spider bites the daughter on her foot
f207a What do the boxes hold? [The pictures (of the boy)]
f207b Where does the spider bite the pictures? [On her foot]

208a The ladies wore the dresses to the ball
208b The worker trains the dresses in the zoo
208c The worker trains the tiger in the zoo
f208a Who wore the dresses to the ball? [The ladies]
f208b Where does the worker train the dresses? [In the zoo]

209a The waiter makes the cocktails very fast
209b The nanny combs the cocktails every day
209c The nanny combs the doggy every day
f209a Who makes the cocktails very fast? [The waiter]
f209b What does the nanny comb every day? [The cocktails]

210a The teacher asked the questions very fast
210b The barman drinks the questions very fast
210c The barman drinks the cocktails very fast
f210a How did the teacher ask the questions? [Very fast]
f210b How does the barman drink the questions? [Very fast]

211a The TV shows the program on cooking
211b The helper ate the program this morning
211c The helper ate the breakfast this morning
f211a What is the TV program about? [Cooking]
f211b What did the helper eat this morning? [The program]

212a The husband cooks the salmon on the stove
212b The lady sings the salmon cheerfully
212c The lady sings the ballad cheerfully

f212a What does the husband cook on the stove? [The salmon]
f212b What does the lady sing cheerfully? [The salmon]

213a	The	brother	sees	the	tiger	in the zoo
213b	The	grandpa	skims	the	tiger	in the park
213c	The	grandpa	skims	the	paper	in the park

f213a What does the brother see in the zoo? [The tiger]
f213b Who skims the tiger in the park? [The grandpa]

214a	The	trainer	fears	the	tiger	when it's free
214b	The	father	trims	the	tiger	in July
214c	The	father	trims	the	garden	in July

f214a When does the trainer fear the tiger? [When it's free]
f214b What does the father trim in July? [The tiger]

215a	The	toddler	likes	the	biscuits	with some milk
215b	The	nephew	phoned	the	biscuits	this morning
215c	The	nephew	phoned	the	plumber	this morning

f215a How does the toddler like the biscuits? [With some milk]
f215b Who did the nephew phone this morning? [The biscuits]

216a	The	mother	saw	the	paintings	of her child
216b	The	learner	drinks	the	paintings	of water
216c	The	learner	drinks	the	bottle	of water

f216a What did the mother see? [The paintings (of her child)]
f216b Who drinks the paintings of water? [The learner]

217a	The	sailor	ate	the	pasta	with the fork
217b	The	cyclist	rides	the	pasta	on the road
217c	The	cyclist	rides	the	tandem	on the road

f217a What did the sailor eat with the fork? [The pasta]
f217b What does the cyclist ride on the road? [The pasta]

218a	The	master	taught	the	classes	on Monday
218b	The	hikers	walk	the	classes	happily
218c	The	hikers	walk	the	distance	happily

f218a Who taught the classes on Monday? [The master]
f218b What did the hikers walk happily? [The classes]

219a	The	children	help	the	parrot	learn to speak
219b	The	couple	sealed	the	parrot	yesterday
219c	The	couple	sealed	the	bathtub	yesterday

f219a Who helps the parrot learn to speak? [The children]
f219b When did the couple seal the parrot? [Yesterday]

220a	The	father	cleans	the	doorstep	of his house
220b	The	doctor	ties	the	doorstep	to the tree

220c	The	doctor	ties	the	doggie	to the tree
f220a	What does the father clean? [The doorstep (of his house)]					
f220b	What does the doctor tie to the tree? [The doorstep]					
221a	The	buildings	have	the	gardens	on the roof
221b	The	soldier	threw	the	gardens	to the floor
221c	The	soldier	threw	the	bullets	to the floor
f221a	Where do the buildings have the gardens? [On the roof]					
f221b	What did the soldier throw to the floor? [The gardens]					
222a	The	author	writes	the	paper	on Tuesday
222b	The	dolphin	swims	the	paper	easily
222c	The	dolphin	swims	the	distance	easily
f222a	When does the author write the paper? [On Tuesday]					
f222b	What does the dolphin swim easily? [The paper]					
223a	The	actress	sees	the	painter	every day
223b	The	tourist	posts	the	painter	to Sydney
223c	The	tourist	posts	the	boxes	to Sydney
f223a	What does the actress see every day? [The painter]					
f223b	What does the tourist post to Sydney? [The painter]					
224a	The	trainer	trains	the	tiger	in the zoo
224b	The	granny	plants	the	tiger	in the pot
224c	The	granny	plants	the	flower	in the pot
f224a	Who trains the tiger in the zoo? [The trainer]					
f224b	Who plants the tiger in the pot? [The granny]					
225a	The	parents	pay	the	teacher	every week
225b	The	Frenchman	flies	the	teacher	in the park
225c	The	Frenchman	flies	the	chopper	in the park
f225a	When do the parents pay the teacher? [Every week]					
f225b	Where does the Frenchman fly the teacher? [In the park]					
226a	The	father	hates	the	traffic	every day
226b	The	sailor	posts	the	traffic	to his son
226c	The	sailor	posts	the	package	to his son
f226a	Who hates the traffic every day? [The father]					
f226b	Who posts the traffic to his son? [The sailor]					
227a	The	tutor	writes	the	story	for the class
227b	The	shark	bites	the	story	on her foot
227c	The	shark	bites	the	daughter	on her foot
f227a	What does the tutor write for the class? [The story]					
f227b	Where does the shark bite the daughter? [On her foot]					
228a	The	children	share	the	pastry	on birthdays

228b	The	army	marched	the	pastry	up the hill
228c	The	army	marched	the	soldiers	up the hill
f228a	When do the children share the pastry? [On birthdays]					
f228b	Who marched the pastry up the hill? [The army]					
229a	The	father	paints	the	ceiling	in summer
229b	The	brother	fought	the	ceiling	in the park
229c	The	brother	fought	the	teacher	in the park
f229a	Who paints the ceiling in summer? [The father]					
f229b	Who did the brother fight in the park?					
230a	The	brothers	spoke	the	sentence	loud and clear
230b	The	hunter	chased	the	sentence	with a stick
230c	The	hunter	chased	the	puppy	with a stick
f230a	Who spoke the sentence loud and clear? [The brothers]					
f230b	What did the hunter chase with a stick? [The sentence]					
231a	The	builder	built	the	kitchen	in a week
231b	The	gamer	paused	the	kitchen	frequently
231c	The	gamer	paused	the	program	frequently
f231a	What did the builder build in a week? [The kitchen]					
f231b	What did the gamer pause frequently? [The kitchen]					
232a	The	farmer	cooks	the	chicken	at the farm
232b	The	mother	zips	the	chicken	for her child
232c	The	mother	zips	the	backpack	for her child
f232a	Where does the farmer cook the chicken? [At the farm]					
f232b	What does the mother zip for her child? [The chicken]					
233a	The	children	read	the	chapters	this morning
233b	The	farmer	dusts	the	chapters	once a year
233c	The	farmer	dusts	the	bookshelf	once a year
f233a	When did the children read the chapters? [This morning]					
f233b	How often does the farmer dust the chapters? [Once a year]					
234a	The	father	cleans	the	kitchen	every day
234b	The	student	asked	the	kitchen	some questions
234c	The	student	asked	the	teacher	some questions
f234a	When does the father clean the kitchen? [Every day]					
f234b	What did the student ask the kitchen? [Some questions]					
235a	The	witness	saw	the	jury	in the court
235b	The	uncle	drained	the	jury	in the sink
235c	The	uncle	drained	the	pasta	in the sink
f235a	What did the witness see in the court? [The jury]					
f235b	Where did the uncle drain the jury? [In the sink]					

236a	The	mother	tells	the	story	at bedtime
236b	The	sister	teased	the	story	at bedtime
236c	The	sister	teased	the	brother	at bedtime

f236a Who tells the story at bedtime? [The mother]
f236b Who teased the story at bedtime? [The sister]

237a	The	granny	reads	the	stories	very well
237b	The	children	crashed	the	stories	at the park
237c	The	children	crashed	the	cycle	at the park

f237a What does the granny read very well? [The stories]
f237b Where did the children crash the stories? [At the park]

238a	The	camel	leaves	the	desert	in summer
238b	The	actress	wore	the	desert	for the show
238c	The	actress	wore	the	dresses	for the show

f238a Who leaves the desert in summer? [The camel]
f238b What did the actress wear for the show? [The desert]

239a	The	children	like	the	tiger	in the zoo
239b	The	father	mends	the	tiger	together
239c	The	father	mends	the	pieces	together

f239a Who likes the tiger in the zoo? [The children]
f239b Who mends the tiger together? [The father]

240a	The	children	clean	the	shower	all the time
240b	The	boyfriend	calms	the	shower	at his house
240c	The	boyfriend	calms	the	girlfriend	at his house

f240a What do the children clean all the time? [The shower]
f240b What does the boyfriend calm at his house? [The shower]

241a	The	tutor	helps	the	students	every day
241b	The	brother	seals	the	students	thoroughly
241c	The	brother	seals	the	boxes	thoroughly

f241a Who helps the students every day? [The tutor]
f241b How does the brother seal the students? [Thoroughly]

242a	The	father	reads	the	journal	on weekends
242b	The	children	pat	the	journal	every day
242c	The	children	pat	the	donkeys	every day

f242a When does the father read the journal? [On weekends]
f242b When do the children pat the journal? [Every day]

243a	The	uncle	gave	the	present	to the niece
243b	The	player	cheats	the	present	without shame
243c	The	player	cheats	the	program	without shame

f243a What did the uncle give to the niece? [The present]
f243b How does the player cheat the present? [Without shame]

244a	The	mother	plants	the	garden	in July
244b	The	teacher	writes	the	garden	in his house
244c	The	teacher	writes	the	program	in his house
f244a	When does the mother plant the garden? [In July]					
f244b	What does the teacher write in his house? [The garden]					
245a	The	runner	turned	the	corner	that morning
245b	The	lawyer	dropped	the	corner	on the table
245c	The	lawyer	dropped	the	pencil	on the table
f245a	When did the runner turn the corner? [That morning]					
f245b	Who dropped the corner on the table? [The lawyer]					
246a	The	captain	took	the	bullets	from his gun
246b	The	driver	crashed	the	bullets	last Friday
246c	The	driver	crashed	the	buggy	last Friday
f246a	What did the captain take from his gun? [The bullets]					
f246b	Who crashed the bullets last Friday? [The driver]					
247a	The	baby	drinks	the	bottle	very fast
247b	The	teacher	skimmed	the	bottle	at the park
247c	The	teacher	skimmed	the	paper	at the park
f247a	Who drinks the bottle very fast? [The baby]					
f247b	What did the teacher skim at the park? [The bottle]					
248a	The	doctor	helps	the	patient	to the chair
248b	The	student	clicks	the	patient	on the mouse
248c	The	student	clicks	the	button	on the mouse
f248a	Who helps the patient to the chair? [The doctor]					
f248b	What does the student click on the mouse? [The patient]					
249a	The	driver	checks	the	petrol	constantly
249b	The	sister	wore	the	petrol	to the club
249c	The	sister	wore	the	trousers	to the club
f249a	Who checks the petrol constantly? [The driver]					
f249b	What did the sister wear to the club? [The petrol]					
250a	The	students	use	the	table	for painting
250b	The	student	clicks	the	table	on the mouse
250c	The	student	clicks	the	button	on the mouse
f250a	Who uses the table for painting? [The students]					
f250b	What does the student click? [The table (on the mouse)]					
251a	The	actor	takes	the	taxi	every day
251b	The	farmer	digs	the	taxi	with a spade
251c	The	farmer	digs	the	ground	with a spade
f251a	When does the actor take the taxi? [Every day]					

f251b Who digs the taxi with a spade? [The farmer]

252a	The	daughter	found	the	glasses	on the train
252b	The	mother	ate	the	glasses	with her son
252c	The	mother	ate	the	pizza	with her son

f252a Who found the glasses on the train? [The daughter]
f252b What did the mother eat with her son? [The glasses]

253a	The	army	wins	the	battle	over night
253b	The	mother	bakes	the	battle	for her kids
253c	The	mother	bakes	the	cookies	for her kids

f253a What does the army win over night? [The battle]
f253b For whom does the mother bake the battle? [For her kids]

254a	The	sister	drank	the	coffee	this morning
254b	The	grandson	flies	the	coffee	with his friends
254c	The	grandson	flies	the	chopper	with his friends

f254a Who drank the coffee this morning? [The sister]
f254b What does the grandson fly with his friends? [The coffee]

255a	The	boyfriend	bought	the	flowers	for his date
255b	The	couple	ends	the	flowers	in Europe
255c	The	couple	ends	the	journey	in Europe

f255a What did the boyfriend buy for his date? [The flowers]
f255b Where does the couple end the flowers? [In Europe]

256a	The	grandma	phoned	the	doctor	yesterday
256b	The	brother	posts	the	doctor	in July
256c	The	brother	posts	the	package	in July

f256a When did the grandma phone the doctor? [Yesterday]
f256b What does the brother post in July? [The doctor]

257a	The	partner	closed	the	building	in August
257b	The	teacher	dropped	the	building	on the table
257c	The	teacher	dropped	the	pencil	on the table

f257a What did the partner close in August? [The building]
f257b Where did the teacher drop the building? [On the table]

258a	The	landlord	phoned	the	couple	this morning
258b	The	worker	sealed	the	couple	on Monday
258c	The	worker	sealed	the	pipeline	on Monday

f258a When did the landlord phone the couple? [This morning]
f258b Who sealed the couple on Monday? [The worker]

259a	The	painter	saw	the	building	from the park
259b	The	handler	whipped	the	building	in the show
259c	The	handler	whipped	the	tiger	in the show

f259a What did the painter see from the park? [The building]
f259b Where did the handler whip the building? [In the show]

260a The children solved the puzzle in two hours
260b The painter eats the puzzle on the go
260c The painter eats the pizza on the go
f260a What did the children solve in two hours? [The puzzle]
f260b How does the painter eat the puzzle? [On the go]

261a The winners raised the glasses happily
261b The couple rode the glasses in summer
261c The couple rode the tandem in summer
f261a Who raised the glasses happily? [The winners]
f261b Who rode the glasses in summer? [The couple]

262a The sailors caught the salmon from the wharf
262b The farmer drives the salmon in summer
262c The farmer drives the tractor in summer
f262a What did the sailors catch from the wharf? [The salmon]
f262b When does the farmer drive the salmon? [In summer]

263a The possum eats the cherry on the ground
263b The tenant rents the cherry in April
263c The tenant rents the cottage in April
f263a Where does the possum eat the cherry? [On the ground]
f263b When does the tenant rent the cherry? [In April]

264a The builder leaves the platform at seven
264b The owner drives the platform very fast
264c The owner drives the taxi very fast
f264a Who leaves the platform at seven? [The builder]
f264b How does the owner drive the platform? [Very fast]

265a The tourists knew the journey very well
265b The worker scrubs the journey after work
265c The worker scrubs the table after work
f265a Who knew the journey very well? [The tourists]
f265b Who scrubs the journey after work? [The worker]

266a The tourists feed the pigeons in the square
266b The artist strums the pigeons very well
266c The artist strums the banjo very well
f266a Who feeds the pigeons in the square? [The tourists]
f266b How does the artist strum the pigeons? [Very well]

267a The sister wrote the story on Tuesday
267b The plumber flushed the story on Monday

267c	The	plumber	flushed	the	pipeline	on Monday
f267a	When did the sister write the story? [On Tuesday]					
f267b	Who flushed the story on Monday? [The plumber]					
268a	The	pirate	threw	the	bottle	yesterday
268b	The	nanny	helped	the	bottle	with the food
268c	The	nanny	helped	the	baby	with the food
f268a	What did the pirate throw yesterday? [The bottle]					
f268b	What did the nanny help with the food? [The bottle]					
269a	The	bishop	meets	the	people	on Sundays
269b	The	waiter	drinks	the	people	of water
269c	The	waiter	drinks	the	bottle	of water
f269a	Who meets the people on Sundays? [The bishop]					
f269b	Who drinks the people of water? [The waiter]					
270a	The	helmet	fit	the	pilot	perfectly
270b	The	boyfriend	sings	the	pilot	to his girl
270c	The	boyfriend	sings	the	ballad	to his girl
f270a	How does the helmet fit the pilot? [Perfectly]					
f270b	What does the boyfriend sing to his girl? [The pilot]					
271a	The	daughter	caught	the	salmon	on Tuesday
271b	The	mother	plants	the	salmon	near the house
271c	The	mother	plants	the	garden	near the house
272a	The	waiter	left	the	people	at the bar
272b	The	student	sings	the	people	of music
272c	The	student	sings	the	pieces	of music
273a	The	toddler	missed	the	parents	terribly
273b	The	sailor	drinks	the	parents	near the wharf
273c	The	sailor	drinks	the	coffee	near the wharf
274a	The	uncle	sent	the	package	to his son
274b	The	waiter	heats	the	package	for breakfast
274c	The	waiter	heats	the	pastry	for breakfast
275a	The	teacher	ate	the	pizza	after work
275b	The	ranger	stopped	the	pizza	in the park
275c	The	ranger	stopped	the	party	in the park
276a	The	lawyer	picked	the	colour	that morning
276b	The	judges	jailed	the	colour	for four years
276c	The	judges	jailed	the	killer	for four years
277a	The	owner	cleans	the	cottage	on Mondays
277b	The	builder	mixed	the	cottage	for the house

277c	The	builder	mixed	the	concrete	for the house
278a	The	brother	cooks	the	pastry	for breakfast
278b	The	chemist	pours	the	pastry	in the glass
278c	The	chemist	pours	the	product	in the glass
279a	The	colleague	filled	the	bottle	this morning
279b	The	father	sails	the	bottle	with his friend
279c	The	father	sails	the	cruiser	with his friend
280a	The	girlfriend	spreads	the	butter	on the toast
280b	The	typist	tapped	the	butter	very fast
280c	The	typist	tapped	the	keyboard	very fast
281a	The	captain	trained	the	soldiers	in winter
281b	The	dancer	wore	the	soldiers	in the show
281c	The	dancer	wore	the	trousers	in the show
282a	The	pilot	fixed	the	panel	on the plane
282b	The	doctor	drugs	the	panel	in the zoo
282c	The	doctor	drugs	the	tiger	in the zoo
283a	The	hunter	caught	the	creature	last Thursday
283b	The	singer	fills	the	creature	for the show
283c	The	singer	fills	the	program	for the show
284a	The	student	saw	the	picture	in the class
284b	The	doctor	calms	the	picture	with some pills
284c	The	doctor	calms	the	patient	with some pills
285a	The	teachers	run	the	classes	at the school
285b	The	daughter	chops	the	classes	for dinner
285c	The	daughter	chops	the	carrots	for dinner
286a	The	nanny	sets	the	table	at lunch time
286b	The	father	grew	the	table	in July
286c	The	father	grew	the	carrots	in July
287a	The	monkey	likes	the	jungle	very much
287b	The	lady	makes	the	jungle	for her son
287c	The	lady	makes	the	sandwich	for her son
288a	The	hiker	saw	the	tower	on the hill
288b	The	uncle	woke	the	tower	on Sunday
288c	The	uncle	woke	the	children	on Sunday
289a	The	cleaner	dried	the	shower	with a cloth
289b	The	people	tip	the	shower	very well

289c	The	people	tip	the	tourguide	very well
290a	The	nephew	drives	the	taxi	very fast
290b	The	husband	read	the	taxi	in the park
290c	The	husband	read	the	paper	in the park
291a	The	cyclist	spots	the	castle	far away
291b	The	burglar	spills	the	castle	on the floor
291c	The	burglar	spills	the	coffee	on the floor
292a	The	brother	cleans	the	bedroom	on weekends
292b	The	waiter	shakes	the	bedroom	very well
292c	The	waiter	shakes	the	cocktails	very well
293a	The	mother	cooks	the	dinner	every day
293b	The	servant	teased	the	dinner	in the yard
293c	The	servant	teased	the	kitten	in the yard
294a	The	speaker	guides	the	tourists	through the town
294b	The	mother	tastes	the	tourists	at the shop
294c	The	mother	tastes	the	carrots	at the shop
295a	The	farmer	grows	the	flowers	on the farm
295b	The	partner	rents	the	flowers	in winter
295c	The	partner	rents	the	cottage	in winter
296a	The	seller	raised	the	prices	of the books
296b	The	granny	grows	the	prices	in her yard
296c	The	granny	grows	the	tulips	in her yard
297a	The	lawyer	found	the	papers	in the box
297b	The	colleague	drinks	the	papers	after work
297c	The	colleague	drinks	the	cocktail	after work
298a	The	singer	joined	the	party	at midnight
298b	The	agent	posts	the	party	to Brazil
298c	The	agent	posts	the	boxes	to Brazil
299a	The	seagulls	watched	the	ferry	out at sea
299b	The	sister	cooked	the	ferry	last Monday
299c	The	sister	cooked	the	cabbage	last Monday
300a	The	golfer	beats	the	colleagues	easily
300b	The	children	cleaned	the	colleagues	thoroughly
300c	The	children	cleaned	the	kitchen	thoroughly
301a	The	children	hit	the	button	playfully
301b	The	person	chased	the	button	down the street

301c	The	person	chased	the	burglar	down the street
302a	The	husband	bought	the	presents	for Christmas
302b	The	baker	cooked	the	presents	last Tuesday
302c	The	baker	cooked	the	biscuits	last Tuesday
303a	The	diver	filled	the	bottle	with water
303b	The	speaker	guides	the	bottle	in Russia
303c	The	speaker	guides	the	tourists	in Russia
304a	The	engine	needs	the	petrol	urgently
304b	The	brother	danced	the	petrol	with his wife
304c	The	brother	danced	the	polka	with his wife
305a	The	student	broke	the	silence	in the church
305b	The	helper	grinds	the	silence	for the soup
305c	The	helper	grinds	the	pepper	for the soup
306a	The	surfer	wins	the	trophy	every time
306b	The	captain	ate	the	trophy	at lunchtime
306c	The	captain	ate	the	sandwich	at lunchtime
307a	The	worker	sold	the	cottage	in July
307b	The	baby	drinks	the	cottage	on his own
307c	The	baby	drinks	the	bottle	on his own
308a	The	driver	sent	the	signal	just in time
308b	The	artist	stained	the	signal	in green ink
308c	The	artist	stained	the	paper	in green ink
309a	The	couple	drank	the	cocktails	at the bar
309b	The	captain	wore	the	cocktails	on the ship
309c	The	captain	wore	the	jacket	on the ship
310a	The	soldiers	took	the	silver	from the vault
310b	The	council	guides	the	silver	round the town
310c	The	council	guides	the	tourists	round the town
311a	The	doctor	shot	the	question	at the nurse
311b	The	brother	baked	the	question	for dinner
311c	The	brother	baked	the	turkey	for dinner
312a	The	hunter	caught	the	tiger	in a trap
312b	The	expert	clicked	the	tiger	with his hand
312c	The	expert	clicked	the	button	with his hand
313a	The	daughter	gave	the	dollar	to her friend
313b	The	hiker	trimmed	the	dollar	of the trees

313c	The	hiker	trimmed	the	branches	of the trees
314a	The	rider	fixed	the	basket	on his bike
314b	The	carer	fed	the	basket	with some milk
314c	The	carer	fed	the	puppy	with some milk
315a	The	captain	moved	the	cannon	off the ship
315b	The	couple	ate	the	cannon	at midnight
315c	The	couple	ate	the	pizza	at midnight
316a	The	princess	left	the	castle	by herself
316b	The	children	ate	the	castle	in the sun
316c	The	children	ate	the	peaches	in the sun
317a	The	navy	fought	the	pirates	with courage
317b	The	dancer	planned	the	pirates	all week long
317c	The	dancer	planned	the	party	all week long
318a	The	expert	ran	the	system	remotely
318b	The	kitten	licked	the	system	endlessly
318c	The	kitten	licked	the	doggy	endlessly
319a	The	teacher	marked	the	paper	with a pen
319b	The	army	jailed	the	paper	last Monday
319c	The	army	jailed	the	killer	last Monday
320a	The	banker	held	the	contract	to his chest
320b	The	daughter	dressed	the	contract	for dinner
320c	The	daughter	dressed	the	salad	for dinner

Appendix IV: Adult case history form

Participant ID:

Age:

Gender:

Appointment date:

General complaint:

Audiological History:

(Circle the appropriate answer)

Hearing loss: Yes No

Which ear: Right Left Both

When did you first notice the problem?

Have used an amplification device: Yes NO

If yes: Right Left Both

Type and style of hearing aid:

How long have you been wearing hearing aids?

In-case you are using an amplification device, do you face any of the following difficulties:

1) Trouble understanding in quiet
2) Trouble understanding in noise
3) Feedback issues
4) Difficulty in identifying the direction of sound
5) Not able to appreciate the quality of sound
6) Trouble using telephone
7) Excessive wind noise

Others:

History of ear pain/ ear discharge:	Yes	No
History of ear infections:	Yes	No
Previous ear surgery:	Yes	No
Dizziness or Unsteadiness	Yes	No
Use of tobacco:	Yes	No

Medical History

For testing purposes, it would bode well to have the medical history of an individual. This information will not be included anywhere to personally identify any individual. However, it would enable the examiner to keep in mind the adequate measures to ensure comfortable participation in the experiment.

(Circle the appropriate answer)

1)	Diabetes	Yes	No	Under medication
2)	Heart Problems	Yes	No	Under medication
3)	Head Injury	Yes	No	Under medication
4)	High Blood Pressure	Yes	No	Under medication
5)	Vascular Problems	Yes	No	Under medication
6)	Stroke	Yes	No	Under medication
7)	Cancer	Yes	No	Under medication
8)	Arthritis	Yes	No	Under medication
9)	Psychiatric issues	Yes	No	Under medication

(depression/anxiety)

10) Eye Problems (blurred vision /pain) Yes No Corrected /Uncorrected