Hearing Loss and Driving: Does Auditory Distraction Have a Disproportionate Effect on the Hearing Impaired?

by

Nicholas Charles Herbert

Submitted in accordance with the requirements
for the degree of Doctor of Philosophy

The University of Leeds
Institute for Transport Studies & School of Healthcare
September 2015

Acknowledgements

This thesis has been a substantial undertaking and one which has been made possible through the help and support of many. I'd like to take this opportunity to express my heartfelt thanks to those who have been particularly supportive and benevolent over the past four years.

First and foremost, profound thanks to my supervisors Natasha Merat, Nick Thyer and Sarah Isherwood. Having your expertise, advice and encouragement behind me has made the completion of this thesis an enjoyable experience. You have been patient, helpful and understanding, and your input has allowed for my development as an independent researcher.

Thanks to all of my friends at the Institute for Transport Studies. In particular, thanks to you for all of your support Daz - neither one of us could count the amount of time you have spent selflessly listening and reassuring.

Steve and Dini - it has been an absolute pleasure sharing this experience from the beginning with you. I know that without your support (and the welcome 'coffee breaks') this would have been a much more difficult undertaking. Thanks for being there and for making this such an enjoyable experience.

Thanks to my parents, who have been there for me not only during this PhD, but throughout the nine years I have spent at the University of Leeds. I can't express my appreciation for your support in a single paragraph, but you have provided the platform for me to be able to pursue this PhD and stuck by me throughout. Without your help, input and support this quite simply would not have been possible.

And thanks finally to you Ananya - I am so very lucky to have had your encouragement, support and understanding whilst writing this thesis. You don't know how important you've been in the latter stages of this undertaking, but I couldn't have done it without you.

To everybody that has helped, influenced and guided me during this process - thank you. You have made this an undertaking which I will always look back on with fond memories.

Abstract

Research showing differences between the driving outcomes of hearing impaired and normally hearing individuals (such as raised road traffic accidents), proposes this has occurred due to two main reasons: (1) that sound present in the driving environment is inaudible for hearing impaired drivers, and (2) that audible sound is disproportionately distracting for the hearing impaired driver.

This thesis reports on a series of experiments which investigated the latter of these proposals. A questionnaire study was used to explore driving patterns and experiences of hearing impaired individuals. Empirical studies were also conducted to investigate the effect of hearing loss on driving performance and visual attention, under auditory task conditions.

Questionnaire responses suggested that hearing impaired individuals did not perceive hearing loss as problematic for driving performance. However, the self-reported hearing of respondents predicted reports of driving difficulty better than any other independent variable. A laboratory-based study hinted that extra visual task performance decrements as a result of auditory engagement occurred in hearing impaired individuals.

Since these findings were in older adults, the influence of factors co-existing with hearing loss (such as cognitive decline) were questioned. These confounds were removed by presenting an auditory task subject to simulated hearing loss in a dual-task driving simulator experiment; allowing for a young, normally hearing sample, and within-subjects design. The resulting data showed no disproportionate effect of hearing loss on driving performance during the concurrent auditory task.

Accordingly, distortion to sound arising from hearing loss may not be entirely responsible for the disproportionate effects of auditory distraction in hearing impaired drivers. Other factors, co-existing with hearing loss, appear to act synergistically to cause problems. Future work should investigate further the aspects of hearing loss (and co-existing factors) responsible for changes in driving outcomes, by, for instance, using a group of young hearing impaired participants.

Contents

List of Figures

List of Tables

Abbreviations

aCMT Auditory Continuous Memory Task.

DBQ Driver Behaviour Questionnaire.

dCMT Digit Continuous Memory Task.

DHLQ Driving and Hearing Loss Questionnaire.

DRT Detection Response Task.

DSP Digital Signal Processing.

ELU Ease of Language Understanding Model.

HASTE The Human Machine Interface And the Safety of Traffic in Europe Project.

HFC High Frequency Component of Steering Angle.

HHIA Hearing Handicap Inventory for Adults.

HHIE Hearing Handicap Inventory for the Elderly.

HHIE-S Hearing Handicap Inventory for the Elderly (screening version).

IHCs Inner Hair Cells.

KIPS Clinical Information Processing System.

LED Light Emitting Diode.

MMSE Mini Mental State Exam.

MRT Multiple Resources Theory.

NASA-TLX National Aeronautics and Space Administration Task Load Index.

NHS National Health Service.

OHCs Outer Hair Cells.

PASAT Paced Auditory Serial Addition Task.

PDT Peripheral Detection Task.

PRC Percent Road Centre.

PTA Pure Tone Audiometry.

PTC Psychophysical Tuning Curve.

RMS Root-Mean Squared.

RTAs Road Traffic Accidents.

SCP Stimulus Cycle Period.

SDLP Standard Deviation of Lane Position.

SimHL Simulated Hearing Loss.

SNHL Sensorineural Hearing Loss.

SRT Speech Reception Threshold.

SSW Staggered Spondaic Word test.

tCMT Tone Continuous Memory Task.

TTLC Time to Line Crossing.

UFOV A computerised assessment of the useful field of view.

UoLDS University of Leeds Driving Simulator.

vDRT Visual Detection Response Task.

Chapter 1

Introduction: The Effect of Hearing Loss on Driving

1.1 Introduction

Driving is the primary mode of travel in many developed countries and possession of a driver's license in a number of societies is an important symbol of personal independence (Owsley and McGwin Jr, 1999). However, driving is considered one of the most complex tasks in modern society (Groeger, 2000) and its safety implications if performed incorrectly are profound; during 2013 in the United Kingdom 21,657 people were seriously injured as a result of road accidents (Department for Transport, 2014). Due to the safety critical nature of driving, a great deal of academic research has focused on identifying related performance limiting factors and how they may be improved.

One particular area of research which has emerged is the impact of changes in sensory function on driving safety; though given the reliance of driving on vision (Sivak et al., 1996), this work has primarily focused on visual sensory changes (see e.g. Anstey et al., 2005 for a review). However, in his commentary on the different senses used during driving, Sivak et al. (1996) also describes that (in addition to vision) audition has a role to play.

Hearing loss is one of the most common chronic conditions (Collins, 1997), yet despite its high prevalence, it has not been given much academic attention in terms of its affect on driving. As such, the relationship between driving and hearing has been seen as ill-defined (Burg et al., 1970), and authors have pointed out that the specific auditory requirements for safe driving are not entirely known (Henderson and Burg, 1973).

In the 1960–70s there was an emergence of discussion in the literature regarding profoundly deaf individuals' ability to drive safely, with particular reference to commercial motor vehicle drivers. However, a rather simplistic view of hearing impairment was taken, whereby many authors assumed that sound was not at all accessible to drivers with hearing loss. Work based on this assumption led to suggestions that hearing loss limited audition of warning signals, vehicle function problems, vehicle inspection processes, and communication with other road users (Wagner, 1962; Henderson and Burg, 1973, 1974).

Since the debate of this topic in the 1960–70's there has not been a concerted effort to empirically investigate the driving habits or ability of the hearing impaired demographic. Indeed, Songer (1993) carried out a risk assessment of hearing disorders for driving ability on behalf of the US Department of Transportation Federal Highway Administration. His review of the existing literature referenced one *unpublished* study which had investigated road traffic accident risk in hearing impaired individuals since 1974; some 19 years earlier.

All of the work cited by Songer (1993) related to profoundly deaf individuals. Whilst it is important that driving behaviour in this group of individuals is studied, the exclusive investigation of driving performance in this demographic group prior to 1993 meant the neglect of those who had a hearing loss, but were not profoundly deaf. Indeed, Burg et al. (1970, p. 289) pointed out that "deafness is not an all or none phenomenon" and that "there are degrees of hearing impairment", leading him to the conclusion that "many variables are involved in evaluating the driving capability of the hard of hearing".

After the publication of the report by Songer (1993), however, results of studies in to the effect of partial hearing loss (rather than profound deafness) on driving began to be published, although these were far from exhaustive. Furthermore, the methodologies adopted usually incorporated a wide range of age-related conditions as explanatory variables for driving outcomes. Thus they were not aimed explicitly at investigating the effect of hearing impairment (McCloskey et al., 1994; Ivers et al., 1999; Sims et al., 2000; Gilhotra et al., 2001; Unsworth et al., 2007; Green et al., 2013). This has made it difficult to isolate the exact influence of hearing impairment on driving performance and outcomes. However, some research has recently been carried out which explicitly investigates hearing loss as a factor for driving performance (Hickson et al., 2010; Thorslund et al., 2013a,b,c, 2014).

The publications arising in the 1960–70s were not in agreement on whether deafness had a negative effect on driving. Some studies found an increase in road traffic accident likelihood (Coppin and Peck, 1963, 1965), whereas others found a decrease (Finesilver, 1962; Wagner, 1962; Ysander, 1966; Roydhouse, 1967; Schein, 1968). More recent work on those with partial hearing impairments has exhibited the same disagreement between studies, with some showing no effect of hearing loss (McCloskey et al., 1994; Sims et al., 2000; Green et al., 2013), but others showing an increased risk of road traffic accident (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008). This disagreement in the literature, twinned with the general lack of investigation in this area has led to disjointed legislation regarding the acceptability of driving in the deaf and hearing impaired demographics around the world. The studies which have been performed in this area and their findings, an overview of current legislation, and the importance of driving for hearing impaired individuals is provided in the next section.

1.1.1 Hearing loss and driving performance

In the examination of the effect of deafness on driving, much of the historic evidence draws on observations of individual cases. For example, Songer (1993) cites authors who published in the magazine *The Deaf American*, providing case studies of deaf drivers who had not had an accident history over long periods of time. Observations on larger samples who had been involved in road traffic accidents were also carried out, and results suggested that only a very small proportion of those experiencing an accident were deaf (McFarland and Moore, 1955; Finesilver, 1962; Norman, 1962; Grattan and Jeffcoate, 1968). This suggested that deafness did not have a significant bearing on driving performance.

Early case-control studies also found no effect of deafness on driving (Finesilver, 1962; Wagner, 1962; Ysander, 1966; Roydhouse, 1967; Schein, 1968). In fact, the results of his study led Wagner (1962) to conclude that "Deaf-Mutes are the safest motorists on Pennsylvania's highway system". However, interspersed with these findings, other case-control research was showing that deafness was associated with a higher accident risk (Coppin and Peck, 1963, 1965).

Coppin and Peck (1963) produced a report for the California Department of Motor Vehicles and, using a case-control methodology, found that profoundly deaf drivers differed from those with normal hearing across a number of variables: (1) the deaf had more accidents and violations on their driving records, (2) the deaf drove a greater number of miles per year, (3) the distribution of deaf drivers among occupational categories differed from that of the non-deaf, and (4) the deaf and normally hearing drivers differed with respect to the shape of their age distributions. However, because cases and controls were not adequately matched on variables such as annual mileage, occupation or age it could not be inferred that the finding of an increased number of accidents in the deaf sample was as a direct result of sensory loss. In fact, it is a fair criticism of the majority of this early work studying the driving outcomes of deaf individuals that annual mileage was not controlled (Songer, 1993).

Coppin and Peck (1965) later addressed the limitations of their previous study (Coppin and Peck, 1963) in a new observational study and controlled for the previously omitted variables, and showed that deaf males had a significantly higher number of road traffic accidents than normally hearing drivers (Coppin and Peck, 1965). The results are curious, and the authors themselves questioned why gender should interact with hearing impairment. Their conclusion was that deaf males may spend more time driving in situations where hearing is important, such as during rush hour or in heavy traffic. However, this was in no way suggested by their data, which did not investigate the types of roads driven by deaf individuals.

The work carried out in the 1960–70s is now approximately 50 years old, and focused not on hearing impairment, as does this thesis, but on profound deafness. However, the work investigating the effect of *hearing impairment* on driving performance has found a similar trend of disagreement. Case-control methodologies have been used in order to establish the influence of partial hearing loss on various measures of driving safety (e.g. road traffic accident risk, speeding citations). Whilst some suggest a higher risk of road traffic accidents in the hearing impaired demographic (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008), others exhibit no such association (McCloskey et al., 1994; Sims et al., 2000; Green et al., 2013).

Other authors have used similar case-control designs, showing that hearing impairment may encourage people to cease driving, or alter their driving habits (Gilhotra et al., 2001; Unsworth et al., 2007). A recent questionnaire study has also highlighted some differences in transportation habits between hearing impaired and normally hearing individuals (Thorslund et al., 2013c).

More detailed research carried out during on-road and simulated environments has shown that hearing loss significantly alters driving behaviour whilst under dual-task conditions: hearing impaired individuals appear more distracted by concurrent tasks performed whilst driving (Hickson et al., 2010), tend to drive slower than their hearing counterparts (Thorslund et al., 2013b), have altered eye movement behaviour (Thorslund et al., 2014), and are less inclined to engage in secondary tasks whilst driving (Thorslund et al., 2013b).

These findings have been explained in terms of an 'effortfulness hypothesis' (Rabbitt, 1991); whereby hearing impaired individuals have to use more cognitive resources in the processing of auditory information than their normally hearing counterparts, thus leaving fewer available for the completion of other tasks. Accordingly, tasks performed whilst processing auditory information will experience greater performance decrements. Various effects of auditory task engagement on driving have been shown in normally hearing individuals (Jamson and Merat, 2005; Engström et al., 2005b; Victor et al., 2008), and Hickson et al. (2010) hypothesise that these effects will be magnified for hearing impaired drivers, given that extra cognitive resources will be required for the processing of the auditory task.

However, alterations in eye movement behaviour and travelling speed in the hearing impaired demographic have also been replicated in an on-road study not using a dual-task methodology, suggesting that an adaptation to driving style may be, at least in part, responsible (Thorslund et al., 2013a).

Though noteworthy, the above studies involve a number of methodological limitations. Amongst these are the use of self-reported hearing loss as a method of classifying hearing impaired individuals (McCloskey et al., 1994; Ivers et al., 1999; Gilhotra et al., 2001; Unsworth et al., 2007; Green et al., 2013), limited sample diversity (Barreto et al., 1997; Picard et al., 2008), and uncertainty regarding how well matched the experimental groups were (Hickson et al., 2010). Accordingly, whilst the possibility of negative effects of hearing loss on aspects of driving are suggested by this work, the results derived cannot be considered entirely conclusive.

A more detailed discussion of each individual study cited is given in Chapter 2, where limitations will be discussed in greater depth, and the results of each study will be reviewed to give an overview of the current state of knowledge in this area. These studies all contribute to the wider picture on the effect of hearing loss on driving, and show a much more complex situation than simply a distinction between profoundly deaf drivers, and those who can hear, as was inferred by earlier work performed during the 1960–70s.

In this regard, a key consideration is that the consequences of *partial hearing impairment* may be very different to *profound deafness* for driving performance (see Chapter 2). Profound deafness means a complete loss of audibility (e.g. hearing warning signals), whereas hearing impairment presents a partial loss of audibility, giving rise to issues which may occur as a result of sound which *is* audible (e.g. distraction as a result of speaking on a mobile phone). It is important to consider, for example, that improved visual perception in the deaf demographic might actually lead to an increased awareness whilst driving (Bavelier et al., 2000; Bosworth and Dobkins, 2002; Bavelier et al., 2006). Furthermore, considerations regarding driving performance may not only be governed by the magnitude of hearing loss, but may also be intertwined with other co-existing factors given the age profile of the hearing impaired demographic (Davis, 1995).

It is also important that other factors are considered, such as how hearing impaired individuals might alter their driving behaviour in order to counteract any negative effects on their driving performance; a suggestion which Burg et al. made as early as 1970. For example, one research group (Thorslund et al., 2013a,b, 2014) have argued that they observed adaptive driving behaviour by which hearing impaired individuals nullified the negative consequences of hearing loss on driving performance. Whether or not this approach to driving is successful is unclear, though the studies which have found an increased accident rate in the hearing impaired demographic would tend to suggest not (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008).

The heterogeneous nature of the methodologies and outcomes of past research in this area has made it difficult to infer whether hearing loss does have an effect on driving performance. This has lead to disjointed policy decisions which are summarised in the following section.

1.1.2 Hearing loss and driver licensing

As a result of the uncertainty over whether hearing loss has an effect on driving performance, the licensing of hearing impaired drivers is entrenched in debate, some of which continues today. In the 1920's deaf individuals were banned from driving in a number of U.S. states, a piece of legislation which was met angrily by the deaf community (Burch, 2004). Subsequent action from the National Association of the Deaf, supported by accident statistics and reasoned arguments, was highly successful in overturning all bans (Tabak, 2006). Nevertheless, there is some evidence that deaf drivers are still discriminated against today. For example, in the United States of America a case was successfully brought against the United Parcel Service in 2007 for discriminating against hearing impaired individuals by not allowing them to be employed as drivers (Bates vs. United Parcel Serv., Inc., 04-17295). Furthermore, as recently as 2010 there was legislation in place in Jamaica requiring deaf individuals to install special systems in their cars to alert them to external vehicular sounds. These two examples highlight that some view deafness as a barrier for safe driving, despite a lack of empirical support for this assumption.

Current licensing regulations worldwide appear to be somewhat varied. For instance, in a number of developing countries profoundly deaf individuals are not allowed to drive. In a report for the World Federation of the Deaf and Swedish National Association of the Deaf, Haualand and Allen (2009) surveyed 93 countries regarding their stance on deaf drivers. Although not all of the countries responded, 31 indicated that they did not allow profoundly deaf individuals to obtain a driving license (see Figure 1.1 for locations). In some of these cases, there was no written legislation in place, but responses from respective countries indicated that suitable infrastructure was not in place for deaf people to be able to drive and/or authorities saw deaf drivers as dangerous and prevented them from practicing this behaviour.

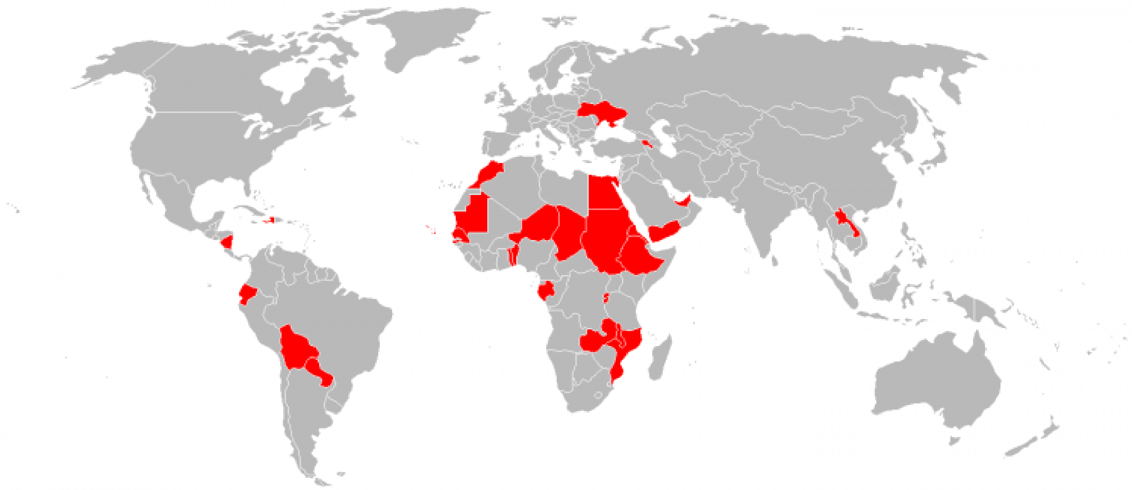


Figure 1.1 Countries in which deaf individuals are prevented from obtaining a driving license (shown in red). N.B. These are the countries *known* to ban deaf people from driving, there may be others. Source: World Federation of the Deaf and the Swedish National Association of the Deaf (2008).

There appear to be no such prohibitions in place in the developed world. In the United Kingdom, people with a hearing loss are not currently required to report their sensory impairment to the Driver and Vehicle Licensing Agency unless they are a commercially employed driver (Driver and Vehicle Licensing Agency, 2012). There is no explanation as to why this is the case, or what potential effect this type of sensory impairment may have on licensing. However, it appears that the main concern is with regard to an ability to communicate over the telephone in emergencies. The questions asked are:

1. Is your hearing good enough to receive information using a telephone, with or without the use of a special appliance? e.g. Minicom
2. Do you have access to an alternative means of communication in an emergency? e.g. Text telephone

Similarly, in Australia, commercial drivers are the only group who need to declare their hearing loss, though it appears that this is more because of safety concerns. The legislation states that drivers must have an awareness of changes in engine or road noise and external warning signals, and that this may be compromised by a hearing loss. Accordingly, commercial drivers must have a clinical evaluation and may only be granted a conditional license if their hearing reaches a certain standard, though hearing aids can be employed in order to reach this standard (Austroads and the National Transport Commission Australia, 2014). The licensing agency in Australia are, therefore, mainly concerned with the problems of audibility for hearing impaired drivers, suggesting that they do not view milder forms of hearing impairment as a problem for driving.

1.1.3 The importance of driving for hearing impaired individuals

Driving is considered an important factor in the maintenance of independence and is linked to other activities which are important for daily living (Persson, 1993; Retchin and Anapolle, 1993). The continuation of driving may, therefore, guard against some of the social consequences of hearing loss such as social isolation, increased dependence and depression (Marottoli and Drickamer, 1993; Sindhusake et al., 2001; Tambs, 2004). Conversely, retirement from driving, which increases the risk of isolation and depression (Wiseman and Souder, 1996), may exacerbate these problems for hearing impaired individuals. Thus, the ability to drive contributes strongly to the concept of health-related quality of life (Patrick and Deyo, 1989). Accordingly it is important for people with hearing loss to be able to continue driving.

The previously described legislation, and the lack of research and debate surrounding this topic threatens the ease with which the hearing impaired can continue to drive. Indeed, some authors have questioned the provisions in place for deaf drivers in terms of the ease with which they can learn to drive. Steinhardt and Wishart (2006) carried out a review of licensing practices for deaf individuals across Australia, the United Kingdom, Ireland, New Zealand and Canada, concluding that there is significant variation in the support provided for deaf learner drivers across licensing authorities. In certain areas, licensing test materials do not cater for deaf individuals, and support from outside parties is not permitted during assessments; a highly problematic situation given that literacy rates in this demographic can be low (Mayer, 2007). Other authors have highlighted the safety considerations in terms of communicating with the police once deaf drivers have obtained their license, pointing out that many officers are inept at communicating effectively with the deaf demographic (Ohene-Djan et al., 2010). Research regarding this topic is, therefore, of paramount importance not only for the development of knowledge, but also in terms of identifying measures which can be taken to improve these considerations for deaf and hearing impaired drivers.

1.1.4 Thesis focus

The aim of the work presented in this thesis is to begin to unpick the effect of partial hearing loss on driving in order to inform knowledge in this area. Most of the existing work looking at the effect of partial hearing loss on driving has simply investigated accident or cessation rates; it does not inform on the specific driving practices of people with a hearing loss. Whilst it is important to assess the accident risk arising as a result of hearing impairment, this information does not provide knowledge regarding the underlying reasoning behind potential driving complications. This depth of information could be used to inform the development of suitable countermeasures, which may aid the continued safe driving of hearing impaired individuals.

The work presented here is primarily concerned with expanding the understanding of how partial hearing loss *specifically* affects driving performance. In line with the thinking of Hickson et al. (2010), the studies described are interested in whether auditory distraction has a disproportionate effect on hearing impaired drivers. Only one prior study has investigated the effect of hearing loss on driving whilst subjects performed a concurrent auditory task (Hickson et al., 2010). Indeed, data regarding the specific driving practices of those with a hearing loss is sparse, and so the course of study described in this thesis fills an important gap in the academic literature on this topic. This new knowledge should contribute to more informed decisions for policy makers and practitioners when considering the driving performance of hearing impaired individuals.

Chapters two and three provide a detailed overview of the different manners by which hearing loss might affect driving performance. However, it is the disproportionately distracting effect of sound for hearing impaired drivers, described by Hickson et al. (2010), which becomes the focus of this thesis. This document reports on a series of experiments aimed at investigating the effect of auditory distraction on driving in partially hearing impaired individuals.

Chapter four reports on a questionnaire study which was performed on hearing impaired individuals to gather self-reported problems related to everyday driving. This was a novel approach which has been entirely neglected by previous research in this area. Having investigated what hearing impaired individuals identified as being problematic for driving, objective work in which the distracting effect of speech comprehension was compared between normally hearing and hearing impaired individuals. Research suggests that the efficiency with which visual information is processed can be affected by the concurrent performance of an auditory/cognitive task (Pomplun et al., 2001; Wood et al., 2006). Thus ***chapter five*** describes a laboratory-based experiment was performed where normally hearing and hearing impaired individuals were asked to simultaneously perform a computer-based visual task with a speech comprehension task. This study was suggestive of a disproportionate reduction in the functional visual processing abilities of the hearing impaired sample. However, there was some concern that factors co-existing with hearing loss may be having an effect on study outcomes.

Chapters six and seven describe a method of hearing loss simulation which was selected for continuing work in this area, in order to control extraneous factors. This method was analysed in terms of its accuracy, validity, and effect on listening-based working memory tasks. The simulation provided an accurate representation of hearing loss, and as such was employed in a final study assessing the effect of hearing loss on driving using the University of Leeds Driving Simulator (UoLDS). ***Chapter eight*** reports on this study, in which participants were asked to drive whilst performing some of the working memory tasks both under normally hearing and Simulated Hearing Loss (SimHL) conditions. Various measures of driving performance, eye movement behaviour and cognitive workload were used in order to establish the effect of hearing loss on driving ability. ***Chapter nine*** summarises and discusses the work described in this thesis, and provides some questions and directions for future work which have arisen from undertaking this project.

Chapter 2

Literature Review

2.1 Introduction

This chapter provides a review of existing literature relevant to how hearing loss affects driving. However, it will begin by giving a brief overview of what hearing loss is, what effect it has on various aspects of the perception of sound, an explanation of how it is measured, and defining certain technical terms which will be used throughout this thesis. Following this overview, studies which have explicitly investigated the effect of partial hearing loss on driving will be reviewed, and literature which is relevant to this topic will be discussed. Finally a summary of the current state of knowledge in this area will be presented, as well as the research questions addressed by work described in this thesis.

2.2 A brief overview of hearing loss

Hearing loss is a highly prevalent condition (Roth et al., 2011) which is considered to affect one in twelve people aged 18–80 in the United Kingdom (Akeroyd et al., 2014). As a commonly age-related condition (Davis, 1995), the prevalence of hearing loss appears to be growing in accordance with an aging population (Laplante-Lévesque et al., 2010). Furthermore, the emerging leisure activities of adolescents (e.g. prolonged personal stereo use) are suggesting that hearing impairment may become a problem for the younger demographic (Niskar et al., 2001; Crandell et al., 2004; Chung et al., 2005). Research on the implications of hearing loss and management strategies for its effects are, therefore, more pertinent than ever.

The Oxford Dictionary 2012 defines the phrase *hearing impaired* as 'partially or completely deaf', and the term *deaf* as 'lacking the power of hearing or having impaired hearing'. In this thesis a distinction is made between those who are 'completely deaf' and those who are 'partially deaf', given that the considerations for driving are likely to be different for each group. Henceforth, in accordance with the World Health Organization (2015) classifications, the term '**deaf**' will be used to describe individuals who can hear no sound and rely entirely on lip-reading and/or sign language in order to communicate. Conversely, individuals who have the ability to hear sound, but subject to distortions and reduced sensitivity associated with damage to the auditory system will be described as '**hearing impaired**' or having a '**hearing loss**'. The focus of this thesis is the driving performance of *hearing impaired* individuals.

Although the dictionary definitions of 'deaf' and 'hearing impaired' are accurate, they fail to indicate the vast number of problems that arise from such a sensory loss (Graham and Baguley, 2009). Plomp (1986) discusses two separate facets of hearing loss: (1) *attenuation* to sounds, which arises as a result of loss of sensitivity within the auditory system, and (2) *distortion* to sounds, a degradation in the quality of sounds which are above the threshold of hearing. This distortion to sounds is not accounted for if hearing loss is simply seen as something which limits audibility in the driving environment.

The effect of sound distortion is important, given that its implications cannot be reversed. Rehabilitative interventions such as hearing aids provide greater audibility. However, despite aiming to minimise the influence of distortion to sounds (Moore, 1996), problems with speech understanding persist, even when sound is audible. This is true especially in unfavourable listening conditions, such as in background noise (Ricketts, 2001). In fact, in some cases, the louder the sound, the less information can be extracted from the signal by an individual with hearing loss (Studebaker et al., 1999).

There are a number of pathologies which can cause hearing loss (e.g. noise exposure, aging, the use of ototoxic drugs), though it is beyond the scope of this thesis to provide an in depth discussion of them all. Accordingly, the main complications that arise as a result of generic sensory hearing loss will be discussed. The following section will provide a brief overview of how human hearing operates, and how it can be tested in order to establish normal functioning.

2.2.1 A brief overview of human hearing

The human ear is a complex system consisting of multiple structures which can be broadly classified in to three main components: the outer, middle, and inner ears (see Figure 2.1).

Sound is heard through a series of sequential events: vibrations of the air are focused by the pinna and are propagated down the external auditory canal where they strike the 'tympanic membrane', which vibrates according to the waveform of a sound. Attached to the tympanic membrane is a chain of three bones in the air-filled middle ear (the malleus, incus and stapes; collectively known as the 'ossicles') which move in accordance with vibrations of the tympanic membrane. The last of the three ossicles in the chain, the stapes, is attached to the fluid-filled sensory organ of hearing (the cochlea) via a structure known as the 'oval window', a flexible membrane which separates the inner and middle ears.

The function of the ossicles (in conjunction with the tympanic membrane) is to overcome an 'impedance mismatch' between the air-filled middle ear and fluid-filled inner ear and ensure efficient transfer of sound to the inner ear (Moore, 2007). The term 'impedance

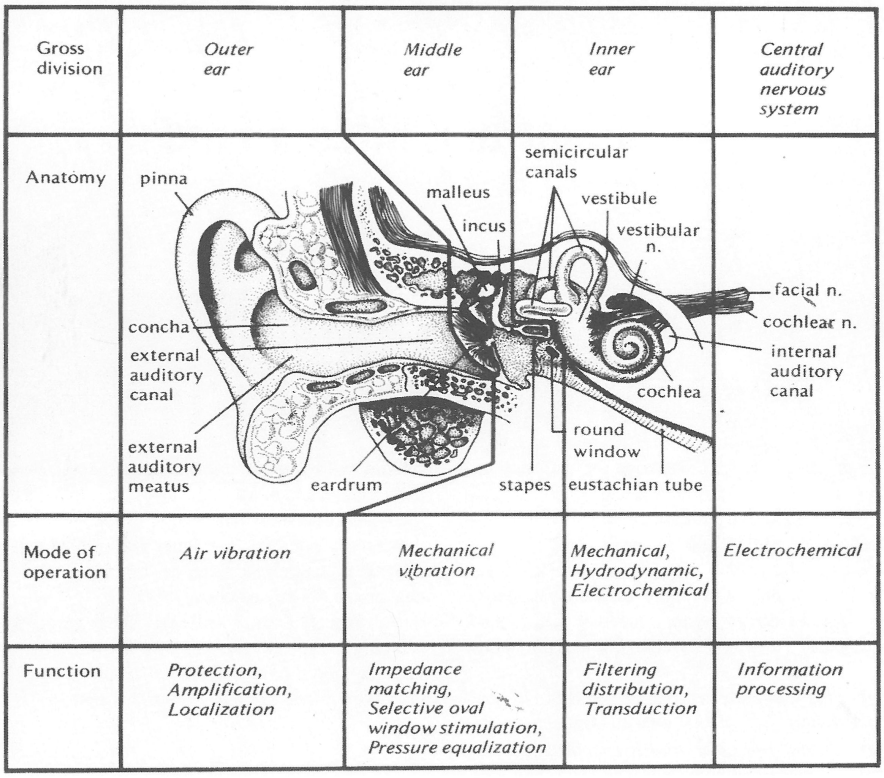


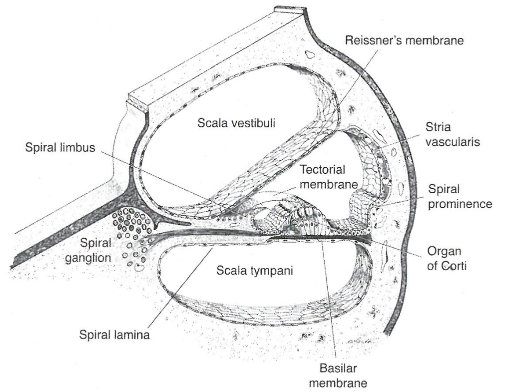
Figure 2.1 The anatomy of the human ear, how each part operates and their respective functions. Source: Yost (2000).

mismatch' refers to the difference in resistance between air (low-impedance) and the fluid of the inner ear (high-impedance), meaning that if sound impinged directly on the oval window, most would simply be reflected back, leading to a large loss (between 30–40 dB) of acoustic energy (Goode, 1986).

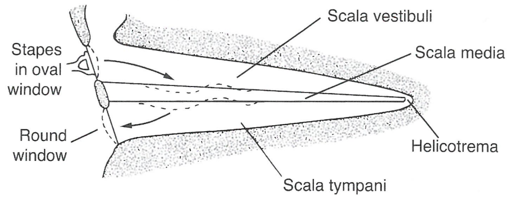
The oval window is attached to one of three chambers (or scalae) within the cochlea, the 'scala vestibuli' (see Figure 2.2). Lateral movement of the stapes causes waves, congruent with the acoustic source, to travel through the fluid within the cochlea. These waves follow the path shown in Figure 2.3, causing movement of the various membranes within the cochlea, and terminate at the 'round window'.

As can be seen, the cochlea is essentially a tube which is divided in half along its length by a structure known as the 'Organ of Corti'. The Organ of Corti contains rows of two different types of hair cell (stereocillia), which are positioned along the length of the cochlea: (1) Inner Hair Cells (IHCs), and (2) Outer Hair Cells (OHCs). The structure of the Organ of Corti, and the progressive nature of the stereocillia continuing along the length of the cochlea can be seen in Figure 2.3.

The motion of the fluid within the cochlea causes the 'basilar membrane' (a structure within the Organ of Corti on which the stereocillia are located) to vibrate, and these different types of stereocillia to deflect. The physiology of the basilar membrane progressively changes from the base of the cochlea to the apex; at the base the basilar membrane is

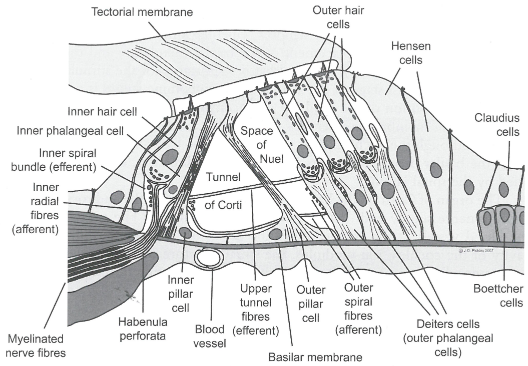


(a) A magnified cross section of the cochlear duct

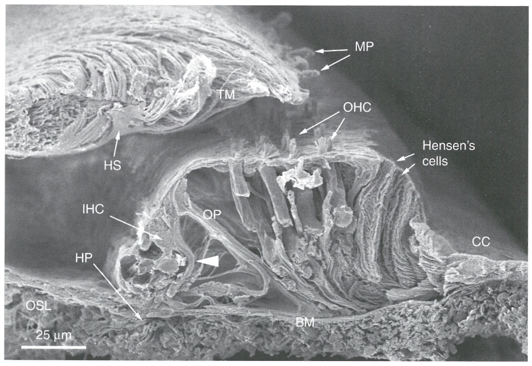


(b) A schematic diagram of the cochlear duct depicted as unrolled. The path of vibrations is shown

Figure 2.2 The physiology of the human cochlea. Source: Pickles (2012).



(a) Cross section of the Organ of Corti



(b) Scanning electron micrograph of a cross section of the Organ of Corti

Figure 2.3 The physiology of the Organ of Corti. MP: marginal pillars, OHC: outer hair cell, CC: claudius cell, OP: outer pillar cell, HP: habenula perforata, IHC: inner hair cell, TM: tectoral membrane, OSL: osseous spiral lamina, HS: Hensen's stripe. Source: Pickles (2012).

relatively narrow and stiff, whereas at the apex it is wider and less stiff. Due to the mechanical properties of travelling waves this means that different frequencies produce peaks at different points on the basilar membrane (see Figure 2.4). This is known as a 'tonotopic' arrangement, meaning that the cochlea is arranged in a progressive, (high–low) frequency-specific manner.

The deflection of the IHCs activates them to depolarise, causing action potentials to be sent along the cochlear nerve to higher auditory centres. Given the frequency-specific nature of the cochlea's physiology, IHCs will respond to a specific frequency, depending on their location within the cochlea. OHCs are also frequency specific, depending on their location, but instead of relaying auditory information to higher auditory centres, are involved in an active process within the cochlea whereby, as part of an efferent feedback loop, they utilise somatic electromotility (oscillate their own length through active vibrations of the

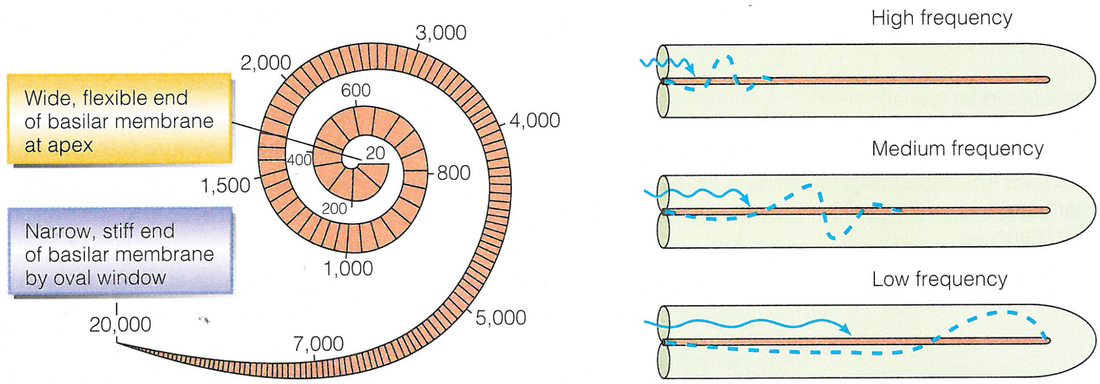


Figure 2.4 A depiction of the physiological differences in the basilar membrane at the base and apex of the human cochlea. These differences produce distinct vibratory patterns by sounds of different frequencies (shown on the right with the cochlea unwound). This leads to frequency specificity at certain points in the cochlea, the regions of maximal vibration for different frequencies (Hz) are provided on the left. Source: Chiras (2013).

cell body; Brownell, 1990). The motion produced by OHCs increases basilar membrane vibration at specific frequencies, thus acting as an amplifier and fine tuning frequency response within the cochlea. Therefore, IHCs can be described as the 'true sensory cells of the inner ear', as OHCs do not provide sensory information about sound to higher auditory centres (Yanz, 2002).

Hearing impairment can arise from damage to, or abnormalities associated with, any of the structures within the outer, middle, or inner ear, or at higher auditory centres. Loss of hearing occurring at the gross division of the inner ear or thereafter is known as Sensorineural Hearing Loss (SNHL), whereas 'conductive' hearing loss occurs at, or prior to, the gross division of the middle ear.

Given the function of associated structures, the perceptual consequences of SNHL are more complex than conductive hearing loss (Moore, 2007). Conductive hearing loss generally only subjects a listener to a loss of auditory sensitivity, given that the auditory system is compromised in terms of its ability to overcome the impedance mismatch between the air-filled middle ear and fluid-filled inner ear. Within the inner ear, however, an 'active mechanism' is at work (Moore, 1996), meaning that damage to these structures not only reduces audibility, but also distorts other aspects of sound; this is discussed further in subsection 2.2.3.

The common clinical methods used to measure hearing function are discussed in the following section.

2.2.2 The measurement of hearing loss

The standard method of assessing hearing in clinical practice is a technique known as 'pure tone audiometry'. Using an 'audiometer', a calibrated device capable of producing sinusoidal pure tones at a known intensity across different frequencies, the quietest sounds that a subject can hear across the frequency range 250–8000 Hz are established; these are known as ’absolute thresholds’. Pure tones of different frequency and intensity are produced (each lasting 1–3 seconds), and subjects are asked to indicate when they are able to hear these sounds via a button press. Generally, patients are tested at frequencies of 0.25, 0.5, 1, 2, 4, and 8 kHz, one ear at a time. A staircase method is used to establish each respective absolute threshold.

This assessment is normally carried out in a sound-proofed booth, minimising the influence of background noise. Plotting these absolute thresholds for each ear produces a graph known as an ‘audiogram’. Figure 2.5 shows an example audiogram for a patient, with the absolute thresholds for both ears. Note that ‘air conduction’ and ‘bone conduction’ values are shown. Air conduction is measured using headphones that pass sound through the entire auditory system (outer, middle, and inner ears), whereas bone conduction is performed by using a vibrating pad placed on the mastoid bone behind the outer ear. This propagates sound through vibration of the skull, bypassing the outer and middle ear, sending sounds straight to the inner ear, thus testing underlying sensory ability. A difference in the air and bone conduction absolute thresholds is, therefore, indicative of a conductive hearing loss.

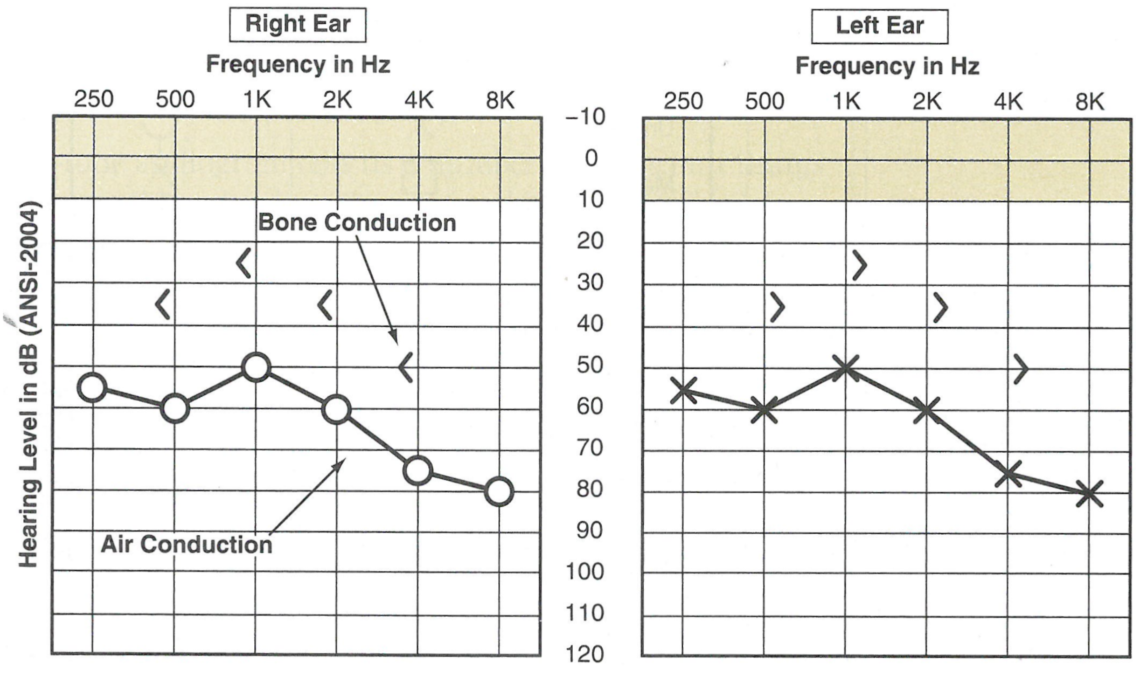


Figure 2.5 An example audiogram. Source: Stach (2008).

From these hearing thresholds an average (usually from data at 250, 500, 1000, 2000, and 4000 Hz) is taken to classify the degree to which an individual has an impairment; the common clinical classification guidelines for the United Kingdom are shown in Figure 2.6. These are the descriptors which will be used throughout this document.

Though it provides a measure of physiological function, pure tone audiometry cannot provide information about the level of damage to different types of hair cell within the cochlea (i.e. differentiate between OHC and IHC damage), nor can it discern whether there is an influence of any central auditory processing deficit. Given the variety of functions associated with these different types of structure within the auditory system (e.g. frequency, temporal and loudness processing), it is not possible to predict the extent to which an individual will experience issues in day-to-day living as a result of their sensory impairment. For example, the extent to which an ear is able to distinguish between two different frequencies is not very well predicted by audiometric thresholds (Simon and Yund, 1993). Indeed, measures of hearing sensitivity, such as pure tone audiometry, are often not very well correlated with more subjective reports of hearing ability (Weinstein and Ventry, 1983; Newman et al., 1990; Stephens and Zhao, 1996; Nondahl et al., 1998).

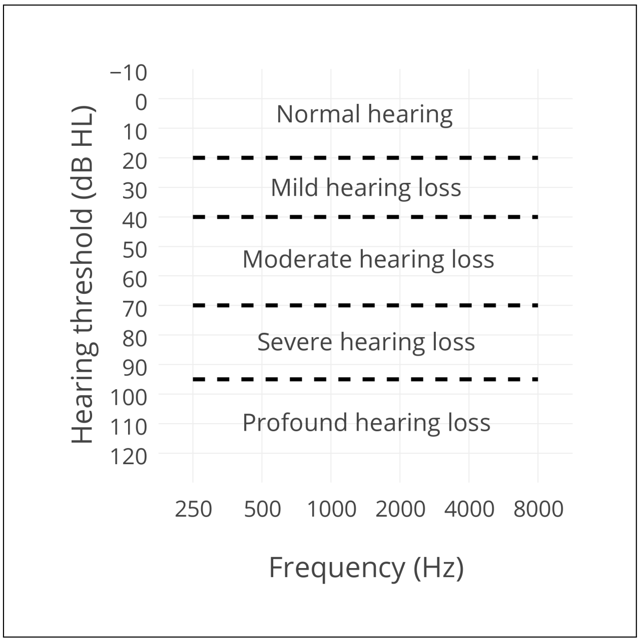


Figure 2.6 Audiometric descriptors for hearing loss severity used in the United Kingdom. Mean thresholds are calculated from data at 0.25, 0.5, 1, 2, and 4 kHz, and are specified for each ear individually. Source: British Society of Audiology (2011).

In order to establish what effect hearing loss has in a more ecologically valid manner, two main approaches have been taken: speech testing and self-reported experiences of individuals.

During speech testing, a pre-defined list of words or sentences are played at different intensities to the subject, who is asked to repeat back aloud what was heard. A percentage correct score as a function of intensity can then be plotted, resulting in what is known as a 'speech audiogram' (see Figure 2.7). Further validity can be incorporated by testing speech perception in noise, thus providing a measure of the ability to extract auditory information of interest from a background masker. A speech audiogram sometimes highlights the distortion to sound brought about by SNHL. The example shown in Figure 2.7 exhibits what is termed 'rollover' - above a certain threshold, the louder a sound is made, the less intelligible it becomes.

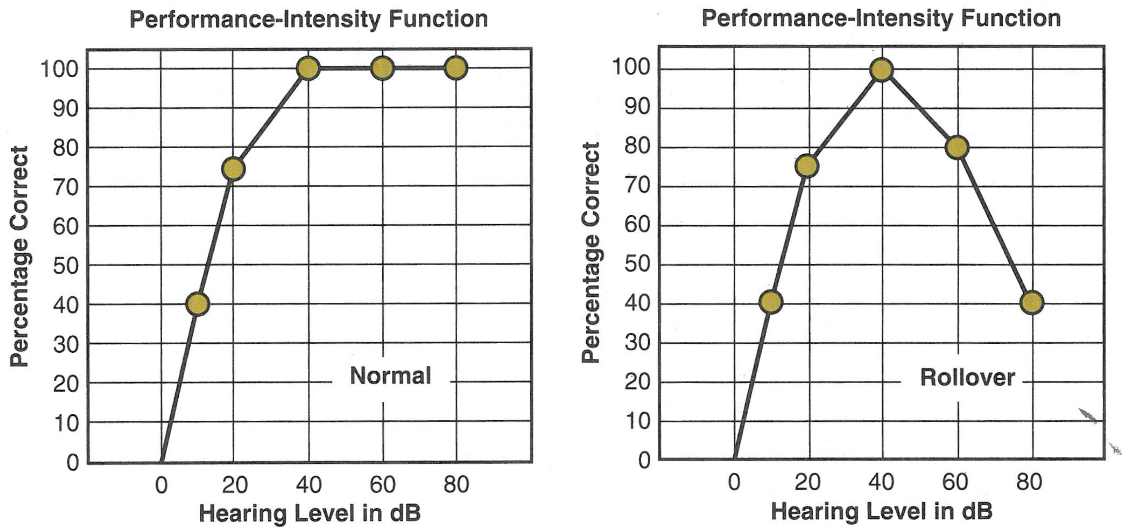


Figure 2.7 An example speech audiogram. The percentage of correct words in a list, or phonemes in a set of words, are plotted against the intensity of the signal used. Source: Stach (2008).

Self-reported experiences of hearing loss are also used to measure the extent to which an individual has a problem with their hearing. This assessment technique is usually carried out in a structured manner through the use of a validated questionnaire. One of the most commonly used examples of this is the Hearing Handicap Inventory for the Elderly (HHIE), which is shown in Figure 2.8.

Self-reported hearing loss, assessed in this manner, measures a different construct to speech or pure tone audiometry, a distinction which is highlighted by the use of the word 'handicap' in the title of the questionnaire. The term 'handicap' was defined by the World Health Organization (1980) as: "a disadvantage for a given individual resulting from an impairment or a disability, that limits or prevents the fulfilment of a role that is normal (depending on age, sex, and social and cultural factors) for that individual". Impairment was defined as "any loss or abnormality of psychological, physiological, or anatomical structure or function" and disability as "any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being".

Though this document has since been superseded (World Health Organization, 2000), and the terms replaced, the notion remains that the extent to which an individual is affected by a sensory impairment is not entirely governed by the characteristics of their disability, but more so by the associated social and environmental factors.

Accordingly, self-reported hearing loss establishes the extent to which loss of hearing impacts upon the performance of other activities and roles. This distinction can, therefore, explain the fact that objective and subjective measures of hearing function are not always related, as might perhaps be expected (Weinstein and Ventry, 1983; Newman et al., 1990;

The Hearing Handicap Inventory for the Elderly

Please answer all of the following questions with either (1) 'yes', (2) 'no', or (3) 'maybe'.

1. Does a hearing problem cause you to use the phone less often than you would like?
2. Does a hearing problem cause you to feel embarrassed when meeting new people?*
3. Does a hearing problem cause you to avoid groups of people?
4. Does a hearing problem make you irritable?
5. Does a hearing problem cause you to feel frustrated when talking to members of your family?*
6. Does a hearing problem cause you difficulty when attending a party?
7. Does a hearing problem cause you to feel "stupid" or "dumb"?
8. Do you have difficulty hearing when someone speaks in a whisper?*
9. Do you feel handicapped by a hearing problem?*
10. Does a hearing problem cause you difficulty when visiting friends, relatives, or neighbours?*
11. Does a hearing problem cause you to attend religious services less often than you would like?*
12. Does a hearing problem cause you to be nervous?
13. Does a hearing problem cause you to visit friends, relatives, or neighbours less often than you would like?
14. Does a hearing problem cause you to have arguments with family members?*
15. Does a hearing problem cause you difficulty when listening to TV or radio?*
16. Does a hearing problem cause you to go shopping less often than you would like?
17. Does any problem or difficulty with your hearing upset you at all?
18. Does a hearing problem cause you to want to be by yourself?
19. Does a hearing problem cause you to talk to family members less often than you would like?
20. Do you feel that any difficulty with your hearing limits or hampers your personal or social life?*
21. Does a hearing problem cause you difficulty when in a restaurant with relatives or friends?*
22. Does a hearing problem cause you to feel depressed?
23. Does a hearing problem cause you to listen to TV or radio less often than you would like?
24. Does a hearing problem cause you to feel uncomfortable when talking to friends?
25. Does a hearing problem cause you to feel left out when you are with a group of people?

Figure 2.8 The Hearing Handicap Inventory for the Elderly (Ventry and Weinstein, 1983); the screening version (Weinstein et al., 1986) is highlighted with asterisks.

Stephens and Zhao, 1996; Nondahl et al., 1998).

Since the development of the HHIE, its correlation with absolute thresholds has been assessed (Weinstein and Ventry, 1983), in order to establish if it can be used as a screening tool to identify individuals with a hearing loss. Data suggested that the absolute thresholds of 100 elderly subjects accounted for less than 50% of the variance in their HHIE scores, and word recognition accounted for less than 20%. This weak correlation with pure tone audiometry and word recognition data has also been shown for a version of the HHIE adapted for younger adults, the Hearing Handicap Inventory for Adults (HHIA) (Newman et al., 1990). Both Weinstein and Ventry (1983) and Newman et al. (1990) argue that audiometric data alone is insufficient to gauge an individual's reaction to their own personal hearing impairment. Though this is the case, given the test-retest repeatability of the HHIE and HHIA (Weinstein et al., 1986; Newman et al., 1991), and the ease of administration, it has been suggested that these measures may identify individuals in a community setting in need of more thorough audiological examination. To this end, a shorter version of the HHIE was produced; the Hearing Handicap Inventory for the Elderly (screening version) (HHIE-S) (Ventry and Weinstein, 1983). This version contained 10 of the original 25 HHIE items (see Figure 2.8), and retained its validity (Weinstein, 1986).

Differences in the impact of hearing loss can arise, even when individuals exhibit identical absolute thresholds (Halpin and Rauch, 2009). This is because pure tone audiometry cannot distinguish between the damage that has occurred to different structures within the auditory system, rather it provides a measure of *overall* function. Different perceptual consequences can arise as a result of damage to different parts of the auditory system (e.g. the complete loss of IHCs would have very different outcomes compared to the complete loss of OHCs). The next section will provide a brief overview of the perceptual consequences which arise as a result of SNHL.

2.2.3 The perceptual consequences of hearing loss

It is beyond the scope of this document to cover all of the perceptual consequences associated with SNHL (for a detailed overview see Moore, 2007). However, four of the main perceptual consequences, 'elevation of absolute threshold', 'loudness recruitment', 'reduced frequency selectivity and discrimination', and 'impaired temporal processing' are key concepts which are referred to extensively later in this thesis. They are described below.

2.2.3.1 Elevation of absolute threshold and loudness recruitment

Elevation of absolute threshold is the aspect of hearing loss that is measured by pure tone audiometry. It refers to the fact that sounds have to be made louder before they can be perceived by somebody with a hearing loss, i.e. the auditory system has a lower sensitivity. This reduction in sensitivity can manifest in a frequency specific manner. For example, noise induced hearing loss causes a sharp dip in sensitivity at 3–6 kHz (Rabinowitz, 2000), and age-related hearing loss exhibits progressively less sensitivity with increasing frequency (Gates and Mills, 2005). Although the elevation of absolute threshold also occurs for conductive hearing loss, SNHL has the added complication of 'loudness recruitment'.

Loudness recruitment is a well-established and extensively studied phenomenon which most (if not all) individuals with SNHL exhibit to some extent (Moore, 2007). It describes an abnormal growth of (perceived) loudness level with increasing (physical) sound level at intensities above absolute threshold. This abnormal growth of loudness continues for sounds up to a level of between 90-100 dB SPL, after which loudness growth returns to normal (Moore, 2007). This is depicted in Figure 2.9, which shows what would be expected if somebody with a unilateral SNHL was asked to match the loudness of a tone played to their normal ear (the reference tone) against another tone played to their impaired ear (the comparison tone) (Moore and Glasberg, 1997, 2004; Moore et al., 1999).

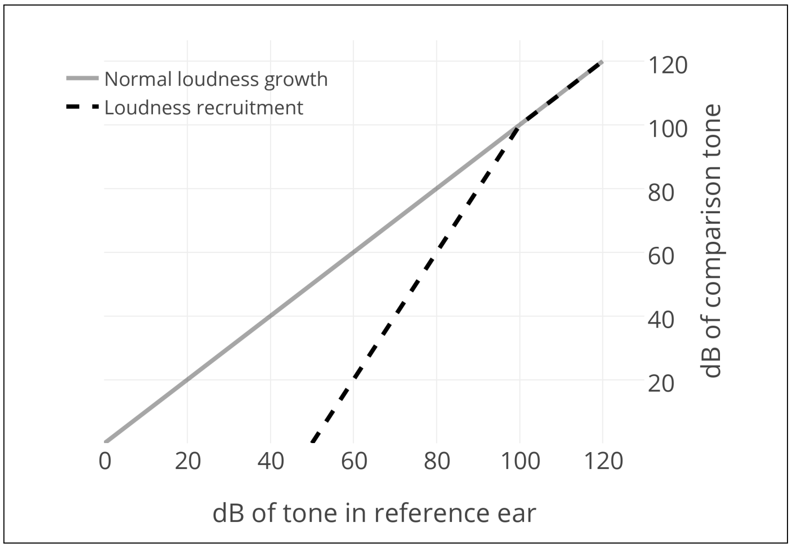


Figure 2.9 An example of loudness recruitment for a hearing loss of absolute threshold 50 dB HL. The graph reflects the expectation if a subject with unilateral SNHL were asked to match the loudness of a tone played to their normal ear against the loudness of a tone in their impaired ear.

In some cases, hearing impaired individuals can experience what is termed 'over recruitment', where loudness growth does not return to normal at high sound intensities (Moore, 2007). This can lead to a reduction in the loudest comfortable noise intensity for those with a hearing loss.

There are a number of practical implications of elevated absolute thresholds and loudness recruitment:

1. Missing auditory information.
   A loss of sensitivity in the auditory system means that certain sounds are simply not heard by the listener. This applies to complete sounds, but also gives rise to problems in speech perception as phonemes or whole words within a passage may

be missed. Of particular concern in this regard is the fact that certain consonant sounds are often weak or are easily masked by other content, and are thus missed more often (Moore, 2007). This presents problems as consonants are the part of speech which tend to carry most meaning (Yost, 2000), and as such people with a hearing impairment may often mishear words.

2. A reduced 'dynamic range'.
   Due to the abnormal growth of loudness, reduced sensitivity in the auditory system, and over recruitment, a reduced 'dynamic range' (the range between absolute threshold and the highest comfortable level) is sometimes noted (Moore et al., 1992; Moore, 2003b). This reduced dynamic range may present problems for rehabilitative interventions such as hearing aids, as a certain degree of amplification may cause some sounds to be uncomfortably loud, whilst still not providing enough amplification for other sounds to be heard.

3. Altered loudness cues used in the perception of speech.
   The loudness relationships between components of speech sounds are thought to be important for speech intelligibility (Plomp, 1988; Shannon et al., 1995). However, loudness recruitment leads to a distortion of these loudness relationships, as the difference in level between soft and loud phonemes of speech will be exacerbated (Moore, 2003b). Thus, the intelligibility of speech will be compromised.

2.2.3.2 Reduced frequency selectivity and discrimination

'Frequency selectivity' refers to the ability of the auditory system to separate out the elements in a sound made up of many components (Moore, 2007). For example, if two pure tones of distinct frequency were played to somebody with normal hearing, they would be able to hear each tone individually. This is an important feature of the auditory system, as frequency selectivity plays an important role in many aspects of auditory perception (Moore, 2007).

Frequency selectivity can be measured using *masking* experiments. In these experiments a stimulus tone of a fixed low intensity is played simultaneously with a masker noise covering a specific band of frequencies. The masker is played at different intensities until the subject indicates he/she can no longer hear the stimulus tone. The procedure of establishing the quietest masker noise needed to cease perception of the stimulus is repeated for masking noises of various frequency bands, and the results are plotted to produce a graph called a Psychophysical Tuning Curve (PTC), an example of which is shown in Figure 2.10.

The masker provides less interference with the perception of the stimulus tone as its centre frequency is moved away from the frequency of the tone. This is because, due to the tonotopic arrangement of the cochlea, different IHCs are activated by the two sounds. Given the specificity of IHCs, and the fine tuning provided by OHCs, however, it can

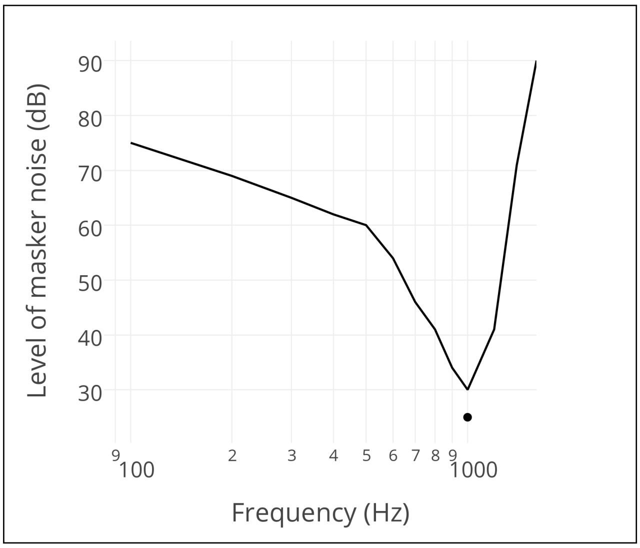


Figure 2.10 A PTC measured at a stimulus frequency of 1 kHz (shown by the dot). Adapted from: Gelfand (2009).

be seen that the stimulus tone is perceived even when its frequency is very close to the frequency content of the masker, hence this example exhibits good frequency selectivity.

When PTCs are recorded for a range of frequencies, the result is a number of overlapping PTCs (see Figure 2.11). These results have led to the cochlea being modelled as a bank of overlapping 'bandpass filters', which are able to pass sound information of interest and filter out interfering off-frequency noise (Moore, 2003a).

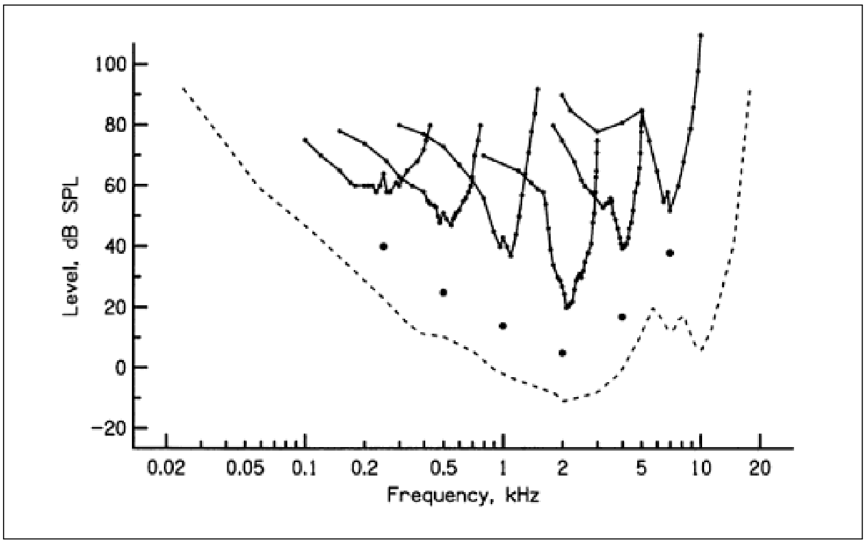


Figure 2.11 PTCs measured for a range of stimulus frequencies. The solid line represents the masking level required to halt perception of the signal. The dashed line is the subject's absolute threshold, and the dots below each PTC represent the various stimuli tones. Source: Moore (2003a).

In individuals with SNHL, these auditory filters sometimes appear to be broader than they are for normally hearing subjects (see Figure 2.12); thus showing a reduction in frequency selectivity, because two pieces of auditory information are more likely to fall within the same auditory filter. Furthermore, in some cases, all of the IHCs at a certain place within the cochlea may be absent, or non-functioning, rendering the ear incapable of responding to corresponding frequencies (Moore, 2001). In this case, off-frequency listening occurs whereby IHCs from a different region in the cochlea relay information about the sound to higher auditory centres (see Figure 2.12); this causes distortion to the quality of sound.

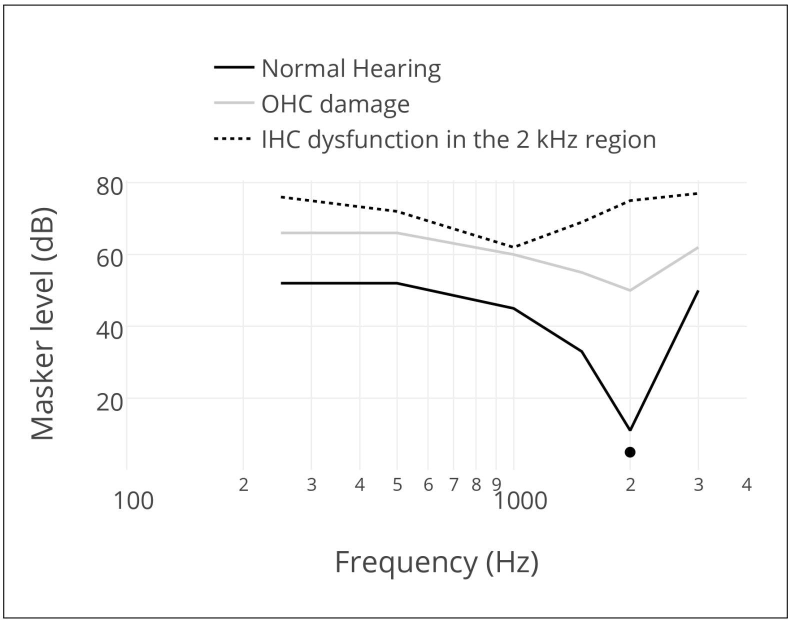


Figure 2.12 Hypothetical PTCs measured to a 2 kHz stimulus from three ears: (1) normal hearing - the PTC shows sharp tuning; (2) an ear with OHCs damage - a broader shape is noted with less frequency specificity; (3) an ear that has no functioning IHCss corresponding to 2 kHz, the tone is perceived by IHCs at a different place along the basilar membrane. Adapted from: Yanz (2002).

A reduction in frequency selectivity can have a number of practical implications:

1. Extraneous masking sounds have a greater influence on successful listening.
   Because auditory filters are wider in those with SNHL, sounds extraneous to the source of interest are more likely to have a masking effect. This may lead to an increased difficulty in listening during very noisy conditions. In addition to this, complications with temporal resolution[1], another common perceptual consequence of SNHL, mean that hearing impaired individuals are less able to take advantage of dynamic gaps in a masking noise and 'listen in the gaps' in order to maintain successful speech understanding (Moore, 2003b).

2. Reduced perception of spectral components in a sound.
   The output of the auditory filters in the cochlea resembles a blurred version of

[1]The ability to resolve sounds with respect to time.

the input spectrum (Moore and Glasberg, 1997). The perception of this spectral shape is important for speech recognition, but in cases of SNHL, auditory filters are broader, and as such the spectrum is more 'smoothed' or less distinct (Moore, 2003b). Accordingly in some cases, small spectral details of a sound may be imperceptible, and the addition of a background noise may exacerbate this problem by reducing this spectral detail further, thus degrading speech understanding.

3. Impaired 'timbre perception'.
   Timbre is often referred to as the *quality* of a sound, and allows for distinction between sources of sounds, e.g. which instrument has played a note (Halpern et al., 2004). Certain abilities associated with timbre perception, such as the differentiation of steady-state vowels, are heavily reliant on the subtle spectral differences in sounds (Moore, 2007). As such SNHL, which makes it difficult to pick-up on these spectral differences as a result of impaired frequency selectivity, hinders successful understanding of speech in this regard.

2.2.3.3 Impaired temporal resolution

'Temporal resolution' refers to an ability to detect changes in sound over time (Moore, 2007). Individuals with SNHL often exhibit poor temporal resolution, as damage to some of the structures in the cochlea alter aspects of temporal processing. For example, loudness recruitment leads to altered loudness relationships between sounds (Moore, 2007). Therefore, natural fluctuations in the waveform of a sound (e.g. white noise) can be confused as gaps within it, rather than natural variation (Glasberg and Moore, 1992). Phenomena such as this may lead to an impaired ability of hearing impaired individuals to detect gaps in a sound relative to those with normal hearing (Fitzgibbons and Wightman, 1982).

Temporal cues such as the above are thought to be important for speech understanding. For example, fricatives[2], such as 'f', rely on the ability to accurately detect duration to distinguish them from affricatives, such as 'ch' (Raphael and Isenberg, 1980). The confusion of these two types of sound has obvious implications for speech recognition and understanding. Likewise the duration of gaps in speech is thought to be important for the identification of phonemes (Rawool, 2006). Duration detection, however, appears to be impaired in those with a hearing loss (Irwin and Purdy, 1982), presenting difficulties for processing the temporal aspects of sound.

Another common observation in hearing impaired individuals is that it takes them longer to recover from 'forward masking' (Kidd Jr et al., 1984). Forward masking is a phenomenon whereby a masker sound played shortly before a stimulus can stop perception of the stimulus (Moore, 2007). This is thought to occur as a result of a reduction in

[2]A speech sound characterised by audible friction produced by forcing the breath through a constricted or partially obstructed passage in the vocal tract.

sensitivity of recently stimulated cells, or a persistence in the pattern of neural activity evoked by the masker (Moore, 2012). Thus, a loud sound quickly followed by a quieter one (i.e. as commonly occurs in speech) would be less perceptible for those with SNHL than it would for an individual with normal hearing, and thus portions of a sound of interest would not be heard.

These impairments to temporal processing ability render hearing impaired individuals at a greater disadvantage when perceiving speech, particularly in the presence of background noise. Moore (2007) argues that most sounds in everyday life are characterised by rapid fluctuations in amplitude from moment to moment, and because of inefficiencies in temporal processing, those with a hearing loss will be at a disadvantage in following the temporal profile of these sounds. Furthermore, in acoustically adverse environments, such as in excessive background noise, the ability to temporally resolve a sound source of interest may be hampered by the presence of fluctuating competing noise.

2.2.3.4 Summary of the perceptual consequences of sensorineural hearing loss

The overview of perceptual consequences associated with SNHL given here is far from exhaustive. However, this section has shown that the effect of SNHL goes far beyond a simple loss of sensitivity within the auditory system. Although SNHL manifests as a reduced ability to hear acoustic information, it also presents a number of problems for the perception of sound once it is at an audible level.

It is this difficulty in processing and understanding auditory information that has led authors to hypothesise that those with a SNHL have to employ more ‘listening effort’ in order to achieve successful auditory perception (Hornsby, 2013). The increased listening effort in hearing impaired individuals is highly pertinent in the context of this thesis. Thus, this consideration is discussed further in Chapter 3.

Given that various technical terms and concepts have now been introduced, the following section provides an overview of the work which has been carried out investigating the effect of hearing loss on driving. A review of directly related work is included, but there is also some discussion regarding work which has looked at the effect of auditory information on normally hearing drivers. These factors are considered in terms of their transferability to the hearing impaired demographic.

2.3 Current evidence regarding hearing loss and driving outcomes

Chapter 1 has summarised the limited evidence available regarding the effect of hearing loss on driving, and the disjointed policy decisions in the area. The following sections provides a more detailed review the existing literature in this area. These studies fall in to one of three categories with respect to the effect of hearing loss on driving: (1) road traffic accident rates, (2) driving cessation rates, and (3) measures of driving performance. This section will discuss Road Traffic Accidents (RTAs) and driving cessation rates that have been observed in hearing impaired individuals, section 2.4 then goes on to suggest why these observations might have occurred.

2.3.1 The effect of hearing loss on road traffic accident rates

A number of studies have investigated road traffic accident rates in hearing impaired drivers, and do not form a strong consensus.

2.3.1.1 Ivers et al. (1999)

Ivers et al. (1999) collected data from an older population ($\geq$ 49 years old) using a questionnaire administered to a large sample ($n = 2,326$) by trained researchers in an interview setting. The questionnaire included information regarding driving habits, RTAs during the past year, and level of hearing loss. Hearing loss was stratified into four categories: none, mild, moderate, and severe. Ivers et al. (1999) calculated prevalence ratios for RTAs relative to normally hearing individuals, which were adjusted for age and sex, and found that self-reported *severe* hearing loss was associated with a significant increase in the likelihood of self-reported car accidents. They also found that a hearing impairment in the right ear was significantly associated with accidents, and argued that in a country with right-hand drive vehicles (Australia), this ear may aid with hazard detection. These conclusions must be considered taking in to account that a propensity to self-report one variable (e.g. hearing loss) may be reflective of a participant's willingness to report another (e.g. driving accidents). As such, the relationship between hearing loss and RTAs may be inflated as a result of using self-reported measures.

2.3.1.2 McCloskey et al. (1994)

However, McCloskey et al. (1994) also investigated road traffic accident risk in this population, but found no effect of hearing loss. They performed a matched case-control study investigating the motor vehicle collision injuries of older drivers and their association with certain sensory impairments. They identified cases as older drivers (65 years or older) who had been involved in at least one road traffic accident reported to the police in Washington, USA between 1987 – 1988. The authors then assigned two controls to each of their cases, using age, sex and county of residence as matching criteria. They were able to access pure tone audiometry and speech test data, but found no significant effect of either on the risk of RTAs. Contrary to the results of Ivers et al. (1999), this would suggest that an inability to hear sounds whilst driving does not have a bearing on road traffic accident risk. McCloskey et al. (1994) did, however, find that hearing aid ownership was significantly associated with an increased risk of road traffic accidents. They also noted that those who reported wearing their hearing aids whilst driving were more at risk of having an accident, and that those who reported not wearing their hearing aids whilst driving also had an increased risk of accidents, though the latter of these trends did not reach significance. The authors suggested that extraneous sounds emitted from hearing instruments (e.g. feedback) might serve to distract drivers wearing hearing aids.

2.3.1.3 Sims et al. (2000)

Sims et al. (2000) also found no link between hearing loss and RTAs. They undertook a prospective cohort study in which a source population of older drivers ($\geq$ 55 years) was assembled and followed for five years. Information about the number of crashes that subjects had experienced during the study period was collected from state records. Their primary aim was to develop a structural equation model which predicted crash frequency according to visual and cognitive data, but they also collected self-reported hearing loss data using the HHIE-S and information regarding subjects' hearing aid use. Their data showed no significant association between hearing loss or hearing aid use and the frequency of road traffic accidents during the five year observation period.

2.3.1.4 Green et al. (2013)

More recently Green et al. (2013) have replicated the finding that hearing impaired individuals were not at an increased risk of RTAs. They performed an observational study using an elderly demographic aged 70 or older. The authors asked participants whether they had ever been diagnosed with a hearing impairment, and used this to classify people into a 'yes/no' hearing impairment group. Driving accident records from the past five years were obtained and participants were asked to complete a questionnaire regarding their driving habits. Again, contrary to Ivers et al. (1999), Green et al. (2013) found no significant association between hearing loss and an increased risk of motor vehicle collisions. However, they did find a significant increase of road traffic accidents in people who had both hearing and visual acuity impairments. Green et al. (2013) conclude that older drivers with dual sensory impairment are more at risk of road traffic accidents.

The above studies were all carried out in an older demographic, and investigated the risk associated with road traffic accidents for hearing impaired individuals alongside a number of other variables (e.g. visual acuity). However, two studies have explicitly investigated the effect of occupational noise exposure on RTAs, one of which specifically investigated the effect of noise induced hearing loss on accident rates (Barreto et al., 1997; Picard et al., 2008). These studies were performed on younger cohorts than the previously cited studies, thus reducing potentially confounding factors which are present in older drivers' accident records, e.g. an increased likelihood of injury from RTAs or a low-mileage bias (Langford et al., 2006).

2.3.1.5 Barreto et al. (1997)

Barreto et al. (1997) undertook a nested case-control study in a cohort of Brazilian steelworkers employed at a single mining plant. They investigated the socio-demographic, medical and occupational risk factors underlying an increased likelihood of mortality from motor vehicle injury (Barreto et al., 1996). The authors classified a case as workers who had died as a result of a motor vehicle accident whilst under employment at the mining plant within a given epoch. They do not present the age of their sample, but do divulge that 50% of cases were under the age of 35 years. Four controls were selected at random from all workers that were under employment at the same time, and born in the same year, as each respective case. Barreto et al. (1997) were able to collect medical data from routine measurements that the Occupational Health Department had made, and amongst these was whether the employee had a hearing deficit - although the authors provide no explanation of the criteria for this classification. When calculating odds ratios for death from road traffic accidents, they found a significant inflation of death risk in those diagnosed with a hearing deficiency.

2.3.1.6 Picard et al. (2008)

More recently, Picard et al. (2008) built upon the results of Barreto et al. (1997) by performing a retrospective case-control study on the very specific demographic of workers exposed to daily noise levels of over 80 L_{Aeq8hr} in Québec, Canada (age range = 16–64). They wished specifically to establish whether noise induced hearing loss was associated with an increased risk of road traffic accidents and/or violations. They linked state driving to public health records, and analysed the factors underlying road traffic accidents and violations during a five year study period. The public health records contained individually measured audiograms, as well as the level of occupational noise that workers were being exposed to. Picard et al. (2008) only analysed noise induced hearing losses. The authors found that hearing loss significantly increased the risk of having at least one road traffic accident in the five year period studied. The results also showed an increasing prevalence of road traffic accidents with increasing hearing loss severity, suggesting that the degree of hearing impairment is positively associated with accident risk. Picard et al. (2008) also found that speeding violations were less frequent in those with a hearing loss, and hearing loss severity was negatively correlated with speeding offences. However, traffic offences *not related to speeding* were *positively* correlated with hearing loss. Thus the data showed that those with a hearing impairment were more likely to commit traffic offences than their hearing counterparts, whereas they were less likely to be caught speeding.

In summary, it is clear that there is disagreement between the studies performed in this area, an overview of which is provided in Table 2.1. Some have found that hearing loss inflates accident risk (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008), whereas others have found no such trend (McCloskey et al., 1994; Sims et al., 2000; Green et al., 2013). One striking difference in the methodologies of these studies might explain this difference in outcomes; all of the studies finding an effect of hearing loss on driving failed to control for driving experience or annual mileage, whereas those which did not, had

Table 2.1 Statistically significant risk factors (relative to control conditions) associated with different driving performance indicators for the hearing impaired demographic.

Reference	Trend noted	Demographic group	Odds Ratio (OR) / Prevalence Ratio (PR) (95% CI)
McCloskey et al. (1994)	Increased risk of road traffic accident injury	Hearing aid owners Hearing aid users whilst driving	PR: 1.8 (1.1–2.8) PR: 2.1 (1.2–3.8)
Barreto et al. (1997)	Increased risk of death from motor vehicle injury	Those with a hearing loss	OR: 2.36 (1.15–2.85)
Ivers et al. (1999)	Increased risk of a self-reported car accident in the preceding year	Those with a self-reported severe hearing loss	OR: 1.5 (0.7–3.4)
Sims et al. (2000)	None	-	-
Picard et al. (2008)	Increase in risk of having at least one accident in the preceding five years	Just noticeable hearing loss Mild hearing loss Moderate hearing loss Severe hearing loss	PR: 1.06 (1.01–1.11) PR: 1.13 (1.05–1.21) PR: 1.18 (1.08–1.27) PR: 1.31 (1.20–1.42)
	Reduced risk of at least one speeding citation in the preceding five years	Barely noticeable hearing loss Mild hearing loss Moderate hearing loss Severe hearing loss	PR: 0.90 (0.86–0.94) PR: 0.87 (0.81–0.93) PR: 0.89 (0.82–0.97) PR: 0.80 (0.73–0.87)
	Increased risk of at least one non-speeding citation in the preceding five years	Barely noticeable hearing loss Mild hearing loss Moderate hearing loss Severe hearing loss	PR: 1.04 (1.01–1.07) PR: 1.06 (1.02–1.10) PR: 1.08 (1.03–1.13) PR: 1.10 (1.05–1.16)
Green et al. (2013)	None	-	-

accounted for these factors.

Hole (2013) notes that one of the main limitations of accident rate data is the difficulty in determining the exposure rate of people involved in recorded crashes. This is a complication because those who drive more miles per year have a greater exposure to involvement in accidents, yet those with a lower annual mileage tend to be less experienced drivers, and so have a higher crash risk when calculated per kilometre driven (Langford et al., 2006). Accordingly, it is of paramount importance to control for this factor in analyses of RTAs. The fact that certain studies cited here did not, casts doubt over their accuracy (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008).

In addition, Ivers et al. (1999) used self-reports of accident involvement, which can be easily biased by intentional or unintentional misrepresentation (Elander et al., 1993). This is thought to be a particular problem in samples of older adults (McGwin Jr et al., 1998; Boufous et al., 2010); the demographic being studied by Ivers et al. (1999). Furthermore, Ivers et al. (1999) quantified hearing loss through self-reports, rather than audiometric data. This method is apparent in other cited studies (Sims et al., 2000; Green et al., 2013), whereas some have used pure tone audiometry data in order to confirm hearing loss (McCloskey et al., 1994; Barreto et al., 1997; Picard et al., 2008). The use of different assessments of hearing loss does not appear to have a bearing on study outcomes, because studies using self-reported hearing loss do not form a consensus regarding driving outcomes, and likewise this is the case for studies using pure tone audiometry data. However, as mentioned in subsection 2.2.2, these two assessment types do not measure the same constructs, and as such it is implausible to compare results from them.

The study of Barreto et al. (1997) used a small number of observations, which is often a complication in accident rate data (Hole, 2007). They identified only 13 individuals with a hearing loss who had been killed as a result of a road traffic accident, but 132 who did not have a hearing loss. This very low sample size may have artificially inflated their estimation of accident risk in the hearing impaired sample, thus bringing their findings under further scrutiny.

The sample size of 11,683 hearing impaired participants used by Picard et al. (2008) was much greater, and they also used state-recorded accident data which are not prone to misrepresentation. However, although Picard et al. (2008) controlled for a number of variables in their analyses (age, noise exposure levels, and the length of noise exposure in career), annual mileage and driving experience were not amongst these. This, again, calls the results of this study in to doubt, just as was the case for Ivers et al. (1999) and Barreto et al. (1997).

Thus, all of the studies which have found an effect of hearing loss on road traffic accident rates are questionable because of methodological oversights. Other studies which have been cited tend to have stronger methodologies. In particular, Green et al. (2013) based their calculations on accidents per kilometre driven, and controlled for a number of extraneous variables (race, gender, age, number of medical conditions, and three measures of cognitive abilities). The latter three of these variables are considered important, given the older demographic in the majority of studies investigating the effect of hearing loss on RTAs. Hearing loss is heavily correlated with age, and so other age-related factors (e.g. cognitive slowing; Salthouse, 1991) should be sufficiently accounted for in analyses. Particularly as many age-related changes in function are considered important factors in the maintenance of driving safety (Anstey et al., 2005).

A number of studies did not investigate accident involvement as a function of hearing loss severity, instead simply classifying hearing loss as ‘present’ or ‘absent’ (Barreto et al., 1997; Sims et al., 2000; Green et al., 2013). Of the studies which did investigate hearing loss severity, one found an increase in road traffic accidents only as a result of severe hearing loss (Ivers et al., 1999), one found that *all* degrees of hearing loss (classified as $\geq$ 15 dB in both ears at 3, 4, and 6 kHz) resulted in an increase in accident risk, and that this accident risk was positively correlated with hearing loss severity (Picard et al., 2008), and one study did not find an increase in accident rate regardless of severity (McCloskey et al., 1994). Thus it cannot be concluded that the severity of hearing loss is an important consideration for changes in driving performance.

Studies which did not find a distinct effect of hearing loss on driving, did identify two outcomes of interest. The first is that, when co-existing with a vision impairment (defined either in terms of contrast sensitivity of visual acuity), hearing loss did cause a significant increase in road traffic accident risk (Green et al., 2013). The authors do not provide an explanation as to why this may have been the case, but it is considered here that it may have arisen as a result of a ‘common cause’ theory, which essentially postulates that sensory functioning is an indicator of the overall condition of an individual’s neurological status (Baldwin, 2002). The presence of a dual-sensory impairment may, therefore, predispose an individual who has less ability to perform complex mental tasks (such as driving). This is an idea which will be discussed in more detail later (see Chapter 3).

The second finding of interest is that hearing aid owners and hearing aid users are more at risk of having a road traffic accident (McCloskey et al., 1994). This finding cannot be considered conclusive, particularly as Sims et al. (2000) found no significant effect of hearing aid use on the number of road traffic accidents. However, McCloskey et al. (1994) claim that extraneous noise produced by hearing aids may serve to distract the driver from the primary task of driving. This is an important consideration, and one which will be discussed in depth later in this chapter (see subsection 2.4.2).

There are three studies which have investigated driving cessation as a result of hearing loss, though they also do not reach a consensus. These studies are reviewed in the following section.

2.3.2 Driving cessation habits in hearing impaired individuals

Gilhotra et al. (2001) ran an observational study similar to that of Ivers et al. (1999) using data collected as part of the same survey, thus their age demographic was similar (participants aged $\geq$ 49 years). However, instead of studying road traffic accident involvement, they investigated the likelihood of individuals relinquishing their driving license as a result of various sensory impairments and medical conditions. One of these impairments was hearing loss, which was self-rated and categorised as ‘none/mild’, ‘moderate’, or ‘severe’. Results showed that those with a severe hearing loss were significantly more likely to cease driving than those who reported no/mild hearing loss, thus suggesting that severe hearing loss has a bearing on individuals’ decision to stop driving.

Unsworth et al. (2007) performed a longitudinal study investigating factors associated with driving cessation in an elderly demographic. They drew a sample of people aged 65 years or older from an existing baseline survey (The Melbourne Longitudinal Studies on Healthy Ageing Program). The survey gathered information on a range of variables including information about driving habits, and a self-rated measure of hearing which was scored on a four-point Likert scale (‘excellent’, ‘good’, ‘fair’, or ‘poor’). From the questions about driving habits, participants were classified in to one of three driving groups: ‘continuers’, ‘modifiers’, or ‘relinquishers’, pertaining to their driving status. The authors found that poor self-rated hearing was related to an increase in people’s decision to modify or relinquish their driving. However, Unsworth et al. (2007) noted that the independent variables used in the study were correlated, and performed a logistic regression, building a model in order to establish which independent variables could be used to predict the categorical outcome of driving cessation. In this analysis, hearing loss status was not found to be a significant factor in peoples’ decision to modify their driving behaviour or relinquish driving. This suggests that other factors inextricably linked with hearing loss (e.g. age; Davis, 1995) may be more responsible for the earlier significant findings of Unsworth et al. (2007).

Although not explicitly investigating causes of driving cessation, Thorslund et al. (2013c) performed a questionnaire study with hearing impaired individuals, aiming to derive their transport safety and mobility concerns. Their survey included information regarding driving licence ownership, whether people had stopped driving recently, annual mileage, the avoidance of driving under certain conditions, and how often people drove as opposed to being a passenger. They were able to link survey responses to audiometric data for each respondent, thus allowing the measurement the influence of hearing loss on this data.

Although Thorslund et al. (2013c) found that profound hearing loss was associated with an increased likelihood of not owning a driving licence, they clarify that the reasons for this were related to other medical motives such as vision disorders or disabilities. This lower license ownership in profoundly hearing impaired respondents is also partly contradicted by annual mileage, which was significantly higher for those with a profound hearing loss. Hearing loss status was not significantly associated with items asking whether people had stopped driving recently, whether they preferred being a passenger or driver, or whether they actively avoided driving under certain road conditions.

Table 2.2 Statistically significant odds ratios associated with driving participation for the hearing impaired demographic.

Reference	Trend noted	Demographic group	Odds Ratio (95% CI)
Gilhotra et al. (2001)	Increased risk of earlier driving cessation	Those with a self-reported severe hearing loss	1.6 (1.0–2.5)
Unsworth et al. (2007)	Higher likelihood of driving cessation	Those with relatively poor self-reported hearing	Not calculated
Thorslund et al. (2013c)	Higher annual mileage	Those with a profound hearing loss	6.49 (1.07–42.5)
	Higher ownership of driving license versus people with a profound hearing loss	Those with normal hearing	5.42 (1.00–29.2)
		Those with a mild hearing loss	9.42 (2.11–42.0)
		Those with a moderate hearing loss	6.45 (1.86–22.4)
		Those with a severe hearing loss	4.22 (1.04–17.1)

These results (summarised in Table 2.2) are, therefore, similar to the accident rate studies in that they exhibit a mixture of conclusions. The most important point in the consideration of these results is the same highlighted by the study of Unsworth et al. (2007), that hearing loss increases driving cessation, but that a number of other factors also contribute.

Regardless of their methodological limitations, these observational studies investigating crash risk and cessation rates identify trends which warrant further investigation. It is only possible to speculate the reason behind these observed trends, as studies in the area do not investigate the underpinning driving behaviour changes which occur as a result of hearing loss. The next section outlines the possible reasons why hearing loss might alter driving behaviour, and thus result in a potential increase in road traffic accidents and driving cessation.

2.4 Reasons for altered driving trends in hearing impaired individuals

A number of studies suggest two broad presupposed manners by which hearing loss is likely to pose problems for skills relevant to driving:

1. Hearing loss causes a failure to perceive relevant auditory information in the driving environment, and this impacts on overall driving ability.

2. SNHL distorts auditory signals (even at audible levels), leading to a disproportionately distracting effect of acoustic information in the driving domain.

These two considerations will be discussed in this section, although there is limited research that can be drawn upon. Therefore, some of the research that has been carried out in normally hearing individuals investigating the effect of reduced audibility on driving performance will also be discussed. This work is considered applicable as it replicates one of the perceptual consequences of SNHL; threshold elevation.

2.4.1 Missing driving-relevant auditory information

Artificial reductions of auditory information in driving relevant situations have been shown to affect aspects of driving performance in normally hearing individuals. These situations are outlined in this section because it follows that a reduction in audition as a result of hearing loss would likely result in the same observations.

It should be noted, however, that unless an individual has a hearing loss of a more severe nature, access to road-relevant auditory information will be reduced, rather than eradicated. For example, the pass/fail criteria for police sirens being tested in the UK is a level of 97 dB recorded at a distance of 50 metres (Metropolitan Police, 2014), a level which is well above threshold for people with a mild or moderate hearing loss, and should also be audible for some people with a severe hearing impairment (British Society of Audiology, 2011). Thus a lack of auditory information is something which is likely to primarily affect profoundly deaf individuals, rather than those with a hearing loss.

2.4.1.1 The ability to hear warning signals

A consequence of an inability to hear auditory information in the car is the lack of access to warning sounds such as sirens from emergency services vehicles, or the horns of other cars on the road. This consideration was cited by early work investigating the driving habits of deaf individuals (Coppin and Peck, 1963, 1965), and has recently been pointed out by authors investigating the safety consequences of listening to loud music whilst cycling (e.g. de Waard et al., 2011). It also gains anecdotal support from situations such as that shown in Figure 2.13, depicting a deaf cyclist pointing out to other road users that he does not have access to auditory information. However, there have been no formal investigations on to the ability of those with a hearing loss to hear external auditory warning signals, or how this may affect their driving performance.

2.4.1.2 Reductions in situation awareness

Hearing is a sense which offers highly important information about the surrounding environment, but is often ignored at a conscious level (Horowitz, 2012). Humans are able to perform the complex task of organising sounds from the surrounding environment into perceptually meaningful elements in an automatic fashion (Bregman, 1994). This makes it possible to form a rich, conscious experience of the surrounding environment (Snyder et al., 2012). As such, the inability to hear sound, or a difficulty in doing so, is likely to

Figure 2.13 A photograph taken by Mary Evans entitled 'deaf cyclist in the 1930's'. The sign on the riders back reads: 'Beware, I am deaf'. Source: Ohene-Djan et al. (2010).

impact on this formation of auditory scenes and awareness of the surrounding environment. It follows that situation awareness, and its related processes, may be affected by hearing loss. Situation awareness is a key element of real-time tasks (Gugerty, 1997), and even small disruptions to this psychological state can have profound safety implications in terms of crash risk (Fisher and Strayer, 2014). The investigation of whether impaired hearing affects successful situation awareness is, therefore, of importance.

The term 'situation awareness' has been given a number of definitions, but is most simply put as "what is going on around you" Endsley (2000). In earlier work, Endsley (1988) described situation awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". She subsequently published a conceptual model of how situation awareness informs dynamic decision making (Endsley, 1995; see Figure 2.14). The model suggests that a person's perception of relevant elements in the environment form the basis of situation awareness. Specifically Endsley (1995) notes that this information is gauged via in-vehicle system displays, or directly from the senses.

To date, one study has linked a lack of sound in the driving environment to reduced situation awareness (Walker et al., 2008). The function of the two-part experiment was to determine which vehicle characteristics had a bearing on the situation awareness of drivers. Walker et al. (2008) hypothesised that feedback from vehicles is important for drivers to understand what has been accomplished from their actions whilst driving, and pointed out that a body of research has shown sensitivity of drivers to vehicle feedback whether it be vibratory, tactile or auditory. Thus, in line with Endsley (1995), their suggestion was that if perception of relevant elements in the environment were removed, situation awareness would be reduced. This standpoint was compounded by their first experiment in which participants drove their own vehicles (classified as high- or low-feedback from

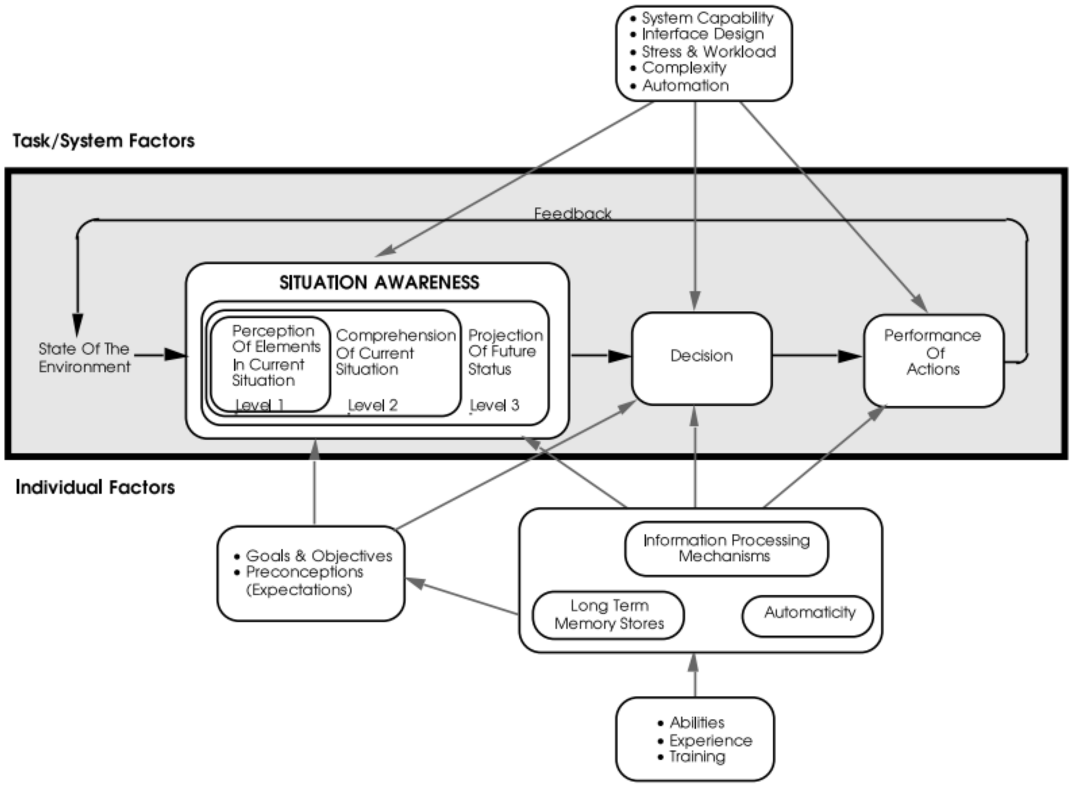


Figure 2.14 A model of situation awareness and how it links to decision making. Source: Endsley (1995).

characteristics such as power to weight ratio, drive, instrumentation and dynamics) and gave a running commentary of their thoughts whilst driving. Walker et al. (2008) performed a thematic analysis on these verbalisations and classified them in to four themes: own behaviour, behaviour of the car, road environment, and other traffic. They found that participants with higher feedback cars supplied significantly more information about the road environment.

Walker et al. (2008) went on to use a driving simulator under a number of different conditions in which auditory, steering force, and tactile feedback were entirely removed both individually, and simultaneously, at various points during a drive. They used a 'freeze probe technique', whereby the simulated environment was randomly frozen, display screens were blanked, and participants were asked to rate how confident (on a scale of 1–7) they were regarding the presence or absence of probed information in the driving environment. The authors paused the driving scene 36 times during a 30 minute drive, and during each pause 7 relevant probes were selected from a pool of 47 individual items which were developed from a 'hierarchical task analysis' of driving (Walker et al., 2001). This process involves the identification of information necessary for the completion of operational aspects of driving. Probe items consisted of statements such as: "there's [some salient feature] on the [right/left]", "the road conditions there had a significant effect on the car's performance", or "the car felt like it was losing grip". Results showed that the inclusion of vehicle feedback information in modalities other than visual resulted in significant improvements in sensitivity to information in the driving environment. Analyses showed that applying vibratory and steering feedback on top of auditory feedback yielded no significant improvement in situation awareness over and above simply providing auditory feedback alone. The authors argue that these results promote auditory feedback from vehicles as an important source of environmental information whilst driving.

It is, however, unclear how situation awareness may be impacted by SNHL. In this experiment, auditory information was *entirely* removed, rather than being attenuated, presenting a situation which more closely resembles how profoundly deaf individuals would perceive the driving environment. Furthermore, it may be that adaptive driving behaviours would negate any issues posed by this potential reduction in situational awareness. Thus the consideration of a reduced situation awareness whilst driving for hearing impaired individuals is more complex than is suggested by the experimental paradigm used by Walker et al. (2008).

2.4.1.3 Perception of travelling speed

Vehicles inherently create internal noise whilst in motion (Eisele et al., 2005), and past research suggests that the level of noise present reflects our perception of travelling speed. The ability to estimate travelling speed under normal listening conditions appears to be accurate up to a threshold velocity (approximately 90 km/h), but above this level, speed is increasingly underestimated (Wang and Wang, 2012). However, a number of studies using on-road (Evans, 1970; Matthews and Cousins, 1980), driving simulator (Merat and Jamson, 2011; Hellier et al., 2011), or video clip methodologies (Horswill and McKenna, 1999; Horswill and Plooy, 2008) have generally shown that the louder the noise levels during driving, the faster the perception of travelling speed.

Typically these studies have manipulated the level of engine noise present whilst driving, either by attenuating it in some manner, or by removing it completely. When engine noise is reduced, participants estimate a slower speed (Evans, 1970; Horswill and Plooy, 2008), and consequently choose to drive at a faster speed (Matthews and Cousins, 1980; Horswill and McKenna, 1999; Merat and Jamson, 2011; Hellier et al., 2011). This argument is feasibly transferable to the case of hearing loss, in that the level of car noise is likely to be lower than it is for a normally hearing individual (given the reduction in hearing sensitivity). As a result, the perception of this demographic should be of a slower travelling speed, and so this is likely to manifest in an increase in travelling speed.

However, this inference may not hold true when the reduction in vehicle noise is brought about by SNHL, which usually occurs in a frequency-specific manner; sensitivity to all frequencies of sound are not reduced to the same extent, resulting in the equivalent of an audio filter[3] applied to sound. Particularly in the case of age-related, and noise-induced

[3] An audio filter is a device which applies frequency dependent gain/attenuation to a sound source, such that the frequency response of a signal can be manipulated. A low-pass filter applies attenuation to frequencies

hearing loss, low frequency information will be largely preserved, whereas high-frequency information will be degraded (Gates and Mills, 2005).

This is relevant because recent results suggest that the frequency content of noise in the car can alter the perception of travelling speed; in some cases the reduction of sound at certain frequencies can actually improve the accuracy with which travelling speed is estimated. Wang and Wang (2012) performed a video-clip based study whereby they dubbed real-world recordings of engine noise at different speeds over the top of a visually simulated driving scene. They applied two filters to their sound recordings; low- and high-pass filters using a cut-off frequency of 600 Hz and a third condition providing attenuation across all frequencies. They also collected data from a baseline condition where sound was congruent with the video clips used. Their results exhibited poorer speed estimation when sound was attenuated across all frequencies, but little difference between the other three conditions up to a speed of 100 km/h. Above this threshold speed, however, the high-pass filter condition resulted in an improved accuracy in speed estimation, whereas the control and low-pass conditions remained similar. Wang and Wang (2012) argue that speed estimation has a relationship with the frequency content of interior vehicle noise, and therefore measures aimed at attenuating certain frequencies may actually improve velocity estimation. The fact that a cut in high-frequency information causes an improved perception of travelling speed would agree with data which shows that speeding violations are not significantly higher in the hearing impaired demographic (Picard et al., 2008).

2.4.1.4 Summary of an inability to hear driving-relevant auditory information

The removal of auditory feedback in the driving environment has been shown to lead to reduced situation awareness and an alteration in the perception of travelling speed in normally hearing individuals. It is also suggested that hearing will lead to a reduced audibility of warning sounds. This work may be applicable to those with hearing loss, as hearing impairment results in a loss of audibility. However, it should be noted that hearing loss does not lead to a complete reduction in audibility, nor does it always manifest in a non-frequency specific manner. Accordingly, these trends may not be entirely replicated as a result of hearing loss.

2.4.2 A disproportionate distracting effect of acoustic information

Alongside an inability to hear auditory information in the driving environment, there is also concern that sound information which *is* audible causes a problem for hearing impaired individuals. McCloskey et al. (1994) touch on this when explaining their finding that hearing aid ownership increases the risk of road traffic accidents. They argue that superfluous sound emitted by hearing aids may distract hearing impaired drivers. Their exact reasoning behind this suggestion is not entirely clear, though they cite hearing aid

above a certain cut-off, and a high-pass filter applies attenuation to frequencies below that cut-off.

feedback as a source of this disturbance. This would appear to suggest that they view transient, non-speech sounds as the most problematic for driver distraction. However, correctly fitted hearing aids should not produce extraneous noise such as feedback (Dillon, 2001), particularly given novel techniques aimed at reducing this issue (Guo et al., 2012).

Other authors have argued that the processing of auditory information can be disproportionately distracting for the hearing impaired demographic, regardless of hearing aid use (Hickson et al., 2010; Thorslund et al., 2013b). This line of thinking relies on two underpinning assumptions: (1) that cognitive engagement in auditory tasks (e.g. conversing on a mobile phone) whilst driving causes changes in driving performance, and (2) that auditory processing is more 'effortful' for people with a hearing loss (Rabbitt, 1991), causing the performance of auditory-based tasks to be more cognitively demanding. Thus, it is suggested that the extra cognitive demand associated with auditory task performance in hearing impaired individuals will lead to a more marked propensity for driving behaviour changes compared to normally hearing individuals (Hickson et al., 2010; Thorslund et al., 2013b).

The hypothesis that auditory processing is more effortful for hearing impaired individuals is discussed in depth in Chapter 3, but this section will present work relevant to the specific changes in driving performance which have been observed in normally hearing individuals as a result of auditory task engagement. It is considered that these changes will be more marked in the hearing impaired demographic.

2.4.2.1 The effect of auditory task engagement on driving in normally hearing individuals

A wealth of research has been undertaken to quantify the effect of various auditory distractions on driving performance in normally hearing individuals. A prime example is mobile phone conversations and their affect on driving performance (e.g. McKnight and McKnight, 1993; Redelmeier and Tibshirani, 1997; Haigney et al., 2000; Hancock et al., 2003; Strayer et al., 2003; McEvoy et al., 2005; Törnros and Bolling, 2005; Horberry et al., 2006; Horrey and Wickens, 2006; Drews et al., 2008). Young et al. (2007) summarise that early work in this area suggested an effect of mobile phone conversation on driving performance as a result of physical interference caused by handling and manipulating the phone. However, subsequent research has shown that hands-free phone use can also have serious safety implications as a result of the cognitive demands of engaging in a conversation (Ho and Spence, 2012).

The effects of performing auditory-based cognitive tasks on driving performance were actually observed as early as 1969 by Brown et al. They asked 24 male drivers to judge whether a vehicle could be manoeuvred through a set of twenty openings that they had laid out on a test track. Some of the openings were just wider than the car, whereas others were slightly narrower. At the same time as performing this task, participants were also asked to complete a secondary task which involved listening to a statement regarding the order of two letters (e.g. "A follows B - B A") and answering whether it was true or false. They found that, when completing the auditory task, participants' judgement of the gaps was impaired, though their ability to steer through them was not. The authors concluded that automated aspects of driving (such as steering) were not affected by the simultaneous performance of a cognitive task, whereas perception and decision making abilities were. They hypothesised that this was as a result of repeated attention-switching between visual and auditory modalities. The majority of work which has been performed in this area since the study of Brown et al. (1969) has supported their early conclusions (Ho and Spence, 2012).

In this vein, Logan and Crump (2009) present a hierarchical control model which Cooper et al. (2013) argue is applicable to driving processes. The model makes a distinction between automated and attentionally controlled processes, suggesting that skilled performance is subsumed by two separate control loops (outer and inner) which are encapsulated (i.e. do not monitor each other). The outer loop is resource demanding, and plays a pivotal role during the initial learning of a task, whereas the inner loop is automatic and does not require attention or effort. This account explains the findings of Brown et al. (1969), because it follows that more automated aspects of driving (e.g. lateral vehicle control; Michon, 1985) will not be affected by cognitive task engagement, as they do not require attentional control in the first instance. However, the hierarchical control model proposed by Logan and Crump (2009) predicts that when attention is allocated to inner loop processes, their performance actually decreases. It follows that when cognitively engaging tasks are performed during driving, there will be a reduction in attention that can be allocated to inner loop process, and their performance will actually 'improve'. Conversely, the reduction in attention allocated to outer loop processes will result in a decrement to their performance. Indeed, a specific pattern of results has been observed in dual-task driving studies whereby specific behaviours are observed as a result of auditory task engagement; some exhibiting 'improvements' in driving skills, and others exhibiting decrements.

One such behaviour that has been established is an increase in gaze concentration to the road centre, or a decrease in visual scanning (Cooper et al., 2013). For example, Victor et al. (2005) reports a study, performed as part of The Human Machine Interface And the Safety of Traffic in Europe Project (HASTE), in which participants were asked to perform a continuous memory task whilst driving at three different experimental sites (two fixed-base simulators, and one on-road instrumented vehicle). The task consisted of remembering a set of target numbers and counting how many times they occurred in a randomly generated list. Eye tracking technology was used to establish where participants were looking during each experimental condition. The results showed that during auditory task engagement participants spent significantly more time looking at the road centre, and the standard deviation of gaze was also significantly reduced under the same conditions.

Similar results of concentrated spatial gaze whilst under auditory task conditions have been obtained from a wider set of experimental studies performed in on-road driving settings.

Nunes and Recarte (2002), for example, asked participants to drive an instrumented vehicle under a number of different auditory/cognitive task conditions. They offer little description of the tasks, but do divulge that: "...there were listening and learning audio messages, several verbal production tasks with either abstract or spatial imagery contents, memory, arithmetical calculation etc." They found that when a demanding secondary task was used, the gaze pattern of participants was significantly more focused on the road centre, and that this pattern became more marked as the difficulty of the cognitive demand of the auditory task was increased.

Similarly, Harbluk et al. (2007) performed an on-road study of the effects of auditory distraction on visual behaviour whilst driving. They asked participants to perform a mental arithmetic task whilst driving, and used two levels of difficulty (single-digit and double-digit numbers). They also found a propensity for their participants to fixate directly ahead significantly more often when performing the secondary task. Additionally they noted that the more difficult the cognitive task, the greater the effect on visual attention. Figure 2.15 exhibits the results obtained, showing an increased rate of fixations on central visual areas with a concomitant decrease in monitoring of peripheral areas, mirrors and the driving instruments. They also exhibit an exacerbation of this trend under more difficult task conditions.

In explanation of this phenomenon, Jamson and Merat (2005) argue that "drivers, either consciously or subconsciously [develop] a strategy to reduce primary task load whilst performing concurrent secondary tasks" in order to "[attempt] to free up resources for the secondary task by simplifying the primary task". They go on to infer that auditory task engagement leads to 'cognitive narrowing', whereby visual resources are focused more to the area of greatest interest and hazard likelihood - the lead vehicle. This explains the results summarised here that show a reduced span of visual scanning during auditory task engagement.

Visual scanning whilst driving is, however, of paramount importance given that the performance of several visual functions degrade towards the periphery of the visual field (Findlay and Gilchrist, 2003). Victor et al. (2005) therefore state that delays in reaction times to critical events strongly depend on instances of looking away from the immediate road scene and scanning for such occurrences. Indeed, the reduction in visual scanning triggered by cognitive task engagement whilst driving appears to lead to failures of visual attention.

Strayer et al. (2003) examined how mobile phone conversations affected drivers' attention to objects encountered whist driving. They used a car following paradigm in a high-fidelity driving simulator. During their experiment, a lead vehicle would suddenly brake at random intervals, and when participants applied their brake, sped back up to its constant travelling speed. At points in the experiment, participants were asked to hold a hands-free mobile phone conversation with an experimenter. The density of traffic on the road was also manipulated to give two different conditions: low and high density. Participants drove

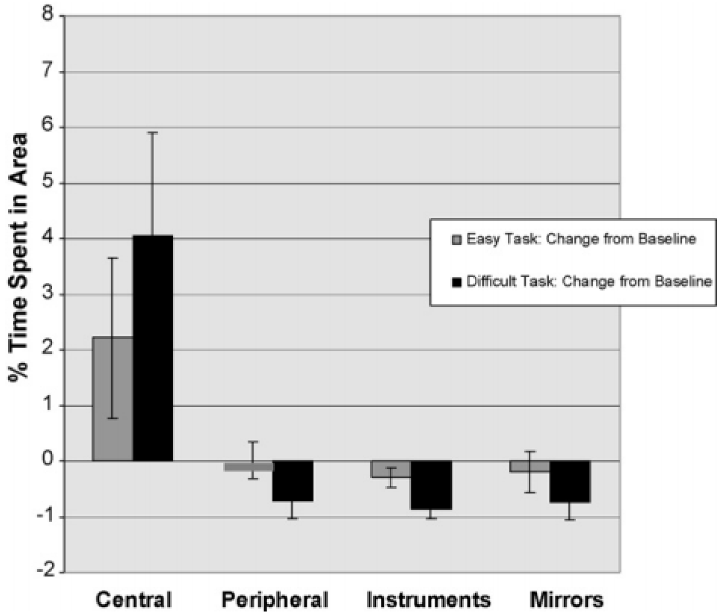


Figure 2.15 The change in the proportion of time drivers spend looking at areas of interest as a result of performing an auditory task whilst driving. Source: Harbluk et al. (2007).

this simulated environment, without prior knowledge that their recall of objects in the driving scene would be subsequently tested. Once the drive had finished, the authors asked participants to discriminate billboards which had been present in the driving scene from foils which were not. They contrasted the successful recall of billboards in a condition where participants were conversing on a mobile phone against a control condition, and found a significantly lower successful recall rate in the auditory task condition.

The ramification of such failures of visual attention is that drivers will be unable to react to salient events as quickly as they might without a cognitive task simultaneously present. It should be noted, however, that some work has suggested that cognitive distraction may not interfere will all types of salient event. Specifically, cognitive distraction may focus attention toward the road centre, reducing the number of glances away from the roadway (see e.g. Jamson and Merat, 2005). This potentially has the capacity to cause some events to become *more* salient in the presence of cognitive distraction, in turn decreasing reaction times to them (see e.g. Victor et al., 2015). However, Strayer et al. (2003) found that participants were more likely to crash in to the lead vehicle whilst conversing on the mobile phone during high traffic density situations. They also found that, regardless of traffic density, brake reaction times were slower during the phone conversation condition. An increased traffic density exacerbated this trend. Other research has also shown that engagement in cognitively demanding auditory tasks leads to a reduced reaction to events in the driving environment.

Lamble et al. (1999) investigated drivers' ability to detect the deceleration of a lead car whist undertaking mobile phone related tasks. They performed an on-road study in which they asked participants to follow a lead vehicle (driven by an assistant) on a 30km section of motorway. The experimental vehicle was equipped with dual-controls, and an experimenter (seated in the passenger seat) positioned the vehicle 50m behind the lead vehicle and engaged cruise control prior to the start of each experimental trial. The participant was asked to follow the lead vehicle, whilst cruise control was still engaged, with his or her foot above the brake pedal, and to brake as soon as the lead vehicle started to decelerate. They asked participants to perform a number of different tasks whilst driving, one of which was the Paced Auditory Serial Addition Task (PASAT) in which the experimenter sat in the passenger seat called out random integers between 1–9 one at a time, and the participant had to add the two most recent numbers together. A significantly smaller time to collision was noted when participants performed PASAT whilst driving than when they drove in a single-task condition. Brake reaction times were also significantly slower for participants when they performed PASAT.

As part of HASTE, Jamson and Merat (2005) examined the alterations to driving performance that were brought about by the performance of a visual or a non-visual (auditory) cognitive task in a simulated driving environment. They asked 48 participants to drive a simulator whilst simultaneously completing an auditory secondary task, the Auditory Continuous Memory Task (aCMT), which involved memorising a number of complex sounds and keeping a mental tally of how many times each occurred within a list. This was an adaptation of an earlier visual version of this task (Veltman and Gaillard, 1998). Participants were asked to follow a lead vehicle on a single-carriageway, the time headway of which was manipulated to be 3s. At some points during the drive, the lead vehicle rapidly reduced its speed, meaning that participants had to brake to avoid a collision. Jamson and Merat (2005) found that, as this auditory task was made more difficult (by increasing the number of target sounds), participants had increasingly slower brake reaction times, and were therefore increasingly closer to colliding with the lead vehicle. However, they also found that participants adopted an increasingly longer headway. Alm and Nilsson (1995), argue that longer following distances can be associated with an increased ‘safety buffer’, as they give drivers more time to react to sudden changes in behaviour of the lead vehicle.

Other authors appear to share a similar viewpoint, providing similar explanations after having noted more variable longitudinal vehicle control during cognitive task engagement. Haigney et al. (2000), for example, asked thirty participants to undertake four simulated drives whilst they performed a grammatical reasoning task. The auditory task led to significantly slower mean speeds and less standard deviation of accelerator travel. Haigney et al. (2000) argue that this speed reduction was a compensatory strategy to minimise risk which had arisen as a result of an increased mental workload during the auditory task. They also hypothesise that the reduction in deviation of accelerator pedal travel is indicative of a reduction in driver reactivity to road or traffic conditions during cognitive task engagement.

Strayer and Drew (2004) noted a similar trend. In a driving simulator, the authors asked participants to follow a lead vehicle whilst conversing on a hands-free mobile phone with an experimenter. The lead vehicle was programmed to brake at random intervals throughout the drive, and when participants deployed the brake to avoid a collision, the lead vehicle accelerated back to travelling speed. If a participant did not deploy the brake, a collision would take place. Strayer and Drew (2004) found that, during periods of auditory task engagement, their sample adopted a longer headway to the lead vehicle. They argue that this was a compensatory strategy to give drivers an additional buffer for responding to unpredictable events.

These compensatory behaviours may have the capacity to nullify negative effects of auditory task engagement whilst driving. As a result of the increased accident risk that has been identified by laboratory studies investigating the effect of mobile phone conversation on RTAs, legislation has been implemented outlawing the use of hand-held mobile phones whilst driving. However, recent results from naturalistic driving studies, where drivers are able to make their own decisions about when to engage in mobile phone conversation, actually support a ‘protective’ effect of hands-free mobile phone use, whereby drivers have been found to be at lesser risk of RTAs whilst conversing hands-free (Dingus et al., 2006; Olson et al., 2009; Hickman et al., 2010). There are a number of explanations why this trend may have emerged, but one explanation is that drivers adapt their driving behaviour in order to negate negative effects of mobile phone conversation (Metz et al., 2015).

As well as longitudinal vehicle control, it appears that the reduction in visual scanning occurring as a result of cognitive task engagement also affects lateral vehicle control. As research has shown a concurrence between an increased gaze concentration on the road centre and *improved* lateral vehicle control (Engström et al., 2005b), Jamson and Merat (2005) suggest that this cognitive narrowing “indirectly leads to a superior perception of the roadway, allowing an improvement to the lane keeping performance of the driver”. Cooper et al. (2013) questioned whether the improvement in lateral vehicle control might result from drivers’ propensity to steer in the direction of gaze; straight ahead under conditions of cognitive workload. However, their subsequent investigation, in which they manipulated workload and eye movements independently, suggested that eye movements only have a small role to play in the improvement of lateral vehicle control. Thus, they concluded that the effect of cognitive workload on lateral vehicle control is independent of eye movements. Regardless, there are examples of lateral vehicle control improvements as a result of cognitive task engagement in previous studies.

Brookhuis et al. (1991) performed an on-road experiment using an instrumented vehicle to study the effects of operating hand-held and hands-free mobile phones whilst at the same time driving in three different traffic situations: light traffic on a relatively quiet motorway, heavy traffic on a four-lane ring-road, and in city traffic. The authors asked participants to perform the PASAT task, which was presented aurally. As a result of performing the auditory task, participants had a smaller standard deviation of lane position, particularly whilst driving on the motorway.

Jamson and Merat (2005) showed a similar trend in their simulator experiment. Although they noted a reduced reaction time which concurred with an increase in demand of their auditory task, they also noticed a greater stability of lateral position within their lane. Their results showed that, as the demand of the auditory task was systematically increased, the standard deviation of lane position was increasingly decreased. Furthermore, Jamson and Merat (2005) noted a similar trend for minimum time to line crossing data, suggesting that auditory task engagement reduces the likelihood that drivers will deviate from their lane of travel.

Engström et al. (2005b) also noted the trend of a reduced degree of lateral deviation during periods when drivers were under conditions of auditory task engagement. As part of HASTE, they used two different driving simulators (fixed-base and moving-base) and a field study in order to investigate the effect of in-vehicle information systems on eye movements and vehicle control measures. In all three cases, participants were asked to drive a motorway route whilst concurrently undertaking supplementary tasks. One of the tasks they asked participants to perform whilst driving the simulator was a memory task presented in the auditory modality; memorising a number of target sounds and keeping a mental tally of how many times these occurred throughout a list. Results from the two simulator studies showed a significant reduction in lane deviation, and the field trial showed a propensity for this to be the case, although the data did not reach significance.

Cooper et al. (2013) summarises that perceived unsafe or dangerous driving practices (such as driving and conversing on a mobile phone) actually lead to an "improvement" in lateral vehicle control.

Summary of driving outcomes as a result of auditory task engagement in normally hearing individuals

Research shows that auditory task engagement leads to a number of effects on measures of drivers' performance and behaviour. These effects all appear to be linked, and arise from an alteration in visual behaviour, whereby visual scanning is reduced and individuals fixate more exclusively on the point directly in front of their vehicle.

1. Reduced visual scanning, which leads to;
2. Failures of visual attention, causing;
3. Reduced reaction times, which mean that drivers adopt;
4. Lower speeds and longer following distances;
5. But this visual behaviour also leads to *improved* lateral vehicle control.

Increasing the demands of the auditory task leads to a more marked trend of some of these observations (Jamson and Merat, 2005; Harbluk et al., 2007). It follows that the increased demand posed by SNHL will also lead to a more marked trend of these observations, as it will essentially raise the demands of the auditory task being undertaken concurrently with driving. There is very little work, however, that has been performed to investigate this inference. A number of authors have raised the demands of an auditory task by making the cognitive processing associated with it more difficult; e.g. Harbluk et al. (2007) asked participants to add together double-digit, rather than single-digit, numbers. However, very little work has assessed the effect of making the perception of sound the source of increased task difficulty; this is the primary concern for hearing impaired drivers. Some research has been carried out to this end, but it largely neglects suprathreshold complications associated with SNHL, and does not assess the above aspects of driving explicitly (Baldwin and Struckman-Johnson, 2002; Baldwin, 2007). Regardless, this work is of interest because it assesses the effect of stimulus presentation level, essentially emulating the reduction in sensitivity aspect of SNHL.

The effect of reduced auditory stimulus presentation level on auditory distraction whilst driving

In a dual-task, low-fidelity driving simulator study, Baldwin and Struckman-Johnson (2002) investigated the alteration in mental workload by different presentation levels of auditory stimuli (in the range 45–65 dB). They argued that an optimal presentation level range for auditory-based systems has been established, but that variations within this range might have an impact on cognitive workload. Accordingly, they asked 28 participants with normal hearing to drive a vehicle on a computer game at a steady speed, whilst they simultaneously performed an auditory task. The auditory task consisted of 3–4 word statements, and participants were required to decide whether they made sense (e.g. stimulus: "dogs have five legs"; response: "false"). Baldwin and Struckman-Johnson (2002) measured the number of crashes and off-road occurrences (defined as the number of times the participant ran off the road) during dual-task conditions. They found no significant effect of stimulus presentation level on these measures of driving performance. They did, however, find that at higher presentation levels, participants made fewer sentence processing errors and responded faster than they did at lower presentation levels. However, when the listening task was performed as a single-task paradigm, this trend was not apparent. This suggests that hearing impaired individuals, who have a lower auditory sensitivity, are likely to make more auditory processing errors and respond more slowly to auditory information whilst driving.

Baldwin (2007) investigated the effect of altering stimulus presentation level (in the range 60–70 dB SPL) on the reaction time to-, and accuracy of, a tone matching task in which participants had to say whether musical notes presented differed from a reference stored in memory. The main aim of her study was to examine the effect of stimulus intensity of echoic persistence, but she used a concurrent simulated driving task to load participants' processing resources. A low-fidelity driving simulator was used, and Baldwin (2007) recorded the number of times a single tire crossed a lane demarcation (a minor lane deviation), the number of times the vehicle's centre-line crossed a lane demarcation (a major lane deviation), and the number of times more than one major lane deviation took place within a single instance (e.g. the centre of the car crossed the left and then right lane demarcations). Again, none of these measures were significantly altered by a change in the presentation level of auditory stimuli, but performance on the auditory task was; participants performed more quickly when stimuli were presented at higher levels. Baldwin (2007) argued that echoic persistence is related to presentation intensity, and that because of this, under low presentation level conditions, extra effort needs to be applied to speech processing. In turn, this will reduce the resources available for the performance of concurrent tasks, and may manifest in their performance being affected. This suggests that hearing impaired individuals, who have a lower auditory sensitivity, are likely to experience this type of performance decrement more often than their normally hearing counterparts.

This work does not explicitly link to all of the driving behaviour changes described above, but the measurement of lane deviations does link to an improvement in lateral vehicle control. Because Baldwin and Struckman-Johnson (2002) or Baldwin (2007) did not find a change in this variable as a result of auditory task presentation level, it suggests that a reduction in auditory sensitivity is unlikely to manifest in changes to lateral vehicle control. As the improvement in lateral vehicle control is possibly linked to changes in eye movement behaviour, it also suggests that auditory sensitivity will not have a bearing on eye movement behaviour, and its associated driving behaviour outcomes. Taken in isolation, this study could, therefore, be evidence that increased task difficulty as a result of perceptual changes may not affect driving performance. However, it may be that lane deviations may not be a sufficiently sensitive measure to show this improvement in lateral control. Furthermore, the reduction in presentation level might relate to a reduction in auditory sensitivity, but it does not incorporate the array of sensory problems which SNHL presents. This aspect is considered pertinent, given the influence that suprathreshold complications associated with SNHL have on speech understanding. Some work has, however, begun to investigate the effect of cognitive task engagement on driving performance and behaviour in individuals with a SNHL. This work *does* take in to account all of the perceptual consequences associated with SNHL, and presents a different outcome.

2.4.2.2 The effect of hearing loss on auditory task engagement whilst driving

Hickson et al. (2010) investigated the effect of distraction on the driving of hearing impaired individuals and hypothesised that auditory task performance would have a disproportionate effect on them. They recruited 107 drivers aged between 62–88 years and undertook three different measures of hearing impairment: audiometry, speech testing, and self-reported problems (measured using the HHIE). The sample constituted a range of hearing losses, with a mean better-ear pure tone average of 27.0 ± 14.5 dB HL (range 2.5–82.5) at frequencies of 500, 1000, 2000, and 4000 Hz. 45% of the sample had some degree of hearing impairment, while fewer than 5% had a hearing loss of a severe or profound nature. 78% of the sample had bilaterally symmetrical hearing thresholds. Of the 48 participants who had some degree of hearing loss in the study, Hickson et al. (2010) identified 46 of them as having a sensorineural origin, thus the results of the study largely reflect the effects of SNHL rather than conductive hearing loss.

The experimental closed-road circuit used by Hickson et al. (2010) was 5-km long and was representative of a rural road, free of other vehicles. Along this course three tasks were included for completion by participants:

1. 54 road signs were located along the driving course containing a total of 77 pieces of information (e.g. stop, give way). Participants were asked to report back this information as and when it occurred;

2. Large, low-contrast foam rubber pads were placed across the centre of the driving lane to act as hazards. Participants were asked to report the presence of these pads, and avoid hitting them;

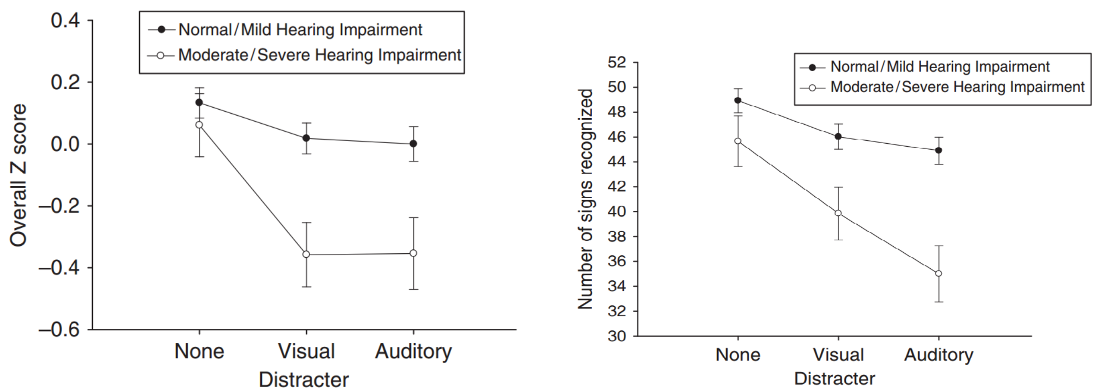
3. Pairs of cones were strategically placed in the roadway to create 'gates' for the vehicle. These gaps varied in their width producing gates which were not wide enough, just wide enough, and obviously wide enough for the test vehicle to pass through. Participants were asked to report whether gaps were big enough to fit their vehicle, and (if so) to drive through. Where the gaps were perceived to not be big enough, participants were instructed to drive around the pair of cones.

Hickson et al. (2010) used success on these three tasks, alongside the time taken to complete the road course as measures of driving performance. They also derived an overall driving z-score, which was a composite of the previous four measures (with each given an equal weighting). Participants were asked to drive this course three times in a randomised order; once without distraction, once with an auditory distraction, and once with a visual distraction. The distraction task was similar between the visual and auditory conditions, requiring participants to add two random numbers together. In the auditory condition these numbers were presented in the auditory domain at a comfortable listening level (the authors did not divulge the method of presentation), and in the visual condition the numbers were presented on a liquid crystal display mounted on the dashboard of the vehicle (just to the left of the steering wheel, slightly below driver eye height).

Although both the visual and auditory tasks required cognitive effort, it was hypothesised that hearing impaired individuals would require a greater cognitive effort than their normally hearing counterparts to complete the auditory task, given the listening demands that hearing loss poses (see e.g. Sarampalis et al., 2009). However, a similar level of cognitive effort was expected on the visual task for both normally hearing, and hearing impaired individuals. The authors therefore expected that, as a result of an increase in effort required to perform the auditory task, hearing impaired participants would be more affected by auditory task engagement than normally hearing participants, but affected to the same extent as their hearing counterparts by the visual task.

In order to establish the most predictive measure of hearing loss for driving performance, bivariate correlations between the overall driving z-score and the different measures of hearing function were performed. Although no single measure significantly predicted overall driving performance when controlling for age, better-ear pure tone average thresholds were found to be most strongly correlated with the driving z-score. As a result, subsequent analyses were performed between two groups which were established through better-ear pure tone audiometry data: those with normal hearing/mild hearing loss and those who had a moderate/severe hearing loss.

The authors found a main effect of distraction, in that overall z-scores were reduced during the performance of either the visual or auditory secondary task (see Figure 2.16). However, there was no difference between the visual and auditory conditions, suggesting that the auditory and visual tasks had a comparable effect on overall driving performance. An effect of hearing loss level was also apparent, such that those with a moderate-severe hearing loss were compromised to a far greater extent when required to undertake either of the secondary tasks whilst driving. However, there was no interaction between hearing loss and secondary task type, meaning that the visual distraction had just as much of a negative effect on the driving performance of hearing impaired individuals as did the auditory secondary task. These results are curious, as they suggest that the driving performance of hearing impaired individuals is compromised to a greater extent than normally hearing individuals as a result of visual distraction. This was not expected, given the hypothesis that it is an increased effort in processing auditory information which underpins driving performance decrements. However, the authors offer no explanation as to why this may have been the case, but it is considered that there must have been some differences between the two experimental groups beyond their hearing capabilities.



(a) Overall Z-score

(b) Number of signs recognised

Figure 2.16 The overall Z-scores and number of road signs recognised by the two experimental groups under different conditions in the study of Hickson et al. (2010). Source: Hickson et al. (2010).

The time taken to complete the course was significantly increased by visual distraction (but *not* by auditory distraction). The number of road signs recognised was also significantly decreased by visual distraction, but to an even greater extent by auditory distraction for all participants. This is in line with the previously noted patterns of failures in visual attention as a result of auditory task engagement in normally hearing individuals. Further to this trend, a significant influence of hearing loss on road sign recognition was also noted, whereby significantly fewer road signs were recognised by the hearing impaired group whilst performing either the visual or auditory secondary tasks.

However, for the hearing impaired group, the difference in road sign recognition was not significantly different between the visual and auditory distracter conditions, though the trend for fewer signs to be recognised in the auditory task condition did approach significance ($p = .08$). Again these results are curious as they exhibit a disproportionate effect of visual task engagement in the hearing impaired sample, a trend which was not hypothesised.

Hickson et al. (2010) argue that their results show driving performance decrements for people with a moderate to severe hearing loss when they perform concurrent tasks. Accordingly, they suggest that this demographic should be advised not to engage in cognitively challenging tasks whilst driving.

This study only used older participants, so it is likely that the demographic studied consisted primarily of those with an age-related hearing loss. This assertion fits with the majority of the sample exhibiting a SNHL. Age-related hearing loss may have some unique physiological features, such as the development of central auditory processing problems (Humes et al., 2012), and so information from Hickson et al. (2010) cannot be generalised to the hearing impaired population as a whole who may not exhibit these physiological changes. Accordingly, whilst these shortcomings in driving performance could explain the results of studies which have shown an increased accident risk in older hearing impaired individuals (Ivers et al., 1999), they may not necessarily be relevant to the younger hearing impaired demographic (Barreto et al., 1997; Picard et al., 2008).

Furthermore, it is unclear how these findings may transfer to a more ecologically valid situation. These findings were apparent in a driving environment void of any other traffic, or real risk of crashing. Thus, participants may have been more inclined to engage fully with the secondary task. Indeed, the results suggest that people obliged in performing the secondary task reliably, with an overall accuracy of 67% on all sums presented. The performance decrements associated with secondary task engagement may lead hearing impaired individuals to withdraw from this behaviour whilst on the road, or adapt their driving style so that it is more cautious (e.g. slower speeds, more vigilant visual behaviour etc). This could potentially negate the effect of distraction noted by Hickson et al. (2010) so that it is no longer an issue.

This notion has, in fact, been observed by another research group investigating driving performance decrements as a result of hearing loss (Thorslund et al., 2013a,b, 2014), suggesting that hearing impaired individuals exhibit an altered driving behaviour in order to counteract the negative consequences of hearing loss for driving.

Thorslund et al. (2013b) performed a study which investigated the effect of cognitive workload on driving in situations of varying complexity. The authors asked a normally hearing group ($n = 24$) and a hearing impaired group ($n = 24$) to drive a simulated environment in which they presented drivers with impending near-collision events. This was achieved in one of two manners:

1. *Critical event*: participants had their visual attention taken away from the road scene by performing a secondary task on a screen placed at a large downward angle (40°–45°). Whilst this happened a manipulation of the steering angle was introduced into the simulated vehicle such that it was 'pushed' towards an oncoming vehicle. This presented participants with a situation in which they needed to take evasive action quickly.

2. *Parked car event*: A parked car with its warning lights flashing was seen at a distance of 360m and (for trials incorporating the secondary task) when the distance from the car reached 70m, participants were asked to perform a secondary task.

In both of these situations, the secondary task consisted of four letters presented in sequence on a screen in the car cabin, with participants asked to repeat them back in order. The difficulty of the task was manipulated through the phonological similarity effect (Conrad and Hull, 1964), such that some lists were phonologically alike (e.g. B-D-P-T) and others were not (e.g. R-K-N-J).

It is curious that the authors used a visually delivered secondary task, but hypothesised that persons with a hearing loss should be more distracted by this secondary task, given that aspects of the auditory processing system deteriorate as a function of poor auditory stimulation (Andersson, 2002). Therefore, Thorslund et al. (2013b) reasoned that the storage of these letters in memory and their subsequent retrieval would be compromised, particularly when the letters being stored were phonologically similar. The secondary task was also administered during baseline driving, when neither the parked car or critical event was present.

Driving performance measures were compared between both experimental groups during the critical and parked car events, but also during baseline driving (driving whilst performing the secondary task, but without the critical or parked car event occurring).

Thorslund et al. (2013b) outlined a number of expected observations. They hypothesised that hearing impaired participants would show a more cautious driving style in which speed and the motivation to perform the secondary task would be lower, and safety margins would be larger. They also thought that increasing the demand of the secondary task would have a greater effect on the hearing impaired participants. Finally, they expected that increasing the complexity of the driving situation (e.g. as a result of the parked car or critical event) would have more of an effect in the hearing impaired participants such that their brake distance before the parked car would be longer, their driving speed around it would be slower and secondary task performance would be worse. Performance correlates for these three main hypotheses are shown in Table 2.3, which also shows the authors' observed results in relation to these hypotheses.

Table 2.3 The experimental expectations of Thorslund et al. (2013b) and a summary of whether their results support these as a result of significant statistical tests.

Expectation	Performance correlates for hearing impaired participants	Significant difference observed from data?
Hearing impaired drivers will show a more cautious driving behaviour	Lower driving speed	Yes
	Larger safety margins within travelling lane	No
	Lower motivation to perform secondary task	Yes
The effect of increasing the complexity of driving situations will be larger for the hearing impaired participants	Braking distance before parked car longer	No
	Driving speed around the parked car slower	Yes
	Worse secondary task performance when under dual-task conditions	Yes
Increasing secondary task complexity will have more of an effect on hearing impaired participants	Effect of phonological similarity effect greater for those with hearing loss	Yes

When performing the secondary task under baseline driving conditions (with a concurrent secondary task, but no critical or parked car event), hearing loss was found to significantly reduce the speed at which participants drove by an average of 6 km/h. Hearing impaired drivers also had a significantly smaller time to line crossing when performing the secondary task than did the normally hearing group (by approximately 1 second).

In terms of the performance on the secondary task itself during baseline driving, the normally hearing group had a significantly higher percentage of correct responses compared to the hearing impaired group. The hearing impaired group also skipped significantly more letters than their normally hearing counterparts.

Whilst driving around the parked car and performing the secondary task, hearing impaired individuals drove significantly slower, on average, than their hearing counterparts. This difference in speed was approximately 5 km/h. Under this driving condition there were no differences noted in the performance of the secondary task, itself, between the hearing loss and normally hearing groups.

Thorslund et al. (2013b) did not present driving variables during the critical event, but did present the effect this driving event had on secondary task performance; hearing impaired drivers were significantly poorer in their performance of the secondary task, skipping more of the letters presented and recalling less correct letters. Furthermore, when the difficulty of the secondary task increased (through the phonological similarity effect), the hearing impaired participants were affected more than the normally hearing participants. This was evidenced by the statistical interaction between hearing loss and task difficulty, when the number of skipped letters was analysed.

The results of Thorslund et al. (2013b) corroborate those of Hickson et al. (2010), in that secondary task engagement had a disproportionately negative effect on the driving of hearing impaired individuals. However, the specific measures which differed did not match between the two studies; whilst Thorslund et al. (2013b) found an effect of cognitive task engagement on travelling speed, Hickson et al. (2010) did not. Furthermore, whilst Hickson et al. (2010) found no difference in the performance of their secondary task between experimental groups, Thorslund et al. (2013b) found that hearing impaired drivers were less able to perform the secondary task whilst driving.

These differences are not likely to have occurred as a result of the variation in driving scenarios used. Although Thorslund et al. (2013b) used two specific near-collision events, they also measured driving performance in a baseline condition in which no near-collision events were presented, and participants were simply required to drive and perform the secondary task. During this condition participants still exhibited reduced driving speed and less engagement in the cognitive task. This condition was considered comparable to the situation studied by Hickson et al. (2010), which involved general driving with some specific tasks (related to everyday driving) interspersed.

A possible reason for the discrepancy in findings between these two studies might have been a distinct difference in the delivery of cognitive tasks used. Whilst both studies involved secondary tasks which involved phonological processing, the task used by Hickson et al. (2010) was delivered in the auditory modality, whereas Thorslund et al. (2013b) delivered theirs in the visual modality. However, Hickson et al. (2010) also included a visually presented version of their secondary task and assessed its effect on driving performance. Participants took significantly longer to complete the course in the visual distracter condition, but, contrary to the results of Thorslund et al. (2013b), there was no significant interaction of hearing loss with this dependent variable.

The fact that a visually presented distracter had a disproportionate effect on the road sign recognition task (Hickson et al., 2010), and on the travelling speed and secondary task performance (Thorslund et al., 2013b) of hearing impaired participants is of concern; as perception in the visual modality should be comparable between hearing impaired and normally hearing subjects. Thus it is possible that factors extraneous to hearing loss may have had an influence on study outcomes, or that the premise behind the hypothesis proposed by Hickson et al. (2010) is incorrect.

Thorslund et al. (2013b) cite work performed by Andersson (2002) as their reason for expecting a difference in the driving performance of hearing impaired and normally hearing individuals. Andersson (2002) showed that a small number of participants ($n = 16$) with an acquired severe hearing loss in older adulthood (average thresholds at 0.5, 1, and 2 kHz were all greater than 85 dB HL) were significantly slower and less accurate than a normally hearing group at rhyme judgement and generation. He argued that this was because the hearing impaired participants had poor phonological representations in their mental lexicons. Lyxell et al. (2003) went on to summarise that the deterioration of these representations is progressive; indeed Classon et al. (2013) state that mental representations of both speech sounds and non-speech sounds become less well-defined as a result of cumulative years with an impoverished auditory input.

However, the serial recall task used by Thorslund et al. (2013b) is incongruent with the findings of Andersson (2002). Andersson (2002) showed no difference between their hearing impaired and normally hearing participants on a letter span task, regardless of the phonological similarity of stimuli, and concluded that the verbal working memory of hearing impaired individuals was intact. Accordingly, there should have been no difference in the groups studied by Thorslund et al. (2013b), as the task used was not explicitly tapping phonological representations in the lexicon. Furthermore, Thorslund et al. (2013b) specifically recruited participants with a moderate hearing loss (average absolute thresholds of 41–70 dB HL), whereas the results of Andersson (2002) were only apparent in subjects who had pure tone thresholds of $\geq$ 85 dB HL. These discrepancies cast doubt over the hypothesis presented by Thorslund et al. (2013b).

In a subsequent investigation, Thorslund et al. (2014) analysed eye tracking data collected during their earlier study (Thorslund et al., 2013b). Eye movements during baseline driving, and during periods of driving where they had asked participants to perform a secondary task were analysed. They found that during secondary task engagement, hearing impaired drivers made significantly more glances to their rear view mirrors than under baseline driving conditions (in this case twice as much). This was also noted to be the case for glances in the left and right wing mirrors. None of these trends were apparent for normally hearing participants.

Thorslund et al. (2014) also showed that during the critical event (which required a deviation of gaze from the driving scene), hearing impaired drivers looked away from the road more often than those with normal hearing. However, these glances away from the road were shorter for the hearing impaired group than the normally hearing group. The authors suggested that this type of visual behaviour occurred because hearing impaired individuals are reluctant to look away from the driving scene, given that they are likely to compensate for a lack of audibility by visually checking for potential hazards which normally hearing individuals might be aware of aurally. However, although differences in visual scanning were not entirely evident from the data, the authors did notice a propensity for their hearing impaired sample to spend more time checking all directions before deviating their view from the straight ahead position. They argue that this is a cautious approach to driving during secondary task engagement, again because hearing impaired individuals appeared to be visually scanning for hazards which could otherwise be aurally perceived. Interestingly, this cautious approach to driving was also apparent during baseline driving (without a concurrent secondary task). Thorslund et al. (2014) found that hearing impaired participants made significantly more glances towards their rear view mirrors than did the normally hearing participants whilst under baseline driving conditions. The significant difference in eye movement behaviour under baseline driving conditions, and the results of an earlier field trial in which no secondary task was used (Thorslund et al., 2013a; discussed in the following section), suggest that adaptive driving behaviour may be present in the hearing impaired demographic when there is no concurrent cognitively engaging auditory task present.

A change in baseline driving behaviour as a result of hearing loss

In one study, Thorslund et al. (2013a) investigated the driving performance of hearing impaired individuals to understand the design needs of support systems for hearing impaired drivers by contrasting driver preferences and performance metrics associated with a stand-alone visual route guidance system, and the same system supplemented by a tactile signal.

A normally hearing and hearing impaired group (16 participants in each) with mean ages of 56.4 years and 52.5 years respectively, were asked to drive an instrumented vehicle around a pre-defined road course in Linköping, Sweden. The course was indicated to participants either via either of the two route guidance systems. The authors wished to establish whether there were differences in driving behaviour between each system configuration.

An experimenter, seated in the passenger seat of the car, recorded driving behaviour and performance using a previously developed protocol (Selander et al., 2011). This protocol comprised of a matrix which covered driving behaviours regarding: manoeuvres, attention, position, speed adjustment, interaction and planning. These behaviours were graded in a number of driving scenarios: roundabouts, crossings, traffic lights, straights, speed bumps, and "other". Each time a driving error was made, the experimenter noted this in the relevant position on the matrix. It should be noted that the protocol is unpublished, but is in use at a driving assessment centre in Stockholm, Sweden.

Participants also wore eye-tracking SMI ETG glasses (SensoMotoricInstruments, 2013) for all conditions, and a frame-by-frame analysis of the eye tracking video data (30 Hz) was undertaken by an assessor blinded to the groups and task. Data was coded by the experimenters to identify the percentage of time participants spent looking at, the duration and frequency of glances towards specific regions of interest: windscreen, speedometer, navigation system, rear view mirror, left window and mirror, right window and mirror, and 'other'. A hardware GPS-based data logger was also used to collect objective speed data about the drive.

Results showed that hearing impaired drivers travelled significantly slower than the normally hearing participants (approximately 4 km/h less) during 70 km/h speed limited sections of road. Although a similar trend was noted in 50 km/h speed limited sections (hearing impaired drivers were approximately 2 km/h slower), this difference did not reach statistical significance. The experimenter also rated hearing impaired drivers as being significantly more likely to drive too slow, and have an uneven speed control. Additionally, hearing impaired drivers spent a significantly greater percentage of their time in the vehicle looking in their rear view mirror than normally hearing participants (1.4% more) and performed this action on average three times more frequently (0.3 compared to 0.1 times per minute).

The authors maintain that their results support an alteration in driving behaviour in hearing impaired individuals, whereby a more cautious approach to driving is taken. Although a measure of situation awareness was not made in this experiment, Thorslund et al. (2013a) comment that it is a reduced situation awareness in the driving environment which causes an adaptation in driving behaviour as a compensatory method.

It is unclear whether this adaptive driving behaviour is undertaken consciously or subconsciously, however one study can inform this consideration. Holland and Rabbitt (1992) evaluated older individuals' (age range 50–80 years) awareness of their sensory abilities and the extent to which these govern changes to driving behaviour and self-reported accident rates. Alongside collecting pure tone audiometry data, Holland and Rabbitt (1992) asked 68 participants whether they thought their hearing had worsened over the prior ten years, whether they found it difficult hearing in background noise, and whether they often misheard speech in conversations. They also gathered information about how far people drove in a year, their driving experience, motorway use, whether any changes to driving patterns had been made, whether various errors (such as misreading signs) were commonly experienced during driving, and the anxiety of participants when driving in certain situations. Self-reported accident data was also included on the questionnaire, as was a section addressing attitudes toward certain issues such as what they thought were the causes of increased accident rates amongst older drivers.

Results showed a significant correlation between pure tone audiometry data and answers to self-assessments of hearing. However, those reporting that they had poor hearing did not report making any changes to their driving behaviour or an increase in road traffic accidents. Thus, the adaptive driving behaviour of which Thorslund et al. (2013b,a, 2014) talk appears to be subconscious in nature, as those with a hearing loss do not divulge knowingly making changes to their driving behaviour.

2.5 Summary of past research

The results obtained from studies in this expanding area do not definitively inform on the effect of hearing loss on driving; results are varied and, in some cases, contradictory.

Despite noted methodological limitations, however, the reviewed literature does provide some potential differences in driving outcomes as a result of hearing loss which warrant further investigation:

- **Driving with a hearing loss might raise the risk of having a motor vehicle collision.**
  This has been shown in an elderly demographic (Ivers et al., 1999) and in younger populations likely to have sustained a hearing impairment as a result of noise exposure (Barreto et al., 1997; Picard et al., 2008). However, three studies with stronger methodologies exhibited no such associations (McCloskey et al., 1994; Sims et al., 2000; Green et al., 2013).

- **Hearing loss may cause people to consider to stop driving, or adapt their driving habits.**
  Two studies suggest that elderly individuals with a hearing loss are more likely to cease driving compared to those with normal hearing (Gilhotra et al., 2001; Unsworth et al., 2007). This is supported by other work which has shown a lower driving license ownership in the hearing impaired demographic (Thorslund et al., 2013c).

- **Those with a hearing loss may be less likely to commit speeding offences, but are more likely to commit other traffic offences.**
  Hearing loss severity has been shown to be negatively correlated with the number of speeding tickets (Picard et al., 2008). A few behavioural studies have also exhibited a slower driving speed in the hearing impaired demographic (Thorslund et al., 2013a,b). However, Picard et al. (2008) also noted a positive association between hearing loss and other types of traffic offences, though they do not detail exactly what these were.

The observation of these trends is not compounded by any information about why they have arisen. However, two possibilities about how hearing loss might affect driving have been identified:

1. **There will be a loss of auditory sensitivity, which may have a deleterious effect on certain road-relevant auditory information:**

    - Warning signals such as sirens and horns may be missed by the hearing impaired demographic.
    - Sound information that raises awareness of the surrounding environment might be absent, or reduced, for people with a hearing impairment.
    - Aerodynamic and vehicular noise that aids the perception of travelling speed may be altered for people with a hearing loss.

2. **Sound which *is* audible causes a problem for hearing impaired individuals:**
   Hickson et al. (2010) found that, when asked to perform a superfluous auditory task

in the driving environment, the number of road signs recognised and overall driving performance of their hearing impaired participants was more affected than for those with normal hearing. The authors argue that this arises as a result of the extra demand that hearing loss places on auditory task completion.

Also,driving performance, and related measures, are affected by auditory task engagement in normally hearing individuals. Reduced reaction times to events, failures of visual attention, reductions in visual scanning, changes in longitudinal vehicle control and an improvement in lateral vehicle control are all noted in the driving environment. Varying the difficulty of the auditory task results in a more marked observation of some of these trends. Thus it is suggested that hearing impairment will have the same effect.

As a result of the two above considerations (Thorslund et al., 2013a,b, 2014) suggest that hearing impaired drivers exhibit an adaptation of driving behaviour, whereby a more cautious driving style is adopted:

- **Hearing impaired drivers make more frequent glances at mirrors.**
- **Hearing impaired individuals tend to drive at slower speeds.**
- **Individuals with a hearing loss seem to have a disinclination to look away from the roadway during driving.**
- **Hearing impaired individuals exhibit a reluctance to engage in other tasks whilst driving.**

These outcomes have been noted as a result of a number of studies in the area, some of which are subject to limitation, but the research is far from extensive. Indeed, some of these assertions have been made from research performed within a single research group. It is clear that further work is required in order to establish more definitively what effect hearing loss has on driving ability. The aim of the work described in this thesis was to begin to investigate this topic. The specific aims of the work are identified in the following section.

2.6 Thesis aims

Clearly the effect of hearing loss on driving is a contentious issue, and one which presents a number of important considerations. These considerations are diverse and complex, and are likely to be dependent on a variety of variables (hearing loss type and severity, the specific driving situation etc). Work carried out to investigate driving behaviour in the hearing impaired demographic is sparse, and therefore presents an unclear picture of how hearing loss interacts with driving performance. Regardless, the literature review provided in this chapter has identified two manners by which a loss of hearing might have an impact on driving performance: (1) an inability to hear sound, and (2) a disproportionately distracting effect of sound which *is* audible. However, only the former of these suggestions is relevant for deaf individuals, and a majority of studies have concluded deaf drivers are not at an increased road traffic accident risk (Finesilver, 1962; Wagner, 1962; Ysander, 1966; Roydhouse, 1967; Schein, 1968). In contrast, other work has shown that partially hearing impaired drivers might be at an increased risk of road traffic accidents (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008), and further study has exhibited driving behaviour changes in hearing impaired individuals (Hickson et al., 2010; Thorslund et al., 2013a,b, 2014). Thus, those with a loss of hearing who were *not* profoundly deaf were the subject of investigation in this programme of research.

Limited work has investigated the effect of auditory distraction on driving performance in hearing impaired individuals (Hickson et al., 2010). Accordingly, the second of the two assertions given above was the focus of work described in this thesis: "Certain types of hearing loss distort auditory signals (even at easily audible levels), and this leads to a disproportionately distracting effect of acoustic information in the driving domain."

The potentially disproportionate effect of driver distraction for those with a hearing loss is an important consideration given that the driving environment is becoming increasingly intricate due to the development and incorporation of complicated in-car technologies (Hickson et al., 2010). A number of these systems function in the auditory modality, and so driving can often involve the simultaneous performance of multiple, cognitively demanding tasks, some of which are presented in the auditory modality. Existing work in this area has shown that auditory distraction affects aspects of driving performance, but it is curious that visual distraction also seems to be disproportionately distracting for hearing impaired drivers (Hickson et al., 2010; Thorslund et al., 2013b). This finding requires further investigation, given that it is incongruent with the hypothesis used to explain why hearing impaired individuals are more affected by engagement in cognitive tasks whilst driving.

Furthermore, the only study assessing the effect of auditory distraction on driving in hearing impaired individuals did so in an older sample ($\geq$ 62 years old). This makes it difficult to generalise results to other age groups of hearing impaired individuals, but also brings about potential influences from confounding factors, as is discussed in Chapter 3.

Hickson et al.'s (2010) study also used very few objective measures of driving performance and related skills. Driving research has identified a specific set of observations which arise as a result of cognitive task engagement: improvement in lateral vehicle control, reduced reaction times, visual attention failures, reductions in visual scanning, and changes in longitudinal vehicle control. The hypothesis that SNHL increases the cognitive demands associated with auditory processing suggests that a more marked observation of these trends should be apparent. However, none of these performance metrics were explicitly studied by Hickson et al. (2010).

The overarching aim of this thesis is, therefore, to investigate whether hear-

ing impairment has an effect on driving, and especially whether engagement with simultaneous auditory tasks whilst driving has a disproportionate effect on performance, when results are compared to those with normal hearing. Through the course of research described in this thesis, an attempt is made to address the research questions detailed in Table 2.4.

In order to answer the research questions posed it is useful to refer to theoretical frameworks/models which can explain how hearing impaired individuals might be at a disadvantage whilst driving under conditions of distraction. Whilst this chapter has alluded to the fact that auditory processing is more effortful for those with SNHL, it does not divulge why or how it interacts with the performance of other tasks. Understanding this relationship is key, as it can provide insights about the types of tasks, and the driving conditions which are particularly challenging for hearing impaired individuals.

Thus, in the next chapter, models of human multi-task performance are presented and discussed in order to provide an overview of how dual-task performance is undertaken, what might affect it and in what way. A model of listening effort, and how it is affected by hearing impairment will then be discussed, in order to establish why the hearing impaired demographic need to exert more effort in order to ensure successful listening. How this listening effort model feeds in to the model of human task performance will then be discussed, in order to identify the specific situations which may be problematic for those with a hearing loss.

Table 2.4 The research questions posed in this document and studies which have addressed them.

	Research question	Description of study
1.	Is hearing impairment seen as a cause of any problems for driving by people with a hearing loss?	Chapter 4 reports on a study which investigated the self-reported driving behaviours of hearing impaired individuals. An existing, validated measure of driving behaviour (the Driver Behaviour Questionnaire; Reason et al., 1990) and a questionnaire which had been created to investigate specific driving issues relevant to driving and hearing loss were used. Studies investigating road traffic accident risk in hearing impaired individuals have mixed the use of self-reported and objective measures of hearing loss, so differences in outcomes between these two measures were contrasted.
2.	Do people with a hearing loss report any alterations to their own driving behaviour?	
3.	Is there a difference between self-reported and pure tone audiometry measures of hearing loss in terms of their affect on experienced driving problems?	
4.	Does hearing impairment disproportionately alter visual processing efficiency during auditory task engagement?	Auditory task engagement whist driving leads to visual attention errors (Richard et al., 2002; Strayer et al., 2003; McCarley et al., 2004), this appears to affect the hearing impaired demographic disproportionately (Hickson et al., 2010). Chapter 5 reports on an experiment which explicitly assessed the visual attention of hearing impaired individuals whilst performing a simultaneous auditory task.
5.	Is the performance of auditory-based cognitively demanding tasks made more difficult by sound distortion representative of hearing loss?	A SimHL was used in order to isolate the effect of peripheral hearing loss from other confounding factors. Chapter 7 reports on a study which assessed the effect of SimHL on the performance of a number of auditory based memory tasks. This informed on how listening effort requirements are affected by peripheral hearing loss.
6.	Does the distortion to sound brought about by hearing impairment at a *peripheral level* have the capacity to affect driving performance when a simultaneous auditory task is present?	By using a SimHL in younger, normally hearing adults it was possible to isolate the effect of peripheral hearing loss on driving performance. Participants were asked to drive a simulator whilst simultaneously performing two different auditory tasks. Driving performance measurements corresponding to previous research findings were used in order to investigate the influence of SNHL. A measure of workload was also included in order to investigate whether SNHL raised the cognitive demands of performing a simultaneous task whilst driving. The results of this study are reported in Chapter 8.
7.	What are the measurable vehicle control and behavioural correlates of this effect on driving performance?	
8.	Do people limit engagement in secondary tasks in order to maintain successful driving performance?	

Chapter 3

Models of Human Task Performance and Listening Effort

3.1 Introduction

Chapter 2 has provided an overview of research which has specifically investigated the effect of hearing loss on driving, and has also summarised how hearing loss *might* affect driving. The main focus of this thesis is the investigation of whether auditory distraction has a disproportionately distracting effect on drivers with a SNHL. The premise under which this hypothesis has been suggested is that hearing impairment raises the processing demands of auditory-based cognitive tasks, and that this manifests as a disproportionate degradation in various facets of driving performance.

But why should an alteration in the processing demand of a listening task affect the performance of the predominantly visual task (Sivak et al., 1996) of driving? This question can be answered by drawing upon theoretical models of dual-task performance in humans. These models have been informed by experiments which have investigated performance decrements as a result of undertaking different types of tasks simultaneously (e.g. Pashler, 1994). Therefore, they can provide information regarding the extent to which tasks of different modalities interact (e.g. auditory and visual tasks).

The focus of this chapter is to consider the dual-task performance of individuals with a SNHL in the context of these models. Various models which have been used to explain dual-task performance in humans will be summarised, and the implications of an increased listening effort on the most valid model, in terms of its ability to explain past experimental findings (e.g. Hickson et al., 2010; Thorslund et al., 2013b), will be discussed. The outcome of this chapter is the identification of models of task performance and listening effort which can be used to predict outcomes from experiments performed in this programme of research.

3.2 Human task performance

The distracting nature of engaging in concurrent auditory-based activities whilst driving has been shown to have an impact on various measures of driving performance (see Chapter 2). It has long been the focus of driver safety research to investigate what types of secondary tasks impair driver performance, to what extent, and how their effect can be minimised. To this end, a plethora of dual-task experiments have been undertaken in laboratory, driving simulator, and field driving settings. These experiments usually take a format in which subjects are asked to perform two or more separate tasks at the same time (e.g. driving and conversing on a mobile telephone). Their performance in either (or both) task(s) is then calculated, and inferences are drawn about the extent to which certain task combinations/types limit performance.

Normally the understanding of results derived from these studies is aided by models of dual-task performance. These models are used to predict what effect a certain type of distracter might have on a primary task (such as driving). There are a number of distinct models of multi-task information processing which have been suggested, and a brief overview will be given in this section.

In order to understand how hearing impairment might affect driving in terms of its susceptibility to the effects of distraction, an empirically supported, pre-existing model of human task performance which can explain past research results (e.g. Hickson et al., 2010; Thorslund et al., 2013b) will be identified. This will allow for an easier understanding of the implications of hearing loss for driving, and will provide information as to why listening effort is increased in hearing impaired individuals. Therefore, the types of auditory task which are likely to impact on driving performance in this demographic, can be identified.

3.2.1 Theories of information processing

Two main approaches have been used for modelling dual-task interference in the past: those that focus on processing in **serial** and those that focus on it in **parallel**.

Serial-processing models (e.g. Broadbent, 1958; Treisman, 1960) take the view that parallel processing of tasks is not possible, i.e. there is a limitation in processing capacity at a single, serial processing stage - a *bottleneck*. At this bottleneck, processing resources can only be allocated to a single task at any given time, and so it is presumed that at some point one task will have to be prioritised over another for processing, whilst the other is briefly held in a sensory store[1] before being completed. As such, if tasks occur simultaneously then they cannot be performed together, and this will manifest in a delayed response to one or both of the tasks.

A number of authors have suggested theories as to the location of this bottleneck within the processing chain. Broadbent (1958) proposed an early filter theory whereby he inferred

[1] A temporary buffer from which information can be accessed for a short time after a stimulus has ceased (Winkler and Cowan, 2004).

that a sensory buffer in the processing chain would select a single stimulus to pass at a time, based on the physical characteristics of all incoming stimuli. He argued that this filter prevented overloading of a hypothesised limited capacity mechanism located thereafter. A large amount of evidence for this theory was derived from work performed by Cherry (1953) who found that listeners could not separate out two different spoken messages played to separate ears when they had similar physical characteristics.

However, Treisman (1960) proposed an alternative to this filter theory, whereby unattended information is attenuated rather than filtered out. This was supported by her finding that single words played to the unattended ear of listeners were sometimes recalled, particularly if they were probable in the context of the attended message. Deutsch and Deutsch (1963) postulated that the processing bottleneck is nearer the response portion of the processing system. They argued that all incoming stimuli are processed semantically before the most relevant one is selected for further in-depth processing.

More recently Lavie (2005) has argued for a combination of these early- and late-selection models in her ‘perceptual load’ model. This model proposes that everybody has a limited attentional capacity, and that the amount of attentional capacity allocated to the main task depends on its perceptual load. Beyond this, remaining capacity is automatically allocated to irrelevant stimuli. Accordingly, early selection occurs when perceptual load is high, and when it is low, late selection is preferred. Whilst this model has gained support from experimental evidence (e.g. Lavie, 1995), it is mainly limited to presentation within the visual modality (Eysenck, 2000). Contrary to this, recent evidence suggests that ‘load’ does not modulate auditory distracter processing (e.g. Murphy et al., 2013). As such, this model is considered inapplicable for the work described in this thesis, as it does not adequately explain the processes underlying auditory distraction.

Whilst serial-processing models have gained some empirical support, they fail to adequately explain why some tasks can be time-shared with seemingly no decrement in performance (Edwards, 2010). Well-cited examples of this are the ability of trained pianists to successfully shadow a spoken message whilst playing sight read music (Allport et al., 1972), expert typists who can sight-type whilst shadowing speech (Shaffer, 1975), or individuals who could be trained to read and write down dictated words simultaneously (Spelke et al., 1976).

Parallel processing models (e.g. Kahneman, 1973; Wickens, 1984), on the other hand, postulate that two tasks can be time shared, but view mental resources as a limited entity which are shared amongst these various tasks. It is supposed that, if two tasks are competing for resources, performance in one or both of the tasks suffers. Central-resource models are, therefore, seen as a manner in which this ‘time-sharing’ of certain tasks can be successfully accounted for. Two types of parallel processing model have been proposed in past literature:

Single resource models of attention suppose that humans have a single limited ‘pool’ of processing resources, and that the performance of any task imposes a demand on these.

Therefore, when the processing demands of tasks are greater than the finite resources possessed, a performance decrement results. One such model was suggested by Kahneman (1973), who postulated that an undifferentiated pool of resources could be allocated to any task or processing stage. As such, this model does not predict that tasks of different modalities can be time-shared entirely efficiently, rather that if the overall demands of any concurrently performed tasks exceed the available resources, performance decrements will occur. The relative simplicity of this model has caused it to be largely dismissed, with some authors doubting whether it can explain the complex nature of attention (Neisser, 1976; Allport et al., 1993). Another problem is the prominence of task similarity as a major factor in dual-task studies. Whilst distinct modality tasks can suffer a dual-task cost, the dual-task cost is greater when two tasks of the same modality are being performed (Lund, 2002). This type of finding is better explained by models which envisage information processing comprising of *multiple resources*.

The existence of *a number* of single processing pools, *multiple resources*, has been suggested by other authors. These processing pools have been conceptualised as ‘specialised mental resources’ (Navon and Gopher, 1979) or ‘modules’ (Allport, 1980); distinct, limited-capacity processing resources which deal with a particular skill or ability (Lund, 2002). In this case, it is thought that if two tasks differ in terms of their modality (e.g. a visual and an auditory task) they can successfully be performed simultaneously, as they do not share common resources.

Whilst the concept of modules suggested by Allport (1980) does support some studies which have found successful time sharing in separate modality tasks (e.g. Allport et al., 1972; Shaffer, 1975; Spelke et al., 1976), it cannot explain findings that exhibit a dual-task cost associated with two modality specific tasks (e.g. Hickson et al., 2010), as, theoretically, these tasks should draw upon distinct processing resources. Furthermore, these accounts of information processing do not specify the number of modules that exist, or precisely what the modules deal with. Accordingly, testing models of this type is problematic, as results can be explained by simply suggesting the existence of a new, distinct module (i.e. the model is non-falsifiable). There is also no explanation as to how the modules interact with each other; tasks require co-ordination from senses, but the module account of information processing does not explain how information from these modules is interrelated. The notion of Navon and Gopher (1979) is more accomplished in this manner. They maintain the view of specialised modules, but view information processing in economic terms, suggesting that performance in one modality can be traded for performance in another, depending on the demands and priorities of the situation.

These theories, however, do not explain how it is that separate resources co-ordinate (Lund, 2002). Indeed, Ho and Spence (2012) comment that, in attention research, there has been a great deal of focus on establishing independent sensory modality resources. However, the authors postulate that incoming sensory information is integrated in order to provide a multisensory perceptual representation of the external world. These apparent cross modal links have been used to explain the finding that mobile phone conversation leads to difficulties in driving cars; as people will find it hard to visually attend to the road scene whilst simultaneously attending to a sound source which is incongruent in terms of its spatial location (Spence and Driver, 2004).

Whilst the assertion that dual-task decrements are exacerbated by incongruent spatial locations of stimuli is interesting, it fails to explain why it is that SNHL has a disproportionate effect on driving performance in the presence of a simultaneous auditory task. In the study of Hickson et al. (2010), hearing impaired and normally hearing individuals were presented with visual and auditory tasks that originated from the same spatial location, yet the tasks had a more distracting effect on the hearing impaired demographic. Hearing loss may cause disturbances in auditory localisation (Moore, 2007), but this cannot explain Hickson et al.'s 2010 results; an alteration in the perceived source of auditory stimuli in their experiment would have resulted in one of two outcomes: (1) a perceived sound source that was comparable to that for normally hearing individuals - one which was incongruent with the visual area of interest (the windscreen), or (2) a perceived sound source which was congruent with the windscreen - thus theoretically improving driving performance. Accordingly, models of cross modal attention cannot be used to explain greater driving performance decrements in hearing impaired individuals compared to normally hearing individuals.

Contrary to the theory of cross modal attention, Wickens (1984) also supports the idea of 'modules' (Navon and Gopher, 1979; Allport, 1980), though he suggests an alteration in the manner by which these modules are used in that they may deal with different aspects of a particular task. His Multiple Resources Theory (MRT) (Wickens, 1984, 2002, 2008) proposes that modules exist for distinct stages of task processing: input mode, processing mechanism, and output mode. This model is reviewed in more detail below.

3.2.1.1 Multiple Resources Theory

Wickens (1984; 2002; 2008) developed the *MRT* to account for the differences found in dual-task performance across different modalities. The model proposes that the human processing system consists of independent processing mechanisms across five dichotomous resource pools (see Figure 3.1):

1. Input modality (visual/auditory);

2. Processing code (spatial/verbal);

3. Visual processing (focal/ambient);

4. Processing stage (perception-cognition/response selection);

5. Response type (manual spatial/vocal verbal).

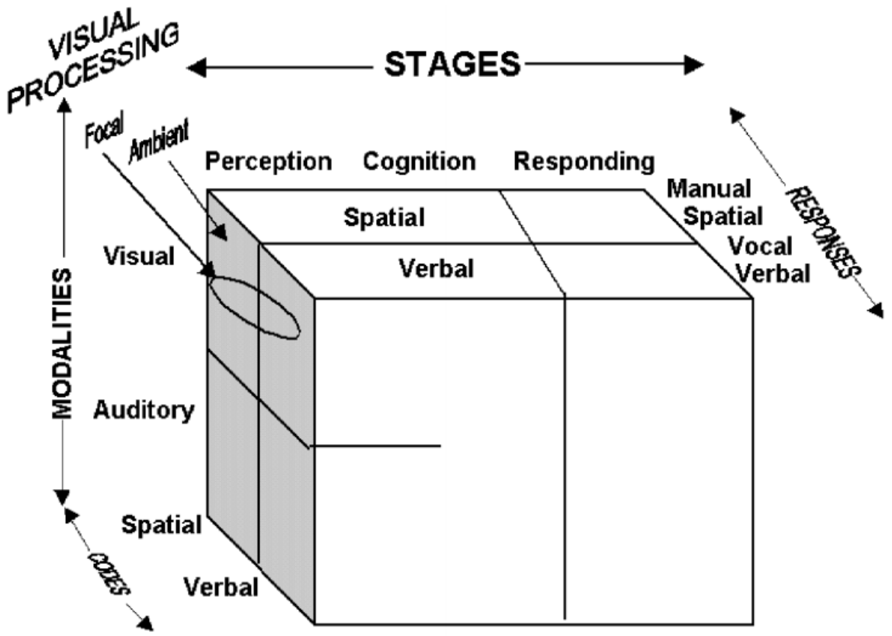


Figure 3.1 A depiction of Wickens' four-dimensional Multiple Resources Theory. Source: Wickens (2008).

This approach to dual-task modelling supposes a limited processing capacity, but posits that these limits exist only in separate resource pools. As a result, performance decrements are hypothesised to be governed by the extent to which tasks share processing stages/demands. As each of these dimensions is assumed to possess distinct processing resources, it is suggested that certain tasks can be performed in parallel provided that they do not draw on the same processing resources. For example, the perception of auditory and visual stimuli can be carried out simultaneously as the resources required are drawn from different pools. However, Wickens (2008) suggests that two tasks which appear dissimilar are still likely to share some common processing demands, and as such perfect time-sharing between two tasks is unlikely.

MRT has been applied extensively in driver safety literature, perhaps because it allows for tangible predictions about the extent to which two tasks will interfere with each other. For example, and pertinently for this thesis, the simultaneous performance of an auditory and visual task is likely to result in a lesser performance decrement than the performance of two visual tasks. This is the case as auditory and visual input modalities draw from separate resource pools.

A number of examples from driver safety literature are in accord with predictions of MRT. For example, in a driving simulator, Liu (2001) assessed the difference in driving performance as a result of route guidance information offered by visual only, auditory only and visual and auditory information. They asked participants to drive a simulated road course, following instructions presented under these three conditions, and at certain points presented warnings under these same three conditions. Participants were required to push one of two buttons (corresponding to the type of information presented) in response to these warnings. The authors found that response times to the warnings, the number of correct turns, and subjective workload ratings were all better under auditory, or auditory-visual conditions. Thus it was suggested that visual information conflicted more with driving than did auditory information. This is in agreement with MRT, as driving can be considered a visual-spatial-manual task across MRT dimensions (Jamson and Merat, 2005). In the study of Liu (2001), the visual task (visual-spatial-manual) shared more common processing resources with driving than did the auditory task (auditory-spatial-manual), thus more competition for resources was present in the visual task, leading to driving performance decrements.

However, when applying MRT in the domain of hearing loss and driving performance, it cannot fully explain the outcomes of previous research. The hypothesis proposed by Hickson et al. (2010) was that hearing impairment increases the cognitive resources required to understand a spoken message, and that it is this extra perceptual load which interferes with the primary task of driving. According to MRT, this extra perceptual effort in the auditory modality should not interfere with driving, because the input stage of driving can be considered predominantly visual (Jamson and Merat, 2005), and so in Hickson et al.'s (2010) study their driving and secondary tasks should have drawn upon separate input modality processing pools. However, the authors found that hearing impaired individuals' driving performance was disproportionately affected in relation to normally hearing individuals as a result of performing an addition sum presented in the auditory modality. Whilst perceptual differences were likely to be present between the two experimental groups at this processing stage in MRT, the driving and auditory tasks were drawing from distinct processing pools, and so driving decrements should not have occurred as a result (see Figure 3.2).

In accordance with MRT, some of the driving outcomes measured by Hickson et al. (2010) must have been due to conflicts at the cognition and response portions of MRT. They noted a reduction in the number of road signs recognised in their hearing impaired sample. This primarily draws upon the verbal pool of resources at the cognition and response stages of processing, as did the performance of their auditory task (see Figure 3.2). Accordingly, using MRT as a model to explain outcomes, it is clear that the hearing impaired group must struggle to a greater extent with verbal processing at either the cognition or response stage of processing, as these are the only stages at which a dual-task cost should be apparent. This does not fit with the explanation offered by Hickson et al. (2010) as to why it is that hearing impaired individuals are more affected by an auditory task.

MRT also fails to adequately explain the findings of Thorslund et al. (2013b). This study asked participants to perform a visual task which drew upon verbal processing (repeating back visually presented letters), which was hypothesised to be less efficient in hearing impaired individuals (Andersson, 2002). They noted a difference in various driving performance measures (e.g. increased gap around other vehicles, slower driving

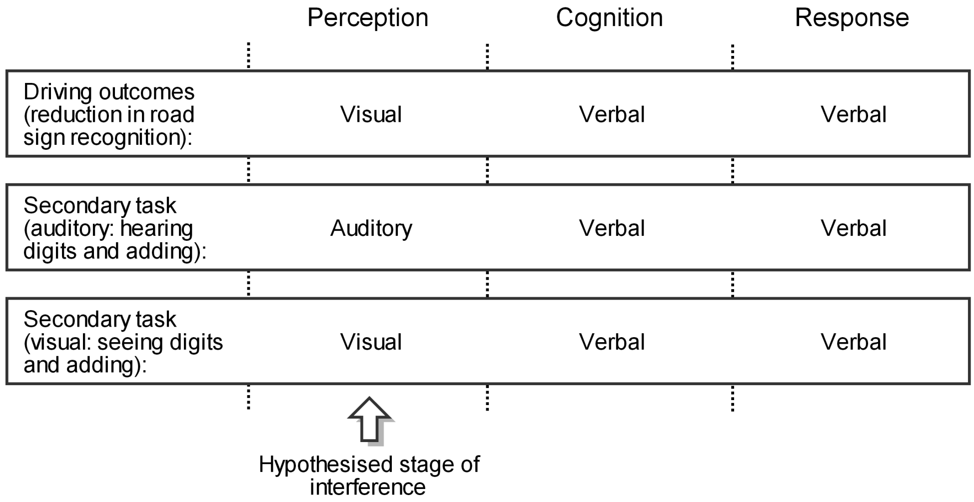


Figure 3.2 The resource pools used (with reference to Multiple Resources Theory) at each stage of processing during the study of Hickson et al. (2010). The task of recognising road signage whilst driving was performed simultaneously with a mental arithmetic task which was either visually or aurally presented. In each condition a significant decrease in the number of signs recognised was noted for the hearing impaired participants.

speed) between normally hearing and hearing impaired individuals when performing this task. However, Thorslund et al. (2013b) hypothesised that normally hearing and hearing impaired individuals would differ from each other in terms of the cognition portion of their secondary task. However, at this stage of MRT, the secondary and driving tasks used different processing resources (i.e. verbal and spatial respectively; see Figure 3.3). One would, therefore, not expect the secondary task used to have different outcomes for hearing impaired and normally hearing individuals. Accordingly it would appear that Wickens' MRT may not be the best model in the explanation of differences in distraction susceptibility for hearing impaired drivers.

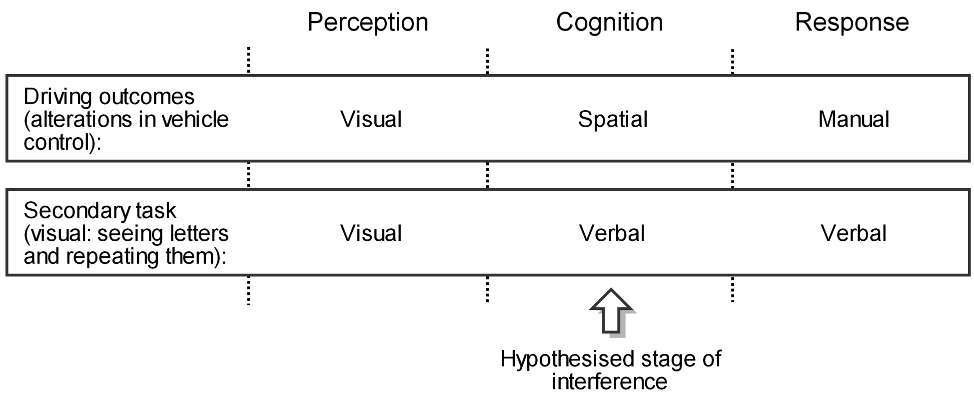


Figure 3.3 The resource pools used at each stage of processing during the study of Thorslund et al. (2013b). The task of driving was performed simultaneously with a secondary task which was visually presented.

The inconsistency between the results of Thorslund et al. (2013b) and MRT can perhaps be explained by a criticism of the model, in that it accounts only for bottom-up processes, whereas top-down processes can also have a significant impact on the performance of dual-task paradigms (Engström, 2011). For example, self-regulation of attentional effort has the capacity to interfere with bottom-up processes. Van der Hulst et al. (1998) suggest that drivers allocate their attention to tasks based on how task performance meets their overall goals of driving safely. Indeed, Thorslund et al. (2013b) argue that hearing impaired individuals adapt their driving behaviour in order to counteract problems which they experience. Their top-down influence on driving processes may, therefore, alter the outcomes which would be predicted by MRT. Models such as MRT do not take this factor in to account, and so they must be considered when making predictions based on the model.

3.2.1.2 Working memory

Baddeley and Hitch (1974); Baddeley (1992, 2000, 2003) have favoured an approach to attention and performance limitations which resembles a synthesis of central capacity and multiple-resource models: the 'Working Memory' model, which is proposed to be responsible for the temporary storage and manipulation of information. However, Working Memory was originally borne out of a link between perception, long-term memory and action (Baddeley and Hitch, 1974; Baddeley, 2003), and as such can be thought of in terms of predicting processing performance on one or more tasks.

Working Memory is seen as a limited capacity model which is arranged in a hierarchical structure and is used to temporarily store and process information required to carry out complex cognitive tasks (Rönnberg et al., 2013). However, it postulates the co-existence of modality specific limited capacity pools *as well as* a general limited capacity store (Eysenck, 2000). The modality specific resource pools are envisaged as two, non-interfering slave systems which are coordinated by the general resource pool known as the *central executive* (see Figure 3.4):

1. A phonological loop, which holds speech-based information for a period of one to two seconds before being lost. This loss of verbal material can be avoided if sub vocal rehearsal is undertaken (Baddeley, 1997).

2. A visuospatial sketchpad, which manipulates and processes spatial and visual information.

A third slave system, the 'episodic buffer', which is also controlled by the central executive, was a later addition to the model by Baddeley (2000), and is considered a non-modality-specific temporary storage system. It is thought to integrate information from the other two slave systems and long-term memory.

Admittedly, the structure of Working Memory mirrors MRT to a certain extent, but differs in the fact that it encompasses the central executive (a general resource pool). This

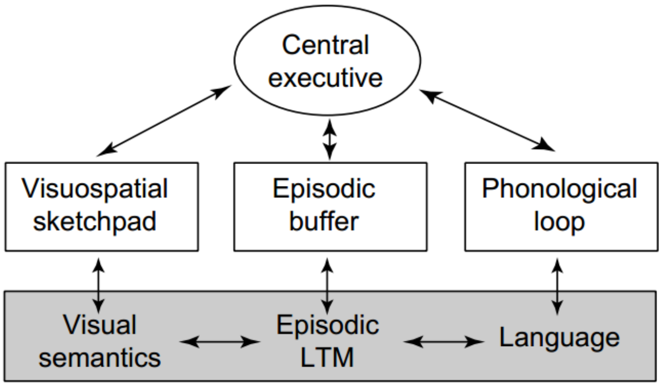


Figure 3.4 A version of the multi-component Working Memory model. Source: Baddeley (2000).

aspect of Working Memory was, until recently, a relatively unknown entity. Indeed, upon the conception of this model Baddeley et al. (1986) described this portion of the model as a 'ragbag' which dealt with any poorly grasped, or complex, phenomenon. The function of this system is now better understood, and it is thought to be responsible for focusing, dividing, or switching attention (Baddeley, 2003). As such, although the phonological loop and visuospatial sketchpad are distinct subsystems which do not interfere with each other, both systems are coordinated by the central executive. Thus, in order to function efficiently, they rely on the general pool of resources possessed by the central executive not being depleted or otherwise engaged.

As the central executive is responsible for attention switching between the two slave systems, it is considered that it might be the source of a performance decrement if more than one subsystem requires its input simultaneously, or the central executive itself is under load. It is this aspect of Working Memory that allows it to explain dual-task interference, even when two distinct subsystems are performing concurrent tasks. This addresses the problems associated with MRTs ability to account for the findings of Hickson et al. (2010) and Thorslund et al. (2013b). The dual-task paradigm presented by Hickson et al. (2010) included mental arithmetic, which requires extensive involvement from the central executive (de Rammelaere et al., 2001; Seitz and Schumann-Hengsteler, 2002). The inability of the central executive to efficiently carry out other necessary functions for satisfactory driving performance may, therefore, have been the source of interference on aspects of the driving task. Although the primary task of driving, and particularly the road sign recognition task (which showed a decrement in hearing impaired individuals), relies heavily on the modality specific visuospatial sketchpad, this subsystem is coordinated by the central executive. In the complex environment devised by Hickson et al. (2010), where participants had to navigate a number of highly complex tasks simultaneously, success would have been dependent upon successful attentional control. Given that the central executive was under a high load (from coordinating the subsystems and completing a mental arithmetic task), it is likely that this attentional control was compromised to an extent, and resulted in decrements in performance on various aspects of each task. Therefore, hearing impaired participants would have struggled to a greater extent with the driving task than those with normal hearing, since their perception of auditory stimuli would have been impaired. This would have required more attentional control to be placed on their phonological loop, a process mediated by the central executive. The implications of hearing loss for Working Memory processes will be covered later in this chapter, and the discourse shows that explicit processing undertaken by a construct similar to the central executive is hypothesised to be used more often in hearing impaired individuals than normally hearing individuals. Thus hearing impairment is proposed to engage central executive resources for listening processes, which would otherwise be used to aid other concurrent processes such as driving.

In a similar vein, the results of Thorslund et al. (2013b) can be explained under the premise that phonological loop operations are less efficient in persons with an acquired hearing loss (Andersson, 2002). Presenting their participants with a task which relied heavily on the phonological loop portion of Working Memory may have, again, instilled more explicit processing, placing a load on the central executive during periods of secondary task engagement. This may have impaired the ability of the central executive to adequately control visuospatial sketchpad operations, and as a result driving performance suffered. This explanation is also relevant to the study of Hickson et al. (2010), who found that a visually presented task which uses phonological loop operations (the addition of two numbers presented visually) impaired driving performance disproportionately in their hearing impaired sample.

The ability of Working Memory to explain past results in the field of hearing loss and driving, and results which have shown an effect of auditory task engagement on driving performance, suggest that it is a more applicable model in this programme of research than MRT. To summarise, it is hypothesised that the phonological loop portion of Working Memory requires greater mediation from the central executive in hearing impaired individuals in order to successfully process auditory information. This will lead to a reduced attentional control of the visuospatial sketchpad and episodic buffer, and less efficiency in tasks which explicitly use the central executive (see Figure 3.5). The consequence is that decrements in tasks which make use of any of these constructs (of which driving is one) are likely to be observed.

An assumption has been made, however, that hearing impairment does, indeed, lead to a disproportionate engagement of the central executive. This assumption is discussed in the following section.

3.3 Cognitive consequences of hearing loss

Hearing loss leads to a loss of audibility, but also distortion to sound once it is above the threshold of hearing (see Chapter 2). Speech understanding is a complex multi-stage task which draws upon a number of different cognitive processes (Fritz et al., 2007).

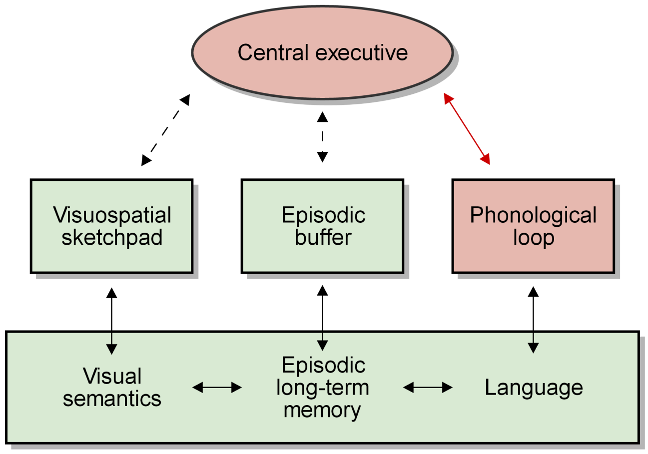


Figure 3.5 How Working Memory processes might be adversely affected by hearing loss. Phonological loop processes are put under more demand by the hearing loss, thus demanding more input from the central executive. This may lead to erratic control of the visual-spatial sketchpad and episodic buffer.

However, perception is only one of these processes; Craik (2007, p. 545) stresses that *"attention, perception, comprehension, memory and thinking are all aspects of the same cognitive system and that, as such, deficiencies in one aspect will have consequences for other aspects"*. Despite the complexities of listening described by Craik (2007), speech understanding is often automatic and effortless for young adults with normal hearing sensitivity. However, this is often not the case for those with a SNHL (Pichora-Fuller et al., 1995), and cannot simply be rectified by the use of hearing aids because the perceptual consequences associated with SNHL mean that simply increasing sound level does not restore efficient listening processes (Killion et al., 2004).

However, although SNHL will lead to imperceptibility of portions of an auditory signal, or a distortion beyond recognition, linguistic knowledge can be used to reconstruct a spoken message drawing on contextual support. For example, Warren et al. (1970) asked subjects to listen to recordings of sentences which had single phonemes replaced by a cough. After listening they were asked to circle, on a typewritten version of the sentence, where the cough had occurred, and whether it completely replaced their circled section. All but one of their twenty subjects said that the sentences had been complete, and the one who did not, incorrectly indicated the position of the cough. Thus participants had 'perceptually completed' the missing portion of speech, a phenomenon which the authors termed 'phonemic restoration'. It has since been shown that this perceptual filling occurs for non-speech sounds, and is known as 'auditory induction' (Warren, 1982).

Linguistic knowledge is well preserved into older adulthood (Wingfield et al., 2005) and, as such, phonemic restoration is a manner in which SNHL can be adapted to. However, a number of studies have shown that individuals with greater levels of hearing loss are unable to perform phonemic restoration as efficiently as those with normal hearing (Başkent et al., 2010). Furthermore, the retrieval and employment of linguistic knowledge to inform current discourse requires cognitive resources (Baddeley, 2003). Indeed, a number of authors have agreed that the perceptual decrements associated with hearing loss lead to an increase in the required cognitive resources to understand an auditory message (Pichora-Fuller et al., 1995; Edwards, 2007; Stenfelt and Rönnberg, 2009). It is not surprising, therefore, that cognitive skills are related to speech understanding when listening conditions are not optimal. Akeroyd (2008) reviewed twenty papers published since 1989 which investigated a link between speech understanding in noise and some measure of cognitive function. He summarised that there was a link between cognition and speech understanding, secondary to the predictive power of hearing loss. He found that measures of Working Memory, such as reading span, were most related to speech understanding, whereas measures of general ability (e.g. IQ) were less predictive.

Stenfelt and Rönnberg (2009) explain this link between hearing loss and cognition by suggesting that that listening under optimal conditions is fast and implicit, whereas distortion to a signal (e.g. through hearing loss or masking) leads to an additional *top-down* strategy, whereby attention and explicit decoding of phonological content is necessary (see Figure 3.6), raising the cognitive resource requirements. Top-down processing refers to a voluntary allocation of selective attention (Klingberg, 2010), thus (in terms of the Working Memory model) engaging the central executive, and drawing from its general pool of resources. The obvious implications of SNHL are, therefore, that a top-down listening strategy will be more extensively used than it would for a person with normal hearing. Therefore, in order to maintain understanding of an auditory message, those with a hearing loss must allocate more cognitive resources to processing sound than do people with normal hearing (Hornsby, 2013).

Stenfelt and Rönnberg (2009) base their arguments on a model of language understanding, which has been reported in recent literature, to explain this increase in cognitive resource requirements for successful listening in terms of Working Memory: the Ease of Language Understanding Model (ELU) Ronnberg (2003); Rönnberg et al. (2008, 2013). This model envisages language understanding as a Working Memory system which can describe and predict the dynamic interplay between explicit and implicit cognitive functions, particularly in the case of poorly perceived acoustic signals. Accordingly, it is considered a useful tool in the development and explanation of the studies performed in this programme of research, and is discussed in further detail in the following section.

3.3.1 The Ease of Language Understanding model

The ELU (see Figure 3.7) has been developed based on a programme of work performed over the past thirty years. Rönnberg et al. (2008) argue that Working Memory is highly related to language comprehension, and as such the ELU is heavily based on Working Memory processes. This inference arises from work whereby Working Memory capacity has been shown to be a significant predictor of speech understanding. For example, Lyxell and Rönnberg (1989) asked participants to perform a number of language tasks whereby parts

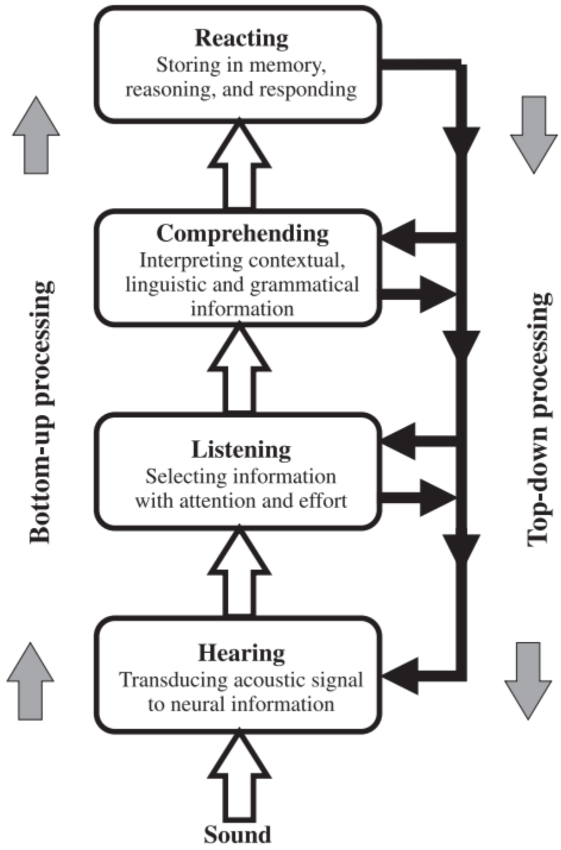


Figure 3.6 A generalized model for bottom-up and top-down processing of auditory input. Source: Stenfelt and Rönnberg (2009).

of written words or sentences were deleted and subjects were asked to fill in the gaps to derive what the word or sentence was. They found that successful inference making about these excerpts of language was highly predicted by Working Memory capacity, as measured by a Working Memory span test. They argued that a capacious Working Memory allows information to be buffered up until there is enough to make an inference about the content of the message.

Lunner (2003) reports similar findings, whereby the speech recognition in noise of first-time hearing aid users was significantly correlated with reading span and verbal information processing speed. This correlation remained even when controlling for age, degree of hearing loss and regardless of hearing aid use.

Accordingly, Rönnberg et al. (2013) argue that during conversations, those with a hearing loss must coordinate the interplay between a distorted perceptual input, long-term memory and contextual cues. They suggest that the skills reflected in complex Working Memory tasks are central to the performance of these compensatory interactions in people with hearing loss. This explains why Lunner (2003) found a correlation between Working Memory skills and speech recognition in noise.

Pichora-Fuller (1996) also suggests that language comprehension is related to Working

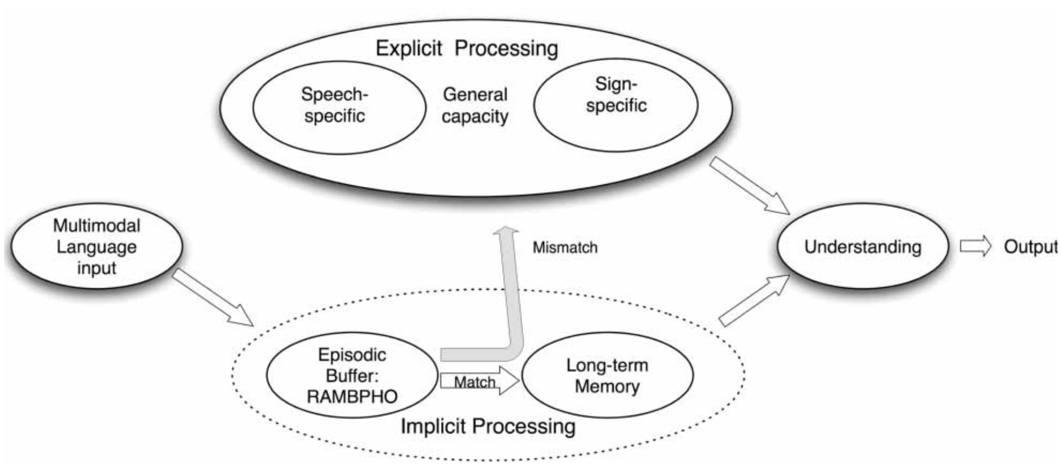


Figure 3.7 A Working Memory system for ease of language understanding. Source: Rönnberg et al. (2008).

Memory, requiring the perception and recognition of words, though the on-going uptake of information must also be interpreted with reference to information stored in long-term memory and recently stored information derived from earlier portions of the signal. In particular she points out that in adverse listening conditions (when listening is effortful), mental resources are allocated with priority to word recognition, thus leaving fewer resources available for storage and deeper processing of the information; an inference which she bases on findings that word recall is poorer when stimuli are presented at low signal-to-noise ratios (Rabbitt, 1968; Pichora-Fuller et al., 1995).

Rabbitt (1968) performed an experiment in which participants were asked to remember a list of eight digits presented either in isolation or through a masking noise. He found that, although his participants were able to correctly transcribe the numbers with nearly no errors in both conditions, their aptitude for remembering them in the masked condition was significantly lower. He argued that this may have been because digits in noise are less discriminable, or that the process of recognising the digits overloaded the available processing capacity, which had an effect on immediate memory processes.

He tested the second of these theories by playing only half of the digit lists through noise and asking for recall. Results showed that if the second half of the list was played in silence, recall of the first half of the list was significantly better regardless of whether it had been in the presence of masking noise, or not. When the second half of the list was presented in the presence of a background noise, this effect was not apparent. Because of this finding, Rabbitt (1968) concluded that channel capacity was being pre-empted by the perceptual effort associated with recognising digits in noise, rather than the digits being inaudible.

Pichora-Fuller et al. (1995) showed a similar pattern of results when asking participants to listen to a set of sentences played at different signal-to-noise ratios, repeating what they had heard and then recalling each of the sentence-final words. She found that there was no difference between the recall of the words in quiet and at high signal-to-noise ratios (easy listening conditions). However, when the signal-to-noise ratio was lowered such that it became challenging to hear the stimuli, word recall was significantly reduced, despite participants' ability to successfully shadow the words. Pichora-Fuller et al. (1995) concluded that re-allocable processing resources were used to support auditory processing when listening became difficult because of noise.

Pichora-Fuller (1996) therefore reasons that, whilst reduced perception and consequent failures in recognition jeopardise comprehension, Working Memory abilities are likely to account for the ability of people to comprehend language. Because of the reallocation of processing resources in acoustically adverse situations, those with better Working Memory abilities are better equipped for a reduction in resources available for processes after the perceptual stage. Thus, those with good working memory skills are likely to be able to perform other cognitively demanding tasks better than those with poor working memory skills in adverse acoustic environments, or in the presence of sensory loss.

The ELU essentially encapsulates the sentiments of Pichora-Fuller (1996), describing how and when Working Memory is engaged to support listening in adverse conditions. Rönnberg et al. (2008) assume that multimodal speech information is **R**apidly, **A**utomatically, and **M**ultimodally **B**ound into a **PHO**nological representation in an episodic buffer; a process they refer to as 'RAMBPHO'. They go on to assume that this representation is then matched against phonological representations held in semantic long-term memory. This assumption appears to be based loosely on findings such as those reported by Poeppel et al. (2008) and Bendixen et al. (2009), where it has been shown that the auditory system exhibits 'predictability'; it can 'predict' a sound that is about to occur, based on contextual factors. If RAMBPHO corresponds to phonological representations, lexical access and speech understanding is successful with no need for top-down processing. In this case, lexical retrieval occurs implicitly and at a rapid rate, explaining why young, normally hearing adults are able to perform effortless speech understanding in acoustically favourable environments.

However, if information from RAMBPHO is unclear and cannot be immediately or unambiguously related to phonological representations held in semantic long term memory, a mismatch occurs and top-down processing strategies are employed in order to aid language understanding. This assertion is supported by studies such as that performed by Foo et al. (2007). The authors altered the compression settings of habitual hearing aid users' hearing aids, thus inducing a mismatch between RAMBPHO and phonological-lexical representation. The authors tested participants' speech recognition thresholds in noise whilst they wore the altered hearing aids, and found that successful perception with the new settings was predicted by a measure of Working Memory ability (reading span). Thus the study suggested that the ability to overcome mismatches between RAMBPHO and phonological-lexical representations was dependent on Working Memory abilities, inferring that the mismatch had invoked a more explicit method of processing.

Likewise, it is also possible that phonological representations in long-term memory are less precise, causing a mismatch between RAMBPHO and phonological-lexical representations. For example, Andersson (2002) showed that severely hearing impaired individuals are less accurate and slower at rhyme judgements and generations than normally hearing individuals, arguing that this is because they have poor representations of words in their mental lexicons.

Giving an overview of the ELU, Rönnberg et al. (2008) point out that it functions as a system separate from the Working Memory model under optimal listening conditions. However, when listening conditions become suboptimal, a more explicit approach to language understanding that more closely resembles the Working Memory model is employed. The authors claim that this highlights maximisation of resource economy, in that the processing of language capitalises on implicit processing where it is possible, and only switches to more effortful processing in cases where listening conditions are suboptimal.

This advocates that, according to the ELU, suboptimal listening conditions will have a profound effect on the performance of concurrent Working Memory processes, as cognitive resources will be reallocated to aid speech understanding. Given the cognitive processes that ELU postulates will be employed in cases of RAMBPHO mismatch (inference-making, semantic integration, switching of attention, storing of information, and inhibiting irrelevant information), Rönnberg et al. (2013) clearly envisage a substantial input of the central executive in aiding language understanding. Indeed, the original suggestion of the model shows 'explicit processes' are drawn from a general capacity store (see Figure 3.7). Therefore, when Working Memory processes are employed to aid speech understanding, other concurrently performed tasks will suffer performance decrements as a result of central executive input being otherwise engaged.

Given the variable conditions under which communication usually takes place with regard to ambient noise, speech level, or acoustic environment, the relative contributions of implicit and explicit processes are likely to fluctuate continuously during a dialogue. However, in the case of hearing loss it is assumed that mismatches between RAMBPHO and long term memory stores will be more common still, given the decreased quality and audibility of the acoustic input. Accordingly, it can be argued that those with a hearing loss will have to employ explicit, effortful processing to a greater extent during conversation than will somebody with normal hearing. For some people with good Working Memory abilities this may not be an issue, as they are able to account for the mismatch of RAMBPHO and phonological representations using the explicit processing that Rönnberg et al. (2008) suggest is employed in suboptimal listening conditions. However, for those whose cognitive abilities are less efficient, it may present a problem in language understanding. This may go some way towards explaining why the experienced perceptual consequences of certain hearing losses are varied, even if they exhibit identical clinical hearing test results (Stephens and Zhao, 1996).

The theory that hearing loss has the capacity to introduce sufficient distortion to an auditory signal to evoke apparent effects on Working Memory processes is supported by empirical work. Rabbitt (1991), in a manipulation of his earlier study (Rabbitt, 1968), hypothesised that the effect he had found by using masking noise to degrade an auditory stimulus would remain for participants with a hearing loss in the absence of any masking noise. Indeed, he found this to be the case, and concluded from his results that "hearing loss will cause recognition errors, but may also impose an additional load on information processing capacity which prevents individuals from optimally rehearsing even those words that they have correctly heard." His results also support the inference that successful language understanding is reliant on cognitive abilities, given that he found an interaction between hearing loss and age, suggesting older adults are less able to cope with the cognitive consequences of hearing loss. This is in keeping with age-related declines in Working Memory processes (Salthouse, 1991), a topic which will be discussed later in this chapter.

A study, subsequent to the work of Rabbitt (1991), also showed that degraded auditory information had a profound effect on Working Memory processes. McCoy et al. (2005) asked older normally hearing and hearing impaired participants to listen to lists consisting of fifteen words. Lists were stopped at random points, and participants were asked to repeat the last three words that they had heard. Whilst the recall of the final word was comparable between the two experimental groups, the preceding two words were more poorly recalled by the hearing loss group, despite all words being presented at an audible level (as indicated by a word shadowing check).

The ELU, therefore, offers an explanation about how degraded auditory information may pose extraneous strain on Working Memory processes, and tie in to a disproportionately negative effect on concurrently performed tasks (such as driving) in the hearing impaired demographic. A new, updated model of the ELU has now been suggested (Rönnberg et al., 2013). The new model incorporates an explicit processing loop which feeds-back information to early stages of language understanding, informing RAMBPHO information until a degree of gist or understanding is obtained. Rönnberg et al. (2013) state that this gist induces a semantic 'framing' of the next processing loop, in other words providing context from which understanding can be achieved. However, the basic premise of the model remains, in that RAMBPHO information is matched against lexical information held in long term memory, and when a mismatch occurs, explicit processing is employed (see Figure 3.8). This is the salient point for this thesis; the model shows a load placed on Working Memory processes in cases where an auditory stimulus is degraded. It is this aspect of the model which explains why hearing loss may pose extraneous effects for driving whilst under dual-task conditions.

However, it should be noted that a number of studies have shown a reduced propensity for using contextual support in language understanding *in older adults* (e.g. Pichora-Fuller et al., 1995). Considering the ELU, this may be as a result of less efficient Working Memory processes in this demographic (Salthouse, 1991). For example, Rönnberg et al.

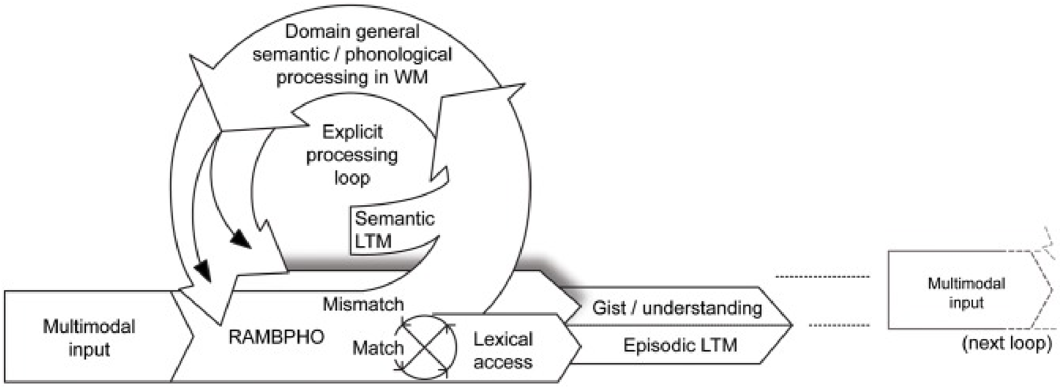


Figure 3.8 A Working Memory system for ease of language understanding. Source: Rönnberg et al. (2013).

(2008) argue that chronological age has no bearing on the RAMBPHO mismatch portion of the ELU, but does on associated explicit functions. In this regard, it is a concern that the degree of hearing loss is positively correlated with age (Davis, 1995), because when RAMBPHO mismatches do occur as a result of age-related hearing loss, explicit cognitive processes will be less efficient in restoring language understanding. Of further concern is that some studies have identified an association between sensory impairments and the slowing of cognitive functions, such as Working Memory processes, meaning that these explicit processing abilities may be reduced to a greater extent in older hearing impaired individuals than older normally hearing individuals. The next section will provide a brief overview of the evidence in this domain, as it is considered a potential concern in the design of experiments carried out in this programme of research.

3.4 The effect of age on auditory perception and task performance

An important consideration for hearing research is the influence of age, given its strong correlation with hearing loss (Davis, 1995). Indeed, it has already been pointed out that most research in the field of hearing loss and its effect on driving performance has been undertaken in an older demographic (McCloskey et al., 1994; Ivers et al., 1999; Gilhotra et al., 2001; Hickson et al., 2010; Green et al., 2013; Thorslund et al., 2013a,b,c, 2014). In two specific cases it is questioned whether factors co-existing with hearing loss (of which age is one) may be significantly confounding, given that visual task performance had a disproportionate effect on the driving performance of hearing impaired individuals (Hickson et al., 2010; Thorslund et al., 2013b), thus suggesting that hearing loss was not the only difference between the two experimental groups studied.

Increasing age has been shown to reduce cognitive skills (e.g. Salthouse, 1991; Lindenberger et al., 1993; Craik, 1994; Salthouse, 1994; Craik, 2000; Cepeda et al., 2001), and Salthouse (2000) summarises that this effect is most apparent for skills related to fluid intelligence[2], but less so for those related to crystallised intelligence[3]. This change in cognitive abilities appears to lead to a degradation of dual-task performance (Verhaeghen et al., 2003). In fact, as early as 1977, Craik wrote that older subjects are penalised when they must divide their attention between two tasks.

There are now numerous examples of dual-task performance decrements in the older demographic. In an example relevant to the content of this thesis, Baldwin and Schieber (1995) investigated the dual-task performance of younger and older participants (mean ages of 19.1 and 72.7 years respectively) by asking them to perform mental arithmetic whilst undertaking a steering (tracking) task. The mental arithmetic task required participants to subtract the larger of two aurally-presented, double-digit numbers from the smaller, and verbally report the answer. The difficulty of the tracking task was manipulated by increasing the apparent speed and curvature of the simulated roadway. The authors measured the reaction times to the auditory task, and the Root-Mean Squared (RMS) of tracking error to reflect participants' steering performance. Although auditory task performance was comparable between groups in the low tracking difficulty condition, they found that reaction times to auditory stimuli were significantly increased for some of the older participants when the difficulty of the tracking task was increased. This was not the case for the younger group of participants.

Examples of age-related difficulties in dual-task performance such as this are thought to reflect impaired cognitive functions, such as slowed information processing or a *decreased Working Memory/attentional capacity* (Baldwin and Ash, 2011). The link between age and reductions in Working Memory abilities is highly pertinent for this thesis, given that Working Memory can be used to explain driving performance decrements as a result of dual-tasking. Hearing impairment has been hypothesised to disproportionately degrade driving performance during auditory task engagement, but the added dimension of age-related cognitive decline may exacerbate this problem by affecting dual-tasking skills directly, regardless of hearing status.

A Working Memory model has also been used to explain an increase in the cognitive demands of listening for hearing impaired individuals. Therefore, age-related cognitive decline not only has the capacity to affect driving performance directly (by reducing dual-tasking ability), but also by increasing the difficulty of sensory perception, leading to a reduced ability to perform dual-task paradigms (see Figure 3.9).

Indeed, Wingfield et al. (2005) explicitly envisage age related changes in processing capabilities as a synergistic influence which adds to the burden of sensory decline on mental processes (see Figure 3.10). In other words, as a result of sensory impairment, more explicit perceptual operations must be undertaken in order to aid speech perception, but the efficiency of these mental processes is already compromised by age-related changes in processing ability. This would suggest that certain hearing loss pathologies may be more

[2]The capacity to think logically and solve problems in novel situations, independent of acquired knowledge (Cattell, 1987).

[3]The ability to use skills, knowledge, and experience (Cattell, 1987).

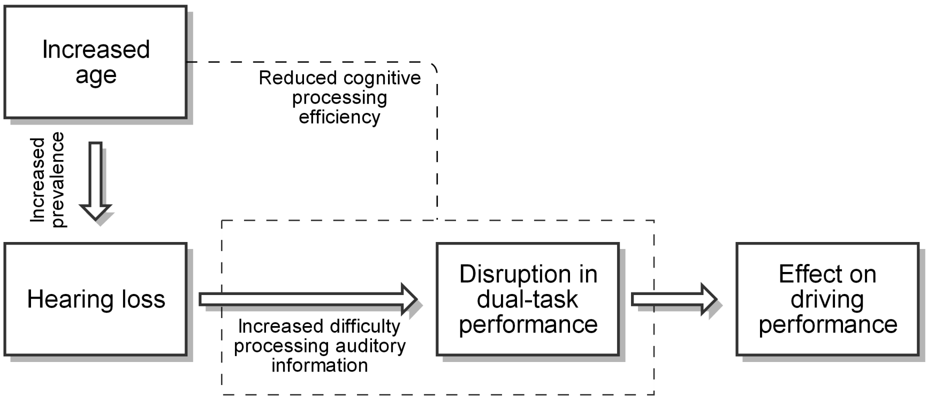


Figure 3.9 The influence that age-related cognitive decline might have on operations associated with driving performance whilst performing an auditory task.

problematic than others for ease of language understanding. For example, age-related hearing loss (presbycusis) is likely to be accompanied by reductions in cognitive processing efficiency and as such explicit processing will be employed more often, but will also be less efficient in individuals with this impairment. Younger hearing-impaired individuals may be more apt at language understanding than older ones, as they are more likely to infer meaning from an auditory source more efficiently as a result of more efficient Working Memory processes.

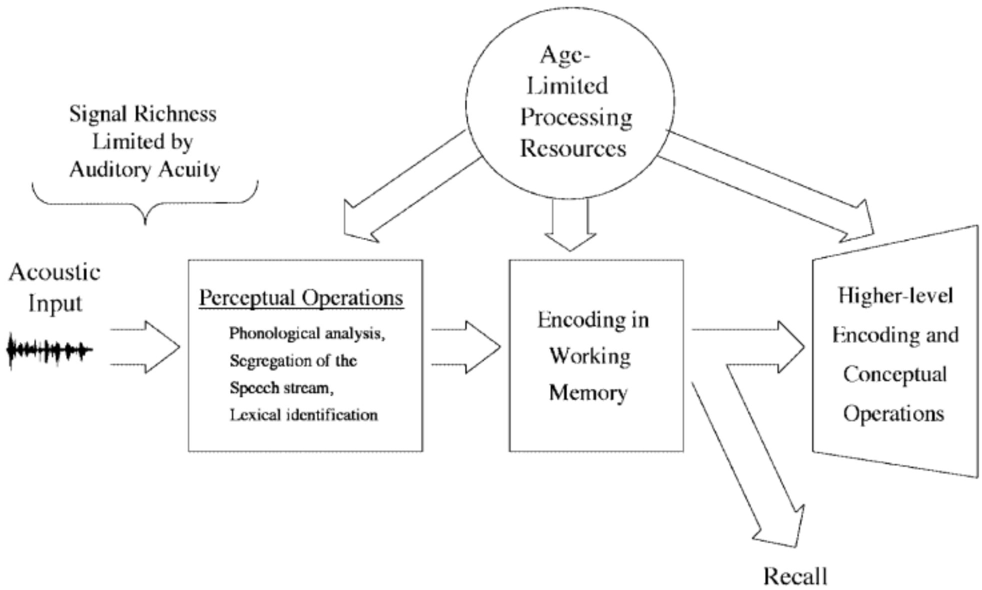


Figure 3.10 A schematic diagram of the operations required for successful recognition of a speech message. Source: Wingfield et al. (2005).

This distinction was highlighted in a study by Baldwin and Ash (2011). They investigated cognitive task performance as a result of altered stimulus presentation level in groups of young (age-range 18–30 years) and old (age-range 60–82 years), normally hearing adults.

They asked the two groups to complete a number of cognitive tasks with stimuli delivered at varied presentation levels above absolute threshold. Their tasks comprised measures of Working Memory capacity, processing speed, and auditory Working Memory span. Their results showed that, compared to the young group, the performance of older adults on the auditory Working Memory span task was significantly more affected by reductions in stimulus presentation levels.

Baldwin and Ash (2011) suggest that declining acuity plays an important role in age-related declines in cognitive ability. However, they also point out that the interaction between sensory and cognitive processes should be considered. They point to a common-cause hypothesis, whereby sensory decline reflects a general age-related degradation of the central nervous system that affects all functions (Li and Lindenberger, 2002). This has also been proposed by Lindenberger and Baltes (1994), who suggested that sensory acuity may act as an index of the physiological integrity of the aging brain. However, Baldwin and Ash (2011) argue that their data supports a modality-specific association in this regard, given that their visual Working Memory span task was not significantly different between their young and old group, whereas the auditory version was. This agrees with research which has shown a degradation of verbally administered cognitive tests in hearing (but not visually) impaired participants (Van Boxtel et al., 2001), and deficits in visually administered cognitive tests in visually (but not hearing) impaired subjects (Gussekloo et al., 2005).

In support of a link between sensory acuity and cognitive functioning, associations have been shown in the literature between the development of age-related hearing impairments and a higher prevalence of cognitive decline. When considering cognitive changes in this context, it is important to note that it is not with explicit reference to disorders such as dementia, rather age-related changes in cognition that occur in many older adults as a result of 'healthy aging' (Humes et al., 2012). Some authors have noted a correlation between the presence of hearing loss and measures of cognitive functioning. For example, Baltes and Lindenberger (1997) present data where they measured the auditory acuity of a large participant group (n = 687), as well as administering a total of fourteen cognitive tests aimed at measuring five intellectual abilities: perceptual speed, reasoning, memory, knowledge and fluency. Their analysis supported an earlier inference (Lindenberger and Baltes, 1994) that age-based changes in the central nervous system affect both cognitive and sensory systems of functioning, noting that a large amount of variance (31%) in cognitive scores could be accounted for by sensory impairment in their older sample.

The link between cognitive status and sensory acuity is a contentious issue, and it is unclear whether changes in sensory abilities cause cognitive slowing, or whether the development of these problems is as a result of more global cognitive changes. Regardless, Humes et al. (2012) points out that central auditory declines in aging are often intertwined with age-related changes in peripheral hearing, cognition, or both. Notwithstanding the underlying aetiology of such a problem, the possibility of a naturally higher prevalence of cognitive slowing in the hearing impaired demographic was considered in the design and analysis of experiments carried out during this programme of research. This was achieved initially through the use of a cognitive test battery in order to assess the underlying cognitive differences between the normally hearing and hearing impaired individuals being recruited. This made it possible to establish whether one experimental group was more predisposed to cognitive slowing, thus potentially affecting their performance on tasks being undertaken. Thereafter, age-related cognitive concerns were removed from experimental paradigms used by simulating a hearing loss for young, normally-hearing individuals. This meant that a within-subjects design could be used, meaning that the cognitive capabilities of both experimental groups (hearing loss and normal hearing) were identical, and older participants did not have to be recruited.

Undoubtedly, not controlling for the issue of cognitive decline would have a disproportionate effect on the interpretation of results in this research programme, particularly since the overarching hypothesis driving this research was that driving is affected by peripheral distortions to a sound source, and not central complications which co-exist with hearing loss.

3.5 Summary

The potential implications of hearing loss for driving and related tasks have already been discussed (see Chapter 2). One key area identified was the potential disproportionate effect of concurrent auditory task performance on driving and relevant skills. In the current chapter, the Working Memory model has been used to explain why auditory tasks affect driving in normally hearing individuals. However, cognitive requirements for successful auditory perception are increased in the hearing impaired demographic, and this is likely to have a further effect on concurrent driving performance. Therefore, this chapter has also presented the likely reasons why this increased listening effort will manifest, and its implications for task performance have been discussed by linking it with the Working Memory model.

According to the model, driving decrements as a result of auditory task engagement will occur in the normally hearing population if the auditory task places sufficient demand on the central executive. The ELU suggests that hearing impaired individuals have to employ more explicit processing in order to understand an auditory message, and that this explicit processing arises from a construct similar to the central executive of Working Memory. Accordingly, greater driving decrements will occur as a result of concurrent auditory task engagement for hearing impaired individuals, as the central executive will be under a greater load and will, thus be less efficient at carrying out its own explicit processes, including attention switching between the phonological loop and visuospatial sketchpad.

Finally, age has been identified as a potentially confounding factor in studies that have been outlined in this thesis. Age leads to a reduction in Working Memory capabilities and explicit processing abilities, which the ELU postulates will be employed more often in hearing impaired individuals.

Chapter 4

Self-Reported Data On Driving Performance and Hearing Loss

4.1 Introduction and study aims

This chapter reports on the first study of this programme of research, which aimed to address the first three research questions presented in Chapter 2:

1. Is hearing loss seen as a cause of any problem for driving by people with a hearing loss?

2. Do people with a hearing loss report any alterations to their own driving behaviour?

3. Is there a difference between self-reported hearing loss and measured hearing sensitivity in terms of its affect on driving?

There is currently little evidence in existence from which to answer these questions. Despite a growing body of research starting to link hearing loss to a number of driving variables (see Chapter 2), the majority of these studies have been hypothesis-driven and were not informed by information taken directly from individuals with a hearing loss.

There are only two reports of driving habits of individuals with a hearing loss:

1. Holland and Rabbitt (1992), who investigated reports of altered driving behaviour in hearing impaired individuals, but found no association between their measures of hearing loss and outcomes. Their study was under-powered (n = 68), did not explicitly focus on hearing loss (they also investigated visual deficits), and they only asked simple questions regarding themes such as avoiding driving on certain types of road, or at certain times of day, rather than driving-specific behaviours.

2. Thorslund et al. (2013c) who also did not exclusively ask about the effect of hearing loss on driving (and specific driving skills), but did gather some information regarding annual mileage and license ownership. Their data suggested a lower likelihood of

license ownership in those with a profound hearing loss, but also a higher annual mileage; these results are considered inconclusive (see Chapter 2).

The study reported in this chapter consisted of a self-report questionnaire, exclusively designed to understand the effect of hearing loss on driving, administered to a large sample of hearing impaired individuals. The questions were concerned with driving behaviour, and specific situations in which hearing impairment might have an effect on driving. The questionnaire aimed to establish an insight into whether this demographic experienced any problems in terms of their own individual driving with a hearing loss, and if so, which issues were most problematic for them. The collection of various measures related to hearing loss allowed for the analysis of whether increasing severities of hearing impairment or functional hearing loss, and different types/lateralities of hearing loss affected the manner by which driving outcomes were reported.

Establishing the opinion of hearing impaired individuals with regard to driving behaviours is important, particularly as one research group has identified that there may be a behavioural adaptation in driving style adopted in this group of drivers (Thorslund et al., 2013a,b, 2014). Whether or not this driving style is intentionally or unintentionally used can only be informed by the limited study of Holland and Rabbitt (1992). However, this information is of value, as the opinions of hearing impaired individuals are likely to be highly correlated with the uptake of any potential rehabilitative measures. If, for example, an individual with hearing loss does not perceive any ill-effects of hearing impairment on driving, he or she will be reluctant to engage with any treatment proposed. A questionnaire is a valid manner by which to investigate this theme; Lajunen and Summala (2003) argue that questionnaires are often used to study driver behaviour, and have several advantages including the ability to collect large amounts of data, and access to driving behaviours which would otherwise be difficult or impossible to study. However, questionnaires are also subject to some limitations, such as self-deception (Lindeman and Verkasalo, 1995), over-confidence in one's own skills (Lajunen et al., 1997), and giving socially desirable responses (Lajunen and Summala, 2003). Furthermore, there may be issues with the recall of relevant information (Gallo et al., 1999); a driver may experience an episode whilst driving and be oblivious to it at the time, or subsequently forget it, meaning that it cannot be recorded through the use of a self-report methodology. Provided that these limitations are acknowledged, a questionnaire approach was considered an ideal manner in which to explore the perceptions of the hearing impaired demographic themselves with regard to driving.

4.2 Experimental hypotheses

Past literature was used to inform the items that were included in the questionnaire; it was considered that responses would follow trends previously described in the literature. Hearing impaired individuals were expected to report a generally cautious approach to driving, whereby purposeful violation behaviour (such as disregarding speed limits) would not be apparent (Picard et al., 2008; Thorslund et al., 2013a,b). On the other hand it was considered that hearing impaired individuals may exhibit an increase in errors whilst driving, induced by lapses in concentration, given that they are hypothesised to be more prone to the effects of auditory distraction (Hickson et al., 2010). These trends were hypothesised to become more marked with increasing degree of functional hearing loss, and pure tone audiometry thresholds (Picard et al., 2008; Hickson et al., 2010).

4.3 Method

4.3.1 Questionnaire creation

The questionnaire was self-administered at National Health Service (NHS) audiology departments. This approach ensured the capture of individuals with a hearing impairment and the ability to access recent, reliably measured pure tone audiometry data from these patients. A self-report format was considered desirable as it removed differences that may have occurred as a result of administration (and therefore influence) by different researchers. Furthermore, it allowed patients to complete information anonymously, which removed the possibility of 'impression management', whereby individuals give answers that are socially acceptable as opposed to those which are more reflective of the truth (Lajunen et al., 1997).

A prototype questionnaire was created, which consisted of four sections:

1. A 24-item adapted version of an existing, validated measure of aberrant driving behaviours; the Driver Behaviour Questionnaire (DBQ) (Reason et al., 1990);
2. A newly-created 23-item survey regarding specific driving concerns related to hearing loss; the Driving and Hearing Loss Questionnaire (DHLQ);
3. Hearing loss information;
4. Demographic information.

Sections 2–4 were developed through discussion and pilot work with a number of stakeholders. This approach ensured the 'face' and 'content' validity of the survey tool used; 'face validity' refers to the 'appropriateness' of items in the questionnaire as judged by untrained observers, and 'content validity' as judged by reviewers with some knowledge of the subject area (Litwin, 1995).

Firstly the questionnaire was discussed with two individuals who had a long-standing hearing impairment (1♂/1♀, 67 and 54 years respectively; both possessed a current, valid UK driver's license). Feedback regarding the questionnaire was positive, and only minor changes in terms of the wording of questions was necessary for better comprehension. No changes to the content of the questions were made.

Following these discussions, the questionnaire was administered in person to twelve hearing impaired individuals (all of whom held a current valid driver's licence) attending a lip-reading class held at the 'Deaf Across Leeds Enablement Service'[1]. The purpose of this exercise was to gain a further insight into problems not addressed by the questionnaire, and to assess any ambiguity in the wording of questions. All twelve participants reported no problems in understanding the questionnaire, completed the survey without issue, and agreed that all relevant information was covered.

Finally the questionnaire was presented to audiologists at two NHS audiology departments in the United Kingdom (Coventry Teaching Hospitals NHS Trust and University Hospitals North Staffordshire NHS Trust). This approach was taken in order to check whether there were any additional items which had been neglected, either as a result of the audiologists' knowledge of hearing science, or as a result of experiences with patients. Furthermore, it was hoped that a group of clinicians might point out issues with the type of hearing loss-related measures used, or the manner in which the questionnaire was planned for implementation at NHS departments. No issues with regard to the content of the questionnaire were noted, but this step aided the design of the experimental protocol with respect to patient recruitment.

The resulting final survey was presented such that it could be completed without the help of an outside party (see Appendix). This was considered a superior approach in terms of potential recruitment success, as suggested by the audiologists consulted, given that participants could complete the questionnaire whilst waiting for their appointment. Furthermore, it was thought that patients would be more inclined to report certain types of driving behaviour in the absence of an outside party, rather than having to admit it to an unfamiliar researcher (Lajunen and Summala, 2003).

A discussion of each of the four sections of the questionnaire and rationale of the content is given below.

4.3.1.1 Section one: the Driver Behaviour Questionnaire

The DBQ, has been used abundantly in past academic research to examine differences in the driving behaviour of different demographic groups. For example, the cultural differences in driving behaviour between individuals from different countries (e.g. Lajunen et al., 2004; Özkan et al., 2006a; Bener et al., 2008). The DBQ is a self-report tool which considers different types of aberrant driving behaviour; respondents indicate (using a 6-point Likert scale) the extent to which they encounter 50 different situations during their driving (de Winter and Dodou, 2010). An example of an item in the DBQ is shown below in Figure 4.1.

The DBQ was originally developed by Reason et al. (1990) to establish whether a distinction between errors and violations was justified for self-reported driver behaviour,

[1]'Deaf Across Leeds Enablement Service' is a service based in Leeds for people aged 18+ and are Deaf, hard of hearing or Deaf blind. N.B. The group with which the questionnaire was piloted were all hearing impaired individuals (not profoundly deaf individuals).

	Never	Hardly ever	Occa-sionally	Quite often	Fre-quently	All the time
Become impatient with a slow driver in the outer lane and overtake on the inside	1	2	3	4	5	6

Figure 4.1 A single item from the DBQ

since the two are thought to have different psychological underpinnings. **Errors** reflect performance limits of the driver such as those related to perceptual, attentional, and information processing abilities; **violations** represent the style in which the driver chooses to drive and habits established after years of driving (de Winter and Dodou, 2010).

Responses to DBQ items are analysed using factor analysis, a statistical technique described by Child (2006) as the orderly simplification of several interrelated measures ('factors'). These factors are 'latent constructs' as they are immeasurable in their own right. Instead, related individual questions are used to provide information about factors. So in the context of the 50-item DBQ, Reason et al. (1990) hypothesised that a factor analysis on the questionnaire data would form two groups: one with items corresponding to violation behaviour, and the other describing error behaviour.

However, analysis of data collected from a number of studies (e.g. Reason et al., 1990; Parker et al., 1995a; Åberg and Rimmö, 1998; Rimmö and Åberg, 1999) has shown that the DBQ often results in three factors. It is, therefore, argued that the DBQ can decipher between more than two types of bad driving:

- Errors - mistakes with potentially dangerous consequences;
- Lapses - attentional failures which cause embarrassment but are unlikely to impact directly on safety;
- Violations - risky behaviours which are engaged in deliberately.

The DBQ has been validated and extensively used in past research; de Winter and Dodou (2010) point out that the DBQ has been used in at least 174 studies, and it is a repeatable measure (Parker et al., 1995a).

There is some discussion as to whether the DBQ is correlated with road traffic accident involvement, though there is some disagreement regarding the specific factors which are predictive of RTAs (see e.g. Stradling et al., 2000; DeLucia et al., 2003; Sümer, 2003; Özkan and Lajunen, 2005; Freeman et al., 2009; af Wåhlberg et al., 2011). The aim of this study was, however, not to assess accident risk, but to understand the driving behaviour of hearing impaired individuals. The DBQ has been shown to be sensitive to differences in the driving behaviour of different demographic groups (West et al., 1993; Lajunen et al., 1998; Parker et al., 1998), without incorporating excessive influence of socially desirable response patterns (Lajunen and Summala, 2003). Thus, by employing this questionnaire it was possible to reliably examine lapse, error and violation type driving behaviours for individuals with differing levels of hearing loss.

Parker et al. (2000) applied a shortened version of the DBQ in an elderly population in order to investigate the relationship between DBQ answers and accident rates. They administered the DBQ to 1,989 drivers aged 50 and above. Although the current study did not have the same aim of establishing a relationship between DBQ answers and accident rate, it was expected that the demographic attributes of the sample in Parker et al. (2000) would be similar to the sample recruited in this study, given the positive correlation between hearing loss and age (Davis, 1995). Parker et al. (2000) report mean and standard deviation scores for their sample on each of the DBQ items, thus their study gave normative data against which the results of the current study could be compared, using statistical analyses.

The likely similarity between the two study samples meant that the previously identified problem of heterogeneous data would be partly controlled, particularly as both study samples were drawn from the same country of residence. Because of this, the demographic information collected in this study was chosen to reflect that collected by Parker et al. (2000). The version of the DBQ used was also matched to that developed by Parker et al. (2000), which was a shortened 24-item version (see Appendix).

4.3.1.2 Section two: the Driving and Hearing Loss Questionnaire

There is currently no questionnaire which can be used to examine the effect of hearing impairment on specific driving behaviours. Accordingly, the creation of a new set of questions was required. This section will describe the synthesis and development of this part of the questionnaire - the DHLQ.

The sparse evidence in the area of hearing loss and driving (see Chapter 2) has identified two underpinning principles regarding how hearing loss *might* have an effect on driving:

- An inability to hear sound (Ivers et al., 1999; Slawinski and MacNeil, 2002; Picard et al., 2008; Ohene-Djan et al., 2010);
- An increase in required listening effort to understand/perceive sound sources, which, in turn, has an effect on attentional control (Hickson et al., 2010).

The majority of items included in the DHLQ were driven by these principles. Specific situations which might be troublesome for drivers with a hearing loss were identified from examples which have been reported in the literature, and from discussion with people who have a hearing loss, as well as clinicians (audiologists). Participants' agreement regarding whether these specific situations are troublesome were sought, as well as their stance generally on whether hearing loss affects driving.

Research on the acceptability of in-car technologies for the hearing impaired demographic has suggested additional difficulties (Thorslund et al., 2013a,c). For example, navigation systems using the auditory modality may be less suited to the hearing impaired demographic

(Thorslund et al., 2013a). The DHLQ also explored this theme by asking about in-car systems using the auditory modality.

Finally, there has been some concern with regard to the effect of hearing aids on driving performance (McCloskey et al., 1994). However, hearing aids are aimed at overcoming deficiencies posed by SNHL (Moore, 1996; Dillon, 2001) and so it is feasible to consider that they may provide benefit in the driving environment, particularly in light of their ability to reduce listening effort requirements (Sarampalis et al., 2009). Therefore, items regarding hearing aid use and acceptability whilst driving were also included in the DHLQ in order to explore this theme.

The questions associated with these themes, and a rationale for inclusion, are presented below. A Likert (1932) scoring system was used.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I have considered limiting the amount I drive because of my hearing loss.	1	2	3	4	5

Figure 4.2 An example question from the DHLQ showing the Likert response type used.

4.3.1.3 Section three: demographic information

Age, gender, annual mileage, length of licence ownership, professional driver status, driving test history, and occupation data were collected and included in the analysis. Previous research indicates that gender and age differences are evident in self-report driving behaviour data (Rimmö, 2002), but that differences can be explained when driving experience (in terms of annual mileage and the number of years for which a licence has been held) is controlled (Groeger and Brown, 1989). Furthermore, age, gender, and driving experience are generally included in studies employing the DBQ (e.g. Reason et al., 1990; Parker et al., 1995b; Bener et al., 2008; af Wåhlberg et al., 2011.

The DBQ was used as a comparison against published data from a similar group presumed to consist of a majority of normally hearing individuals (Parker et al., 2000). Although Parker et al. (2000) did not measure hearing in their sample, it was presumed that the majority of participants they recruited would have normal hearing, given that the prevalence of hearing loss for the mean age of their sample is approximately 44% (Cruickshanks et al., 1998). Thus, the representation of hearing impaired individuals in the sample collected in this study, where this demographic was being purposefully sampled, would be greater. Because data was being compared against Parker et al.'s (2000) study, it was necessary to collect analogous demographic information in this study. It was, therefore, possible to accurately evaluate the similarities between the two separate samples, and highlight any significant differences which may have had a bearing on the results of the

Questionnaire item	**Rationale**
General questions	
I have considered limiting the amount I drive because of my hearing loss.	Two past studies have found that hearing impaired individuals are more likely to cease driving compared to their hearing counterparts (Gilhotra et al., 2001; Unsworth et al., 2007). This question aimed to uncover whether there are many reports of people knowingly limiting their driving as a result of hearing loss.
I think that hearing loss presents some problems for driving.	Hearing impairment might have an effect on driving behaviour and safety (e.g. Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008; Hickson et al., 2010; Thorslund et al., 2013a,b, 2014). Until now, there has been only a small amount of work assessing the opinions of hearing impaired drivers *themselves* (e.g. Holland and Rabbitt, 1992; Thorslund et al., 2013c).Asking this question indicated the experiences of this demographic on driving problems.
I feel that my hearing loss sometimes makes driving more difficult for me.	Instead of asking participants whether they think hearing impairment is a limiting factor for safe driving *generally*, this question asked participants to express thoughts regarding their own *individual* driving. This provided a measure of the extent to which people may inflate their own driving ability (Farrand and McKenna, 2001; Horswill et al., 2004) and answer favourably for themselves.
Use of in-car technology	
I feel that some in-car electronic devices which make use of sound are not accessible to me.	In-car systems may not be accessible for hearing impaired drivers, and some investigation into alternatives has been undertaken (Thorslund et al., 2013a,c). This idea is based on scant evidence, although in-car technology is growing in popularity and complexity, and some authors are suggesting that hearing impaired individuals should refrain from using these devices (Hickson et al., 2010). Therefore, this question aimed to further establish the attitudes of hearing impaired individuals towards in-car technologies (e.g. satellite navigation).
I find it difficult to hear sounds produced by electronic devices in my car (e.g. satellite navigation instructions, parking sensors etc).	This question aimed to establish whether people are unable to hear in-car technologies. This is important as people may feel this type of technology is accessible, but still struggle to hear it. It stands to reason that partially inaudible systems are likely to have more of a cognitively-degrading effect, as the listening task is being made more difficult (see Chapter 3).
I find that talking on a hands-free mobile phone whilst I drive is very difficult because of my hearing loss.	One of the most common forms of technology used in vehicles is the mobile phone (Pöysti et al., 2005). This question aimed to establish whether hearing impaired individuals struggle to use their mobile phone. Phone conversation is a primary example of an auditory distraction which can lead to an increased road traffic accident risk, even when used hands-free (e.g. Redelmeier and Tibshirani, 1997).

Questionnaire item	Rationale
Inability to hear sound	
Being able to hear when emergency services vehicles are near is difficult for me.	It has been suggested that hearing impaired individuals are unable to hear auditory warning signals easily, impacting on their driving safety (Coppin and Peck, 1965; Miyazaki and Ishida, 1987; Ivers et al., 1999; Picard et al., 2008; Ohene-Djan et al., 2010). Hearing emergency services vehicles' sirens may be difficult, particularly for the elderly hearing impaired demographic (Slawinski and MacNeil, 2002).
Working out the direction from which emergency services vehicles are approaching is difficult because of my hearing loss.	Perceiving the approaching direction of emergency services vehicles is important for taking evasive action should it be necessary (de Lorenzo and Eilers, 1991). For drivers with a hearing loss, the localisation of sounds may be difficult; localisation skills are often impaired by SNHL (Moore, 2007), so it is likely that this will be a problem for hearing impaired drivers.
I feel that because of my hearing loss I am sometimes less aware of what is going on around me when I am driving.	This question aimed to derive general information about awareness of all road users and situations for people with a hearing loss. There is evidence suggesting that sound is important for situation awareness (Walker et al., 2008), therefore the reduction of sound by SNHL may hinder this aspect of driving.
My hearing loss sometimes makes it difficult for me to judge how fast I am driving.	It is thought that the quieter background noise levels are, the slower our perception of travelling speed. This may lead to unwitting speeding behaviour (Evans, 1970; Matthews and Cousins, 1980; Walker et al., 2006; Horswill and Plooy, 2008; Hellier et al., 2011; Wang and Wang, 2012). It follows that hearing impairment may reduce the intensity of background noise, thus resulting in a similar phenomenon. However, numerous authors have noted a lower driving speed in the hearing impaired demographic which contradicts this prediction (Picard et al., 2008; Hickson et al., 2010; Thorslund et al., 2013a,b).
I think that sounds from the engine of the car are important for safe driving.	Sounds from the car engine are perceived as important by the Australian driver licensing body, who state that commercial vehicle drivers have to have a level of hearing which allows them to be aware of changes in engine or road noises and external warning signals. If vehicular noise is not perceived as important by hearing impaired individuals, they are unlikely to adopt rehabilitative measures to improve the situation.
My hearing loss makes me worry about parking my vehicle in close proximity to other obstacles (e.g. other cars, fences, walls etc).	During pilot work, a number of hearing impaired individuals expressed concern with manoeuvring their vehicle in close proximity to objects. This question aimed to establish whether this is a common feeling amongst this demographic.

Questionnaire item	Rationale
Indicators of listening effort	
I have problems hearing what passengers say whilst I am driving my car.	Passenger conversation is a potential source of distraction whilst driving (Laberge et al., 2004), and as such this distraction effect may be greater if the listening task is made more difficult (e.g. as a result of hearing loss). Passengers may compensate for this by mediating their conversations during periods of demanding driving (Drews et al., 2008), or alter their speech if they know the driver is hearing impaired. This question aimed to establish whether passenger conversation is particularly difficult for hearing impaired drivers to hear.
When I am talking to people in my car I find it difficult to concentrate on the road.	This question attempted to gain information about the extent to which passenger conversation is distracting for hearing impaired individuals. Rather than trying to establish the difficulty of listening to passenger conversation, it more directly assessed the distractive impact that passenger conversation may have.
Having the stereo on whilst I drive has a negative effect on my driving.	Listening to the stereo whilst driving has generally been found to have a negligible effect on driving performance in normally hearing individuals (Bellinger et al., 2009). Hearing loss may have a bearing on the perception of sound from car stereos, and so it might be that listening to the stereo does have an effect in the hearing impaired demographic. The question also related to a masking effect on other auditory information, whereby the stereo sound 'covers up' other environmental sound. Hearing impairment reduces temporal resolution (Moore, 2007), thus it is more difficult to hear sound of interest during the 'gaps' of a masking sound.
When I am paying attention to sounds produced by electronic devices in the car I find driving more difficult (e.g. satellite navigation instructions).	There has been research regarding the effects of different types of auditory cues on driving performance (see e.g. Ho and Spence, 2012). This research has largely neglected the effect of attenuation and filtering of sounds. As per the reasoning for passenger conversation and stereo use, listening to auditory information provided by electronic devices may also have a distracting effect in hearing impaired drivers.
Importance of environmental sound	
I think that sounds from the surrounding environment are important for safe driving.	This question explored the opinions of hearing impaired drivers regarding the suggestion that environmental sound is important in driving (Walker et al., 2006). An individual with a mild hearing loss may believe that environmental sound is important for driving, because they can still hear and make use of it. Somebody with a severe impairment, however, may not have access to that sound, and may adapt their driving style relying on other cues.

Questionnaire item	Rationale
Efficacy of hearing aid use in the car	
I don't find that my hearing aid(s) improve my ability to drive.	Hearing aids may have some success in improving driving comfort and safety in that they can increase audibility (Moore, 1996; Dillon, 2001), and decrease listening effort requirements (Sarampalis et al., 2009). This question asked whether this demographic notices any driving improvement as a result of wearing hearing aids.
My hearing aid(s) do not allow me to communicate more easily with passengers in the car whilst I am driving.	In the previous sections, respondents were asked about the difficulty they experienced in conversing with passengers. It was argued that the more difficult the perception of passenger conversation, the greater the impact it will have on driving as a result of distraction. As hearing aids are aimed at increasing the audibility of sounds and speech recognition (Dillon, 2001), it is likely that using them will improve this aspect of driving. This question was, therefore, aimed at establishing whether any respondents have any experience of this suggestion.
My hearing aid(s) do not make me feel more aware of my surroundings whilst driving.	Similar to the above reasoning, this question aimed to establish whether the increased audibility provided by hearing aids counteracts the potential issue of being unable to hear driving-related environmental sound.
Using my hearing aid(s) does not allow me to use devices in my car more easily.	Again, it is possible that amplification provided by hearing aids means that in-car systems functioning using the auditory modality may be louder. If people rate these systems as having a low accessibility, it would be beneficial to decipher whether hearing aids have the capacity to improve the situation.
I feel that wearing my hearing aid(s) disorientates me whilst driving.	Despite the positive impact of listening instruments, it is commonplace for those fitted with hearing aids to report negative aspects to their use (Cox, 2005). There is some evidence that wearing a single hearing aid disrupts a person's ability to localise sound (Noble, 2006). This may mean that a driver could perceive a sound as coming from one direction, when it is actually from a completely different direction.
Wearing my hearing aid(s) whilst driving makes sounds uncomfortably loud.	A common report from people wearing hearing aids intermittently is that they are too loud, sometimes uncomfortably so (Smeds, 2004). Given the high level of background noise level in car cabins (Evans, 1970; Matthews and Cousins, 1980), this problem may be excessively reported when using hearing aids in vehicles. Furthermore, Unsworth et al. (2007) suggest that they note an increased road traffic accident risk in people using hearing aids whilst driving as a result of loud, distracting sounds made by hearing aids.

questionnaire. This was particularly important given that de Winter and Dodou (2010) regard differences in DBQ outcomes as a product of sample heterogeneity. In addition to information regarding age, gender and driving experience, Parker et al. (2000) also asked participants their occupation, whether they took a test in order to obtain their driving licence, and whether they had ever been a professional driver.

Participants were also asked whether their driving had increased, decreased or remained constant over the previous three years, in an attempt to understand whether certain types of hearing loss, or hearing loss severity was related to retirement from driving. Finally participants were asked if they avoided driving on certain types of road or at certain times, as visual sensory impairments have been shown to cause people to limit their driving under certain circumstances (Kosnik et al., 1990; Holland and Rabbitt, 1992; Ball et al., 1998; Hakamies-Blomqvist and Wahlström, 1998). Thus it was considered that the sensory impairment of hearing loss may also result in similar behaviour of avoiding driving at certain times, or on certain roads.

4.3.1.4 Section four: hearing loss information

Self-reported hearing loss and pure tone audiometry data were collected in this study. The use of these two measures in past work investigating the effect of hearing loss on driving has been mixed, and this is a concern given that the two measure different constructs (see Chapter 2). Accordingly, it was thought that relationships between questionnaire outcomes and these two measures of hearing loss would vary. It was one of the aims of this study to investigate these differences.

Each participant's most recent pure tone audiogram (from within the past three years) was collated with their completed questionnaire and they were asked to complete the HHIE-S (Ventry and Weinstein, 1983), a widely used, reliable and valid survey tool (Lichtenstein et al., 1988) to measure functional hearing loss.

In addition to these measures of hearing loss, information about hearing aid ownership and use in different circumstances was also collected. Participants were asked if they owned a hearing aid, and if so for how long. They were asked if they used their hearing aids, and how often this was the case (a) generally, and (b) whilst driving. This information was considered pertinent, as it may have had a bearing on certain questionnaire items. For example, those who drive with hearing aids may have no problem hearing what passengers say, whereas those who do not wear hearing aids in the car may struggle to a greater extent.

4.3.2 Procedure

Initially, two separate NHS audiology departments were approached and asked if they would be involved with data collection for this study. Details of the project were also published on the NHS United Kingdom Clinical Research Network database, an online searchable database of research projects that allows hospital research and development departments to identify projects to which they can contribute. Contact through the Clinical Research Network led to the inclusion of six more sites in the study. The author liaised individually with each department's lead prior to data collection to explain the experimental procedure, what was required, and to answer any outstanding questions that arose.

Individuals were considered eligible for participation in the study if they had a hearing loss of any degree (> 20 dB in either ear; British Society of Audiology, 2011) and owned a current driver's license. At each participating site, administrative staff posted information sheets about the study to patients, along with routine appointment letters. The information sheet gave a brief description and rationale of the study, and informed patients that they would be invited to participate upon attendance of their appointment. On the day of their appointment, patients were asked by their audiologist if they would like to take part, and an opportunity was given to review the information or ask the audiologist any questions they may have had about the study.

Participants completed their questionnaire in the waiting room, and were instructed to hand it to their audiologist at the start of their appointment, so that their most recent audiogram could be added to the form. Participants were required to sign informed consent for the inclusion of this test result, and this was taken by the audiologist.

Ethical approval for this study was obtained through the NHS National Research Ethics Service Research Ethics Committee (reference: 12/NW/0721).

4.4 Results

4.4.1 Demographics

Data collection for this study was run over a fifteen month period from February 2013 to June 2014. From the eight NHS departments included in the study, a total of 393 completed questionnaires were collected, which is considered sufficient to draw valid conclusions regarding the wider hearing impaired population, according to a simple power calculation suggested by Krejcie and Morgan (1970). A breakdown of the number of participants recruited at each site is shown in Figure 4.3. Table 4.1 shows a summary of the demographic information, and compares it against Parker et al.'s (2000) study demographic.

The mean pure tone audiometry thresholds across all participants for left and right ears are shown in Figure 4.4. Although the audiograms collected from respondents were suggestive of a range of underlying causes and degrees of hearing loss, the majority of cases suggested acquired, age-related hearing loss, reflected in the sloping, high-frequency nature of the mean audiograms shown. Indeed, the mean age of hearing loss onset was 54.28 (SD = 19.92). Table 4.2 shows that participants had a range of hearing loss severities (as classified using recommended guidelines; British Society of Audiology, 2011), and functional hearing loss severities (using a commonplace categorisation technique for the HHIE-S; Lichtenstein

	Coordinating NHS trust	Number of respondents
1.	Dorset County Hospital Foundation Trust	185
2.	Royal Wolverhampton NHS Trust	100
3.	University Hospitals North Staffordshire NHS Trust	34
4.	Newcastle upon Tyne Hospitals NHS Foundation Trust	25
5.	City Hospitals Sunderland NHS Foundation Trust	20
6.	Cambridge University Hospitals Foundation Trust	14
7.	Shrewsbury and Telford Hospital NHS Trust	13
8.	Leeds Teaching Hospitals NHS Trust	2

Figure 4.3 The breakdown of respondents recruited from each NHS trust involved in the study and their location.

et al., 1988).

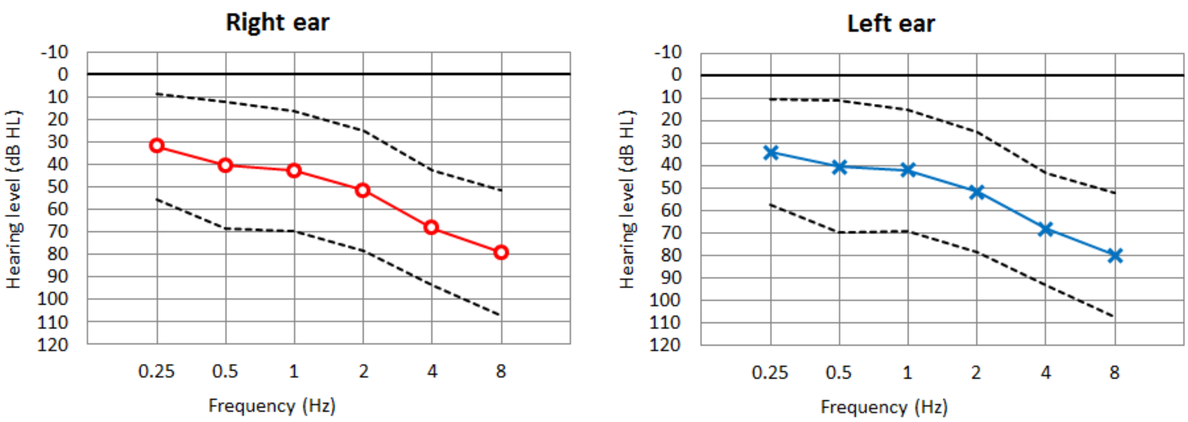


Figure 4.4 Mean audiometric results (± one standard deviation) across the entire sample shown for respondents left and right ears.

In terms of hearing aid use and ownership, 52% of participants owned bilateral hearing aids, 25% owned unilateral hearing aids, and 23% did not own a hearing aid. Of those that did own hearing aids, they had sought rehabilitative help an average of 17.19 years (SD =16.34; range = 0–87) following the onset of their hearing loss. Only 1% of the sample who owned a hearing aid reported not using it. In terms of the extent to which participants

Table 4.1 Summary demographic information for the study sample compared against that of Parker et al. (2000).

Demographic info	Current study	Parker et al. (2000)
Number of participants	393 (♂= 73%; ♀= 27%)	1989 (♂= 62%; ♀= 38%)
Age	69.59 ($SD = 12.29$; range = 23–94)	66 (range = 49–90)
Years driving licence held for	46.05 ($SD = 13.99$; range = 0–75)	N/A
Estimated annual mileage	7,800 ($SD = 7,300$; range = 0–60,000)	8,540 (range = 10–40,000)
Proportion of sample increasing/decreasing driving in the past three years	11% increased; 39% decreased; 50% stayed the same	9% increased; 32% decreased; 59% stayed the same
Proportion of sample reporting active/passive crashes in the previous five years	14% passive; 7% active; 2% both	23% passive; 25% active; 7% both

Table 4.2 The proportion of respondents fitting the criteria for different types of hearing descriptors.

Descriptor	**Proportion of sample**	
BSA audiometric descriptor	Normal	11%
	Mild	43%
	Moderate	33%
	Severe	7%
	Profound	6%
HHIE-S rated handicap	No	20%
	Mild-moderate	45%
	Severe	35%
Laterality of hearing loss	Bilateral	5%
	Unilateral	95%
Site of lesion	Sensorineural	62%
	Conductive	13%
	Mixed	25%

reported using their hearing aid(s) both generally and whilst in the car, the proportion of the samples are shown in Figure 4.5. The majority of respondents generally reported using their hearing aids either most or all of the time. There was a significant increase in the number of respondents wearing their hearing aids ‘all of the time’ whilst driving (65% of the sample) compared to general use (47% of the sample), $Z = -3.692, p < .001$. It is important to note, however, that there was also an increase in people reporting ‘never’ or ‘rarely’ wearing their hearing aids whilst driving, perhaps suggesting that there is a split in opinion within the group regarding their efficacy in the car.

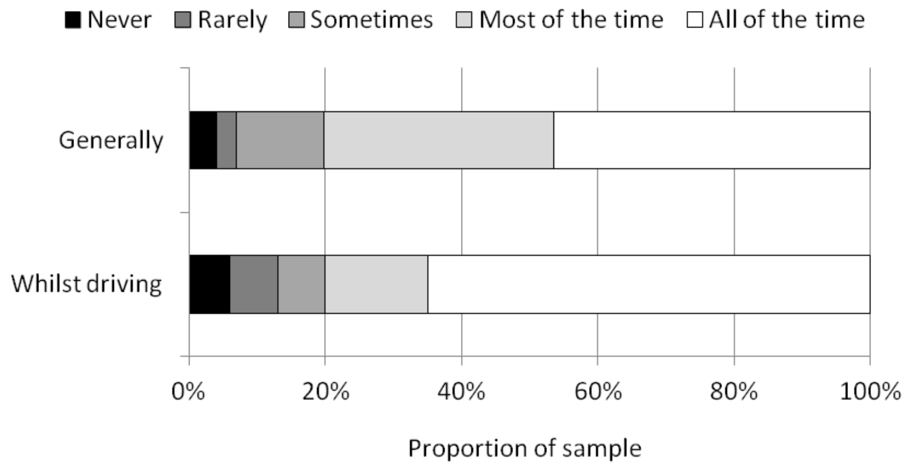


Figure 4.5 The proportion of participants who owned a hearing aid reporting the amount they use it both generally, and whilst driving.

4.4.2 Driver Behaviour Questionnaire

4.4.2.1 Factor analysis

A factor analysis with principal axis factoring (Costello and Osborne, 2005) was performed on the data collected in this study in order to explore the underlying factor structure. The Kaiser-Meyer Olkin measure of sampling adequacy (KMO = .891) (Hutcheson and Sofroniou, 1999), and Bartlett’s test of sphericity $(\chi^2 = 8676.712, p < .001)$, performed on the dataset (Field, 2013), together suggested that the data was suitable for a factor analysis. The direct oblimin (oblique) method of rotation was used, given the likelihood that extracted factors would be correlated in some manner (Costello and Osborne, 2005). Indeed this was the case, with the correlation matrix between items showing a moderate to high degree of association.

Factor analysis results in a number of different components, each of which explains a proportion of variance in the overall dataset (Field, 2013). This variance can be plotted in a ‘scree plot’ (see Figure 4.6). Commonly, the number of underlying factors present in the dataset is identified by those which have eigenvalues of greater than one (Costello and Osborne, 2005; Field, 2013). This method suggested a five-factor structure in this study. However, Field (2013) suggested that applying a simple criterion such as ‘eigenvalues greater than one’ can be problematic in some cases, and an alternative method of factor extraction should be employed. For example, the shape of the scree plot can be examined to identify the 'point of inflection' (the point at which factors begin to explain very little more of the overall variance), and factors scrutinised for their interpretability, e.g. do the items within a factor appear to have a common theme (Field, 2013). The resulting scree plot in this study suggested a two-factor structure was best suited to the data (see Figure 4.6), this solution was found to be more interpretable than the five factor solution. The resulting correlation between the two identified factors was 0.46, suggesting that an oblique method of rotation was applicable (Costello and Osborne, 2005).

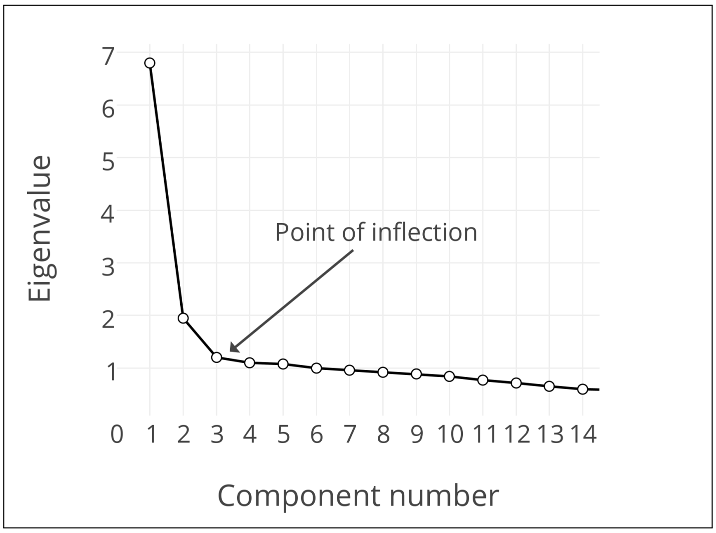


Figure 4.6 A scree plot exhibiting the components generated during the factor analysis performed on the DBQ data.

The two factor structure accounted for 35.4% of the total variance present in the data set. The factor structure and loadings of each individual questionnaire item is shown in Table 4.3 where loadings of less than 0.32 have been omitted for clarity, as this is the minimum value which indicates the loading of an item on to a factor (Tabachnick and Fidell, 2013). It would appear that the commonly derived 'violation' factor is upheld, although two of the items that might be expected to load on to that factor do not (values < 0.32). Conversely, the other two expected factors ('lapses' and 'errors') appear to have been combined into one single factor.

4.4.2.2 Comparison against Parker et al.'s (2000) study

Though DBQ items are rated on a 6-point Likert scale, it is commonplace to treat these values as continuous data (see e.g. Reason et al., 1990; Parker et al., 1995a,b, 2000; Lajunen et al., 2004; Özkan et al., 2006b). Multiple t-tests (using a Bonferroni correction) were performed on questionnaire items to test for significant differences in the reports between the two studies; Table 4.4 shows the mean values of DBQ items which differed significantly.

Parker et al.'s (2000) participants reported the majority of items more frequently than did respondents from the current study. There were a number of significant differences between the two groups, these were all in the direction of a lesser frequency in the current

Table 4.3 The factor structure derived from performing principal axis factoring on the DBQ data collected in this study. Factor loadings of $< .32$ are removed for clarity; this resulted in two DBQ items not loading on to either derived factor.

DBQ item	Error & lapse factor	Violation factor
Misread signs and take the wrong turning off a roundabout	.700	
Get into the wrong lane approaching a roundabout or junction	.674	
Switch on the wrong thing on the instrument panel by accident	.672	
Drive to a more usual destination through force of habit	.600	
Forget where car is parked in a car park	.526	
Fail to check rear view mirror before manoeuvres	.525	
Miss give way signs and narrowly avoid collision	.514	
Realise that you have no recollection of road along which travelling	.477	
Underestimate speed of oncoming vehicle when overtaking	.468	
Hit something when reversing that you had not previously seen	.465	
Fail to notice pedestrians crossing on turning into side road	.435	
Attempt to overtake someone you had not noticed to be signalling a right turn	.422	
Brake too quickly on a slippery road or steer wrong way into skid	.404	
Pay such close attention to the main stream of traffic you nearly hit a queuing car	.393	
Drive away from traffic lights in too high a gear	.377	
On turning left nearly hit a cyclist	.371	
Drive especially close to the car in front as a signal to move out of the way		.578
Become impatient and perform an undertake		.573
Disregard speed limits early in the morning or late at night		.515
Have an aversion to a particular road user and indicate hostility		.454
Run a red light knowingly		.439
Drive even though potentially over the blood-alcohol limit		.410
Give chase to another driver who has angered you		
Get involved in unofficial 'races' with other drivers		

study. By far the biggest discrepancy was with the frequency of reported speeding behaviour late at night and early in the morning. Respondents in this study were significantly less likely to report speeding behaviour (M = 1.67, S.D. = .62) than are those in the study of Parker et al. (2000) (M = 2.17, S.D. = 1.03), $t = 12.88$, $p < .001$.

Table 4.4 The mean scores and standard deviation to DBQ items on which there was a significant difference between this study and Parker et al.'s (2000) study.

DBQ item	Mean (S.D.) Current study	Mean (S.D.) Parker et al. (2000)	Δ
Disregard the speed limits late at night or early on in the morning.	1.67 (0.62)	2.17 (1.03)	0.50
Misread signs and take the wrong turning off a roundabout.	2.13 (1.03)	2.40 (0.64)	0.27
Realise that you have no recollection of the road along which you have just been travelling.	1.83 (0.99)	2.08 (0.92)	0.25
Forget where you left your car in a car park.	1.92 (0.66)	2.08 (0.87)	0.16
Switch on one thing, such as the headlights, when you meant to switch on something else such as the wipers.	1.82 (0.88)	1.97 (0.78)	0.15
Underestimate the speed of an oncoming vehicle when overtaking.	1.57 (0.62)	1.70 (0.64)	0.13
Brake too quickly on a slippery road, or steer the wrong way into a skid.	1.43 (0.36)	1.51 (0.60)	0.08

The other significant differences between the two groups were lapse of concentration behaviours: misreading road signs on a roundabout, driving without any recollection of the road being driven on, switching on the wrong instrumentation in the vehicle, and forgetting the location of a vehicle in a car park. However, the difference in mean values for these items were not as large as for the difference in speeding behaviour. There were a few significant differences in terms of dangerous error behaviour, though the difference in mean scores between the two groups was even smaller in these cases: underestimating the speed of oncoming vehicles whilst overtaking, and braking too quickly on slippery roads or steering the wrong way in to a skid.

4.4.2.3 Logistic ordinal regression

It was of interest to decipher which underlying factors (if any) were the best predictors of participants responses to the DBQ. Accordingly, a logistic ordinal regression was run for each individual DBQ item. This allowed for the derivation of an 'odds ratio' (OR); an assessment of how much influence an independent variable (e.g. hearing loss classification) has on a dependent variable (e.g. the frequency of speeding behaviour) (Szklo and Nieto, 2012). The frequency with which participants reported each of the individual DBQ items was submitted as the outcome to the logistic ordinal regression, and a number of predictor variables were chosen for investigation (see Table 4.5). This allowed some of the research questions posed to be adequately answered (e.g. are driving behaviour patterns and/or driving problems more prevalent in certain types/durations/severities of hearing loss?).

Table 4.5 The variables submitted to the logistic continuous regression.

Fixed factors	**Continuous variables**
• Gender • History of being a professional driver • Hearing loss bilateral or unilateral • Conductive element to hearing loss • Hearing aid owner	• Age • Annual mileage • Driving experience • Duration of hearing loss • Duration of hearing aid ownership • General frequency of hearing aid use • Frequency of hearing aid use in the car • HHIE-S score • Average air conduction threshold of best ear • Average air conduction threshold of worst ear

In establishing whether a logistic ordinal regression model could be used for each question in the DBQ, a number of criteria were considered. The -2 log-likelihood values for the final model and one containing no explanatory variables were compared using the χ^2 statistic (Quinn and Keough, 2002). The Nagelkerke pseudo R^2 statistic was also checked to establish the amount of variance explained by the independent variables used (Nagelkerke, 1991). Finally, the test of parallel lines was used to check that the assumption of proportional odds had not been violated; however this statistic is highly sensitive to multiple explanatory variables (Brant, 1990), the use of continuous independent variables (Allinson, 2001) and large sample sizes (Clogg and Shihadeh, 1994; Allinson, 2001), and was considered accordingly. The goodness-of-fit statistic was also considered in this manner, as it is highly sensitive to large sample sizes.

Where a regression model was considered applicable, independent variables were assessed for their respective influence on the dependant variable of interest. The resulting significant predictors (at the $\alpha = 0.05$) level are shown in Table 4.6 and Table 4.7. Hearing loss was significantly associated with some error (3/9) and lapse (4/7) items, but no violation based behaviour.

Self-reported hearing loss (as measured by the HHIE-S) appears to be related to a greater number of outcomes on questionnaire items than measures of hearing sensitivity. Indeed, HHIE-S score was found to be a significant predictor on 7/24 DBQ items, whereas hearing sensitivity was not significantly associated with any. Similarly, other data related to hearing loss (laterality, site of lesion, hearing aid ownership and use, duration of hearing loss) appeared to have no bearing on the answers participants gave to the DBQ. The association of extraneous factors (see Table 4.5) with DBQ answers also appeared weaker than that of HHIE-S score. Age, gender and driving experience were the only variables associated with any DBQ outcomes, and these variables were only significant predictors of three, two, and one DBQ items respectively.

In terms of the specific driving behaviours which self-reported hearing loss predicted, those with higher HHIE-S scores had a higher likelihood of knowingly running red lights, disregarding speed limits early in the morning or late at night, missing pedestrians on

Table 4.6 Independent variables significantly associated with DBQ items in the 'violations' and 'dangerous errors' categories arising from the logistic ordinal regression performed. An asterisk (*) indicates an independent variable related to hearing.

DBQ item	Trend	Odds Ratio	95% CI	p-value
Violations				
Become impatient with a slow driver in the outer lane and overtake on the inside	More likely in males	2.28	1.24–4.21	.008
Drive especially close to the car in front as a signal to its driver to go faster or get out of the way	Decrease with age	0.94	0.90–0.99	.018
Dangerous errors				
Cross a junction knowing the traffic lights have already turned against you	Increase with HHIE-S score*	1.02	1.00–1.05	.050
Disregard the speed limits late at night or early on in the morning	Decrease with age	0.96	0.93–0.99	.005
	Increase with HHIE-S score*	1.02	1.00–1.04	.019
Queuing to turn left onto main road, you pay such close attention to the main stream of traffic that you nearly hit the car in front	Increase with HHIE-S score*	1.03	1.02–1.05	$< .001$
	More likely in males	2.31	1.23–4.34	.009
Fail to notice pedestrians crossing on turning into a side road	Increase with HHIE-S score*	1.03	1.01–1.05	.017

Table 4.7 Independent variables significantly associated with DHLQ items in the 'lapse of concentration' category arising from the logistic ordinal regression performed. An asterisk (*) indicates an independent variable related to hearing.

DBQ item	Trend	Odds Ratio	95% CI	p-value
Lapses of concentration				
Attempt to drive away from traffic lights in too high a gear	Decrease with driving experience	0.97	0.95–1.00	.034
	Increase with HHIE-S score*	1.02	1.00–1.04	.028
Switch on one thing, such as the headlights, when you meant to switch on something else such as the wipers	Increase with age	1.03	1.00–1.05	.025
	Increase with HHIE-S score*	1.03	1.01–1.04	.002
Realize that you have no recollection of the road along which you have just been travelling	Increase with HHIE-S score*	1.03	1.01–1.04	.001
Get into the wrong lane approaching a roundabout or a junction	Increase with HHIE-S score*	1.03	1.01–1.04	$< .001$

turning left, nearly hitting cars in front whilst queuing, switching on the wrong vehicle instrumentation, having no recollection along the road of travel, getting in to the wrong lane at a junction, and driving away from traffic lights in too high a gear. Whilst the first of these two behaviours are violations, the rest appear to be attention-based lapses in concentration, some of which are dangerous in nature.

4.4.3 Driving and Hearing Loss Questionnaire

Chronbach's alpha was used to calculate the internal consistency (reliability) of the DHLQ (Field, 2013). A suitable degree ($\alpha = .772$) of reliability was found (Lance et al., 2006), thus it was considered that the DHLQ had taken reliable responses.

The trend of answers to the questions asked in the DHLQ are summarised in Figure 4.7–Figure 4.11. In order to clearly see the split of opinion, 'neutral' responses have been removed. Questions are presented under the categories: general effect of hearing loss on driving, listening effort concerns, inability to hear relevant information, barriers for in-car device use, and usefulness of hearing aids during driving.

4.4.3.1 General effect of hearing loss on driving

Figure 4.7 shows respondents generally maintain that hearing loss does not present a problem for their own driving, with only 19% agreeing that hearing loss makes driving more difficult for them, compared to 73% who held the opposite opinion. Accordingly, it comes as no surprise that very few respondents (5%) report limiting their driving time as a result of their hearing loss. A logistic multinomial regression analysis with driving increase/decrease as the dependant variable showed no significant associations with any of the measured hearing loss outcome measures in this study.

However, there was a greater split in opinion when more general questions regarding the effect of hearing on driving were asked. 40% of participants agreed that hearing loss presents some problems for driving, but a similarly sized proportion (43%) disagreed with this statement. This differs from the trend exhibited in people's opinions when they were asked about their own driving, with the majority reporting no difficulty. However, 31% of participants reported avoiding driving under certain conditions. These responses are summarised in Table 4.8, though note that some participants indicated more than one situation they avoided driving in. Therefore, the sum of the 'proportion of entire sample' column is greater than 31%. The majority of these reports were of participants not driving in the dark, on motorways and during busy periods.

4.4.3.2 Listening effort

Figure 4.8 indicates that the majority of participants do not experience an increase in driving difficulty under conditions of auditory distraction. A large proportion of the sample indicated that they undertook passenger conversations (92%), listened to the stereo (75%),

Table 4.8 The number and proportion of participants avoiding driving under certain circumstances.

Driving situation	Number of participants	Proportion of entire sample
In the dark/at night	43	10.9%
On motorways	35	8.9%
During rush hour/busy periods	35	8.9%
During bad weather	11	2.8%
In city centres/busy urban areas	8	2.0%
On A-roads	5	1.3%
In new places	4	1.0%
On country roads	3	0.8%
On roads with speed bumps	1	0.3%
On bank holidays	1	0.3%

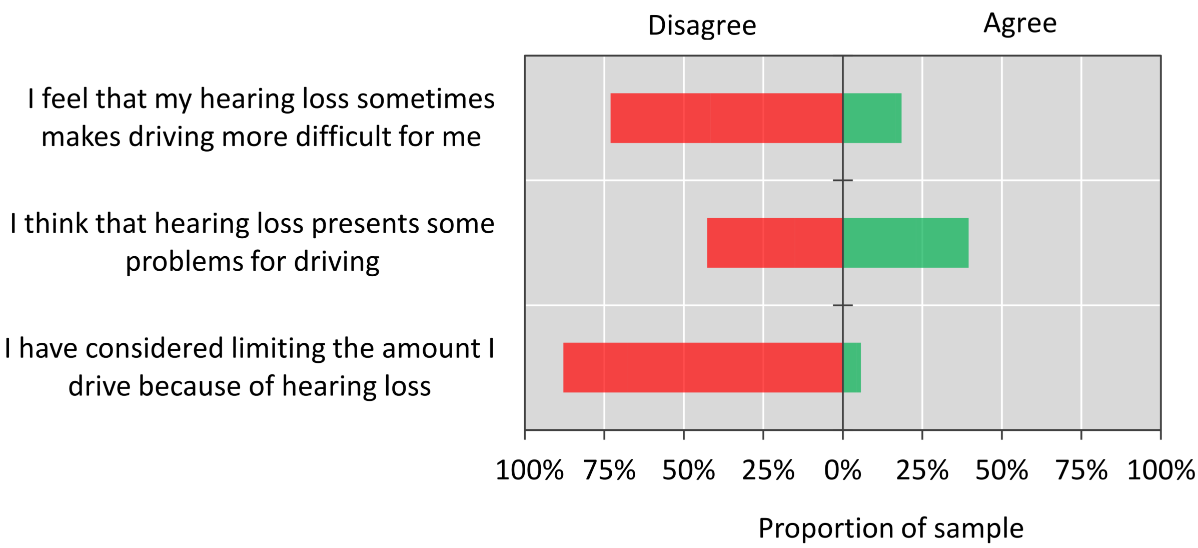


Figure 4.7 Proportion of responses to questions about whether hearing loss presents a problem for driving generally.

and used electronic devices (74%) whilst driving. Of those, 71% and 78% of respondents disagreed with, or were neutral to, the suggestion that driving was made any more difficult by passenger conversations or listening to in-car systems respectively. Likewise, only 31% of people reporting in-car device use believed that these systems were difficult to hear. However a greater proportion of the sample (50%) reported a difficulty in ability to hear passenger conversation. Similarly, the majority of the sample (65%) either disagreed with or were indifferent to the idea that stereo use affected their driving performance (see Figure 4.10). Fewer respondents reported using mobile phones whilst driving (31%), and of those that did, a small proportion reported there being no problem hearing mobile phone conversation (31%).

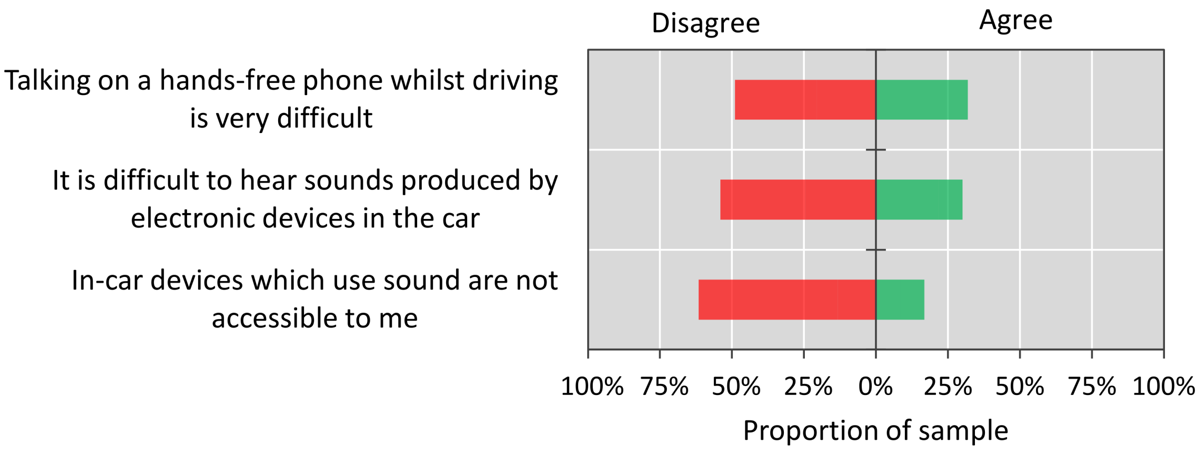


Figure 4.8 Proportion of responses to questions about whether hearing loss increases listening effort on tasks associated with driving.

4.4.3.3 Inability to hear relevant information

Participants disagreed that hearing loss limits relevant auditory information in the driving environment (see Figure 4.9). A large proportion of respondents agreed that auditory information is important for safe driving; only 20% disagree that sounds from the engine of the car are important for safe driving, and 26% disagree that environmental sound is important for safe driving. Despite this result, respondents did not generally consider hearing loss as a limiting factor in accessing driving-related auditory information. 58% disagreed that hearing emergency services vehicles is difficult, although 40% of people did agree that deciphering the direction of approach of these vehicles is difficult. Large proportions of the sample disagreed that hearing loss reduced awareness of the surrounding environment whilst driving (63%), affects the ability to judge travelling speed (88%), and increases anxiety about parking a vehicle (83%).

4.4.3.4 Barriers for in-car device use

In terms of in-car technology use, respondents generally did not appear to feel that hearing loss was a barrier. Indeed, only 17% agreed that sound-based in-car devices were inaccessible to them. Furthermore, few respondents reported having difficulty in hearing mobile phone conversations or sounds produced by electronic in-car devices (31% in each case). Two thirds of the sample indicated that the question regarding mobile phone use in the car was not applicable to them, suggesting that only a third of people used this type of technology whilst driving. In contrast, a greater proportion of the sample answered questions about the use of other types of in-car technology, with only 26% of participants indicating that this question was not applicable to them.

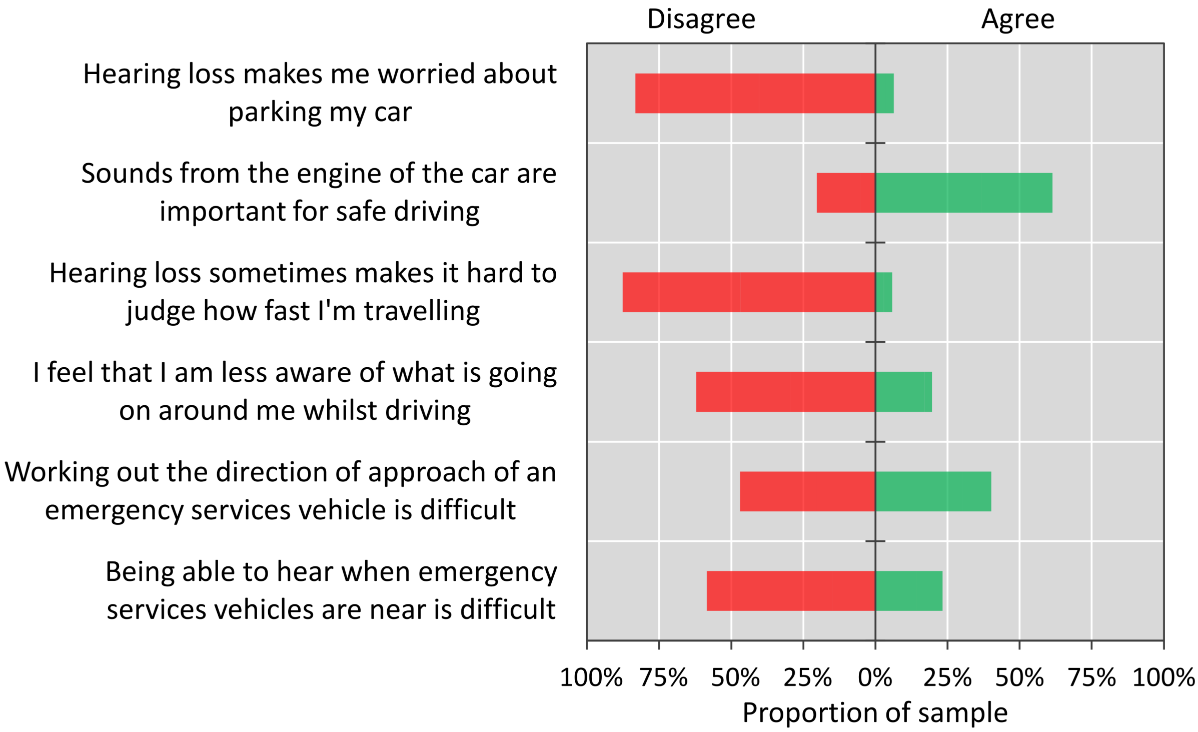


Figure 4.9 Proportion of responses to questions about whether hearing loss limits the amount of auditory information relevant to driving.

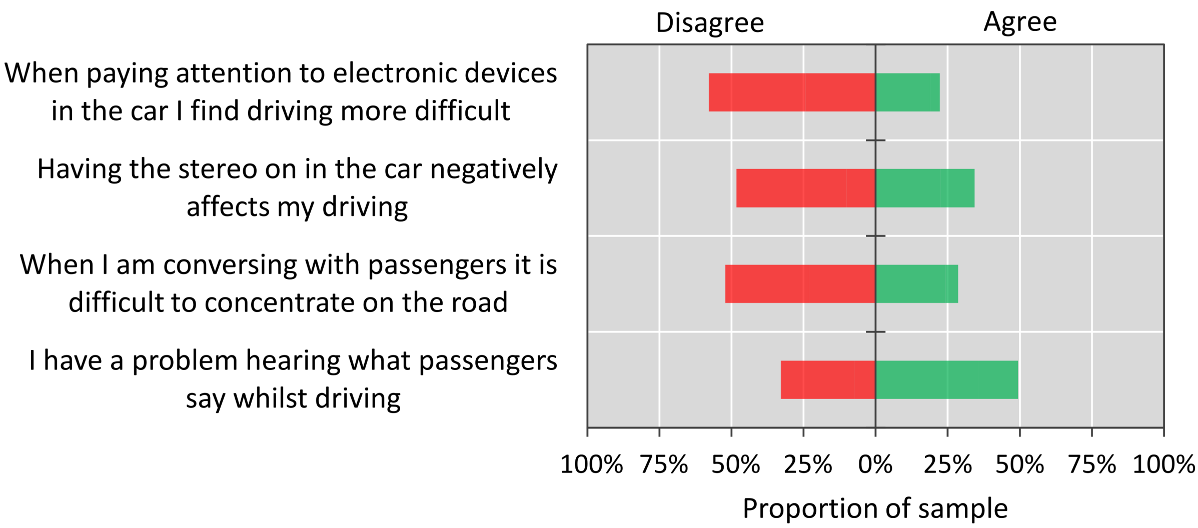


Figure 4.10 Proportion of responses to questions about whether hearing loss presents a problem for the successful use of in-car electronic devices using sound as a means to communicate information.

4.4.3.5 The usefulness of hearing aids during driving

The majority of respondents were positive regarding the use of hearing aids in the car. 62% of the sample disagreed that hearing aids made sounds uncomfortably loud whilst using them in the car, and even more respondents (82%) disagreed that hearing aids served to disorientate whilst driving. In terms of their ability to improve certain aspects of driving, respondents appeared to suggest that hearing aids had some efficacy. Only 17% of the sample agreed that hearing aids did not allow for easier use of in-car devices. A similar proportion (18%) agreed that hearing aids do not increase awareness of surroundings whilst driving. Moreover, only 9% of respondents agreed that hearing aids did not provide any benefit in terms of conversation with passengers in the car. However, a slightly larger proportion of the sample (24%) agreed that hearing aids do not improve driving ability generally.

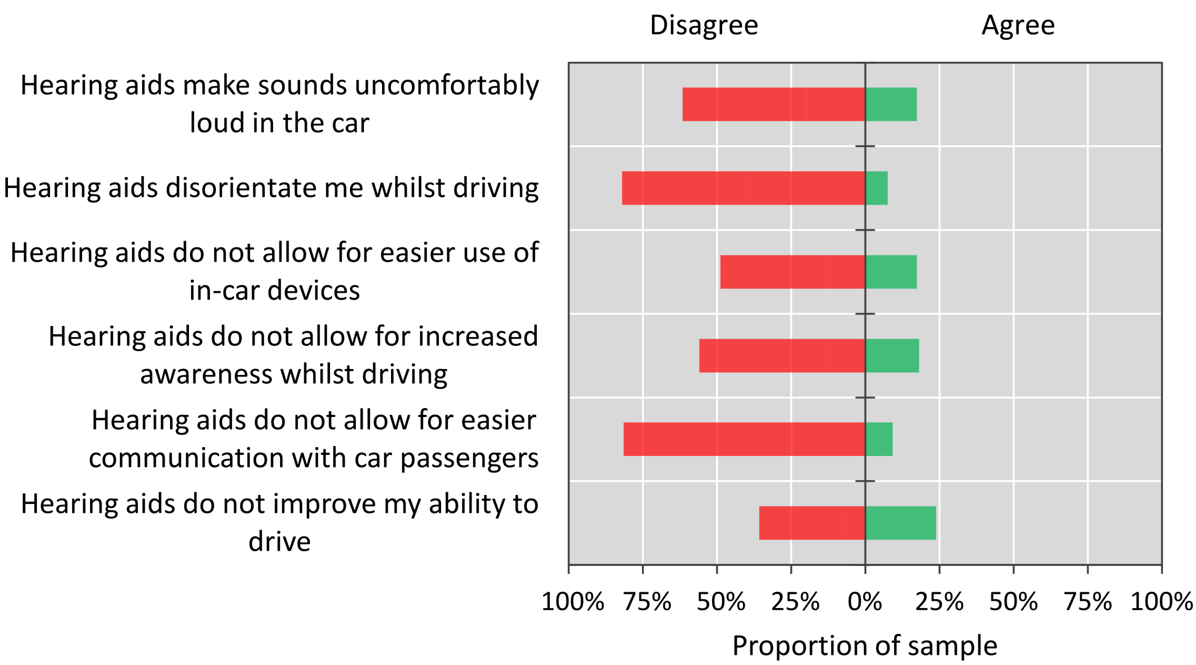


Figure 4.11 Proportion of responses to questions about whether hearing aids provide any benefit whilst driving.

4.4.3.6 Logistic ordinal regression analysis to establish the best predictors of driving difficulties

In order to establish which underlying factors caused people to report specific issues with driving, each of the individual DHLQ items were submitted to a logistic ordinal regression, using the same independent variables detailed in Table 4.5 as explanatory variables. This provided an indication of which independent variables were the best predictors of reported problems with driving.

In establishing whether a logistic ordinal regression model could be applied for each question on the DHLQ, the same criteria detailed in subsubsection 4.4.2.3 were considered. The resulting significant interactions (at the $\alpha = .05$ level) are shown in Table 4.9–Table 4.11, along with their ORs and 95% confidence intervals.

Table 4.9 Independent variables significantly associated with DHLQ items in the 'general questions' and 'indicators of listening effort' categories arising from the logistic ordinal regression performed. An asterisk (*) indicates an independent variable related to hearing.

DHLQ item	Trend	Odds Ratio	95% CI	p-value
General questions				
Hearing loss presents problems for driving	Increase with AC threshold of best ear*	1.01	1.00–1.03	.026
	Decrease with driving experience	0.75	0.62–0.69	.004
I feel that my hearing loss sometimes makes driving more difficult for me	Increase with HHIE-S score*	1.03	1.01–1.05	.001
Indicators of listening effort				
When I'm talking to people it is difficult to concentrate on driving	Increase with HHIE-S score*	1.02	1.01–1.03	.010
	Less likely in those who have been a professional driver	0.59	0.38–0.90	.016
When I am paying attention to sounds produced by electronic devices in the car I find driving more difficult	Increase with HHIE-S score*	1.03	1.01–1.05	.003
Efficacy of hearing aid use in the car				
Wearing my hearing aid(s) whilst driving makes sounds uncomfortably loud	Less likely in those who have been a professional driver	0.64	0.41–0.99	.044
I find that my hearing aid(s) do not improve my ability to drive	Decrease with HHIE-S score*	0.99	0.97–1.00	.050
I feel that wearing my hearing aid(s) disorientates me whilst driving	Decrease with annual mileage	0.96	0.92–0.99	.013
Hearing aid(s) do not allow for the easier use of in-car devices	Decrease with the duration of hearing loss*	0.98	0.96–0.99	.007

Table 4.10 Independent variables significantly associated with DHLQ items in the 'inability to hear sound' category arising from the logistic ordinal regression performed. An asterisk (*) indicates an independent variable related to hearing.

DHLQ item	Trend	Odds Ratio	95% CI	p-value
Inability to hear sound				
Working out the direction of emergency services is difficult for me	Decrease with age	0.98	0.96–1.00	.038
	Increase with HHIE-S score*	1.02	1.01–1.04	.002
Being able to hear when emergency services vehicles are near is difficult for me	Increase with AC threshold of best ear*	1.02	1.01–1.03	.014
	Increase with HHIE-S score*	1.02	1.00–1.03	.024
	Decrease with general hearing aid use	0.67	0.50–0.90	.007
I have a problem hearing what passengers say whilst I'm driving my car	Increase with HHIE-S score*	1.02	1.01–1.04	.001
I feel that because of my hearing loss I am sometimes less aware of what is going on around me when I am driving	Decrease with the length of hearing aid ownership*	0.97	0.95–0.99	.011
	Increase with the hearing loss duration*	1.02	1.01–1.03	.005
	Increase with HHIE-S score*	1.03	1.01–1.04	.001
Sounds from the engine of the car are important for safe driving	Increase with annual mileage	1.04	1.02–1.06	$< .001$
	Increase with HHIE-S score*	1.02	1.00–1.03	.021
My hearing loss makes me worry about parking my vehicle in close proximity to other obstacles	Decrease with annual mileage	.096	0.93–1.00	.026
	Increase with HHIE-S score*	1.02	1.00–1.04	.032
	Decrease with hearing aid use*	0.71	0.51–0.99	.044
	Less likely for those who have been a professional driver	0.54	0.33–0.89	.017
	Less likely for those with a unilateral hearing loss*	0.21	0.08–0.59	.003

Table 4.11 Independent variables significantly associated with DHLQ items in the 'use of in-car technology' and 'efficacy of hearing aid use in the car' categories arising from the logistic ordinal regression performed. An asterisk (*) indicates an independent variable related to hearing.

DHLQ item	Trend	Odds Ratio	95% CI	p-value
Use of in-car technology				
I find it difficult to hear sounds produced by electronic devices in the car	Increase with HHIE-S score*	1.04	1.02–1.06	< .001
I find that talking on a hands-free mobile phone whilst I drive is very difficult because of my hearing loss	Decrease with age	0.95	0.90–1.00	.037
	Increase with the duration of hearing loss	1.03	1.01–1.05	.045
	Decrease with annual mileage	0.91	0.86–0.97	.006
	Decrease with hearing aid usage in car*	0.57	0.38–0.86	.007
	Less likely in those who have been professional driver	0.43	0.21–0.89	.024
I feel that some in-car electronic devices which make use of sound are not accessible to me	Increase with AC threshold of best ear*	1.03	1.01–1.05	< .001
	Decrease with hearing aid use*	0.95	0.49–0.93	.017

It is evident from these data that *self-reported hearing impairment* (as measured by the HHIE-S) appears to predict the outcome of more items than *hearing sensitivity* (as measured by Pure Tone Audiometry). Results showed that, 11/23 of the responses to DHLQ items are significantly associated with HHIE-S scores, whereas clinically measured hearing sensitivity is only associated with outcomes on 3/23 items. Similarly, hearing loss aetiology was not significantly associated with any items, and whether the hearing loss was of a unilateral nature was only significantly associated with 1/23 items.

Other factors outside of hearing loss status were significantly associated with a number of items on the DHLQ (annual mileage, driving experience, history of being a professional driver), although none as frequently as HHIE-S score. None of the measures of hearing loss appear to occur as a significant predictor variable exclusively in any single category of the questionnaire; rather they appear to be spread throughout the survey items.

Interestingly, items associated with HHIE-S scores appear to suggest that individuals with a high degree of functional hearing loss experience problems with their driving. For example, higher HHIE-S scores are significant predictors of people agreeing that: (1) hearing loss sometimes makes driving more difficult, (2) talking to passengers or listening to in-car devices makes driving more difficult, (3) deciphering when emergency services vehicles are near and from which direction they are approaching is difficult, (4) as a result of hearing loss sometimes awareness of surroundings is reduced, (5) following passenger conversation in the vehicle is difficult, (6) parking in close proximity to obstacles is concerning, and (7) sounds produced by electronic devices are difficult to hear. The results also suggest that hearing aids are a source of rectifying these problems, with higher HHIE-S scores associated with an increased feeling that hearing aids improve driving ability.

Indeed, hearing aid use appears to have a positive influence on driving ability. People who report using their hearing aids more often are less likely to report problems such as: (1) hearing when emergency services vehicles are near, (2) worrying about parking their vehicle, (3) using a mobile phone hands-free whilst driving, and (4) the accessibility of in-car devices. The length of hearing aid ownership was also negatively associated with reports of feeling less aware of surroundings; e.g. more experienced hearing aid users were less likely to report being unaware of their surroundings.

Finally, increasing pure tone thresholds are significantly associated with a number of driving outcomes. People with less sensitivity are (1) more likely to agree that hearing loss presents problems for driving, (2) more likely to struggle with hearing the presence of emergency services vehicles, and (3) feel that in-car systems functioning in the auditory modality are not accessible to them.

4.5 Discussion

4.5.1 Driver Behaviour Questionnaire

The DBQ was administered in this study to investigate the types of aberrant driving behaviour commonly undertaken by those with a hearing loss. A factor analysis performed on the data collected in this study revealed a two factor structure. This contradicts a large number of past studies which have indicated a three factor structure (Reason et al., 1990; Parker et al., 1995a; Åberg and Rimmö, 1998; Rimmö and Åberg, 1999), or greater (Lawton et al., 1997; Özkan et al., 2006b). Generally the DBQ is able to differentiate between (non-serious) lapses of concentration and (more serious) dangerous errors, however this was not the case in the current study. Instead, both of these behaviours loaded on to the same factor, suggesting that a distinction could not be made between them in this sample. It might, therefore, be construed that hearing impaired individuals cannot distinguish between driving errors which are not dangerous and those which have more serious consequences. This may go some way towards explaining why their prevalence of highway safety code infringements is higher than the normally hearing demographic (Picard et al., 2008), and may also explain the higher road traffic accident rates noted in elderly hearing impaired drivers (Ivers et al., 1999).

Further, self-reported functional hearing loss appeared to be most related to reports of lapse and error behaviour, whereas it was not highly predictive of violation behaviour. Hearing loss may, therefore, have no bearing on people's propensity for knowingly committing driving violations, rather unwitting mistakes. Accordingly, the higher rate of driving infringements found by Picard et al. (2008) may be a result of errors whilst driving, rather than planned deviations from safe driving practice. This highlights the possibility that the performance of introspection is not possible with regard to the effect of hearing loss on driving, or is perhaps reflective of an apprehension to provide entirely honest answers. Thus, self-reports may not be the most useful manner to measure the effect of hearing loss on driving.

Regression analysis on the DBQ revealed that self-reported hearing loss was the best predictor of questionnaire outcomes. HHIE-S score was a significant predictor of eight DBQ items, no other independent variables related to hearing impairment were associated with DBQ outcomes. This suggests that objectively measured hearing sensitivity is not highly related to changes in driving behaviour, rather it is the day-to-day difficulty experienced as a result of a loss of hearing sensitivity. This questions the influence of a loss of hearing sensitivity *alone* as the issue for driving, and suggests that other factors which coexist may be (at least in part) responsible for difficulties experienced with driving.

One of the driving behaviours predicted by self-reported hearing loss partly conflicts with past research: those with increased self-reported hearing loss were more likely to report knowingly running red lights and disregarding speed limits early in the morning or late at night. Picard et al. (2008) noted a higher prevalence of general traffic violations in their hearing impaired demographic, but also found a lower prevalence of speeding citations. The discrepancy between the increase in reports of speeding behaviour in the current study and the decrease in the study of Picard et al. (2008) highlights the possibility that those who self-report a hearing loss may simply more readily report other outcomes, such as violation behaviour on the DBQ.

A different explanation is that hearing impairment exaggerates cognitive workload whilst tasks are being undertaken concurrently with driving (Hickson et al., 2010; Thorslund et al., 2013b).The majority of the other behaviours that HHIE-S scores predicted were related to errors whilst driving: missing pedestrians on turning left, nearly hitting cars in front whilst queuing, switching on the wrong vehicle instrumentation, having no recollection along the road of travel, getting in to the wrong lane at a junction, and driving away from traffic lights in too high a gear. Thus, errors whilst driving may be more prevalent in those with a hearing loss. The fact that *functional hearing status* and **not** *hearing sensitivity* predicted these reports of errors is of interest. It suggests that it is not the peripheral distortion to sound brought about by hearing loss which is responsible for driving difficulty, rather it is the higher order processes associated with successful listening that are having an impact; hence the link with HHIE-S scores.

There was very little difference in reported driving behaviour between the hearing impaired sample in this study and the normally hearing sample in the study of Parker et al. (2000). However, one main area where this sample appeared to differ was a lower frequency of reported speeding behaviour. However, this finding contradicts the trend that increasing HHIE-S scores were associated with a greater likelihood of reports on disregarding speed limits; reiterating the possibility that those self-reporting a hearing loss are simply more likely to self-report other types of behaviour.

It is unclear why the hearing impaired demographic should be more prone to driving slower than those with normal hearing. It has already been discussed in Chapter 2 of this thesis that, if anything, driving speeds may be faster in this demographic due to the changed auditory feedback they receive from the vehicle and surrounding environment. However, one potential suggestion is that, because of a perceived lower situation awareness (Walker et al., 2008), people with a hearing impairment navigate the driving environment more carefully, and a reduced driving speed is one facet of this alteration in behaviour (Thorslund et al., 2013a,b). Caution should, however, be exercised when analysing this particular result. There has been an improvement in compliance with speed limits in recent years (McKenna, 2007), and behaviour change of this type has the capacity to confound analyses made between the current study and that of Parker et al. (2000), given that they were performed 12 years apart. This change in speeding behaviour over time may be a reason why a lower propensity to speed was found in this study; simply because behaviour has changed over time, and the hearing impaired sample's self-reports of speeding behaviour were taken at a much later stage than their normally hearing counterparts'.

The majority of DBQ items (18/24) had a lower mean score than was recorded from a similarly-aged sample in the study of Parker et al. (2000), meaning that the hearing impaired sample in this study reported performing the DBQ behaviours less often. This may suggest a tendency for hearing impaired people to be more cautious in terms of their driving behaviour than their normally hearing counterparts. Despite this, the reported trends of DBQ behaviours are in line with those of Parker et al. (2000), in that they exhibit a lower frequency of violation and error behaviours than younger samples (Parker et al., 1995a,b). Lapse in concentration behaviour is generally the most frequently reported in this sample, which is typical of the age range being studied (Parker et al., 2000).

It is curious that violation items were not reported differently to the sample in Parker et al.'s (2000) study. This might have been expected, given the finding that people with a hearing loss are at a greater risk of receiving driving citations for highway safety code infringements not related to speeding (Picard et al., 2008), or the suggestion that hearing impaired individuals adopt a more cautious driving style (Thorslund et al., 2013a,b, 2014). The results here, therefore, highlight the need for further research in this regard, or show that people with a hearing loss unintentionally commit highway safety code infringements more often than their hearing counterparts. Picard et al.'s (2008) data should, however, be considered carefully, given that their sample was collected from a very specific demographic group, likely to exhibit a high prevalence of noise-induced hearing loss, in contrast to the predominantly age-related hearing loss sample in this study.

4.5.2 Driving and Hearing Loss Questionnaire

One purpose of this study was to gain an insight on whether hearing impaired individuals *themselves* notice any problems associated with driving as a result of their hearing loss. To this end, a questionnaire (the DHLQ) tailored to investigate this theme was administered along with the other three sections of the questionnaire. Results from the DHLQ generally suggest that people do not see hearing impairment as having a disproportionate effect on their own driving ability, with the majority of respondents disagreeing that hearing loss makes driving more difficult, and even more disagreeing that they had considered limiting their driving as a result of hearing impairment. Furthermore, although all participants in this study were still drivers, data regarding increasing or decreasing driving over a three year window prior to questioning was not significantly associated with any measures of hearing function.

This outcome was not expected, given past research which has suggested people with a hearing impairment are more likely to have ceased driving earlier than their hearing counterparts (Gilhotra et al., 2001). This study suggests that individuals are not consciously limiting their driving as a direct result of hearing loss, or that it is not the difficulties associated with hearing loss *alone* that are causing people to relinquish driving; rather other co-existing factors may contribute to these findings. A feasible example would be the influence of age, which is positively correlated with hearing loss severity (Davis, 1995). Indeed, age was a significant explanatory factor in both of the studies exhibiting a greater risk of driving cessation in the hearing impaired demographic (Gilhotra et al., 2001; Thorslund et al., 2013a).

Despite a low number of respondents reporting on problems associated with hearing loss for their *individual* driving, a greater proportion of the sample were open to the suggestion that hearing loss might present problems for driving *more generally*. It is of little surprise that individuals are less accepting of problems with their own driving, given that it is a common occurrence for people to exaggerate their own driving ability in self-reported driving literature (see e.g. Farrand and McKenna, 2001; Horswill et al., 2004). Furthermore, it is suggested that mental models used for driving are implicit and are thus inaccessible by introspection (Underwood et al., 2002). This may be extendible to the effect of hearing loss on those models, in that hearing impaired individuals cannot identify hearing loss as having an affect on their driving. This is an important consideration for continuing work in this area, as it casts doubt over the use of self-reported methodologies on this theme of study.

There is not an entirely clear picture which emerges from these data in terms of the most prevalently reported aspects of driving which are affected by hearing loss. The greatest problem reported by this sample is hearing passenger conversation. This is of little surprise given that speech is one of the most problematic auditory signals to understand for people with a sensory hearing loss, particularly in adverse listening conditions (Moore, 2007). However, it is uncertain from this data whether it is only hearing loss which is affecting the ability to hear conversation; there is no data from normally hearing people against which reports can be compared, and anecdotally it is thought that speech listening in the car may also be problematic for people with normal hearing. Furthermore, the majority of respondents did not report any difficulty in concentrating on driving whilst conversing with passengers.

It has been discussed in Chapter 3 that an increased difficulty in speech listening whilst driving will have a disproportionately negative affect on aspects of driving performance. However, whilst the current study has identified that speech listening for those with hearing impairment may be difficult, there is little evidence that this makes driving any more challenging for hearing impaired individuals. Suggestions that hearing impaired individuals should limit auditory engagement whilst driving (Hickson et al., 2010) have arisen from the negative effect that auditory based tasks can have whilst driving (see Chapter 2). Therefore, the apparent discrepancy with regard to the distracting nature of passenger conversation identified in this study would benefit from further work.

Compared to passenger conversation, there are fewer reports of an inability to hear sound information from in-car systems. Given the overarching hypothesis presented in this thesis that listening effort is related to driving decrements, this finding suggests a lesser likelihood that in-car systems will have a distracting effect on driving. Although not suggested by this data, a potential reason may be the ability to withdraw more easily from using the systems, or the easier manipulation of the level of sounds. These are options which are not so credible in terms of passenger conversation (Merat and Jamson, 2005).

Access to auditory information in the driving domain does not appear to be greatly affected by hearing impairment. The majority of respondents agree that sounds from the environment and engine of the car are important for safe driving, suggesting that they believe drivers should be able to access these sounds; but do not report any disproportionate problems with hearing sounds associated with travelling speed, parking cars, the presence of emergency services vehicles, the direction of approach of these vehicles, or general awareness sound-based of the driving environment. This finding appears to contradict the views of a number of authors who have cited an inability to hear auditory information as a reason for a higher accident risk in the hearing impaired demographic (Ivers et al., 1999; Picard et al., 2008).

The data suggest that there is a positive reaction to the efficacy of hearing aids whilst driving. Indeed, there is a significant increase in hearing aid use whilst driving compared to general day-to-day use, and the majority of respondents disagreed with statements regarding the redundancy of hearing aids in the car. The only split in opinion regarding this topic was that people were unsure whether hearing aids improved driving ability generally. This may have been because the majority of respondents did not foresee a problem for driving as a result of hearing impairment, and thus there could be no improvement by wearing hearing aids.

During the development of this questionnaire, there was a consensus amongst clinical professionals that hearing aids may be viewed in a negative light in terms of their efficacy whilst driving. This arose mainly from the fact that uptake of and adherence to hearing aids is notoriously low (Cox, 2005; Laplante-Lévesque et al., 2010), and that people generally do not derive benefit from hearing aids in acoustically adverse conditions (Kochkin, 1992), unless certain settings (such as directional microphones/noise cancellation) are activated (Bronkhorst, 2000; Cord et al., 2002). It is encouraging, therefore, that hearing aids have received a positive review in this study, and this finding provides evidence that rehabilitative interventions such as hearing aids have the capacity to improve listening, even in acoustically problematic situations. However, it should be noted that the sample in this study may be disproportionately positive with regard to their opinions about hearing aids generally, because hearing aid ownership and use figures in this sample were a lot higher than expected in the general population. This is likely explained by the recruitment procedure used; seeking participants who are attending NHS services allied to hearing aid provision. Nevertheless, 75% of participants reported owning at least one hearing aid, and of these only 4% reported not using their hearing aids. This is in contrast to research which has shown only around 25% of adults who could benefit from hearing aids own them (Jenstad and Moon, 2011), and, in those that do, only less than half use them (Knudsen et al., 2010). Furthermore, the issue of acclimatisation to newly fitted hearing aids, which can disproportionately affect derived benefit from hearing instruments (Gatehouse, 1993; Willott, 1996; Cox et al., 1996; Mueller and Powers, 2001), will be practically nullified as the majority of the sample were experienced hearing aid users. For these reasons, opinions regarding the usefulness of hearing aids whilst driving in this study should be considered carefully, and future research should also investigate the opinions of hearing impaired individuals who are new to hearing aids, or are not seeking rehabilitative help for their hearing loss.

As for DBQ data, the hearing-related measure most associated with DHLQ items was self-reported hearing status (HHIE-S score), whereas clinically measured sensitivity was less predictive. Past research in the area of hearing loss and driving has hypothesised that it is the distortion to sound brought about by peripheral hearing loss which causes a downstream disruption in driving performance (Hickson et al., 2010). The fact that clinical audiometric test results (which simply measure hearing sensitivity) were not highly predictive of outcomes in this study questions this assertion, and suggests that it is not the quality of sound *alone* which is disrupting driving performance. Instead, it is suggested that outcomes are more reliant on functional hearing loss; an amalgamation of numerous factors (of which sensitivity is just one) which govern ease of listening (Wingfield et al., 2005; Rönnberg et al., 2008). One such factor is the cognitive ability of the individual with hearing loss (Martin and Jerger, 2005). It is the summative effect of these factors which the HHIE-S measures, thus it must take in to account the effect of cognitive skills. It follows, therefore, that the HHIE-S has been shown to be the best predictor of the amount of difficulty people will experience in driving; a specifically cognitively demanding task (Groeger, 2000).

4.5.3 Study direction and limitations

Applying the DBQ in this demographic has been successful in highlighting driving behaviours in hearing impaired individuals. However, some of the intricacies of driving behaviour reports may have been lost by the use of a shortened version of the DBQ. The original survey is a 50-item questionnaire, whereas in this study a shortened 24-item version was chosen to mirror that used by Parker et al. (2000). Although this approach managed to capture a similarly aged demographic group, the use of a shortened version of the questionnaire in both studies might have limited the specificity of the research tool. In addition, the study of Parker et al. (2000) did not collect any data regarding hearing impairment, and as such it is impossible to know whether hearing loss was prevalent in their sample. Thus, caution must be observed when contrasting the results of the current study against that of Parker et al. (2000).

It should be noted that the sample in this study was drawn from clinical settings where the majority of people would be seeking rehabilitative help for their hearing impairment, leading to recruitment bias. This may predispose them to report more difficulty with their hearing loss, as they are presumably more troubled by the effects of auditory impairment than those who have not sought such rehabilitative help. Thus, the reports of driving difficulties in this study may be somewhat greater than are experienced by the wider hearing impaired population. It would be of interest in future work to establish what the opinions of people with hearing loss who have not sought rehabilitative help are, as this group of individuals potentially makes up a large proportion of the hearing impaired demographic in wider society (Laplante-Lévesque et al., 2010).

The possibility that those more readily self-reporting problems with their hearing might self-report other behaviours more easily should be considered. Questionnaires can be subject to socially desirable responses (Nederhof, 1985; Paulhus, 1991). Tools such as those used in the current study are reliant on respondents honesty and ability to give accurate, reliable answers to questionnaire items regarding their driving (Lajunen and Summala, 2003). Indeed, self-reports of driving ability can be subject to self-deception (a positively biased, but subjectively honest self description; Lindeman and Verkasalo, 1995) which leads to over-trust in one's own driving skills (Lajunen et al., 1997). In this study, the manner in which the questionnaire was administered adhered to some past suggestions of how accuracy of self-reports of driving behaviour could be maximised: responses were anonymous, instructions stressed the importance of honest answers, and the survey was carried out in settings where the respondent could not be 'singled out' (Lajunen and Summala, 2003). Despite these steps being taken, there is still some concern that self-deception may have influenced the responses given by participants to a certain extent. As such, in order to compound the trends noted in this study it would be beneficial to apply more objective research aimed at establishing the driving behaviour of people with hearing loss. Answers may also have been influenced by respondents' understanding of the study's purpose; they may have thought its motivation was to argue for punitive measures for licensing hearing impaired drivers

Despite these limitations, this study has brought to light a distinction which may be of great importance for this line of research; hearing *impairment* does not appear to be the most important factor for predicting the effect which hearing loss will have on driving performance. This provides an alternative consideration to previous research suggesting that the severity of hearing sensitivity loss is correlated with negative driving outcomes (Picard et al., 2008; Hickson et al., 2010). Rather it advocates higher-order listening abilities (the manner in which somebody copes with their hearing loss) as being particularly responsible for a disturbance on tasks relevant to driving. This is apparent through the predictive power of HHIE-S scores for increased reports of driving problems. HHIE-S scores are reliant on a number of factors which reflect an individual's ability to cope with their sensory impairment. A simple measure of auditory sensitivity does not capture this same richness of information, and provides only a limited view of the amount of damage an individual's auditory system has sustained.

A factor which is thought to be measured by self-reports of hearing loss is cognitive ability (Martin and Jerger, 2005). Experimental evidence suggests that cognitive factors become progressively more important under difficult listening conditions (Foo et al., 2007; Humes, 2007; Lunner and Sundewall-Thorén, 2007; Baldwin and Ash, 2011), and so those who have greater cognitive abilities will be more apt at counteracting the negative effects of their hearing impairment. This is a possible reason why some people exhibiting identical clinical test results can sometimes have very different perceptual consequences as a result of their impairment (Stephens and Zhao, 1996).

Accordingly, one person might have a more severe hearing loss than another according to audiometric test results, but self-report less problem because they are better equipped to deal with this loss of auditory sensitivity. It is this distinction which is considered to be exhibited in the current study by the greater predictive power of HHIE-S scores compared to audiometric thresholds. In this vein, it might be that other ecologically valid measures of hearing ability (e.g. a speech-in-noise test; Killion et al., 2004) show more of an ability to predict driving difficulties than audiometric thresholds, as they are also likely to be more reliant on higher-order listening abilities (Akeroyd, 2008).

This is not to say that peripheral auditory function has no influence on processes important for driving performance, but that other factors which co-exist with hearing loss may have a synergystic bearing. Thus it appears that the relationship between audibility and its effect on driving performance is highly complex and relies on inextricably linked factors. In the remainder of the studies described in this thesis, measures of hearing sensitivity and their relationship with driving performance were studied, regardless of the predictive power of self-reported hearing impairment found in the current study. This was because the main aim of this programme of research was to assess the impact of peripheral hearing loss on driving performance and related tasks. The use of other measures of hearing loss may have introduced extraneous factors (such as cognitive abilities) which could have confounded investigations about the effect of *peripheral* hearing loss on driving performance.

Nevertheless, the finding related to self-reported hearing loss being a good predictor of driving problems in the current study contributes important knowledge to the topic of the effect of hearing loss on driving *as a whole*. Lending to the design and execution of this study, it is considered that the sample accurately reflects the wider population of hearing impaired individuals, and thus it was considered that reliable and generalisable data had been collected.

4.6 Conclusions

This study was successful in terms of understanding the extent to which people with a hearing loss believe that hearing impairment presents problems for driving. It established a number of areas in which hearing loss appears most problematic for driving-related skills, and these were, to an extent, in agreement with past research. The study has served to present a complex picture of the manner in which hearing loss may affect driving in terms of its synergistic effect with co-existent factors. This is suggested as a result of the finding that it is *self-reported* hearing loss and not objectively measured *impairment* which is the best predictor of experienced driving problems. Functional hearing loss is more reliant on other factors (e.g. cognitive capabilities) than hearing sensitivity, and as such it might be suggested that these may have a bearing on outcomes alongside hearing sensitivity. In the past it has been hypothesised that the distortion to sound brought about by hearing loss is responsible for changes in driving performance, this study has suggested that it may well be other factors which are (at least in part) responsible. This calls in to question the results of previous work suggesting that it is hearing loss *alone* which has a negative effect on driving performance.

Future work as part of this thesis will be aimed at investigating the effect of hearing loss in a more objective, experimentally controlled fashion, given that this study relies heavily on self-reports of driving behaviour. The commonly held view that hearing loss causes no problems for driving, uncovered in this study, is in contrast to past experimental findings which have shown an apparent effect of hearing loss on driving. Thus it is considered that introspection in order to establish these problems may not be possible, or that participants are inclined to give socially desirable responses, or ones which present no licensing issues for the hearing impaired demographic. The study described in the next chapter begins to try and investigate the effect of hearing loss on driving-related skills in a more experimentally controlled fashion. The effect of auditory distraction on a measure of visual attention, which has been linked to driving performance outcomes, was compared between a normally hearing and hearing impaired group.

4.7 Acknowledgements

The support of the National Institute for Health Research, through the Comprehensive Clinical Research Network is acknowledged. I would also like to thank all NHS departments who helped with the data collection for this study.

Chapter 5

The Effect of Hearing Impairment on the Useful Field of View Test Performed Concurrently with an Auditory Task

5.1 Introduction

This chapter reports on a laboratory-based experiment which investigated the difference in performance on a visual task, between normally-hearing and hearing-impaired individuals. This more objective methodological approach was taken given the findings that arose in Chapter 4, that self-reported data may be subject to limitations in terms of introspection and socially desirable responses.

Chapter 4 identified specific problems for driving reported by those with hearing problems: (1) problems detecting the presence of emergency service vehicles, (2) a reduction in general awareness whilst driving, and (3) the performance of simultaneous tasks whilst driving. The former two are related primarily to the audibility of sound, whereas the latter arises as a result of sound which is audible, but distorted. It is the effect of cognitive distraction that distorted sound brings about that is of interest in this thesis, primarily due to the findings of Hickson et al. (2010), that moderate-severe hearing impairment degrades hearing impaired individuals' ability to recognise road signs whilst driving and concurrently performing an auditory task.

A lack of audibility has been discussed as an overly simplistic view of hearing loss. Loss of hearing sensitivity might well be a problem (e.g. for the perception of emergency services vehicles), but can potentially be rectified through the use of hearing aids. Furthermore, it is easily predicted that if somebody has a loss of sensitivity they will obviously require sounds (such as sirens) to be louder before they are heard, as has been shown, for example, by Slawinski and MacNeil (2002). The effect of sound which *is* audible is less predictable, requiring more extensive investigation. Thus, the current study was concerned with the investigation of auditory distraction on a measure of visual attention which has been linked to driving-relevant skills in past work; the Useful Field of View test. This is a test which is based on a construct called the 'functional visual field' or 'visual span', as outlined below.

5.1.1 The functional visual field

Hickson et al. (2010) explain their finding of a reduction in road sign recognition under conditions of auditory task engagement by linking it to evidence which has shown a reduced or restricted 'useful field of view' under auditory task conditions. The useful field of view is a construct originally named the 'functional visual field' by Sanders (1970) and can be defined as "the visual field area over which information can be acquired in a brief glance without eye or head movements" (Edwards et al., 2006, p.275). The importance of this construct for safe driving is apparent from Figure 5.1, which presents what a reduction in the useful field of view might resemble for drivers.

Hickson et al. (2010) hypothesised that the functional visual field is reduced to a greater extent in those with a hearing impairment, under conditions of auditory distraction. This is thought to be because the cognitive requirements for successful listening are greater in those with a hearing loss (see Chapter 3).

Figure 5.1 A depiction of what a reduction in the functional visual field might resemble. This may lead to the driver being unaware of salient information (e.g. the pedestrians crossing from the right hand side in this scene).

A computerised assessment of the useful field of view (UFOV) (Sekuler and Ball, 1986; Ball and Owsley, 1991; Ball et al., 1993), tests the efficiency with which visual information in the functional visual field can be accurately processed. The aim of the study reported in this chapter was to establish whether UFOV performance in hearing impaired individuals was disproportionately affected by auditory distraction in comparison to normally hearing individuals. Accordingly, the foundations of UFOV, its format, what it predicts and how it is affected by auditory distraction are discussed below.

5.1.2 The rationale for UFOV

In past driver safety literature a counter-intuitive trend has been noted suggesting that visual deficits are not correlated with vehicle crashes (Owsley et al., 1991; Gresset and Meyer, 1994; Marottoli et al., 1994; McCloskey et al., 1994; Johansson et al., 1996; Ivers et al., 1999), or only show a weak correlation (Hofstetter, 1976; Davison, 1985; Humphries, 1987; Ball et al., 1993; Marottoli et al., 1998). Ball et al. (1993) argue that this may have arisen as this research predominantly assessed sensory ability (e.g. measures of static visual acuity) and neglected higher-order perceptual and cognitive components (e.g. visual processing speed, attentional resources, the ability to ignore distracting information). Accordingly UFOV was developed to take these factors in to account (Edwards et al., 2005, 2006). It was originally administered using a dedicated computer system, but has now evolved to include touch-screen and mouse-based versions, both of which can be administered on a personal computer (Edwards et al., 2005). The test format of UFOV is described below.

5.1.2.1 A description of UFOV

The UFOV assessment involves identifying the location and appearance of a set of visual stimuli. It incorporates a number of single trials which all follow the same format (shown in Figure 5.2). Each stage of the trial is as follows:

1. The trial begins with a black screen containing a central white square on which participants are asked to fixate.

2. A certain set of stimuli (governed by the subtest type) will then briefly flash up on the screen, and will then disappear.

3. These stimuli are replaced by a 'random noise mask'. The function of this masking screen is to eliminate the visibility of brief stimuli after their presentation (Breitmeyer and Ogmen, 2006).

4. Participants are then asked about the appearance of the stimulus in the centre square (the 'central target'), which is either a car or a truck (the distinction between these two stimuli can be seen in Figure 5.3).

5. Upon providing a response to the central target, participants are asked about the location of the 'peripheral target', which is always a car. The peripheral target occurs at one of eight locations outside the centre square; in place of the outermost triangle located at angles of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° from the centre point.

Task difficulty is altered by changing the length of time that the stimuli are presented on the screen. If a participant provides a correct response to both questions, the presentation

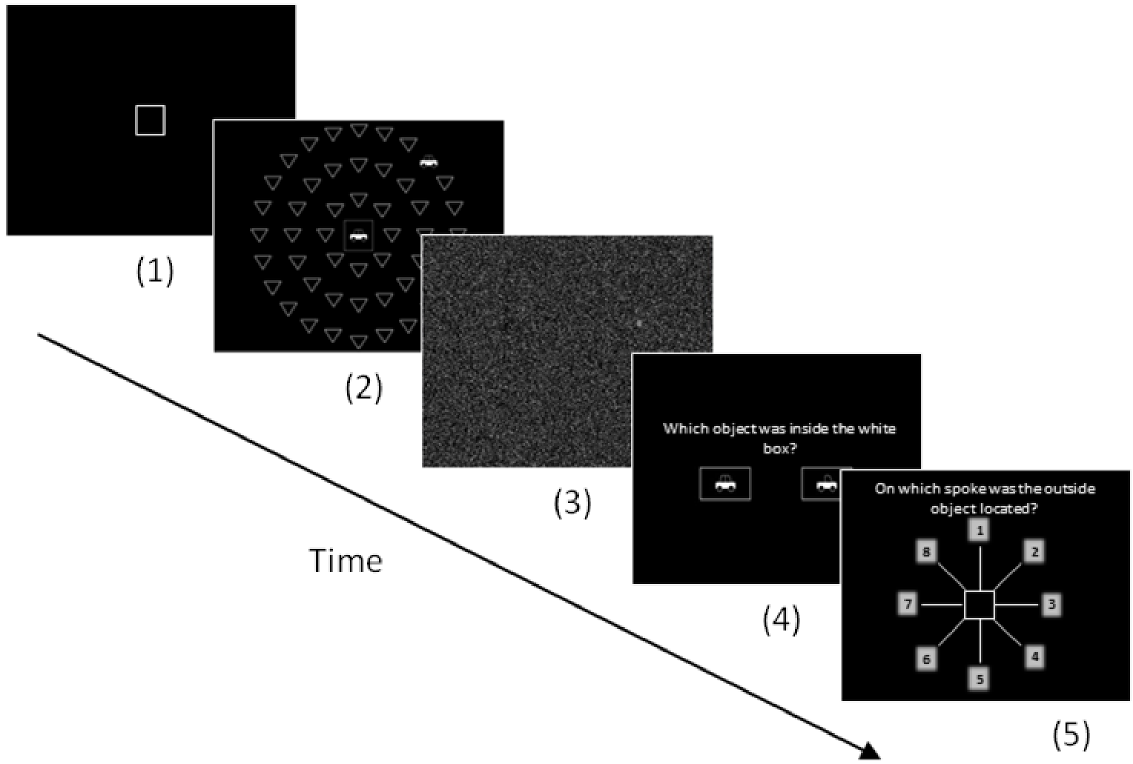


Figure 5.2 The progression of a single UFOV trial.

epoch is shortened, whereas an incorrect response to either question results in a lengthening of the presentation epoch. Thus the participant must be attentive to both foveal and peripheral stimuli. The presentation period ranges between 17-500 ms, and the times are altered using a double staircase method[1] until a level is reached at which a participant is repeatably obtaining a score of 75% on all trials. This threshold presentation time is then recorded as the participant score, so scores range between 17-500, with higher scores reflecting poorer performance.

The exact visual stimuli presented are manipulated resulting in three subtests which assess: (1) processing speed, (2) divided attention, and (3) selective attention (Ball et al., 1993; Myers et al., 2000). The presentation paradigms of these subtests are described below, and examples of these stimuli are shown in Figure 5.3.

1. **Processing speed:** only the central target is presented in each trial. The participant simply needs to indicate whether he/she saw a picture of a car or truck in the centre square.

2. **Divided attention:** both the central target and peripheral target are flashed up simultaneously. The participant has to report whether the central target was a car

[1] A single staircase involves presenting the stimulus at a suprathreshold epoch, and then reducing it until an incorrect response is given, at which point the epoch will be increased again. This process will be repeated until a set criterion is reached; in this case the participant is reliably obtaining a score of 75% on all trials. The double staircase adaptation of this incorporates two such series, the trials of which are randomly interspersed with each other (see e.g. Cornsweet, 1962; Nachmias and Steinman, 1965).

or truck, and the location of the car flashed up in their peripheral vision.

3. **Selective attention:** this task is the same as the divided attention task, but this time a visual distracter array of forty-seven triangles is flashed up simultaneously with the stimuli. The participant is required to ignore the distracters and, again, report whether the central target was a car or truck, and the location of peripheral target.

Figure 5.3 Examples of the three UFOV subtests. The difference between stimuli forms can be seen: a truck is being presented centrally with a car in the periphery.

5.1.2.2 What does UFOV measure?

Studies suggest that UFOV is likely to reflect attentional and cognitive abilities, rather than relying solely on visual sensory function (Owsley, 1994; McDowd and Shaw, 2000). Indeed, although UFOV incorporates stimuli at peripheral visual locations, Sekuler et al. (2000) argue that poor performance on UFOV should be conceptualised not as reflecting a shrinking of the visual field, but as a diminished efficiency in extracting visual information from cluttered scenes. In this regard, Ball et al. (2007) argue that UFOV is essentially a measure of speed of processing difficulties.

Abilities measured by UFOV are thought to reflect those which are relevant to driving. For example, driving requires the simultaneous use of central and peripheral vision, and requires the detection of salient stimuli which occur at uncertain times in the visual field (Ball et al., 1993). UFOV has, therefore, been employed in studies investigating the driving ability of older adults, who may exhibit changes in higher-order perceptual and cognitive components of vision (Ball et al., 1988; Owsley et al., 1991; Goode et al., 1998). Studies have shown that UFOV performance is predictive of both prospective and retrospective vehicle crashes (Ball et al., 1993; Owsley, 1994; Owsley et al., 1998; Clay et al., 2005; Ball et al., 2006), and driving performance during field-trials (Myers et al., 2000; Wood, 2002).

Indeed, Clay et al. (2005) performed a meta-analysis of eight studies which had investigated the ability of UFOV to predict a number of different driving outcomes. Their study included work which had employed either driving records, on-road driving, or driving simulator studies as their measure of driving performance. They argue that poorer UFOV test performance is associated with poorer driving performance. They also point out that UFOV appears to be a particularly robust measure, as the same outcome is preserved regardless of driving measure, or the laboratory in which it is being administered.

These results advocate UFOV as a powerful index of on-road driving performance, and as such some authors have suggested it as a suitable tool for assessing driver suitability in licensing settings (Myers et al., 2000). However, some criticisms of UFOV have arisen, and these should be considered when using this test. Firstly, the test has been extensively used in the elderly demographic, but little research has been carried out with younger subjects. As such it is unknown how UFOV performance interacts with driving performance in the younger demographic. This is not of great concern for the current line of study, given that older adults have been identified as the demographic of interest (see Chapter 4), in line with the link between hearing loss and age (Davis, 1995). Furthermore, a number of studies have documented a ceiling effect on the processing speed and divided attention subtests of UFOV (see e.g. Richards et al., 2006; Bentley et al., 2012; McManus et al., 2015). This is also not of concern for the current study; a worsening of performance is predicted as a result of auditory task engagement - a ceiling effect will not hide a trend in this direction. Additionally, no such ceiling effect is apparent for the divided attention subtest, and so results on this portion of UFOV should still be indicative of the hypothesised trend. The test uses two separate two-choice forced response paradigms, therefore participants have a 25% chance of giving a correct answer, even in cases where they randomly guess. The double-staircase method of presentation nullifies this problem, as evidenced by the high test-retest reliability of UFOV which has been exhibited in past work (Edwards et al., 2005).

The study reported here was concerned with how auditory distraction affects UFOV performance in normally hearing and hearing impaired individuals. Accordingly, the next section provides an overview of work which has assessed the effect of auditory distraction on UFOV performance.

5.1.2.3 The effect of concurrent auditory tasks on the useful field of view

Driving requires the performance of multiple simultaneous tasks (Clay et al., 2005), and this sometimes incorporates the performance of concurrent auditory tasks in the driving domain. There is evidence suggesting that during periods of auditory distraction, the efficiency with which visual information in the functional visual field can be processed is reduced.

For example, Wood et al. (2006) presented young normally-hearing participants with a task aimed at measuring the useful field of view, very similar to UFOV. This task, however, had a fixed presentation period of 90 ms, rather than varying this parameter depending on response. Furthermore, the eccentricity of the peripheral target could be altered such that peripheral targets were presented at visual angles of 10 °, 20°, and 30°. As the presentation period was fixed, the outcome measure was the number of errors made. Wood et al. (2006) only incorporated two visual conditions in their study, which resembled the UFOV subtests of divided attention and selective attention. They asked their participants to complete these subtests under three auditory task conditions: (1) with no auditory task, (2) listening to a concurrent auditory task, and (3) responding to a concurrent auditory task.

The results showed that, during visually complex subtests (incorporating an array of visual distracters), when participants were required to respond to the concurrent auditory task, they made significantly more central errors than when they either had to listen to the auditory task alone, or when there was no auditory task present. Additionally, there was an increase in the number of errors made at far peripheral locations as a result of responding to the auditory task rather than just listening to it (see Figure 5.4). Therefore, it appeared that the type of auditory task affected the magnitude of effect on concurrent visual tasks. Wood et al. (2006) draw attention to the implications of their results in the driving domain, and the finding that listening did not affect visual task performance is in accord with previous research showing that passive listening is likely to have little effect on driving performance (Strayer et al., 2003), whereas more cognitively demanding tasks which require some sort of response formation do (Brown et al., 1969).

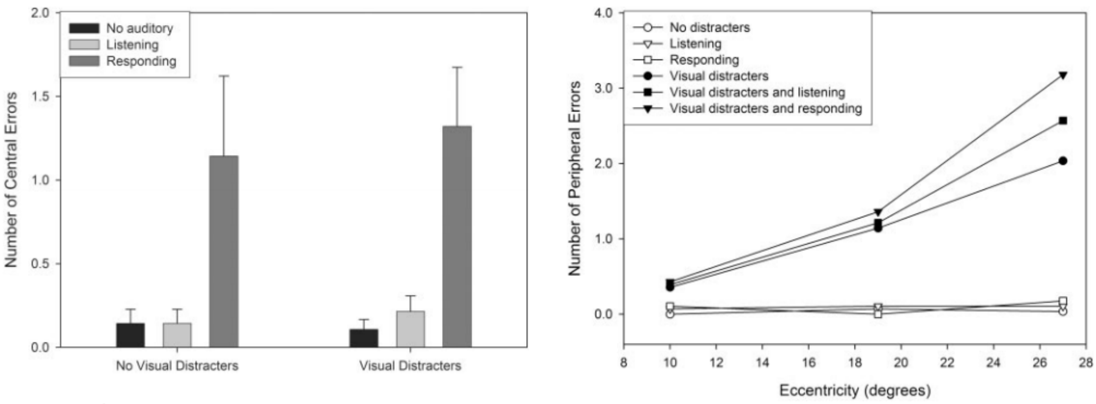


Figure 5.4 Results from the study of Wood et al. (2006). The mean number of errors (± standard error where applicable) made on the central and peripheral tasks as a function of auditory and visual conditions. N.B. visual distracters refers to the array of triangles presented in the visual field.

Results from studies investigating the effect of auditory distraction on visual attention in laboratory settings also support the findings of Wood et al. (2006). For example, a study by Pomplun et al. (2001) concludes that auditory distraction degrades visual search, and that if the difficulty of the auditory task is increased (i.e. more listening effort is required), visual tasks suffer further decreases in performance. The authors used the aCMT task in which participants listened for the occurrence of targets in a list of numbers. The difficulty of this task was raised by increasing the number of targets which had to be held in memory. Other studies investigating the effect of auditory task engagement on the functional visual field have produced similar results, which have then been extrapolated to the driving domain (Atchley and Dressel, 2004).

Based on these results, it was hypothesised that hearing impairment would exacerbate the performance decrements on UFOV during concurrent auditory task engagement, because SNHL would increase the difficulty of the listening task for hearing impaired relative to normally hearing individuals. This notion was the basis for the performance of the current study.

5.1.3 Study aims and hypotheses

The aim of this study was to establish whether hearing loss exacerbated the effect of auditory distraction on visual attention, over and above the difficulty experienced by the normally hearing subjects. A number of specific research questions were posed:

1. Is UFOV performance negatively influenced by the simultaneous performance of an auditory task?
2. Is the reduction in UFOV performance as a result of auditory distraction greater in those with a hearing loss?
3. Does auditory task performance suffer as a result of simultaneous performance with UFOV?
4. Are auditory task performance decrements as a result of simultaneous performance with UFOV greater in those with a hearing impairment?

It was hypothesised that the performance of hearing impaired and normally hearing participants would be comparable under all conditions where there was no simultaneous auditory task present. If auditory processing demands are responsible for disturbances in visual processing, as noted by Hickson et al. (2010), then it would be expected that a concurrent auditory task would degrade visual performance to a greater extent in hearing impaired individuals. This is because extra cognitive processing required to listen to, understand, and perform an auditory task with a SNHL would be required

This trend was hypothesised to occur for both the divided and selective attention subtests of UFOV, given that central errors significantly increase as a result of auditory task engagement when two visual targets are presented in this type of task (Wood et al., 2006). A greater magnitude of task disturbance was expected for the selective attention subtest than the divided attention subtest, given that the presence of visual distracters leads to an increase in the number of peripheral errors, particularly in the presence of a concurrent auditory task (Wood et al., 2006). However, it was difficult to predict the outcome for the processing speed subtest, because the visual task used by Wood et al. (2006) always included two concurrent stimuli.

Wood et al. (2006) did not record the accuracy rate of auditory responses in their study. However, provided that participants placed equal importance on both tasks (as they were instructed to), it was hypothesised that auditory task performance would become increasingly poorer as the difficulty of the visual task increased. In terms of the working memory model, this is because the more demanding the visual task, the more mediation required from central executive processes for visuospatial sketchpad operations, thus degrading the efficiency of phonological loop operations. This reduction in performance is likely to be greater in hearing impaired individuals; they require more listening effort than normally hearing individuals in order to perform auditory operations successfully, and so the reduction in central executive processes from the phonological loop is likely to have a greater effect on this demographic.

5.2 Method

The experiment reported in this chapter was run as part of a collaborative study performed at the Swedish National Road and Transport Research Institute (VTI) in Linköping, Sweden. The study arose as a result of discussions with colleagues at the 5th International Conference on Traffic and Transport Psychology held in Groningen, the Netherlands. As our two forthcoming study protocols required the recruitment of hearing impaired individuals, a collaborative study was agreed using the same participants to undertake our two separate experimental protocols.

5.2.1 Participants

Thirty-two participants in good general health, and free from eye and ear disease were recruited to this study from the local community and from a University Hospital audiology department in Linköping, Sweden. Sixteen of these participants were known to have a hearing impairment (identified through routine clinical testing at Linköping University Hospital), and the other sixteen were presumed to have normal hearing (as there had been no prior history of ear disease and/or concerns about loss of hearing). Pure tone audiometry was conducted on each participant in accordance with the British Society of Audiology guidelines (2011) and participants were split by hearing status into two groups: those with a mild-severe hearing loss, and those with normal hearing, again as defined by the British Society of Audiology (2011).

As a result of these tests, it transpired that one of the participants recruited for inclusion in the normally hearing group had a mild hearing impairment, and as such was included in the hearing loss group. Of the hearing impaired participants, three had a congenital hearing loss, the other fourteen had acquired their hearing impairment. The audiometric attributes of the hearing loss group suggested the majority had developed an age-related hearing loss. Fourteen of the group owned bilateral hearing aids, two owned unilateral hearing aids, only one participant with a hearing loss did not own a hearing aid. Of the sixteen participants who owned hearing aids, eleven wore them all of the time, three wore them occasionally, and two did not wear them. Nobody reported differing behaviour with regard to hearing aid use whilst driving and during their normal day-to-day routine. All participants held a current valid driver's licence and wore any optical correction that they normally wore for driving. Demographic information for each group is given in Table 5.1.

Table 5.1 Summary demographic information for each group in study one.

Experimental group	Number of participants	Mean age (± S.D.)	Level of education
Hearing impaired	17 (8♂; 9♀)	57.88 (± 12.67)	8 School; 9 University
Normal hearing	15 (5♂; 10♀)	51.20 (± 9.31)	8 School; 7 University

5.2.2 Materials

5.2.2.1 Visual task

UFOV test software (version 6.1.1), run on a personal computer, was used in this experiment. Responses were given using a computer mouse, a response method which has been shown to have a high test-retest repeatability (Edwards et al., 2005). All three UFOV subtests (processing speed, divided attention and selective attention) were used in this experiment, and were administered with and without a concurrent auditory task.

Possible visual task scores were in the range 17–500 ms, and were calculated by the UFOV software as the stimulus epoch required to achieve 75% successful performance of trials. Thus, better subtest performance on UFOV translated as a lower score. The UFOV software derived visual task scores by varying the stimulus presentation duration depending upon the accuracy of responses, presenting stimuli using a double staircase method. A correct response was only recorded when both the peripheral and central visual tasks were completed correctly. Subtests ended automatically once the software had a stable estimate of the required stimulus epoch. It should be noted that the processing speed subtest does not incorporate a peripheral visual stimulus, as such scores on this subtest are derived from the accuracy of responses to the central target only. This ensured that participants were fixating on the point of stimulus presentation, providing an isolated measure of processing speed.

5.2.2.2 Auditory task

Task selection

The choice of auditory task to be used in this study required consideration, given that there have been a wealth of such tasks used in past research employing dual-task methodologies (see e.g. Pashler, 1994). Past work has shown that cognitively challenging auditory tasks which require a participant response have an effect on concurrently performed tasks (Strayer and Johnston, 2001; Pomplun et al., 2001; Wood et al., 2006; Hickson et al., 2010). Thus the task had to require a participant response.

Speech stimuli were considered suitable as they are likely to reflect a number of distractions that may occur whilst driving, particularly for people with a hearing loss. This is not to say that non-speech stimuli do not occur in the driving environment, quite the opposite. However, speech is one of the most difficult signals for people with SNHL to process, particularly in the presence of masking noise (Moore, 2007). Alongside in-car systems which use non-speech sounds, speech stimuli can also have a negative effect on driving performance through their distractive nature (see Chapter 2). Accordingly, it is probable that a speech stimulus would be more distracting than a non-speech stimulus for somebody with a cochlear hearing loss, and provides a suitable level of face validity for the purposes of this study.

The task also had to be suitable for employment in the experimental design. As the UFOV software was free-standing, timing the presentation of auditory stimuli so that they *exactly* matched the presentation epoch of visual trials was not possible; stimuli thus had to last long enough to account for this limitation.

Using a longer auditory stimulus, therefore, had the benefit of ensuring that an auditory task was always present during the presentation of visual stimuli. Using a shorter stimulus may have led to discrepancies in presentation such that some trials may effectively become two single tasks (e.g. a visual task followed by an auditory task), instead of one dual-task (e.g. concurrent visual and auditory tasks). Although a longer auditory task time is desirable, it is important to note that it should not be too long. The task had to be concise enough to span a single UFOV presentation, but not so long that it carried on for a disproportionate time following that trial. This may have led to issues in the amount of time the experiment took, perhaps giving rise to fatigue problems, and would also have presented issues for participants keeping the location of UFOV stimuli in their Working Memory whilst the auditory task finished.

Thus the criteria for a suitable auditory task were:

1. Valid in terms of applicability to the driving environment;

2. Speech-based;

3. In the Swedish language (given that it was the mother-tongue of all participants);

4. Suitable presentation epoch;

5. Requires a participant response.

When selecting a task which satisfied these criteria, previous studies that had used similar experimental paradigms were identified, and the auditory tasks that had been employed were scrutinised in terms of their suitability for this experiment. The considered tasks are described and discussed in Table 5.2.

Table 5.2 A description of auditory task types and their suitability in relation to the current study.

Task	Description and discussion
SSW	Single spondee words are presented simultaneously to each ear, but the presentation is staggered such that one word begins before, and ends sooner than the other. Wood et al. (2006) used this task, and it affected the performance of a young, normally hearing sample on a task analogous to UFOV. The test has a degree of ecological validity; it is speech based, and is reminiscent of tasks which are performed in the car (e.g. listening to passengers and the radio simultaneously). However, stimuli are fairly quickly occurring ($\approx$ 600 ms).
Dichotic sentences	A sentence is presented simultaneously to each ear. This task is very similar to the SSW and is, thus, likely to cause a disturbance on visual tasks analogous to that used by Wood et al. (2006). Whereas the SSW has a short presentation epoch, dichotic sentences are longer (lasting $\approx$ 3–4 s). Dichotic sentences are considered ecologically valid, as they are reminiscent of the same in-car situations as the SSW.
Understanding of a prose passage	In the study of Gherri and Eimer (2011), participants listened to a prose passage whilst performing a visual task. The authors asked participants questions about the passage following completion of the visual task trial. This auditory task type offers a great degree of ecological validity, e.g. listening to a passenger's discourse and responding. However, prose passages used were $2^1/_2$ minutes long. Furthermore, it is difficult to monitor the effort exerted on the auditory task at any given moment. For example, pauses at certain stages in the stimulus may coincide with the presentation of visual stimuli.
Memory span tasks	Pomplun et al. (2001) asked participants to memorise four random digits and then indicate when they heard one played back during visual task trials. The task affected visual task performance in these studies. At face value these tests do not appear to offer ecological validity, although these types of task may reflect the manner in which modern in-vehicle systems function (e.g. memorising/understanding information presented by in-car systems such as satellite navigation). However, this task type tests working memory capacity and ability, hence may introduce extraneous factors (e.g. cognitive skills) which may confound the results. This is particularly true given that the demographic being recruited to this study is likely to be old, and age-related changes in working memory capabilities are well documented (e.g. Salthouse, 1991).

The suitability of these tasks in terms of the criteria set out is summarised in Table 5.3. The preceding list of tasks is by no means exhaustive. However, it does provide possibilities for consideration. The most suitable tasks for employment in this study appear to be competing sentences, which is very similar to the Staggered Spondaic Word test (SSW) used in a dual-task study of auditory and visual attention (Wood et al., 2006), or a memory span task (Pomplun et al., 2001). However, there is some concern regarding the potential influence that individual cognitive factors might have on the performance of memory span tasks. Given this concern the decision was taken to use dichotic sentences as the auditory task used in this experiment.

The specific dichotic sentence test used was developed by Hällgren et al. (1998), and consisted of two five-word, low-redundancy[2] sentences, simultaneously played to opposing ears. The test materials were recorded in Swedish by a native speaker.

An audiometer, calibrated to the dichotic sentence test, was used to present auditory stimuli through Telephonics TDH-39P headphones; this ensured an accurate presentation intensity of 50 dB HL *sensation level*. Sensation level refers to the decibel value above threshold (in this case at 1 kHz), such that if a participant had an absolute threshold of 20 dB HL at 1kHz the value at 50 dB HL sensation level would be 70 dB HL (20 dB HL + 50 dB HL = 70 dB HL). Auditory stimuli were presented at a sensation level, rather than set intensity, so that sounds were played at an audible level for all participants, regardless of hearing loss status.

As these stimuli were presented through headphones, and because stimuli were presented at a sensation level, participants were not permitted to wear hearing aids during the experiment, even if they did so under normal driving conditions. In cases where the extent of hearing loss made this sensation level uncomfortably loud, stimuli were adjusted to an intensity which was deemed comfortable by participants.

A single dichotic sentence trial (two sentences played simultaneously) started just prior to each visual stimulus presentation, ensuring that the sentences were playing through the period that the visual stimuli were present. Subjects were required to listen to the sentences in full before repeating back as much of both sentences as they had heard.

A percentage correct score for the auditory task was calculated for each participant, during each subtest, by counting the number of correct words repeated following each stimulus presentation. As there were five words in each sentence, the maximum score for each dichotic stimulus was ten. A similar approach to marking this auditory task has been taken in past research, which asked participants to report the sentence from one ear only (Hällgren et al., 2001). However, the current study asked participants to recall as much of both sentences as possible. This approach was taken in order to avoid the possibility of cueing participants towards a certain side of their visual field as a result of directed auditory stimuli (Ho et al., 2006). Accordingly, sentences were analysed such that if a

[2]Redundancy refers to the likelihood of being able to predict the content of a sentence because of its semantics. In this case (low-redundancy), listeners would not be able to predict the content of a whole sentence based on the successful perception of a fraction of the message.

Table 5.3 Analysis of whether tasks discussed meet the various criteria set out. A tick indicates a particular task fulfils the respective criterion.

Criterion	SSW	Dichotic sentences	Understanding of prose passage	Memory span task
Valid in terms of applicability to the driving environment	✓	✓	✓	✓
Speech-based	✓	✓	✓	✓
Suitable presentation epoch	×	✓	×	✓
Requires a participant response	✓	✓	✓	✓

participant only responded with one-sentence, marks were not awarded for words from both sentences. Instead marks were only given from the sentence that scored highest. For example:

Stimulus: "Elsa borrowed three dark gloves" and "Bosse owned six beautiful rings"
Response one: "Bosse owned six beautiful rings" and *no response*. Score given = $^5/_{10}$
Response two: "Bosse borrowed three beautiful rings" and *no response*. Score given = $^3/_{10}$

Response one scores $^5/_{10}$, as the participant has repeated only one sentence in its entirety, but the sentence given is correct. Response two only scores $^3/_{10}$, as the participant has only repeated one sentence, and the answer given is a mixture of the two sentences. The three marks given are, therefore, for the participant saying 'Bosse', 'beautiful' and 'rings', all three of which are present in the second sentence. Marks are awarded from this particular sentence as the responses recorded to the other sentence would have resulted in a lower score of $^2/_{10}$. This approach was taken in order to reflect the difficulty of the listening task; it was not considered feasible to give the same mark to somebody repeating a mixture of the two sentences, and another person successfully ignoring an interfering stimulus, listening to one of the sentences, and repeating it in its entirety.

5.2.2.3 Cognitive testing

A cognitive test battery was employed in order to control for cognitive differences between the two experimental groups. This was considered important given that UFOV is thought to rely on higher-order processing abilities (Edwards et al., 2006).

The Clinical Information Processing System (KIPS) test battery, a developed, abbreviated version of the cognitive test 'Text Information Processing System' (Lyxell et al., 1998), was administered to each participant. KIPS assesses working memory capacity, lexical access speed and phonological skills (Borg et al., 2008), and is administered (in Swedish) on a personal computer, requiring responses using the mouse and keyboard.

KIPS consists of four sections, and lasts approximately twenty minutes in total:

1. **Physical matching:** participants had to decide whether two letters appearing on the monitor looked the same or different.

2. **Lexical text:** participants had to decide whether words that appeared on the screen one at a time were real, or invented.

3. **Rhyme:** participants had to decide whether two words displayed simultaneously on the monitor rhymed with each other or not.

4. **Reading span:** sets of two 3–5 word sentences were displayed on the monitor one word at a time. Participants had to decide whether or not each sentence made sense or was nonsense. Once this choice had been made, the participant was asked to recall either the first or the last word in both preceding sentences.

This cognitive test battery was chosen as it offered measures of constructs considered important for UFOV performance. For example, it is thought that the reading span section of KIPS is heavily reliant on the central executive portion of working memory (Lobley et al., 2005). It is this component of the Working Memory model that is hypothesised to control attention switching and mediated focused and divided attention (Baddeley, 2002), skills which are likely to be central to the successful performance of UFOV. In a similar vein, there is some discussion that rhyme judgements originate from a similar region of the brain as Working Memory tasks, given that both are affected by articulatory suppression (Besner, 1987; Gathercole and Baddeley, 1993), and may, therefore, rely on similar physiological systems. Therefore, the rhyme portion of KIPS provided some insight into whether cognitive deficits were present in any particular participant, as well as supporting results obtained from the reading span subtest.

Central to success on UFOV is the recognition of an icon from two, almost identical, options (see Figure 5.2). The physical matching portion of KIPS provided some insight into whether individual participants are able to accurately identify, on a computer screen, whether there was a subtle difference between two physical shapes. Thus, any issues regarding a participant's inability to physically decipher the difference between the car and truck presented in UFOV was accurately identified by performance on this aspect of KIPS.

Though the lexical test portion of KIPS was not considered to bear any importance for predicting success on the UFOV test itself, it was considered important for the prediction of auditory task performance. The auditory task involved the recognition of simultaneous sentences containing words which could not be accurately predicted by the semantic content of stimuli. Thus, success on this task was likely to be related to the lexical skills of participants, i.e. their ability to perceive and identify words (Balota and Chumbley, 1984).

At this juncture it is also worth noting that those tasks included in KIPS, which rely on central executive skills (reading span, and perhaps rhyme) not only provide information regarding potential performance of the visual task, but also the auditory task. It is known that the performance of spondaic tasks relies heavily on central auditory processes (Katz and Smith, 1991), and so an inability to effectively switch and focus attention (as is measured by the reading span, and potentially rhyme, sections of KIPS) may have impacted on the performance of the auditory task also.

The KIPS software measured participant performance (percentage correct) on each of the cognitive battery subtests. Each individual section of the test battery was marked individually and thus could be analysed independently.

5.2.3 Procedure

Pure tone audiometry testing and KIPS were both undertaken prior to UFOV performance. Participants' hearing was assessed using pure tone audiometry according to the British Society of Audiology guidelines (2011). Following the hearing test, participants were asked to perform KIPS on a personal computer with a 17 inch screen. Participant responses in all subtests were a two-choice forced response task, and answers were given using the keyboard. In the reading span test, participants also had to recall the first/last word of the preceding sentence, this answer was also a two-choice forced response task and was given using the computer mouse.

For UFOV testing, participants were seated 60 cm away from a 17 inch computer monitor. They were instructed on how to perform UFOV with the aid of sample stimuli and were then given a practice as per the test instructions (Visual Awareness Inc., 2003). This consisted of performing four practice trials for each subtest using long presentation epochs; if the correct response rate was lower than 3/4, a further four practice trials were presented, and so forth. Practice continued until 3/4 trials were correctly performed, or until 16 trials had been presented (Visual Awareness Inc., 2003). Participants were all able to perform the practice task successfully before 16 trials had been presented.

Following training on UFOV as a standalone single task, participants were given the opportunity to practice UFOV simultaneously with the auditory task. Participants were asked to give equal priority to both the visual and auditory tasks. Practice was carried out in a similar manner to UFOV as a standalone task, and was stopped once 3/4 trials had been successfully completed, or a total of 16 trials had been presented, and responses to the auditory task were consistent with an understanding of the task. Again, participants were all able to perform the practice task successfully before 16 trials had been presented.

After the training and practice session, participants went on to complete the three UFOV subtests described above, both with and without the auditory task presented simultaneously. This resulted in six experimental conditions, which were partially counterbalanced using the balanced Latin Square method (Bradley, 1958). This method was chosen in order to remove any potential order effects which may have arisen as a result of all participants carrying out all of the conditions in a set order. A baseline measure of auditory task performance on its own was also taken, whereby participants responded to ten auditory stimuli in the absence of any visual task. Half of each experimental group undertook this baseline measure before performing the six experimental conditions, the other half performed it at the end of the experimental session.

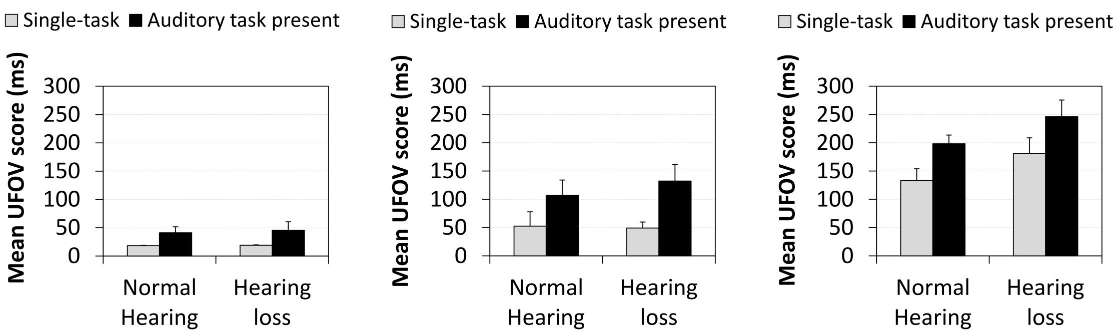
Ethical approval for this study was obtained through the National Health Service National Research Ethics Service Research Ethics Committee (reference: 12/YH/0076).

5.3 Results

Prior to analysis, all data in this experiment was subjected to a Kolmogorov-Smirnov test per group in order to ascertain whether they conformed to a normal distribution. Where this was not the case, non-parametric testing was employed to investigate trends in the data (Field, 2013). At numerous points in the analysis multiple comparisons were made, leading to a potential increase in the familywise error rate (i.e. the probability of making a type I error; Shaffer, 1995). In order to counteract this confound, the Bonferroni Correction was applied (Field, 2013).

5.3.1 Visual task

Kolmogorov-Smirnov tests exhibited that the majority of UFOV data was not normally distributed, and as such the decision to use non-parametric test methods was taken. The mean UFOV test scores for both groups in each individual experimental condition are shown in Figure 5.5.



(a) Processing speed (b) Divided attention (c) Selective attention

Figure 5.5 Mean UFOV scores (± standard error) for the two experimental groups on each individual subtest under different auditory task conditions.

UFOV performance decreased as the visual task became more complex (i.e. as more stimuli were included), and through the use of Friedman Tests this decrease in performance was shown to be statistically significant both with $\left(\chi^2\,(2) = 47.226, \mathrm{p} < .001\right)$ and without $\left(\chi^2\,(2) = 54.264, \mathrm{p} < .001\right)$ a simultaneous auditory task. Further post-hoc analysis using Wilcoxon signed-rank tests and Bonferroni corrections exhibited that there were significant differences between all of the UFOV subtest scores (see Table 5.4). Furthermore, the introduction of a concurrent auditory task had a significantly degrading effect on the performance of UFOV for the processing speed subtest (z = -3.201, p = .001, r = .57), the divided attention subtest (z = -3.690, p = .000, r = .65), and the selective attention subtest (z = -4.937, p < .001, r = .87). Effect sizes (r) for this trend suggest that the more complex the visual task, the more degradation from a concurrent auditory task.

Table 5.4 Wilcoxon test results for comparisons between UFOVscores across different subtests.

Comparison subtests	No auditory task		Auditory task present	
	Medians	$p-$ value	Medians	$p-$ value
Processing speed Divided attention	17.00 ms 23.00 ms	< .001	23.00 ms 82.00 ms	< .001
Processing speed Selective attention	17.00 ms 146.50 ms	< .001	23.00 ms 208.50 ms	< .001
Divided attention Selective attention	23.00 ms 146.50 ms	< .001	82.00 ms 208.50 ms	< .001

The Mann Witney-U test was utilised to test for possible differences between the two experimental groups on UFOV, though no significant differences on any of the three UFOV subtests arose (see Table 5.5).

Table 5.5 Mann-Witney U test results for a comparison between the two experimental groups in terms of their UFOVscores.

Subtest	Normal hearing median	Hearing loss median	$p-$ value
Processing speed (no auditory task)	17.00 ms	17.00 ms	.360
Divided attention (no auditory task)	23.00 ms	27.00 ms	.178
Selective attention (no auditory task)	110.00 ms	157.00 ms	.249
Processing speed (auditory task present)	23.00 ms	23.00 ms	.812
Divided attention (auditory task present)	67.00 ms	97.00 ms	.688
Selective attention (auditory task present)	197.00 ms	267.00 ms	.282

In order to examine whether the inclusion of an auditory task disproportionately affected the UFOV performance of either experimental group, for each participant a difference value was calculated between the auditory task present and auditory task absent conditions of individual subtests. Discrepancies between the two experimental groups on these individual subtest difference values were investigated through Mann-Whitney U tests. No significant differences were found between normally hearing and hearing impaired participants on the processing speed (p = .31), divided attention (p = .48), or selective attention (p = .63) subtests.

As non-parametric testing was performed, the inclusion of covariates in analyses was not possible. Thus, the influence of age, gender, and education level on UFOV scores was established by performing Mann-Whitney U tests between groups for each respective independent variable. As age data is continuous, the sample was split into two groups, one of the younger members ($\leq$ 57 years; mean age = 47 years), one of the older ($\geq$ 58 years; mean age = 65 years), enabling the quantification of any age-related differences in the results obtained.

A significant difference was found for the older vs younger comparison for the selective attention subtest of UFOV, completed in the absence of an auditory task (U = 61.5, z = -2.508, p = 0.011). Curiously, when the same subtest was performed with a concurrent auditory task, this difference between the older and younger group showed no significant difference in scores (U = 96.0, z = -1.207, p = .235). No significant effects of education level or gender were found on UFOV scores.

5.3.2 Auditory task

The mean percentage scores for the auditory task performed as a baseline measure (in the absence of a concurrent visual task) and during each UFOV subtest are shown in Figure 5.6. Kolmogorov-Smirnov tests again showed that the auditory task response data was not normally distributed. It can be seen that, for both groups, as the visual task becomes more complex, accuracy on the auditory task decreases. Indeed, a Friedman test exhibited a statistically significant decrease in auditory task scores as a function of the concurrent UFOV subtest ($\chi^2(3) = 12.343, \mathrm{p} = .005$). Post-hoc analysis of these values using Wilcoxon signed rank tests and the Bonferroni correction exhibited that this interaction arose mainly from the difference between the baseline measure of the auditory task, and the performance measured whilst the auditory task was performed simultaneously with the divided attention (Z = -2.952, p = .002) and selective attention (Z = -3.178, p = .001) subtests of UFOV.

Auditory task scores of the hearing impaired group are marginally lower than those of their hearing counterparts at baseline, and across every UFOV subtest. However, when the differences in auditory task scores between the hearing impaired and normally hearing groups were examined under each condition using Mann-Whitney U tests and the Bonferroni correction, no significant differences arose (see Table 5.6). In fact, the data actually showed that the auditory task performance of normally hearing participants was *more* affected by UFOV performance than the hearing impaired group. The normal hearing group exhibit a greater reduction in auditory task scores than the hearing impaired group for each UFOV subtest (see Figure 5.7). Auditory task scores were also analysed in terms of their difference amongst different demographic groups (age, education level, and gender) using Mann-Whitney U tests. This testing revealed no significant differences in any of the comparisons, suggesting no influence of these demographic variables on auditory task

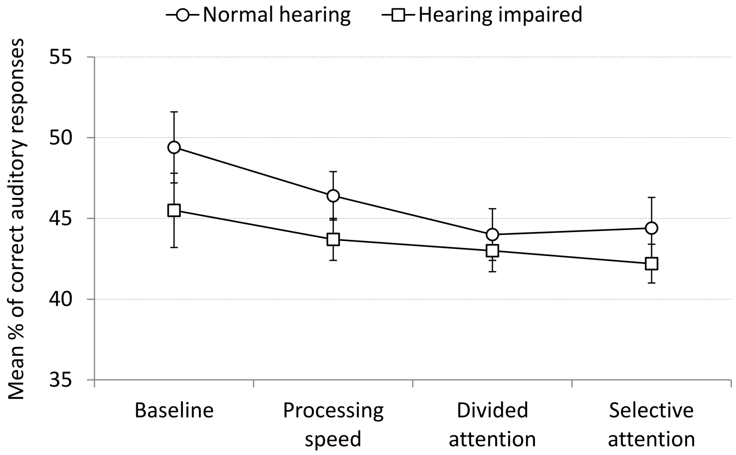


Figure 5.6 Mean auditory task scores (± standard error) for the two experimental groups across UFOV subtests and at baseline.

scores.

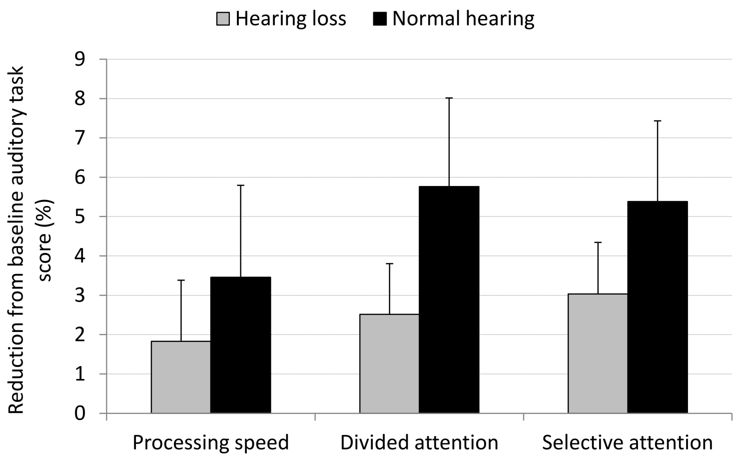


Figure 5.7 Mean reduction in auditory task scores from baseline (± standard error) for the two experimental groups across UFOV subtests.

Table 5.6 Mann-Witney U test results for a comparison between the two experimental groups in terms of their auditory task scores across UFOV conditions.

Subtest	Median		$p-$ value
	Normal hearing	Hearing loss	
Baseline (no visual task)	48.18	46.84	.198
Processing speed	46.47	46.50	.476
Divided attention	45.20	44.51	.816
Selective attention	44.76	42.11	.773

5.3.3 Multivariate analysis

Although the visual and auditory tasks did not show a significant difference between the normally hearing and hearing impaired groups, it was considered that there might be a dual-task cost. As such, there may have been a decrement in both the visual and auditory tasks under a certain experimental condition that differed significantly between the two groups. Accordingly, a MANOVA was run between the two experimental groups for each subtest of UFOV, submitting UFOV subtest score and the corresponding auditory task score as dependent variables. There was no significant difference between the hearing impaired and normally hearing groups for the processing speed ($p = .43$), divided attention ($p = .76$), or selective attention ($p = .36$) subtests of UFOV.

5.3.4 Cognitive tests

The mean scores obtained by both experimental groups on KIPS are shown in Figure 5.8. Accuracy on the majority of these tests was high, with mean scores of 80% or above. However, 'reading span' scores were generally lower than the other three subtests for participants of both groups. This would be expected, given the complex nature of the task which requires participants to hold words in working memory whilst piecing them together.

Scores on each KIPS subtest were not normally distributed. A Mann-Whitney U test showed no significant differences between the hearing impaired and normally hearing groups for the physical matching ($p = .65$) or lexical test ($p = .70$) subtests of KIPS. The difference in rhyme ($p = .069$) scores between the hearing impaired ($M = 82.88$, $SEM = 2.77$) and normally hearing groups ($M = 90.07$, $SEM = 2.76$) tended towards significance, $U = 79.5$, $z = -1.829$, $p = .067$. One significant difference arose between the groups, with reading span scores shown to be lower in the hearing impaired group ($M = 51.65$, $SEM = 2.65$) than the normally hearing group ($M = 61.07$, $SEM = 2.53$), $U = 69.0$, $z = -2.223$, $p = .025$. This suggests that some aspects of working memory ability were poorer in the

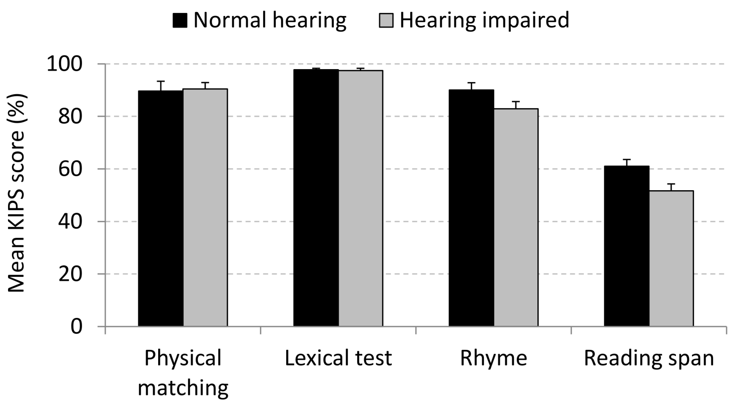


Figure 5.8 Mean results (± standard error) for the two experimental groups on each individual KIPS subtest.

hearing impaired sample than the normally hearing sample in the current study.

5.4 Discussion

5.4.1 Visual task

The results show that the performance of a simultaneous auditory task degrades performance on UFOV, and the more complex the visual task, the greater the effect of an auditory distracter. However, the main aim of this study was to assess the effect of auditory distraction on the performance of a complex visual task (which has been related to various driving outcomes), and to test whether this effect was more pronounced in hearing impaired compared to normally hearing participants.

The data suggest that hearing loss does not lead to an exacerbation of the negative effect of auditory distraction on UFOV, as no significant differences between the UFOV scores of the two experimental groups were found. Nor was there a significant difference between the effect that auditory task engagement had on the individual subtest performance of the two groups. Despite this, differences between the mean UFOV scores were apparent between the two experimental groups, with hearing impaired individuals scoring lower than normally hearing participants on the UFOV divided and selective attention subtests in the presence of a concurrent auditory task. These differences did not reach statistical significance, but the notion that hearing loss causes a disturbance on UFOV in the presence of a concurrent auditory task cannot be categorically discounted; there are a number of tangible explanations for the lack of statistical significance.

Severe hearing impairments were not widely represented in this study. Hickson et al. (2010) noted that the degree of hearing impairment was the best predictor of overall driving ability in their study sample. However, their results suggested that mild hearing impairment is less associated with poorer driving ability in the presence of distracters. This may have been a possible reason why a statistically significant difference was not observed for UFOV performance between the two groups. Over half (10 out of 17) of the hearing loss group in the current study had an impairment classified as *mild*, leaving relatively little data from those with a moderate hearing impairment (7 out of 17). However, post-hoc examination of the data showed no significant differences between the UFOV scores of the mildly hearing impaired participants and the moderately hearing impaired participants. In fact, mean values suggested that the performance of the moderately hearing impaired group was, contrary to what past work would suggest (Hickson et al., 2010), marginally better than that of the mildly hearing impaired participants. This discrepancy may, however, have arisen as a result of the very low, and unmatched sample sizes in these groups, hence no formal statistical testing was reported in this regard.

One manner by which listening effort requirements have been reduced for those with a hearing impairment in the past is the use of hearing aids (Downs, 1982; Sarampalis et al., 2009). The current experiment did not permit participants to wear their hearing aids for the completion of the auditory task. Whilst this could potentially have caused an increase in the required listening effort of the hearing impaired group, auditory stimuli were presented at a specified sensation level, meaning that sounds were presented at an amplified level, achieving the basic aim of hearing aids. This may be a supplementary reason why the results in this study did not reach statistical significance. The attenuation to sound brought about by hearing loss could be responsible for the majority of listening effort increase, and by amplifying sounds for this demographic this difficulty is nullified. Hickson et al. (2010) allowed their participants to wear a hearing aid whilst driving, if they normally did so. However, only around 15% of their sample reported doing so, meaning the benefit of hearing aids would have been largely diluted by their participants who did not wear them. In future studies it may, therefore, be of interest to present sounds at a single, pre-defined level (rather than a sensation level) in order to capture this extra difficulty associated with hearing loss. This would also have the added benefit of reflecting the situation experienced by the large majority of people with hearing loss who do not seek rehabilitative help, or use hearing aids (Laplante-Lévesque et al., 2010).

Although not statistically significant, an interesting trend identified in this study is the pattern of results for UFOV involving no simultaneous auditory task. A lower baseline score on the selective attention subtest of UFOV (incorporating visual, but no auditory distracters) was noted in the hearing impaired group compared to the normally hearing participants. This was not expected, as it was hypothesised that extra attention to the auditory task would bring about a disturbance on UFOV in the hearing impaired sample. A lower score on a particular UFOV subtest in the absence of any auditory information cannot, therefore, be explained by this hypothesis. Interestingly, a similar phenomenon, whereby hearing impaired individuals appear to be more distracted by visual information in the absence of an auditory task has been noted in past research. The data presented by Hickson et al. (2010) suggests that visual distraction had a negative influence equal to that of auditory distraction on overall measured driving performance in their hearing impaired participants. However, there is no explanation as to why this may have been the case from the authors. Thorslund et al. (2013b) also found that their hearing impaired sample were disproportionately affected by visual distraction compared to a normally hearing group. This point requires some consideration, given that a similar trend has been replicated in this study.

A possibility is that there is a difference in the baseline cognitive abilities between the hearing impaired and normally hearing demographics. As UFOV performance (when undertaken *without* a concurrent auditory distracter) reflects the attentional and cognitive abilities of respondents (Owsley, 1994; McDowd and Shaw, 2000), it is feasible to suggest that those who perform worse on a cognitive test battery will also perform more poorly on UFOV than those who have shown themselves more able on the same cognitive tests. In fact, UFOV itself is considered a measure of speed of processing difficulties (Ball et al., 2007). The hearing impaired group in this experiment were significantly poorer at a reading span task and showed a tendency to perform the selective attention subtest of UFOV more poorly in the absence of any auditory stimuli. These two factors, taken together, hint that there may be a higher prevalence of processing speed deficits, or Working Memory deficits in the hearing impaired individuals in this study. There were no significant differences between the ages of the two experimental groups, therefore age is unlikely to be a contributory factor for these results.

The possibility of cognitive deficits in the hearing impaired group is supported by previous work showing deficits in cognitive skills associated with sensory impairment (e.g. Uhlmann et al., 1989; Lindenberger and Baltes, 1994; Baltes and Lindenberger, 1997; Lindenberger and Baltes, 1997; Cacciatore et al., 1999; Naramura et al., 1999; Arlinger, 2003), and is of concern for this line of research; if those with an age-related hearing impairment are predisposed to have deficiencies in cognitive skills, the ability to perform complex tasks may be compromised even before the influence of an increased listening effort is introduced. Given that the samples recruited for both studies described thus far in this thesis have been reflective of an older demographic with age-related hearing loss, it is possible that the outcomes have been influenced by the disproportionate presence of cognitive skill decrements. Likewise, higher-order cognitive factors may also have affected previous work in the area (McCloskey et al., 1994; Ivers et al., 1999; Gilhotra et al., 2001; Unsworth et al., 2007; Hickson et al., 2010; Thorslund et al., 2013a,b,c; Green et al., 2013; Thorslund et al., 2014). Whilst it should not (and cannot) be construed that this study has proven a reduced efficiency of processing in the hearing impaired demographic, it has raised a feasible concern. This concern should be fully accounted for in future work in this area, given the overwhelming reliance of the dependent variables used on higher-order cognitive skills. Controlling for this possibility is the only manner in which the true influence of hearing sensitivity *alone* on driving can be investigated.

Wood et al. (2006) argue that reductions in visual processing as a result of auditory task engagement are of great practical importance for driving as they suggest poor hazard and sign detection. Indeed, UFOV is linked with various measures of driving performance and safety (Clay et al., 2005). The results of this study, therefore, suggest that auditory task engagement whilst driving may decrease road safety, and that caution should be exercised with regard to complex auditory task engagement whilst driving. Given the increasing availability and use of in-car systems which function using the auditory modality, these findings are of clear practical importance. Further, this experiment explicitly suggests that this consideration is particularly pertinent for visually complex situations (e.g. whilst driving through busy urban areas). Effect sizes suggested that the degrading effect of auditory distraction became greater with increasingly complex visual scenes. However, although the data suggests that hearing impaired individuals might be at a further disadvantage in this regard, it cannot be explicitly inferred from the results of this study, since there were no statistically significant differences on UFOV performance between the two experimental groups.

5.4.2 Auditory task

Auditory task scores worsened when performed concurrently with UFOV. However, performance of the hearing impaired group was not found to be significantly poorer than the normally hearing group on the auditory task under any of the UFOV subtests. In fact, the auditory task performance of normally hearing participants appeared more affected by concurrent performance of UFOV than that of the hearing impaired group.

It is not clear why this may have been the case, but one explanation is that the increase in required listening effort in hearing impaired individuals counteracts a significant decrease in auditory task performance. If this trend is considered in the context of the Working Memory model presented in Chapter 3 of this thesis, it might be that the central executive is more involved with mediating phonological loop processes than it is with visuospatial sketchpad processes in the hearing impaired sample. The Ease of Language Understanding model stipulates that explicit processing is called in to action more often in hearing impaired individuals than in normally hearing individuals (Rönnberg et al., 2008, 2013). This explicit processing arises from an analogous construct to the central executive, and is required in order to mediate phonological operations, which are undertaken implicitly by those with normal hearing. As a result, in normally hearing individuals the central executive can allocate more resources to aiding visuospatial sketchpad operations, hence resulting in better UFOV performance.

However, in hearing impaired individuals the central executive cannot dedicate such a proportion of resources to the visual task as the phonological loop is under greater load. It is possible that the extra resources assigned to the phonological loop may actually prevent a stark decrease in auditory task performance, something which may not happen in the case of the normally hearing individual.

Another reason for analysing auditory task data was to ensure that participants were engaging with it, and did not neglect the auditory task in favour of performing UFOV. The data suggests that participants did not neglect the auditory task in favour of maintaining UFOV performance. At baseline, participants were able to successfully repeat approximately one of the two sentences with a suitable degree of accuracy, thus the hearing impaired and normal hearing groups had mean accuracies of 46% and 50%, respectively. This trend continued throughout each of the UFOV subtests, with accuracy rates never dropping below 40%, suggesting that participants continued to engage in the listening task whilst performing the visual task.

5.4.3 Cognitive tests

Studying any differences in the cognitive abilities of the hearing impaired and normally hearing groups in this study gave rise to an interesting finding. Despite the fact that both groups were closely matched in terms of age, gender, and the level of formal education undertaken, there was a significant difference between the two groups for the reading span subtest of KIPS. This task is thought to rely heavily on the central executive of working memory (Lobley et al., 2005). Importantly, this effect was found in the absence of any auditory task, suggesting that it is related to a general inability to process information efficiently, rather than it stemming from auditory distraction. The rhyme section of the KIPS test battery is likely to be performed by a similar area of the brain to working memory tasks (Besner, 1987; Gathercole and Baddeley, 1993), and although performance of this subtest was not significantly different between the groups, it did tend towards it. This is of concern, given that the central executive (or a comparable construct) is hypothesised to be the site of increased dual-task interference for the hearing impaired demographic. Thus, it is possible that the hearing impaired sample in the current study may have been cognitively predisposed to perform more poorly under dual-task conditions, regardless of hearing loss.

These apparent differences in the cognitive capabilities of the two experimental groups cast a new perspective over the previous research conducted in this area. No explicit cognitive testing is included in the study of Hickson et al. (2010), simply a paper-based questionnaire regarding cognitive ability used to indicate more severe forms of cognitive decline, such as dementia (the Mini Mental State Exam (MMSE); Kochhann et al., 2010). Hickson et al. (2010) found that their hearing impaired experimental group were less capable of efficiently dividing their attention between driving and auditory tasks. This difference may have arisen because of a discrepancy in listening effort between participants, as was hypothesised. However, the authors also found that performing two simultaneous *visual* tasks had a disproportionate effect on their hearing impaired sample, something which was also shown by Thorslund et al. (2013b). This is not in accord with the hypothesis that an increased listening effort leads to a poorer driving performance, instead (in light of the results of this study) it perhaps suggests that there may be a lesser processing capability in their hearing impaired group.

A study linking hearing loss with an increased risk of road traffic accidents (Ivers et al., 1999) also failed to control for cognitive factors and relied solely on self-reported hearing loss, which is linked with respondents' mental capabilities (Salonen et al., 2011). Self-reported measures of hearing impairment have also been linked with an increased likelihood of driving cessation (Gilhotra et al., 2001; Unsworth et al., 2007), and have been shown to be the best predictor of reports of driving difficulty (see Chapter 4). The salient point here is that it is not possible to ascertain whether these results have arisen as a result of hearing impairment, cognitive factors or an interaction of the two. Taking this research forward in a useful manner will require a methodology by which the respective influence of each problem can be successfully differentiated.

This may be problematic, given the possibility that, by seeking a hearing impaired sample for participation, what is actually being obtained is a sample which has significantly different cognitive abilities compared to a normally hearing sample. The ability to split the influence of hearing loss and cognitive factors apart is of paramount importance in establishing the effect of *hearing impairment* on driving performance. Accordingly, the following chapter describes a technique that attempted to achieve this distinction. One manner in which the influence of cognition could be negated is through the employment of a more extensive cognitive test battery. One of the cognitive tests used in this study was a measure of Working Memory capacity (the reading span subtest), which is thought to predict performance on higher-order cognitive tasks (Engle, 2002). Alternative or supplementary measures of complex Working Memory span are available (see e.g. Conway et al., 2005), and might be suitable for inclusion in future studies in this area. However, it might not be possible to measure all relevant aspects of cognitive processing experimentally for a number of reasons (e.g. insufficiently sensitive tests, lengthy experimental protocols). For example, the cognitive test battery undertaken here was not entirely diagnostic with regard to processing speed. As a result there may be unmeasured factors, which are potentially more prevalent in the elderly hearing impaired demographic, perhaps confounding the results obtained. Accordingly, an experimental approach which avoids the use of older hearing impaired individuals as participants is considered preferable. This would entirely remove the confound of cognitive changes being more prevalent in those with an age-related hearing loss.

5.4.4 Study limitations

There are some methodological limitations which should be considered when interpreting the results of the current study. For example, the small sample size is a possible reason for the results not reaching statistical significance. It is also important to note that although UFOV has been exhibited as a good predictor of accident involvement in past work (Ball et al., 1993; Owsley, 1994; Owsley et al., 1998; Clay et al., 2005; Ball et al., 2006), this association has been shown through test scores which have been recorded without a concurrent auditory task. The association between UFOV scores under auditory distraction conditions and driving behaviour is unknown, therefore conclusions in this regard cannot be feasibly drawn. For example, those who have issues with multi-tasking may well adapt their behaviour and withdraw from the auditory task in order to increase their road safety. This is particularly relevant for those with a hearing loss, who it is though adapt their driving behaviour in order to negate any driving decrements occurring as a result of their sensory impairment (Thorslund et al., 2013a,b, 2014). More ecologically valid studies of the driving of hearing impaired individuals would, therefore, be of great value in determining if these adaptations in behaviour are likely to be the case.

5.5 Conclusions

This study has shown that the simultaneous performance of a cognitively demanding auditory task and UFOV decreases performance on both tasks. These results are of practical importance, as they indicate that aspects of visual attention are compromised during periods of auditory engagement. Furthermore, the results exhibit a propensity for this visual processing problem to be exacerbated in more visually complex situations, providing an insight in to the most troublesome situations for auditory task engagement whilst driving.

The results also indicate that hearing impairment might exacerbate this problem, although the difference between hearing impaired and normally hearing individuals in this study did not reach statistical significance. A number of feasible reasons for this have been suggested, and two major concerns inform the methodological approach to be taken in future work. The first is that the study primarily reflected the performance of mildly hearing impaired individuals, so a wider range of hearing loss severities is required in order to generalise any conclusions, given that moderate or severe hearing losses better predict driving performance (Hickson et al., 2010). The second is that it is unclear whether the pattern of results observed actually arose as a result of a difference in the measured cognitive abilities of the two experimental groups. The separation of hearing and cognitive impairments is of paramount importance to establish the effect that hearing loss has on driving performance. Thus, continuing work must be planned with these two issues in mind. The next chapter provides a methodological approach by which the effect of hearing impairment can be differentiated from other extraneous factors, and details how it will be employed in the remainder of the studies which are reported in this thesis.

Chapter 6

Hearing Loss Simulation: Explanation and Validation Studies

6.1 Introduction

This chapter reports on a method by which peripheral hearing loss can be controlled and isolated from other factors which may co-exist. This is necessary because, the previously described studies (see Chapter 4 and Chapter 5) have raised concerns regarding the ability to:

1. Differentiate the effects of hearing loss and cognitive factors, which may be intertwined in cases of age-related hearing loss;
2. Focus on a specific level of hearing loss;
3. Determine specifically whether it is the distortion to sound, caused by damage to peripheral auditory structures, which is responsible for the driving decrements in hearing impaired individuals.

These have been identified as issues for the continuing experimental work in this area, but also as confounding factors which may have impacted on past research in the area (e.g. McCloskey et al., 1994; Ivers et al., 1999; Gilhotra et al., 2001; Unsworth et al., 2007; Hickson et al., 2010; Green et al., 2013; Thorslund et al., 2013a,b,c, 2014). As a result, the need for a methodological approach which accounts for these factors is warranted.

Accordingly for the remaining studies in this programme of research, a simulation of SNHL was used to address these concerns. This chapter will provide a brief overview of the methods by which valid hearing loss emulation might be achieved, and the advantages/disadvantages of these approaches. The method of simulation chosen will then be described, and objective and subjective analyses will be performed to ascertain the simulation's appropriate functioning and suitability for use in experiments described in the remainder of this thesis.

6.2 Hearing loss simulation

SNHL results in a number of suprathreshold effects on the auditory system (see Chapter 2). The main effects identified can be summarised as: loudness recruitment, reduced temporal resolution, and reduced frequency selectivity. Of course, these suprathreshold phenomena occur concurrently with a loss of sensitivity in the auditory system, resulting in elevated absolute thresholds. There have been numerous attempts to study suprathreshold complications elicited by hearing impairment using SimHL (Moore and Glasberg, 1993). This approach, provided the simulation is accurate, is a useful manner by which the psychoacoustic effects of SNHL can be studied in normally hearing individuals, given that individual psychoacoustic aspects of hearing loss can be isolated and manipulated (Baer and Moore, 1993).

6.2.1 Why use hearing loss simulation?

Until now, the studies described in this thesis and other work in the area (McCloskey et al., 1994; Barreto et al., 1997; Ivers et al., 1999; Gilhotra et al., 2001; Unsworth et al., 2007; Hickson et al., 2010; Green et al., 2013; Thorslund et al., 2013a,b,c, 2014) have investigated the effect of hearing loss on driving by recruiting participants with a 'real' hearing loss. This approach, whilst valid, has given rise to a number of methodological concerns which have been highlighted by the first two studies described in this thesis. SimHL has the capacity to address these individual considerations, as outlined in Table 6.1.

Simulating hearing loss, therefore, has three distinct advantages for use in the continuing development of studies in this area:

1. Cognitive and other age-related factors can be easily controlled in future studies, so it is highly unlikely that they will have an influence on the results;

2. The degree of hearing impairment can be customised to whatever is desired and kept constant for each participant;

3. The power of studies can be improved by using a within-subjects design, rather than having to rely on a between-subjects methodology.

Therefore, SimHL was considered a suitable experimental approach for continuing work in this area.

However, despite its positives, it should also be considered that hearing loss simulation is subject to some limitations for application in this work. These limitations must be acknowledged, and any results arising from the use of SimHL considered accordingly. First and foremost, using a SimHL removes ecological validity from studies in which it

Table 6.1 The identified issues associated with using 'real' sensory impairment in studies investigating the effect of hearing loss on driving performance, and how SimHL can overcome these.

Problem with 'real' hearing loss	Benefit of SimHL
A potential mismatch in the cognitive capabilities of experimental groups: Results from the previous experiment suggested that there was a significant difference in working memory between hearing impaired and normally hearing individuals. Cognition is important for driving (Withaar et al., 2000), a complex task requiring the integration of a number of visual, cognitive and psychomotor skills (Stutts et al., 1998). Thus a potentially higher prevalence of cognitive slowing in the hearing impaired demographic is of concern.	A young normally-hearing sample can be used in experiments, thus removing the possibility of age-related and hearing loss-correlated increases of cognitive slowing. SimHL requires the use of normally-hearing subjects as Digital Signal Processing (DSP) techniques will present stimuli relative to a normally hearing baseline.
An inability to differentiate between higher-order and peripheral listening processes: 'Real' hearing impairment introduces higher-order listening complications which govern the impact a given peripheral hearing loss has. Chapter 4 suggested that these higher-order listening processes can influence experienced driving problems. In 'real' hearing loss it is not possible to differentiate peripheral listening and higher-order components. Thus the hypothesis that a disproportionate effect of auditory distraction in hearing impaired individuals arises as a result of peripheral distortion to sound cannot be successfully investigated.	A within-subjects experimental design can be used as hearing loss is being artificially administered to normally-hearing individuals. In this case, the same participant is both the control and case condition, meaning that the individual higher-order listening processes remain identical, regardless of hearing loss condition. Accordingly, the influence of peripheral listening components can be isolated, as the SimHL only alters this aspect of the sound, with no other variability arising in the experimental design. A within-subjects design also has the benefit of increasing experimental power (Field, 2013).
A wide range of hearing loss severities: Past work has shown a difference in driving outcomes as a function of hearing loss severity (Ivers et al., 1999; Picard et al., 2008; Hickson et al., 2010); greater severities are generally associated with more negative driving outcomes. Because of this, it was suggested that the results of the previously described study (see Chapter 5) did not show statistical significance because of the inclusion of a number of experimental participants with a mild hearing loss.	A desired degree of hearing loss, in a frequency-specific manner can be specified, and applied across all participants taking part in an experiment (provided that they have normal auditory function themselves). This nullifies any variance that may arise from subtle differences in the audiometric data of participants, and also allows for the study of differing degrees, and configurations of hearing loss. For example, it is possible to emulate the audiometric pattern of an age-related hearing loss, thus providing the possibility to study the peripheral effects of this form of hearing impairment, without the cognitive complications that are associated with an older study sample.

is being applied. There is some suggestion that hearing impaired individuals adapt their driving behaviour in response to a reduced auditory input over time (Thorslund et al., 2013a,b, 2014). It is unlikely that applying an instantaneous SimHL will capture this aspect of driving with a hearing impairment. This was not seen as an issue for this line of research, in which the effect of peripheral sound distortion on distraction whilst driving was being investigated. Thus, removing behavioural change which could confound this aspect of driving was not considered problematic for these studies, though the possibility that behavioural change might counteract the distracting effect of peripheral hearing loss should be considered.

The inability of SimHL to capture every aspect of SNHL should also be considered. Although Moore (2007) suggests that the facets of SNHL covered by SimHL are the most problematic for speech understanding, the influence of those not covered should not be discounted. Hearing loss simulation cannot accurately emulate reductions in temporal resolution, nor can it approximate central auditory processing decrements. Either of these aspects of SNHL may cause problems for driving performance, so caution must be exercised in the analysis of results.

Accordingly, provided that these limitations are considered thoroughly in conclusions arising from work employing SimHL, this methodological approach is ideal for continuing work being described in this thesis. The remainder of this chapter will go on to discuss how simulation is achieved and the specific method which was chosen for employment in this programme of research. The testing performed on the simulation in order to ascertain its proper functioning is then discussed.

6.2.2 Methods of simulating hearing loss

In the past, there have been two broad approaches to simulating the effects of certain aspects of hearing loss:

1. Using a filtered noise masker so that the masked absolute thresholds of a normal ear are the same as an unmasked audiogram of an impaired ear (Fabry and Van Tasell, 1986; Humes et al., 1987; Zurek and Delhorne, 1987; Dubno and Schaefer, 1992).

2. Applying DSP techniques in order to alter sound so that it resembles that which would be perceived by an impaired ear (ter Keurs et al., 1992, 1993; Baer and Moore, 1993; Moore and Glasberg, 1993; Baer and Moore, 1994; Moore and Glasberg, 1997; Nejime and Moore, 1997).

6.2.2.1 The use of a filtered noise masker

A filtered noise masker is applied so that the masked audiogram of a normal ear resembles an unmasked audiogram of an impaired ear. A depiction of how this method works is given in Figure 6.1.

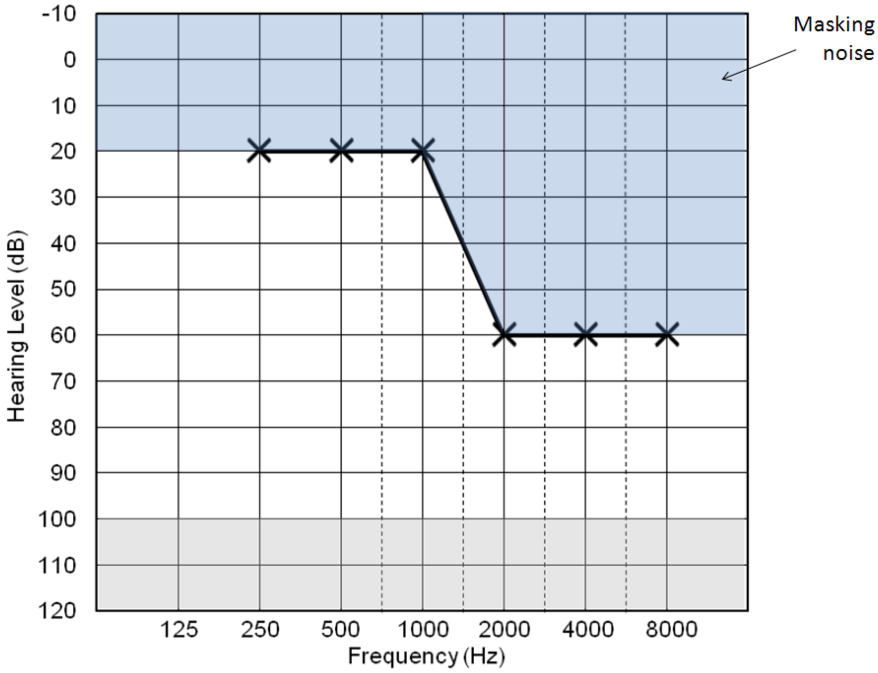


Figure 6.1 An example of how hearing loss simulation is achieved by using a filtered noise masker. Any extraneous sound which falls inside the range of the masker noise is unlikely to be heard.

Moore and Glasberg (1993) summarise that, generally, results obtained from normal ears using this method are similar to those measured from unprocessed stimuli in impaired ears. However, in some cases subjects with 'real' SNHL exhibit worse test performance than is recorded as a result of the simulation. They argue that this approach to simulation produces a loudness recruitment effect, but one which is not comparable to that arising as a result of SNHL, because it is of a central (not peripheral) origin (Phillips, 1987) and is limited to a small range of sound levels around the masked threshold (Stevens and Guirao, 1967). This type of simulation, therefore, provides an emulation of frequency specific threshold elevation, but does not accurately represent frequency selectivity (as a function of broadened auditory filters), or loudness recruitment. Additionally, the simulation of hearing loss through the use of a masker noise is limited to mild-moderate hearing losses, as the level of the masking noise required to produce a severe hearing impairment would be uncomfortably loud (and potentially damaging) for a normal ear to listen to (Moore and Glasberg, 1993; Baer and Moore, 1993).

6.2.2.2 The use of Digital Signal Processing techniques

More recently DSP has been used to alter a sound so that it resembles that which is perceived by an impaired ear. Different DSP techniques have been used to emulate distinct effects of cochlear hearing loss: (1) frequency selectivity, and (2) loudness recruitment and threshold elevation (see Chapter 2 for an explanation of these phenomena). These techniques are summarised below.

1. Frequency selectivity

Reduced frequency selectivity refers to an inability to successfully resolve the different components of a complex sound (see Chapter 2). For those with a SNHL, it can lead to a less distinct representation of sound, which impacts on successful auditory perception (e.g. speech intelligibility) (Moore, 1996). Commonly, reduced frequency selectivity is simulated by 'smearing' or 'smoothing' the frequency spectra of stimuli on a moment-to-moment basis, so that the cochlear excitation pattern in a normal ear resembles that of an impaired ear as a result of broadened auditory filters (Moore, 2007). An example of this technique is shown in Figure 6.2. A number of experiments have taken this simulation approach when investigating the suprathreshold effects of reduced frequency selectivity, and have exhibited results that one might expect from 'real' hearing impaired subjects (ter Keurs et al., 1992, 1993; Baer and Moore, 1993, 1994).

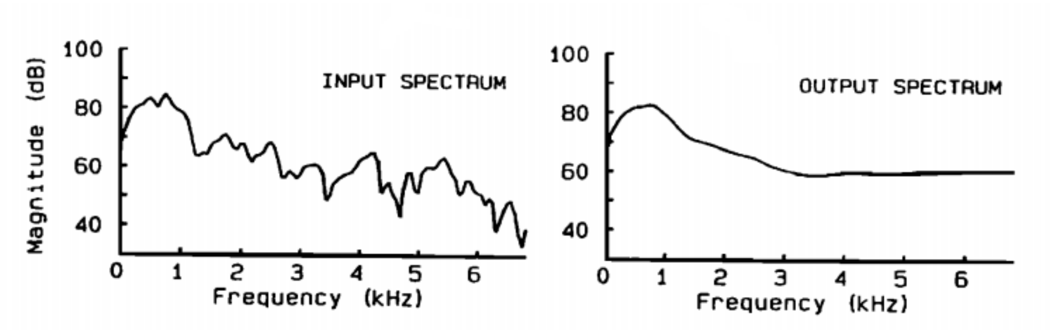


Figure 6.2 The difference between a normal input signal and a 'smeared' or 'smoothed' output signal in the frequency domain. Source: Baer and Moore (1993).

ter Keurs et al. (1992, 1993), for example, measured the Speech Reception Thresholds (SRTs)[1] of subjects listening to smeared stimuli in the presence of different types of masking noise. They found that smeared speech resulted in higher SRTs when the filter bandwidth used in their simulation was at least doubled, suggesting that speech intelligibility had been significantly affected by their smearing paradigm. They also found that the increase in SRTs remained when the noise was a single competing speaker as opposed to speech-shaped noise for processed stimuli (i.e. SimHL conditions). This was not the case for unprocessed stimuli (i.e. normally hearing conditions), and SRTs were reduced when the masker was a single competing speaker. This is exactly what would be expected as those with normal hearing are less susceptible to masking by a single-speaker compared to hearing impaired individuals (Festen and Plomp, 1990; Moore et al., 1991; Peters et al., 1998).

Baer and Moore (1993) used a more advanced smearing algorithm which incorporated the ability to alter the degree of broadening and asymmetry of auditory filter shapes. They

[1] The sound level at which 50% of speech can be successfully understood (American Speech-Language-Hearing Association, 1988).

found that, when using a speech-shaped noise masker at low signal to noise ratios, widening the auditory filters used in the smearing paradigm progressively reduced SRTs. The results of a later study were also in accord with this finding (Baer and Moore, 1994), and agreed with the finding of ter Keurs et al. (1993) that the difference between speech intelligibility in noise and single speaker conditions was smaller for SimHL than it was for unprocessed stimuli.

These results exhibit DSP as a good approximation of the loss of frequency selectivity associated with SNHL.

2. Loudness recruitment

Loudness recruitment refers to an abnormal growth of loudness with an increase in stimulus intensity (see Chapter 2). This leads to a 'reduced dynamic range' in individuals with a SNHL; the difference in level between sounds which are just audible and uncomfortably loud is much smaller than it is for individuals with normal hearing (Moore, 1996). Loudness recruitment has also been simulated (in conjunction with threshold elevation) by employing DSP (Moore and Glasberg, 1993; Moore et al., 1995; Duchnowski and Zurek, 1995; Moore et al., 1997). Commonly a signal is split into various frequency bands (corresponding to the auditory filters on the basilar membrane), the range of levels in each band is then expanded, and the bands are recombined to form a processed waveform. This approach can be used to model a larger range of hearing loss severities (accurately to around 90 dB SPL; Moore and Glasberg, 1993), given that the technique is not reliant on a masking noise which may become uncomfortably loud.

This process of simulating loudness recruitment is performed accurately by using a loudness model; if an individual with a unilateral hearing loss is asked to match the loudness of a reference tone in their normal ear to a test tone in their impaired ear (see Figure 6.3) for a given input level, it is then possible to derive the perceived loudness in dB for those with SNHL. By applying a loudness model which has been derived in this manner, it is possible to re-create the loudness sensations that would be experienced in an impaired ear in a normally hearing ear (Moore, 2007).

There is some evidence regarding the validity of using this approach to simulate loudness recruitment and threshold elevation in normally hearing listeners. Duchnowski and Zurek (1995) used DSP to examine the effects of loudness recruitment and threshold elevation on syllables heard in quiet and in speech. Their algorithm was set up to reflect the characteristics of hearing impaired subjects that had been tested in a prior study (Zurek and Delhorne, 1987), and they presented these simulations to normally hearing subjects. Their results taken from normally hearing subjects matched the pattern that had been exhibited in hearing impaired subjects during the previous study. This suggested that their emulation of auditory dysfunction accurately reflected the subjective experiences of hearing impaired individuals.

Additionally Moore et al. (1997) recruited subjects with a unilateral moderate-severe

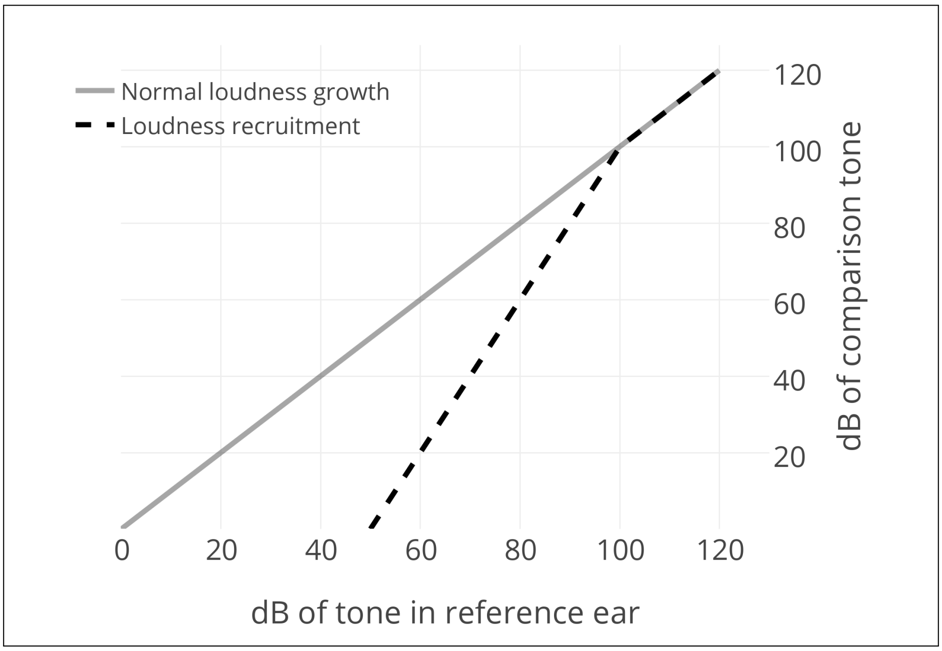


Figure 6.3 An example of a loudness growth function, derived by asking a subject with unilateral hearing loss to match the level of a reference tone in their normal ear, to the loudness of a test tone in their impaired ear.

sensorineural hearing loss and presented simulations of cochlear impairment to their normal ears. The subjects tended to report that these stimuli were appropriate in terms of their loudness and dynamics. However, they did state that the speech appeared a lot clearer for the simulated stimuli in their normal ear, and results showed a markedly worse performance in speech recognition for the impaired ear than for the normal ear when listening to the simulation.

This discrepancy in results was explained by the phenomenon of *neglect*[2], but it was also argued that loudness recruitment and threshold elevation alone do not account for the speech understanding difficulties that hearing impaired individuals experience. Rather, there is a cumulative effect of different aspects of cochlear hearing loss causing a disturbance in speech recognition. Moore (2007) suggests that, based on available data, the most involved aspects affecting speech recognition (for moderate, severe and profound hearing losses) are audibility, frequency selectivity and, to a lesser extent, loudness recruitment. Therefore, when only one (or a selection) of these psychoacoustic phenomena is emulated, there is likely to be a lesser effect on test results compared to if they were all applied simultaneously.

3. Complete simulation of Sensorineural Hearing Loss by Digital Signal Processing

One study has attempted to simulate all of the above aspects of cochlear hearing loss (threshold elevation, loudness recruitment and reduced frequency selectivity) in one DSP

[2]'Neglect' is a phenomenon whereby subjects with a unilateral or asymmetric loss often rely on perception from their 'good' ear (Hood, 1984).

paradigm, and assess its effect on the intelligibility of speech in noise (Nejime and Moore, 1997). The simulation paradigm used in this study was a concatenation of the methodologies used in past hearing loss simulations by the same research group (Moore and Glasberg, 1993; Baer and Moore, 1993). However, it improves previous emulations by taking into account the fact that the broadening of auditory filters is frequency dependent (Faulkner et al., 1990), and that changes in frequency selectivity with level are less pronounced in hearing impaired ears compared to normally hearing ears (Stelmachowicz et al., 1987; Murnane and Turner, 1991). When comparing their results for a simulated moderate hearing loss against a control condition, Nejime and Moore's (1997) results reflected what one might expect in a 'real' case of SNHL. This is the only study that has simultaneously simulated all of these aspects of cochlear hearing loss.

6.2.2.3 Summary

In summary, although DSP and noise masking methods have produced results that are comparable with what one might expect from those with a 'real' hearing loss, applying DSP appears to be a superior approach as it can emulate some aspects of cochlear hearing loss more accurately than a noise masker method can (e.g. loudness recruitment and frequency selectivity). In addition, DSP can be used for a wider range of hearing loss severities.

The emulation approach of DSP has been used to simulate numerous facets of cochlear hearing loss simultaneously, giving a more valid reflection of SNHL than isolated psychoacoustic phenomenon. This is ideal for use in work in this area, given that an ecologically valid approximation of SNHL is sought. It is important to note, however, that SimHL can only provide an approximation of SNHL, and there are some aspects of this impairment which it cannot emulate (e.g. temporal resolution, central auditory processing decrements). Additionally, there are various aspects of damage to the auditory system which it is not possible to emulate simply by employing DSP (e.g. auditory nerve firing patterns).

Whilst these aspects are unaccounted for by SimHL, the aspects of SNHL which are targeted by this methodology (loudness recruitment, threshold elevation and reduced frequency selectivity) are considered the most important for speech understanding (Moore, 2007), and are thus most likely to be responsible for the increase in the required listening effort in the hearing impaired demographic. These psychoacoustic properties can be replicated to a high degree of accuracy, and so if this simulation is used on normally hearing subjects in experiments assessing the effect of hearing loss, the outcomes are likely to be highly reflective of what might be expected from 'real' hearing impaired subjects. However, it is important that the noted omissions are considered when drawing conclusions from methodologies employing SimHL.

6.3 The simulator chosen for use

This section reports on the specific method of simulation that was employed for experiments described in the remainder of this thesis. The evidence suggests DSP is a better approach to modelling a complete hearing loss than the employment of a filtered masking noise. Accordingly, the DSP method described by Nejime and Moore (1997) was implemented using MATLAB (2010).

The following section provides a brief overview of Nejime and Moore's (1997) simulation method, and thereafter testing which was carried out to ensure its accuracy and validity is reported.

6.3.1 Overview

The basic premise of the SimHL is that it applies various DSP techniques to an acoustic waveform, and produces an audio file which is representative of how the original would be perceived by somebody with a SNHL. The basic stages involved in this process are summarised in Figure 6.4, and each of these stages is explained in the following section. However, in order to produce a simulation of a desired level and configuration, various input parameters must first be specified. These include:

- The audiogram of the hearing loss that is to be simulated;
- The calibration dB SPL, in order to accurately apply a loudness model based on the level of the input sound;
- The desired dB SPL of the output file: the user can specify whether the output file should be amplified or attenuated (separate from any effect of the hearing loss being simulated) in relation to the level of the input file.

6.3.2 How the simulator functions

This method of simulation tries to address and emulate three aspects of SNHL: (1) threshold elevation, (2) loudness recruitment, and (3) reduced frequency selectivity. The incorporation of these three psychoacoustic phenomena requires two broad processing steps: one which applies a loudness model, thus emulating threshold elevation and loudness recruitment, and one which applies a smearing function in order to emulate reduced frequency selectivity. However, first the input file must be prepared for these two functions to be applied.

1. File preparation

The RMS value of sound contained within the input file is measured, essentially providing an accurate representation of how intense the waveform is over its duration, removing the effect of natural fluctuations in pressure over time (Rosen and Howell, 2011).

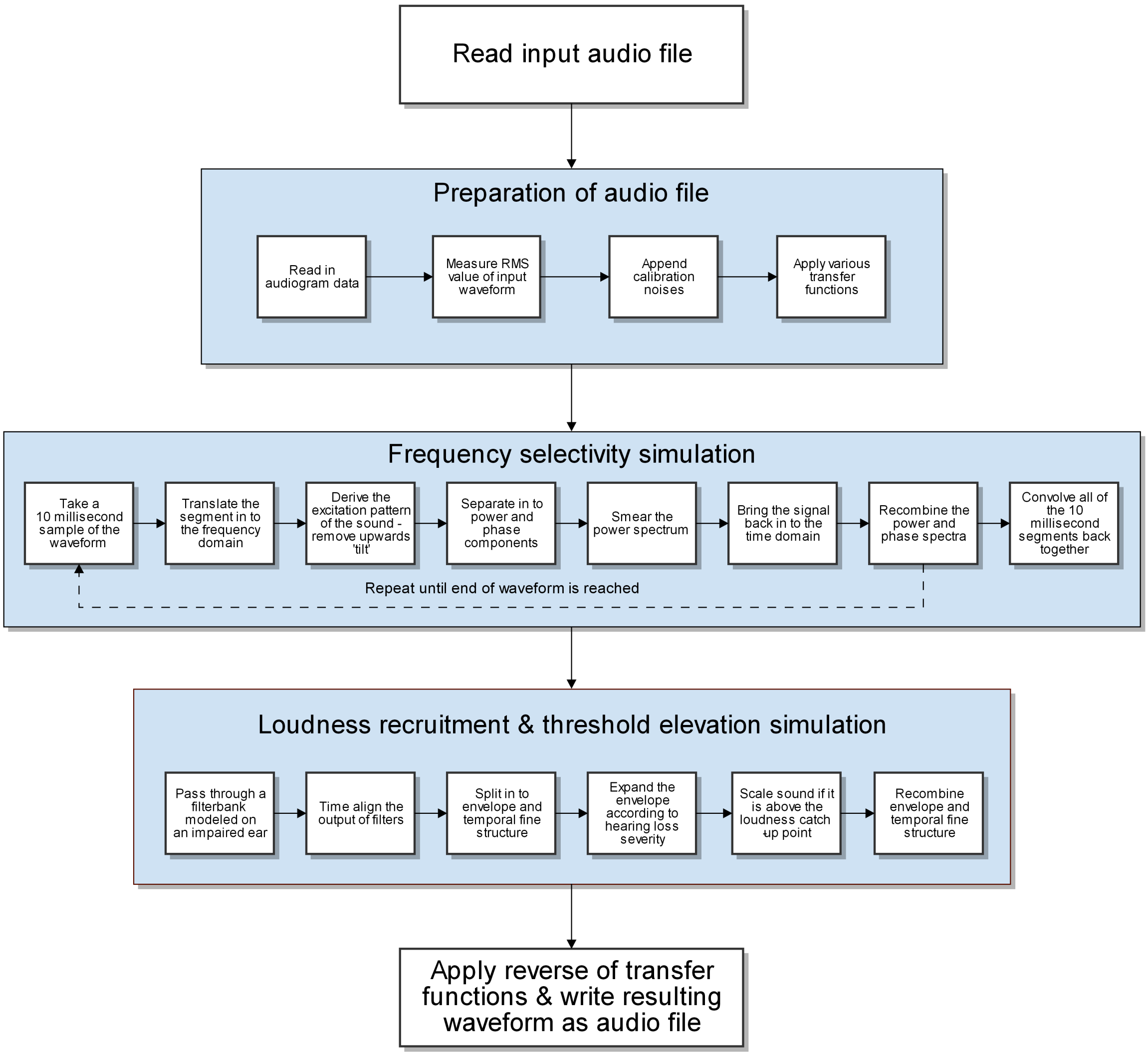


Figure 6.4 A flow diagram depicting how hearing loss simulation is achieved by the chosen methodology.

The RMS value of the input file is then assigned an arbitrary dB value, which was specified as the calibration dB SPL value. Two calibration sounds are then appended to the start of the file: (1) a 520 Hz tone, and (2) a short bust of noise reflective of the frequencies contained in speech (ANSI, 1997). Both of these calibration noises are produced with the same RMS value as that measured from the input file, so that the two correspond to the same level. These will eventually be used in order to ensure that the stimuli are presented to participants at the correct level.

The input file is then sent through a filter which simulates the change in frequency characteristics of a sound as it passes from free field to the cochlea; characteristics of the outer and middle ear mean that sound is attenuated at certain frequencies relative to others before it reaches the cochlea (Yost, 2000). These changes have been quantified in past studies and are known as *transfer functions*, two of which are applied: (1) a *head* *related transfer function*, which describes the acoustic changes to a sound arising from its propagation through the air, into and down the ear canal until it reaches the eardrum (Shaw, 1974), and (2) a *middle ear transfer function*, which describes the acoustic changes to a sound which occur as a result of its passage through the middle ear to the oval window at the entrance to the cochlea (Killion, 1978). The combination of these two transfer functions generally results in attenuation at lower frequencies, and a slight boost at mid-range frequencies (see Figure 6.5).

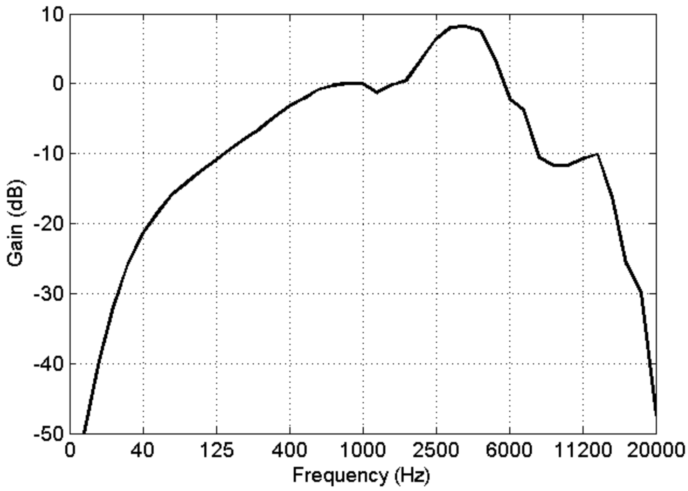


Figure 6.5 The overall gain characteristics of the two transfer functions applied in the simulation to replicate the passage of a sound from free field to the cochlea. Data from: Shaw (1974) and Killion (1978).

2. Spectral smearing

With the calibration sounds appended and the frequency 'stamp' of the two transfer functions applied, smearing is then applied in order to emulate a reduction in frequency selectivity. The degree of smearing to be applied is calculated by averaging the supplied hearing thresholds between 2–8 kHz. Values of 57 dB HL and above are classed as being subject to 'severe' smearing, between 36–56 dB HL are 'moderately' smeared, 16–35 dB HL are 'mildly' smeared, and 15 dB HL and below are not subjected to smearing. The degree of smearing governs the degree of auditory filter widening; the greater the degree of impairment, the greater the broadening, and, thus, the greater the amount of smearing. Table 6.2 shows the factor by which each auditory filter will be widened for differing degrees of hearing loss.

The input file is split into segments, and each segment is transferred from the time domain (i.e. changes in pressure over time) into the frequency domain (i.e. the relative power of the frequencies contained in the waveform). For successive, overlapping frames, the simulation takes the calculated excitation pattern on the basilar membrane of the ear being simulated (i.e. with the filters broadened by the pre-defined factor). This excitation

Table 6.2 The broadening factors for the lower and upper limits of auditory filters applied by the hearing loss simulation for different degrees of impairment.

Degree of impairment	Lower filter broadening factor	Upper filter broadening factor
Normal	1.0	1.0
Mild	1.6	1.1
Moderate	2.4	1.6
Severe	4.0	2.0

pattern can be defined as the output from the auditory filters as a function of the filter centre frequency (Moore and Glasberg, 1983; see Figure 6.6 for an example).

As auditory filter bandwidths increase with rising frequency, these excitation patterns have an upwards 'tilt' (i.e. the excitation pattern is greater at high frequencies) because the wider filters at higher frequencies register more energy than thinner filters spanning a smaller bandwidth. This 'tilt' is removed by deriving a power per hertz estimation in each frequency band. This is necessary as the resulting simulated signal will be passed through a bank of auditory filters in a normal subject's ears during experimental trials, which will have the effect of 'tilting' the excitation pattern itself.

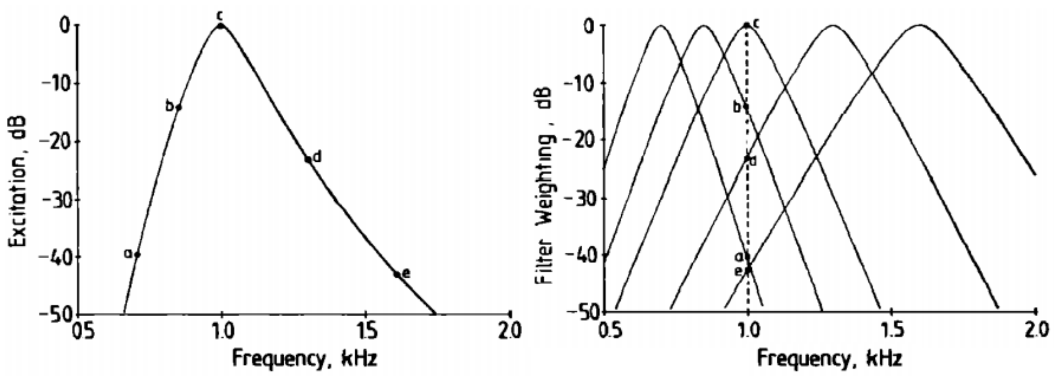


Figure 6.6 An example of the derivation of an excitation pattern from auditory filters. The simplified filter bank for a range of centre frequencies is shown on the right, along with the representation of a 1000 Hz tone (dashed line). The excitation pattern shown on the left is obtained by calculating the output of each filter as a function of centre frequency. Source: Moore and Glasberg (1983).

Following the removal of this 'tilt' at higher frequencies, the resulting excitation patterns are then separated into power and phase components and the power is convolved using a smearing function, whereby each spectral component is replaced by a weighted sum of its surrounding components. This has the effect of 'smoothing' or 'smearing' the frequency spectrum; decreasing the contrast between the peaks and valleys. The smeared power spectrum and the original phase spectrum are then recombined and the signal is converted back from the frequency to the time domain. The frames are then overlapped and added back together to create a signal the same length of the input signal, but with the spectrum having been smeared.

3. Application of loudness model

Following the spectral smearing of the input signal, an emulation of threshold elevation and loudness recruitment is applied. Stimuli are again passed through a broadened auditory filter bank which is modelled on the widths and shapes of those measured from subjects with moderate to severe hearing loss. In order to have as little effect as possible on the spectral components of the sound being processed (these have already been addressed and altered by the spectral smearing algorithm), the *envelope* component of the sound is altered, rather than the whole waveform. The *envelope* of a sound is conveyed by amplitude modulations over time, whereas the *temporal fine structure* refers to rapid oscillations with a rate close to the centre frequency of the auditory band (Moore, 2008; see Figure 6.7), conveying frequency modulations over time (Loughlin and Tacer, 1996; Stickney et al., 2004). Broadly speaking, the envelope holds information about the amplitude (or power) of a signal, whereas the temporal fine structure provides information about the frequency content of that signal. It is for this reason that, when simulating loudness recruitment, changes in the envelope of the sound are desired.

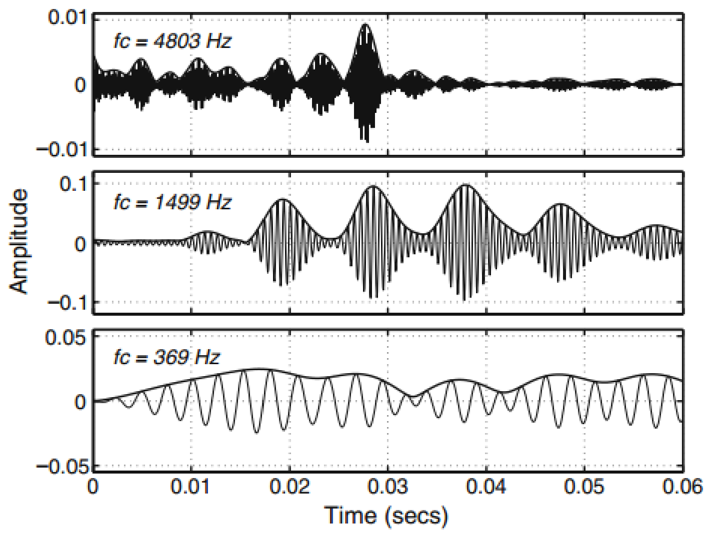


Figure 6.7 A depiction of the envelope of three different sounds, and the temporal fine structure contained within. Source: Moore (2008).

A loudness growth function is then emulated by raising the envelope of the signal for each auditory filter to the power N, which has the effect of magnifying fluctuations in the envelope. Applying independent values of N for different filters means that loudness growth can be simulated in a frequency-dependant manner, allowing for the accurate representation of loudness growth for hearing losses which vary across frequency. For example, Moore and Glasberg (1993) applied different values of N in each frequency band for such sloping, high-frequency hearing losses (the values are shown in Table 6.3).

At some point the loudness perception of an impaired ear usually ‘catches up’ with

Table 6.3 Specification of a hearing loss condition in the study of Moore and Glasberg (1993) and the power by which they expected the envelope to be raised by in each auditory channel.

Channel centre frequency (Hz)	<879	879	1184	1579	2067	2698	3503	4529	5837
Hearing threshold (dB HL)	33	33	38	44	50	57	64	67	67
Value of N	1.5	1.5	1.6	1.8	2.0	2.35	2.75	3.0	3.0

that of a normal ear (see Figure 6.3). This point is usually considered to occur between 90 - 100 dB (Moore, 2007). At sound levels above this 'catch up' point, loudness growth is usually comparable between hearing impaired and normally hearing individuals. Thus the amplitude of the waveform is scaled so that it equals the amplitude of the unprocessed sound when the calculated output level is equal to or greater than the loudness perception 'catch up' level. Without this scaling, loudness would continue to grow in the same manner past this 'catch up' point.

Following the processing of the envelope it is multiplied by the fine structure in each channel to give a resulting waveform, which reflects the loudness sensations associated with SNHL.

4. Simulation output

Finally, a reverse of the two transfer functions originally applied to the input file is employed in order to remove the frequency effects previously applied. This is necessary as the transfer functions will be applied in real time when a subject is asked to listen to the stimuli. This concludes the simulation process and the resulting waveform, complete with the appended calibration sounds, reflects the psychoacoustic phenomenon of loudness recruitment, threshold elevation, and reduced frequency selectivity. In theory, the resulting waveform therefore presents the perception of a sound subject to SNHL to those with normal hearing.

6.4 Validation of the simulation

In order to draw meaningful conclusions from any results obtained using this simulation as the source of hearing loss, it is of paramount importance that the accuracy and validity of the emulation is assessed. This section will provide a description of how the simulation was subjectively and objectively tested in order to ascertain its suitability for application in this research.

6.4.1 Objective analysis

Objective analysis was carried out in two manners: (1) ensuring the simulation produced a loudness model which accurately reflected what would be expected from a 'real' hearing loss, and (2) ensuring that the simulation applied independent levels of loudness recruitment and threshold elevation across different frequency bands.

6.4.1.1 Derivation of the loudness model

The reduction in level of a two second burst of white noise which had been processed using the hearing loss simulation, relative to a reference sound, was ascertained for a range of input levels (0–120 dB in 5 dB increments), and different severities of flat hearing loss (the same Pure Tone Audiometry (PTA) thresholds across all frequencies; 10–90 dB in 10 dB increments). The reduction in level from the reference file was calculated using the formula:

$$\text{dB} = 20\log_{10}\left(\frac{V}{V_{\text{ref}}}\right)$$

where V was the RMS absolute voltage of the sound processed with the hearing loss and V_{ref} was an RMS reference voltage against which V was compared. V_{ref} was obtained by taking the RMS value of the white noise processed with a SimHL of 0 dB HL across all frequencies.

For example, if the white noise was run through the simulation for a normal hearing and hearing loss condition using an input SPL of 60 dB SPL, and the RMS voltage values of 0.8 and 0.4 were measured, the change in dB corresponding to the waveform in the hearing loss condition would be:

$$20\log_{10}\left(\frac{0.4}{0.8}\right) = -6.02 \text{ dB}$$

Therefore, the dB level in the hearing loss condition would be 54 dB (60 dB – 6.02 dB).

It was this type of calculation which was performed for a number of hearing loss severities over a wide range of input sound intensities, enabling the production of a loudness model. The model was then scrutinised to assess whether the simulation had accurately represented abnormal loudness growth across a range of input intensities.

The simulation functioned as expected in terms of loudness recruitment and threshold elevation across a range of hearing loss severities (see Figure 6.8). The dB values produced were accurate to within ±3 dB at threshold level. For each level of hearing loss, sounds at (or near to) threshold crossed the X-axis at 0 dB, signalling that this is the level at which they could no longer be heard (i.e. the wave file contained no sound). For example, for a flat hearing loss of 20 dB the figure shows that an input sound intensity of 20 dB is not heard - the output sound file was at a level of 0 dB, or in other words, contained no sound.

Above the absolute threshold point, there was an abnormal growth of loudness up to a convergence point, after which loudness grew normally. This convergence, or 'catch up',

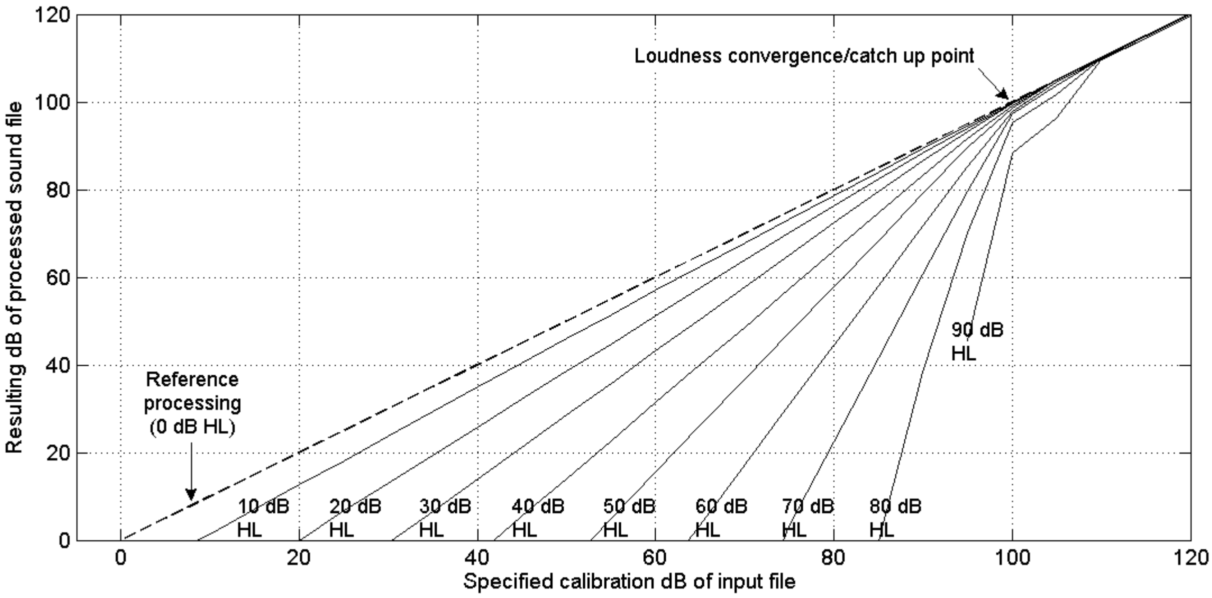


Figure 6.8 An estimation of the loudness model being used by the simulation software for varying degrees of hearing loss. Each solid line represents the loudness growth for a given flat hearing loss across all frequencies. The dotted line exhibits reference processing carried out for a flat 0 dB hearing loss (i.e. normal hearing).

point was 100 dB for the majority of hearing loss severities, and was adhered to in most cases, although at very high degrees of hearing loss the pattern became less predictable. In fact, the linearity of loudness growth exhibited was not present in the most severe hearing loss that was simulated (a flat 90 dB HL hearing loss). Furthermore, the representation of loudness perception at levels around threshold were inaccurate, and so it is pertinent to discount hearing losses of greater than 80 dB from any experiments using this method of simulation.

The gradient of the loudness growth slopes corresponded to those described previously by Moore and Glasberg (1993). For example, the gradient of loudness growth for a hearing loss of 50 dB HL was approximately two, indicating that loudness grew at a rate twice as fast as the reference (normal hearing) condition. The gradient decreased for hearing losses of a milder nature and increased for those of a more severe nature, as would be predicted by models of loudness perception for individuals with a SNHL (Moore and Glasberg, 1993). Thus, in terms of loudness recruitment and threshold elevation, it was shown, through objective testing, that the simulation was accurate to a high degree for a range of hearing losses and input sound pressure levels.

6.4.1.2 Differing sensitivity across frequencies

Although the simulation produced a set of results that might be expected in terms of loudness recruitment and threshold elevation, it did so given a set of simple flat hearing losses across all frequencies. However, individuals with an age-related hearing loss (which previous demographic data suggests is the group of interest in this programme of research; see Chapter 4 and Chapter 5), predominantly have an increasingly reduced auditory sensitivity at higher frequencies (Gates and Mills, 2005). It is unclear, given the validation tests described thus far, whether the method of SimHL is able to accurately emulate threshold elevation when given a hearing loss with differing absolute thresholds across frequencies. This aspect of the hearing loss simulation was assessed by processing a broadband noise under different hearing loss conditions.

Two seconds of white noise, containing equal energy at all frequencies (see Figure 6.9), was generated to act as a test stimulus. The input level of the sound created was defined as 80 dB SPL, as was the desired output level. Four hypothetical hearing losses reflective of differing degrees of age-related sensory decline were created (see Figure 6.10), and the test signal was run through the simulation under each of these conditions. The output of the simulator was then transformed to the frequency domain, and the resulting magnitude spectra were scrutinised in terms of how accurately they reflected the hearing losses simulated.

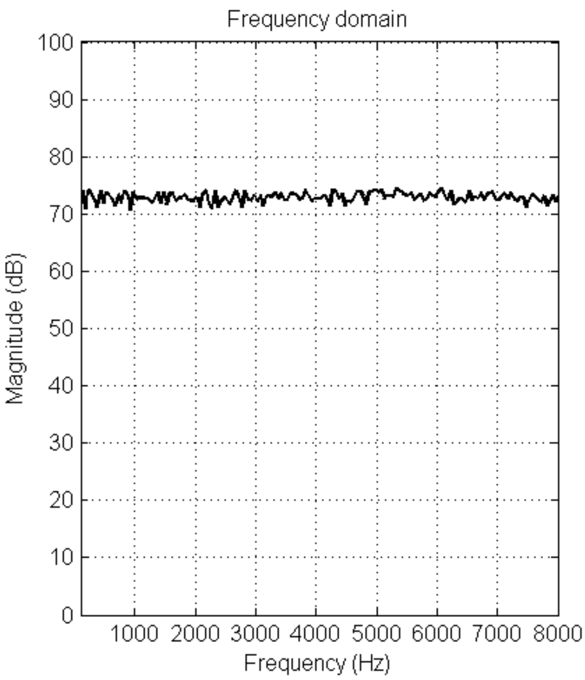


Figure 6.9 The white noise signal generated for use in this validation procedure, shown in the frequency domain.

The expectation was not for the frequency magnitude of processed signals to match the audiogram exactly; rather, at input levels close to threshold it was expected that perceived loudness would be close to 0 dB, but at higher sensation levels there would be abnormal growth of loudness, so output levels from the simulator should have exceeded what might be expected from a linear relationship with the hearing loss magnitude. This was indeed the observation (see Figure 6.10). The resulting frequency spectra accurately reflected the changes in frequency thresholds shown in each respective audiogram. It was also possible to observe the influence of loudness recruitment in these results; at frequencies where thresholds are below the 80 dB SPL level of the input sound, the frequency spectrum followed the audiogram, but not by the same gradient.

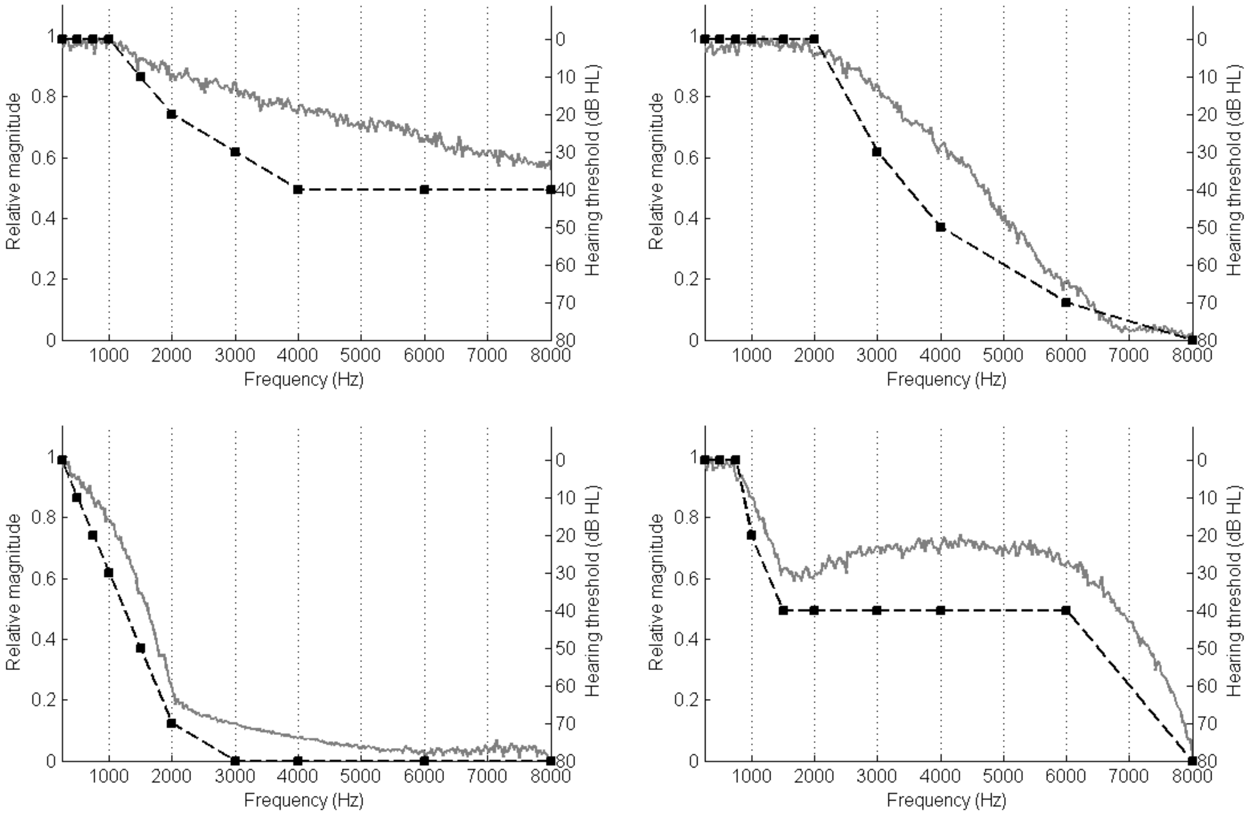


Figure 6.10 The frequency spectra derived from running white noise through the hearing impairment simulation under different hearing loss conditions. Each respective audiogram (dotted line) is included with its resulting spectrum (solid line) for comparison.

This piece of analysis suggests that accuracy of the method of simulation remains for sloped hearing losses. In all examples, where the 80 dB input sound reached threshold at higher frequencies, the relative magnitude of the frequency response became (or was very close to) zero, as should be expected. Where thresholds at higher frequencies were reduced, but not to the extent where they exceed the presentation level of the input sound, the relative magnitude of the frequency response curve did not reach zero. This indicates the sound should be heard, but at a reduced level at these specific frequencies. Additionally, the fact that the frequency response had a different gradient to the absolute hearing thresholds shows that abnormal loudness growth was successfully applied in separate frequency bands. These results, twinned with those obtained using flat hearing losses, support the accuracy of the simulation in terms of its ability to accurately reproduce the modelled effects of loudness recruitment and threshold elevation brought about by SNHL, regardless of hearing loss configuration.

6.4.2 Subjective analysis

The theoretical accuracy of the simulation is important, however, the subjective experience of the SimHL must also be representative of ‘real’ SNHL. Accordingly speech testing was carried out in order to assess the ecological validity of the simulation’s output. By simulating a hearing loss it should be possible to elicit a ‘speech audiogram’ from a normally hearing subject that resembles what one might expect from somebody with an actual corresponding SNHL. This is the basis for conducting speech testing, with a view to proving or disproving the subjective validity of the simulation being used. This will not only give insight into the ecological validity of using hearing loss simulation, but it will also provide further grounds for concluding that the simulation behaves as desired in terms of threshold elevation (sound will need to be louder before being heard). Furthermore it will provide information as to the success with which the simulation is able to ‘smear’ stimuli in order to emulate the reduced frequency selectivity associated with SNHL. Even when sounds are loud enough to be perceived, they may still be unintelligible for some degrees of hearing loss, given the extent of distortion that is brought about by the ‘smearing’ paradigm.

Speech testing is a common clinical procedure aimed at estimating a person’s ability to understand conversational speech (Bess et al., 1995). Patients are asked to repeat words or sentences played to them at a given sound level, and are then given a mark for each stimulus. Their scores on a set of words are then summed and calculated as a percentage correct score, which is plotted as a function of the stimulus presentation level, producing a *speech audiogram.* This typically takes on an ‘S’ shape, though the exact form of this ‘S’ depends upon the type of speech material being used (see Figure 6.11).

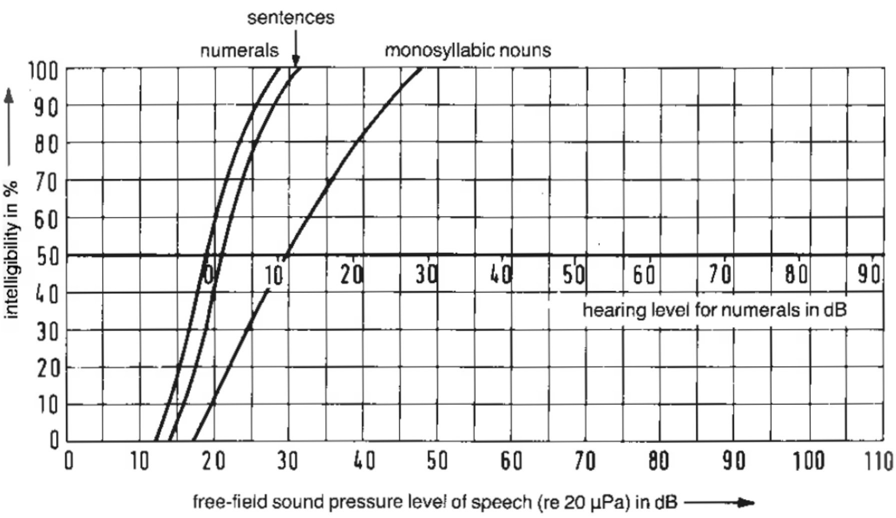


Figure 6.11 Typical speech audiogram results obtained from using different types of speech stimuli. Source: Martin (1987).

The ‘S’ usually shifts positively along the X-axis as a function of increasing hearing impairment and, in some cases of SNHL, the tip of the 'S' will 'tail-off' at high presentation levels, such that it would appear a one-hundred percent speech recognition score is never attainable (Graham and Baguley, 2009). This is not the case for hearing losses of a conductive nature, as the distortion brought about by cochlear damage is not present in these instances (see Figure 6.12).

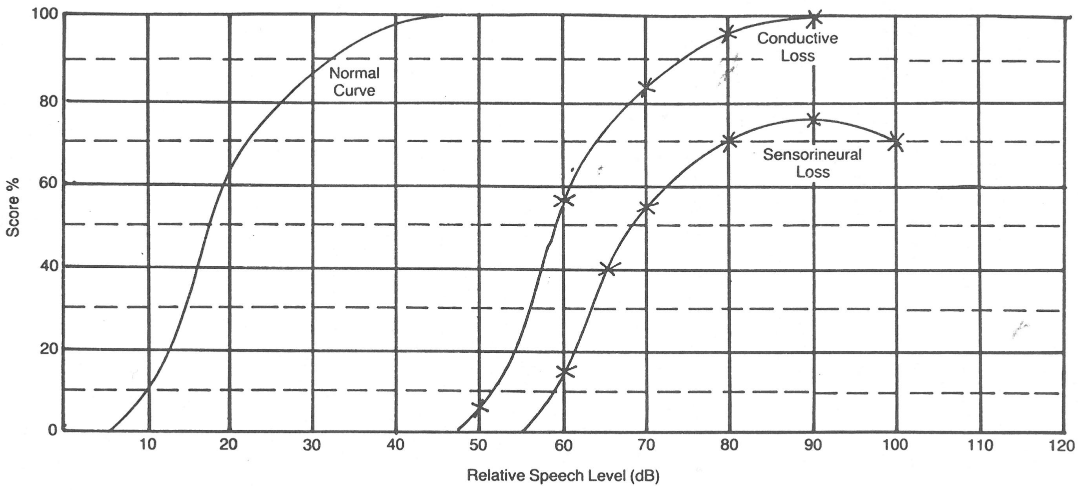


Figure 6.12 Typical speech audiogram results using sentences as the stimuli. Source: Martin (1987).

6.4.2.1 Method

Participants

Speech testing was conducted on twelve English-speaking subjects (6♂; 6♀) in the age range 20-28 years (M = 23.08, S.D. = 2.54). All participants underwent pure tone audiometry testing (as per the British Society of Audiology, 2011), and were confirmed as having bilateral normal hearing; in fact no single absolute threshold of any participant was > 15 dB HL.

Materials

Arthur Boothroyd word lists (Boothroyd, 1968) were used, presented through Telephonics TDH-39P headphones, under three auditory conditions: (1) a reference condition with no hearing loss present, (2) a simulated mild hearing loss condition with a mean threshold of 29 dB HL (250 - 4000 Hz), and (3) a simulated moderate hearing loss condition with a mean threshold of 55 dB HL (250 - 4000 Hz). Both hearing loss conditions were reflective of an age-related hearing impairment; an increasing loss of sensitivity with frequency (see Figure 6.13), as previous work has shown this work is most relevant for individuals exhibiting this type of hearing loss (see Chapter 4 and Chapter 5).

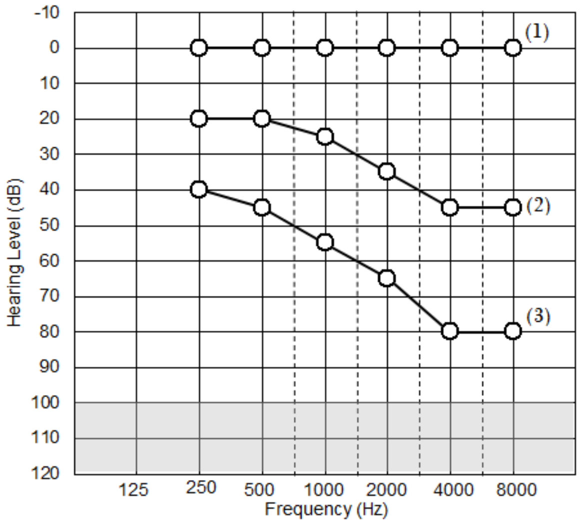


Figure 6.13 The three audiograms used to simulate hearing loss on Arthur Boothroyd word lists for use in speech testing validation: (1) normal hearing; (2) mild hearing loss; (3) moderate hearing loss.

Both reference and hearing loss condition stimuli were passed through the simulation using different calibration dB SPL values pertaining to the level at which they would be presented during the speech test, this ensured the correct calibration of equipment for accurate presentation levels of stimuli. Alterations to the level of stimuli are made relative to a reference sound file, and these loudness relationships had to be preserved. Accordingly, changes to the level of stimuli were pre-empted and executed in the hearing loss simulation environment, rather than by simply changing the dial setting on the audiometer, so that the loudness growth model and level of smearing on stimuli was accurate. Thus, the calibration procedure for a single input intensity is shown in Figure 6.14.

Procedure

Participants undertook the three speech tests in a sound-proofed booth. The order of conditions was balanced across participants so that all possible order permutations were undertaken an equal number of times. Participants were asked to repeat back each word they heard clearly to the experimenter. It was made clear that if participants were unsure about a word, or only caught a part of the word, they should say what it was they thought that they had heard.

In order to ensure there was no effect of running the same word lists at specific presentation levels, the lists used for each input intensity were randomised between participants. Scores for each word were marked out of three (one for each correct phoneme), and as there were ten words in each list, a score out of thirty was derived at each level. This score was then converted to a percentage correct figure and was plotted as a function of presentation level (in dB).

Ethical approval was granted for this study by the ESSL, Environment and LUBS

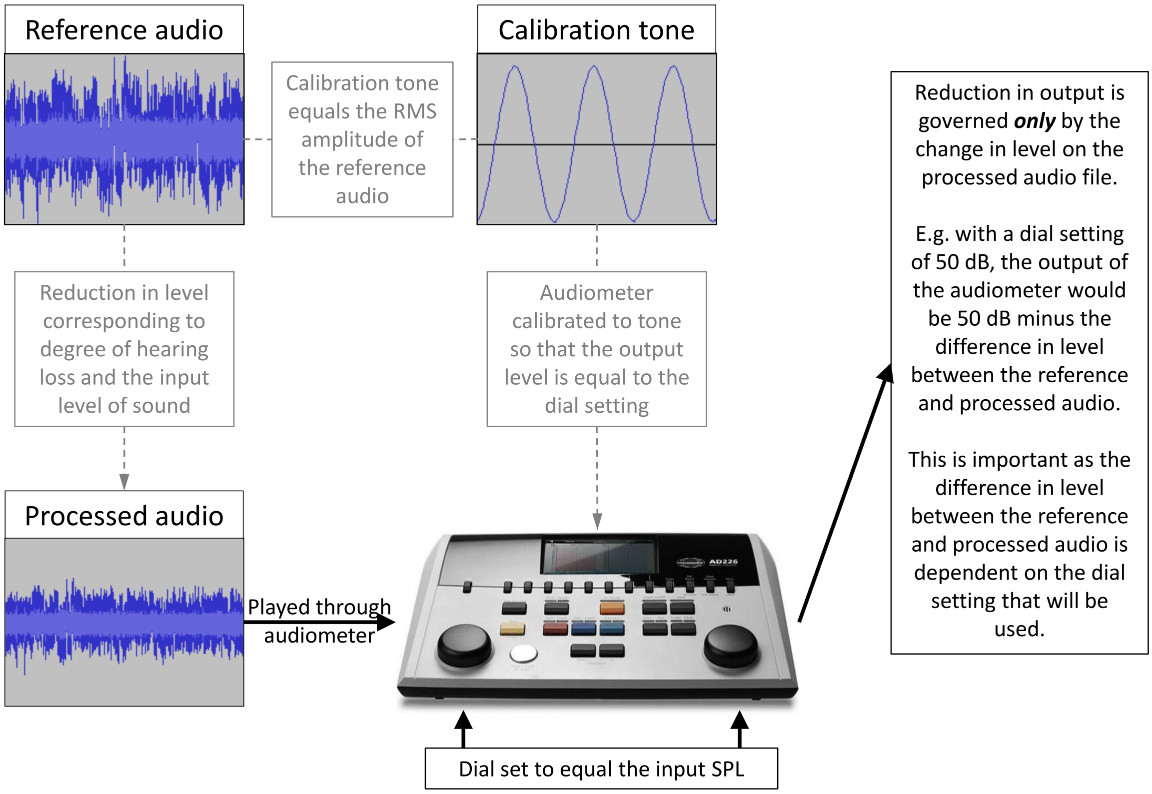


Figure 6.14 The calibration procedure for speech testing with a SimHL. This calibration procedure must be adhered to for each change in input SPL.

(AREA) Faculty Research Ethics Committee at the University of Leeds (reference: LTTRAN-036).

6.4.2.2 Results

The resulting speech audiograms for each separate participant are shown in Figure 6.15. A pattern which approximated data that would be expected from a clinical test with a hearing impaired individual was observed for each participant. One indicator of the simulation's success is its ability to 'shift' the test results positively along the X-axis as a function of hearing impairment severity. This aspect of the speech test results reflects the simulation's ability to accurately emulate threshold elevation; words have to be made louder before subjects are able to detect them and establish what they are. Indeed, the amount by which the graph was shifted along the X-axis approximated to the hearing loss level at between 500–1000 Hz for almost all subjects. Thus the simulation resulted in a similar subjective experience of SNHL regardless of who it was played to, or what slight variations they had in their baseline absolute thresholds across different frequencies.

Another indicator of the simulator's success in subjectively emulating SNHL was its ability to diminish speech recognition, even at levels where participants reported the level

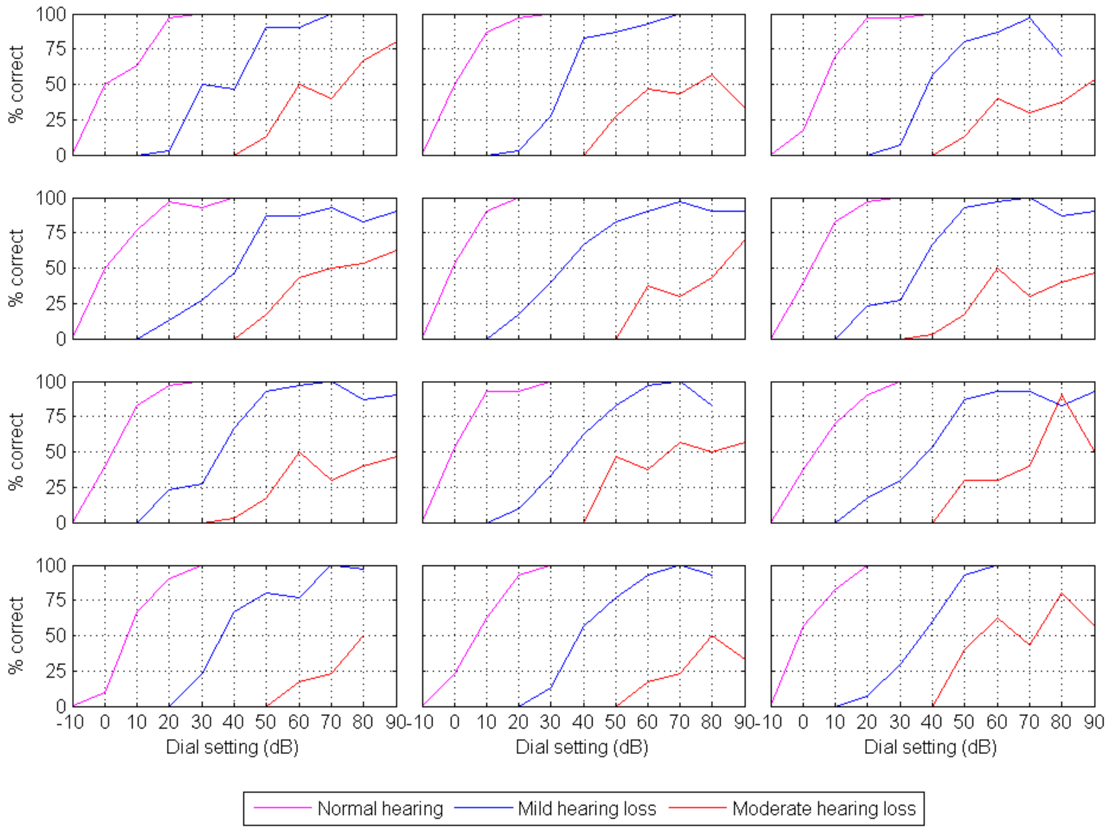


Figure 6.15 Speech test results for each of the twelve participants who completed speech testing under the three hearing loss conditions shown in Figure 6.13.

of stimuli becoming uncomfortably loud. In the current study, no single participant was able to tolerate stimuli presented at a level greater than 90 dB HL. However, Figure 6.15 shows that no single participant scored above 90% for any of the word lists at any level in the moderate hearing loss condition. Similarly, at high dial settings for some participants, it was observed that there was a 'roll-off' of percentage correct scores for the mild and moderate conditions. This is a phenomenon that is apparent in 'real' test data and is thought to occur as a result of distortion brought about by the hearing loss at loud input levels (Martin, 1987).

The distortion as a result of the SimHL also had an effect on the gradient of the speech test curve. That is, for a 10 dB HL increase in dial setting, a greater improvement in performance was seen for the normal condition as opposed to the mild and moderate conditions. Indeed, after collating and averaging the speech test results, the approximate gradients of the speech test curves showed a decrease as a function of increasing hearing loss severity (see Table 6.4). This is a phenomenon that has been shown in past speech test data (Martin, 1987), and suggests that an aspect of hearing loss other than attenuation of sound is having a bearing on the ability of participants to recognise speech. Again, this advocates the successful emulation of reduced frequency selectivity through spectral smearing, which is the only aspect of SNHL other than threshold elevation and loudness recruitment that was simulated.

Table 6.4 The approximate gradient of the averaged speech test curves for each hearing loss condition.

Degree of impairment	Approximate gradient
Normal	2.50
Mild	1.67
Moderate	1.20

These subjective results are further testament to the simulation's accuracy in replicating the perceptual consequences of SNHL, also adding support in terms of the simulation's ecological validity. The DSP being undertaken, regardless of the underpinning rationale, produced stimuli which are subjectively similar to what might arise as a result of 'real' cochlear hearing impairment, as evidenced by these behavioural results.

6.5 Conclusions

A clear case for the use of hearing loss simulation in future work has been made, and its relative advantages and disadvantages have been discussed. The method of emulation identified appears to have a high degree of accuracy and validity according to testing conducted:

1. It has been shown to accurately reproduce threshold elevation for a range of hearing loss severities (up to 90 dB HL).
2. This threshold elevation can be accurately applied in a frequency specific manner, allowing for the emulation of age-related hearing loss.
3. The simulation reliably exhibits the phenomenon of loudness recruitment across a wide range of input intensities.
4. This loudness recruitment is reflective of 'real' loudness perception models (it reliably incorporates a loudness 'catch-up point' with normal hearing).
5. The loudness recruitment model reliably changes depending on the degree of hearing impairment.
6. Furthermore, these changes in loudness recruitment as a result of hearing loss severity can be applied in specific frequency bands.
7. Subjectively, the simulation method ensures that speech stimuli have to be made louder by a relative level before they are perceived.
8. A given increase in level does not result in a comparable increase in intelligibility for the normal hearing and SimHL conditions.

9. Speech is not entirely intelligible, even at clearly audible levels, as a result of the frequency smearing it applies to stimuli.

Thus, the simulation is objectively sound, and can produce results in normally hearing individuals that mirror what would be expected from unprocessed stimuli in those with a ‘real’ SNHL.

Given the increase in experimental power and control that this method offers, as well as the ability to eradicate extraneous variables (such as cognitive capabilities and age), SimHL was used in the study described in the next chapter to investigate the effect that hearing loss had on the performance of auditory memory tasks. This work is applicable as it can provide information regarding the extent to which peripheral hearing loss increases required listening effort, and may, therefore, have a bearing on other concurrently performed tasks (such as driving).

Chapter 7

Analysing the Effect of Simulated Hearing Loss on Auditory Memory Tasks

7.1 Introduction

For normally hearing individuals, during optimal listening conditions, hearing and understanding audible speech is considered a mostly effortless task (Pichora-Fuller et al., 1995). However, when in suboptimal auditory environments, increased listening effort (and thus an increase in the cognitive resources being used) occurs (see Chapter 3). This may reduce the available resources for completion of other, concurrent tasks or cognitive processes. For example, it has been shown that the ability to store and recall auditory information is adversely affected when presented in the presence of background noise (Rabbitt, 1968; Murphy et al., 2000), presumably because more effort, and thus cognitive resources, are required to understand the auditory signal, taking resources away from the ability to perform other cognitive functions.

The distortion to sound associated with SNHL also has the potential to disrupt cognitive processing and impact on the performance of everyday tasks (Shinn-Cunningham and Best, 2008). This is because SNHL too increases the required listening effort to understand auditory signals, even in quiet conditions (Kramer et al., 1997; Stenfelt and Rönnberg, 2009; Zekveld et al., 2011). Further, this effect is likely to be exacerbated in the presence of background noise (Kramer et al., 2006). This inference has already been explained in accordance with an ELU model (see Chapter 3), which postulates that explicit (more effortful) processing is employed when an auditory signal is mismatched against stored phonological representations. This process is thought to happen more often in those with a hearing loss, thus, more effortful processing is used disproportionately in this demographic.

Research agrees with this theory. Rabbitt (1991) showed that auditory distortion, as a result of hearing loss, impaired the recall of words in a hearing impaired sample compared to a normally hearing sample. The effect of hearing loss on recall has also been apparent in other laboratory-based experiments (McCoy et al., 2005; Wingfield et al., 2005). These findings suggest that degradations to an auditory signal, as a result of hearing loss, have the capacity to make the performance of auditory tasks more difficult. This has important practical ramifications, raising questions about the difficulty of everyday tasks in the auditory modality for hearing impaired individuals.

In addition to the difficulty posed for performing an auditory task by stimulus delivery or perception, research has shown that increasing the demand of the task itself results in decreased performance of other concurrent tasks (Pomplun et al., 2001; Strayer et al., 2003; Wood et al., 2006). However, simply listening to an auditory stream has little impact on dual-task performance, whereas auditory tasks which require a participant response degrade performance (e.g. Pomplun et al., 2001; Wood et al., 2006). This suggests that the amount of interference from a concurrent task may also be governed by the demands of the auditory task, regardless of the presence of hearing loss.

It is not yet known how hearing impairment interacts with the difficulty of a concurrently performed auditory task. Some research in normally hearing individuals has involved alterations in the difficulty of concurrently performed auditory tasks by simply asking participants to either listen or respond to a sound message (e.g. Wood et al., 2006). Whilst this approach undoubtedly alters the difficulty associated with a single task, it does not contrast the difficulty between task types, nor does it account for the possibility that a participant could pay no attention to the 'just listening' condition. A variety of auditory tasks are now commonly used in studies investigating the performance decrements associated with undertaking two tasks simultaneously (see e.g. Pashler, 1994). However, there is little data regarding the individual demands and perceived difficulties that these auditory task impose.

The lack of data on the absolute demands associated with individual auditory tasks makes the investigation of auditory distraction on driving in those with SNHL challenging. It is desirable to investigate the effect of different levels of auditory task difficulty on driving, as the relative cognitive workload from these may interact with the demand imposed by hearing loss.

The purpose of this study was to obtain a hierarchy of difficulty for five auditory tasks performed under normally hearing conditions. Performance on three of these tasks (reflecting 'low', 'medium', and 'high' degrees of difficulty) was then analysed when stimuli were presented under conditions of SimHL.

7.2 Study aims

This study consisted of two experiments.

The aim of **Experiment A** in the current study was to gather normative data on the difficulty associated with a number of auditory-based memory tasks in terms of response accuracy, time and self-rated difficulty. It was hoped that a hierarchy of task difficulty could be derived, such that ‘low’, ‘medium’, and ‘high’ demand tasks could be selected to take forward to Experiment B. The aim of **Experiment B** was to test performance under normal, mild SimHL, and moderate SimHL conditions in order to establish how hearing loss affected performance on auditory tasks of different difficulties.

It was hoped that the results of this study would inform the design of the study reported in Chapter 8, which asked participants to perform different auditory tasks under SimHL conditions whilst driving a simulator.

7.3 Experimental hypotheses

In Experiment A, the aim was to establish a clear hierarchy of task difficulty (indexed by task response time, accuracy, and self-reported difficulty). Tasks that were perceived to vary in terms of their difficulty were, therefore, chosen; a decision which was based on the extent of cognitive processing required. For example, a task which requires the storage of two numbers in memory was considered easier than a task which required the storage of two numbers, and their addition, simply because the latter involved an extra level of cognitive processing. A more extensive discussion of the difficulty of chosen tasks is provided in the next section. However, the general hypothesis was that, where a task was thought to be easier, accuracy would increase, and reaction time and self-reported difficulty would decrease.

In Experiment B, the effect of two levels of SimHL (mild and moderate) on three tasks (reflecting a high- medium- and low-demand tasks) was assessed. It was hypothesised that SimHL would increase the difficulty of the three tasks, thus accuracy would decrease and response time and self-rated difficulty would increase. Furthermore, it was considered that an interaction may exist such that the harder the type of auditory task, the stronger the effect of SimHL (i.e. there may be worse performance on more difficult task types with a SimHL compared to normal hearing). This is because SimHL is likely to result in more explicit processing (arising from a construct similar to the central executive) in order for listeners to understand the stimuli (see Chapter 3). Therefore, when an easy task is performed, there will be a small effect as the amount of central executive mediation required to complete the baseline task is relatively little. However, when a more difficult task is performed, there will be greater competition for central executive mediation, as the difficult task will require more cognitive processing. Therefore, listening and task performance are likely to both suffer to a greater extent.

7.4 Experiment A

The two parts of this study shared very similar methodologies. As such, the methodology for Experiment A is reported in this section, however a large proportion of this information is applicable for Experiment B. Thus, only the alterations that were made to this experimental paradigm are reported later in Experiment B.

7.4.1 Method

7.4.1.1 Participants

Young, normally-hearing participants were asked to participate in this study, thereby excluding the influence of age-related declines in processing ability. Participants were recruited via advertisement at the University of Leeds and were screened for normal hearing in a sound-proofed room using pure tone audiometry (as per the British Society of Audiology, 2011). Individuals were excluded from participation if they had hearing thresholds of $\geq$ 15 dB HL at frequencies of 250–8000 Hz. Twenty-five participants (13♀/12♂, mean age = 28.44 ± 4.75 years) were recruited.

Ethical approval was granted for this study by the ESSL, Environment and LUBS (AREA) Faculty Research Ethics Committee at the University of Leeds (reference: LTTRAN-036). Participants were reimbursed £10 for taking part in this experiment.

7.4.1.2 Materials

Auditory tasks

The eventual aim of this study was to identify suitable tasks for employment in the study reported in Chapter 8. As such, auditory tasks which have typically been used in driving safety literature were considered. Five tasks were selected to be used in this study, with a main criterion that response paradigms could be comparable. This was considered important as comparisons between reaction times to tasks were being made. Since sound *perception* is affected by hearing impairment, tasks with an emphasis on listening were used. Some studies have employed auditory-based cognitive tasks such as counting backwards in multiples of seven (e.g. Merat and Jamson, 2007); this type of task should not have a disproportionate effect on hearing impaired individuals as it does not rely on auditory perception. In addition, because an emphasis was being placed on the *listening* aspect of the task, response paradigms were required not to be too complex, as this may have introduced extraneous factors which could have affected study outcomes. For example, Merat and Jamson (2007) used a task in which participants had to listen to a phone number, but were then asked to type it in to an in-vehicle system.

Therefore, Table 7.1 shows a non-exhaustive list of the considered tasks, and it can be seen that only certain tasks were applicable given their response parameters.

Tasks were chosen if they incorporated responses that could be single digits in the range 1–9, this was considered ideal as reaction times could be measured from button presses given on a computer keyboard. This discounted a number of task types detailed in Table 7.1: general knowledge questions, working memory span test, and conversation with experimenter. Furthermore, whilst the memory task and grammatical reasoning test

Table 7.1 Example auditory task types which have been used in past driver safety experiments.

Study	Description of task
Engström et al. (2005b); Jamson and Merat (2005); Victor et al. (2005)	**aCMT:** Participants had to hold in memory two, three, or four target sounds and count how many times each target occurred during a stimulus list, reporting back their answers at the end of the presentation.
Horberry et al. (2006)	**General knowledge questions:** Participants were asked to answer general knowledge questions from two options whilst driving.
Reimer (2009)	**N-back task:** This task has been widely used in Working Memory literature (Baddeley, 2003). A participant is presented with a list of numbers and is asked to report the number that was read n positions ago. For example, if $n = 0$ the participant would repeat the last digit read out, if $n = 1$ the participant would repeat the penultimate digit read out.
Haigney et al. (2000)	**Grammatical Reasoning Test:** Participants were presented with five stimulus letters and were asked a question about the order of two of these letters (e.g. the letter 'D' was read out before the letter 'A'; true or false?)
Alm and Nilsson (1994)	**Working Memory Span Test:** Participants were presented with a number of sentences which contained 3–5 words and took the form "X does Y". Participants were asked to indicate whether the sentence made sense, and then after five sentences were asked to recall the last word in each, in order.
Brookhuis et al. (1991); Törnros and Bolling (2005)	**Paced Auditory Serial Addition Task:** Participants were presented a list of digits and had to add the most recently heard two numbers together, continually stating their answers. McKnight and McKnight (1993) also had a similar task whereby they asked participants to continually perform a string of mental arithmetic sums.
McKnight and McKnight (1993); Strayer and Johnston (2001)	**Conversation with experimenter:** The experimenter conversed with participants about various pre-defined topics whilst they drove.
McKnight and McKnight (1993)	**Memory task:** Participants were read a list of five or six digits and were asked if certain numbers were contained within that list.

may have been adapted to incorporate responses as a digit in the range 1–9, they involve a two choice forced response paradigm, which gives a 50% chance of a correct response, even when guessing. The rejection of these tasks left the following: aCMT, N-back task, and PASAT.

Adaptations to the tasks were made to vary the predicted processing demand they imposed, and to ensure the response paradigm of a single digit in the range 1–9. A description of each individual task selected, and the associated difficulties of each, is given below (in order of hypothesised difficulty):

1. **0-back:** In this study a list of 5–9 single digits was presented to participants at 1 second intervals. The length of the list was randomly assigned, and participants were not aware of the list length prior to completing the task. Participants were not required to respond throughout the list but were instructed to listen and at the end of the list key in the last number in the list. For example:

Stimulus:	8	4	7	4	9	
Correct response:						9

This task requires the storage of the most recent digit in memory, requiring no manipulation of this memory trace. It is unlikely, therefore, that it will place a great demand on working memory, as there is likely to be little interference with rehearsal processes associated with the 'phonological loop' portion of this information processing model (Baddeley, 2000).

2. **Digit Continuous Memory Task (dCMT):** this task is very similar to the aCMT which has been applied in past driving safety research assessing the effect of auditory distraction whilst driving (Jamson and Merat, 2005; Victor et al., 2005; Engström et al., 2005b). The task is an auditory manipulation of a visual version (the Visual Continuous Memory Task; Veltman and Gaillard, 1998), whereby participants are given a target icon and are then required to watch a stream of icons containing a random number of the targets. The task is to count the number of occurrences of the target and then report back this number at the end of the stimulus list. The demand of this particular task can be altered by increasing the number of targets that participants have to remember and match against the string of stimuli (Jamson and Merat, 2005; Victor et al., 2005; Engström et al., 2005b). In the manipulation of the aCMT used in this experiment, participants were given one randomly assigned target (between 1–9), to reduce the processing demands relative to other tasks. After a 5 second pause, a list of 10 random digits was presented to participants at 1 second intervals. Participants were required to listen for the number of occurrences of the target and then key in the answer at the end of the list. For example:

Target number:	6						
Stimulus:		6	1	6	6	2	
Correct response:							3

In terms of the mental processes involved with this task it is somewhat similar to the 0-back in that it requires only one target digit to be held in memory. However, it requires this digit to be matched against a number of others which occur in the list. Unlike the 0-back, this task is more likely to be prone to interference, in that other digits contained within the list may affect the rehearsal processes involved with keeping relevant auditory information in memory (Baddeley, 2000).

3. **Tone Continuous Memory Task (tCMT):** the parameters of tCMT were almost identical to dCMT, except for participants were assigned a random target tone (a sinusoidal wave at one of the discreet frequencies: .25, .5, 1, 2, 4 kHz) instead of a digit. As with the dCMT, this task was played to participants aurally, with a target tone, followed by a 5 second pause, then a list of 10 random tones at 1 second intervals. Participants were again required to listen for the number of occurrences of the target and then key in the answer at the end of the list. For example:

Target (kHz):	1						
Stimulus (kHz):		2	1	1	1	1	
Correct response:							4

This task was chosen in an attempt to provide a further level of difficulty in the task hierarchy. It was thought that in performing the dCMT participants identified their target by recognising and naming the stimulus. It was considered that the majority of participants would not, however, recognise and name the frequency of certain tones. This constant matching of stimuli against an un-named perceptual trace makes tCMT highly subject to interference from competing stimuli. As such, the performance of this task was hypothesised to be more challenging than the completion of dCMT.

4. **2-back:** this task was similar to the 0-back, but instead of recalling the final number in the digit list, participants were required to report the third from last number. Increasing the value of n in the n-back task increases its difficulty (Reimer, 2009). Thus it was considered that applying a different value for n would result in another level of difficulty on the task hierarchy. As for the 0-back, a list of 5–9 single digits was presented to participants at 1 second intervals. The length of the list was randomly assigned, and participants were not aware of how long the list would be prior to completing the task. For example:

Stimulus:	8	4	7	4	9	
Correct response:						7

This task is likely to be made more difficult because it requires the storage of more information in Working Memory than any other task used. The 0-back required the storage of only one digit, and tCMT and dCMT required the storage of only two pieces of information. As the list was able to stop at any random point, it was not possible to identify the specific position at which the target digit would occur. As such, participants needed to constantly remember the past three digits in order to perform the 2-back successfully. This was considered to put more of a demand on the phonological loop portion of working memory, as the rehearsal of all the most recent three digits would be required in order to keep all of the required information in a short-term memory store without decay. This rehearsal process may also have provided some interference for digits being read out as part of the stimulus list. For example, a participant rehearsing three digits repeatedly may hear the next digit being presented, but mix it up with one being rehearsed as part of the most recent three. Accordingly it is feasible that mistakes may occur when updating the digits being held in short-term memory.

5. **Paced Auditory Serial Addition Task (PASAT):** the premise of the PASAT is that random numbers are presented aurally at set intervals, and participants are required to continually add the last two numbers that they have heard together (Royan et al., 2004). For example:

Stimulus list:	2	3		1		3		6	
Correct response:			5		4		4		9

A visual version of the PASAT was originally developed by Sampson (1956) to examine temporal integration. This task was adapted to be presented aurally (Gronwall and Sampson, 1974; Gronwall and Wrightson, 1974), and has become an important neurophysiological test to measure attention and concentration (Gordon and Zillmer, 1997), working memory and speed of information processing (Roman et al., 1991; Diehr et al., 1998). In this experiment there is an emphasis on recording response times to stimuli, as such it was decided that this task should be run at a self-paced rate, rather than having the digit presentations system-paced. Accordingly, random digits between 1–5 were presented to the participant, this meant that answers were never greater than 9, and therefore a single-digit answer was always required. This was considered important in the ability to equate response parameters between task types. Initially two digits were presented at an interval of 1 second, thereafter only once an answer had been given by the participant was a new number presented. This process continued until the list had finished; in total the list was eleven digits long, meaning that in one trial a participant performed ten sums.

The difficulty associated with PASAT is likely to arise primarily from the extra cognitive process of mental arithmetic. As opposed to all other tasks, PASAT required the use of not only short-term memory, but cognitive processes associated with the manipulation of those short-term memory traces (the performance of sums). This is an additional demand which is not imposed by any of the other tasks, simply requiring the storage of information in memory, rather than any extraneous cognitive tasks. In addition, the fact that participants had to add two numbers together to produce their own answer (unrelated to the digit list entirely) increased the chance of interference between stimuli and responses.

Experimental setting

Both experiments were developed and run on a personal computer in a sound-proofed booth, using MATLAB (2010) software with the Psychophysics Toolbox extensions (Pelli, 1997; Brainard, 1997; Kleiner et al., 2007). For use in all tasks except tCMT, audio files of individual numbers from 1–9 were obtained from an open source repository (Voxeo Corporation, 2013), and were normalised in terms of amplitude and duration. For use in the tCMT task, pure tones were generated using MATLAB (2010) software, again each was equated in terms of amplitude and duration. All stimuli were presented using Telephonics TDH-39P headphones at an intensity of 60 dB HL, which corresponds to a normal conversational level (Skinner et al., 1997). The end of digit lists were signalled by a 1 kHz tone, and the end of tone lists were signalled by a burst of white noise (as tones were being used as task stimuli), both of which lasted 0.1 seconds. Participant responses were collected using the number pad of a keyboard, and response times were measured from the end of the 1 kHz tone or burst of white noise.

7.4.1.3 Procedure

Participants were presented with information about the study, and were given the opportunity to ask any questions prior to signing informed consent to take part. After consenting, participants were screened for normal hearing using pure tone audiometry (as per the British Society of Audiology, 2011). Participants were then given a short practice session in which they were presented with two full trials of each task. Following the practice session, participants were asked if they were happy to continue and perform the ten experimental trials, which were run at a self-paced rate (no participants requested extra practice trials). Participants were asked to perform each of the five tasks as quickly and accurately as possible, the order of which were counterbalanced using the balanced latin square method. Each task was performed ten times, and prior to beginning each task participants were given a rest. Participants were informed that they were allowed a break of any duration at any point during the experiment. Immediately following each task, participants were asked to rate how difficult they had found it on a 7-point Likert scale and also on the

National Aeronautics and Space Administration Task Load Index (NASA-TLX) (Hart and Staveland, 1988; Hart, 2006), before continuing with the next task. Two self-reported measures were included in order to provide complex (NASA-TLX) and simple (Likert) measures of perceived difficulty.

Given its increased simplicity of application and comparable sensitivity, ‘Raw TLX’ was employed rather than the original NASA-TLX by eliminating the sub-scale weighting process (Hart, 2006). Whilst the Likert score recorded how challenged participants felt generally, the NASA-TLX has been specifically developed to measure perceived demands across a number of different subscales, thus analysis could be carried out on these individually if desired, although detailed analysis of this nature was eventually considered unnecessary. This was the case because some sub-scales confounded results, given that they were not related to the simple auditory tasks used. For example, the physical demands of the tasks were similar, given that they simply required a key to be pressed on a keyboard. Likewise, the temporal demands of each task were similar; to give an answer as quickly as possible. In these cases, ratings of perceived difficulty were similar between tasks, but this was not considered a fair reflection of the experience of the participant. Furthermore, initial statistical analysis of the sub-scales that did differ between tasks showed an identical trend to pooling all of the sub-scales. Thus, it was considered that individual analysis of sub-scale scores offered no additional, useful information.

7.4.1.4 Statistical analysis

Performance in these experiments was measured in terms of accuracy and response time, given that they are a simple method of assessing on-line cognitive processing (Salthouse and Hedden, 2002). For each task, accuracy was calculated as the percentage correct over all ten trials. Mean response times were calculated from all of the responses given over the entirety of trials. In past work, mean response times have been calculated after removing incorrect responses from the data (e.g. Salthouse and Hedden, 2002). However, if incorrect responses were removed the task difficulty may have essentially been negated, because it is likely that the tasks participants found most difficult would be more likely to produce more errors, but would also have a longer response time (Larsby et al., 2005; Gosselin and Gagné, 2010). As such, removing incorrect trials would discount a large number of the most difficult trials for participants, thus impacting on the stability of the estimate of reaction time.

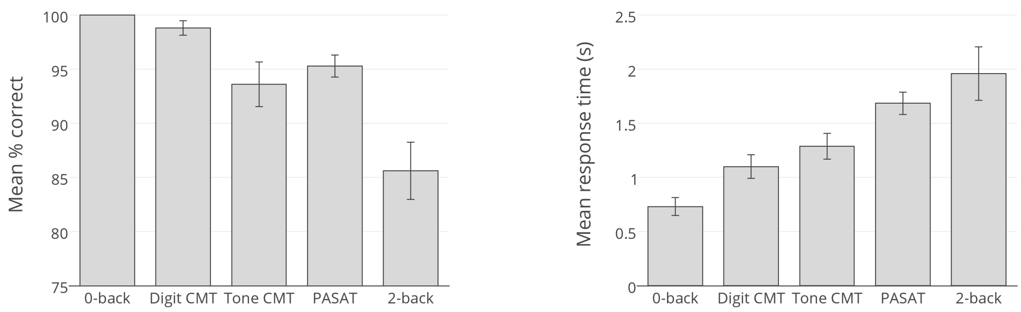
As a general measurement of perceived task difficulty was sought, NASA-TLX scores were summed to give a score across subscales. Shapiro-Wilk tests showed that the data collected was not normally distributed, and, in the case of Likert scores not continuous, thus non-parametric statistical tests of significance were used to analyse the variables: accuracy, response time and perceived difficulty across different tasks.

Accuracy, reaction time, NASA-TLX, and Likert scale data were submitted to separate Friedman tests in order to investigate significant differences across tasks. Where a significant difference was found, Wilcoxon signed rank tests were used to test each pair of tasks for significant differences. These tests were subject to the Bonferroni correction in order to reduce the occurrence of type-I errors (Field, 2013).

7.4.2 Results

7.4.2.1 Objective measures

The mean accuracy rates and response times to each auditory task are shown in Figure 7.1. A Friedman test showed a significant effect of task type on accuracy ($\chi^2(4) = 46.69$, p < .001). Further post-hoc comparisons between the accuracies of tasks resulted in statistically significant differences between some tasks (see Table 7.2). Performance of the 0-back was 100% accurate across trials, and similarly very few errors were made on the dCMT task, where the mean correct response rate was 98.8%. Accordingly, no statistically significant difference between accuracy rates on these two tasks was found. Accuracy rates on the tCMT and PASAT were also similar, reaching 93.6% and 95.3% respectively; this difference was not significant. The most poorly performed task in terms of accuracy was the 2-back, with a correct response rate of 85.6%. This task was performed significantly worse than any other except tCMT, though the difference in performance between these two tasks did tend towards significance (see Table 7.2). There appeared to be a large degree of variability in the accuracy of the tCMT task (S.D. = 10.36%) compared to the PASAT task (S.D. = 5.06%). In some cases, this variability may have led to statistical tests only tending towards significance, rather than reaching it at the $\alpha = .05$ level (e.g. tCMT vs dCMT and tCMT vs 2-back; see Table 7.2).



(a) Accuracy (b) Response time

Figure 7.1 Mean percentage correct scores and response times (± 1 standard error) for each auditory task.

Clear differences in response times to different auditory tasks are also evident from the data, with 0-back performed most quickly, followed by dCMT, tCMT, PASAT and 2-back respectively (see Figure 7.1). Generally, as response time increased, accuracy decreased. This speed/accuracy trade-off was apparent across all tasks except for PASAT which was, on average, slightly more accurately (but more slowly) performed than tCMT.

Table 7.2 p-values derived from Wilcoxon signed rank tests for differences in accuracy between the different task types. Significant results at the $\alpha = .05$ level (after applying a Bonferroni correction) are highlighted (*).

	0-back	dCMT	tCMT	PASAT
dCMT	.083	N/A	N/A	N/A
tCMT	.004*	.013	N/A	N/A
PASAT	<.001*	<.001*	.657	N/A
2-back	<.001*	<.001*	.020	.002*

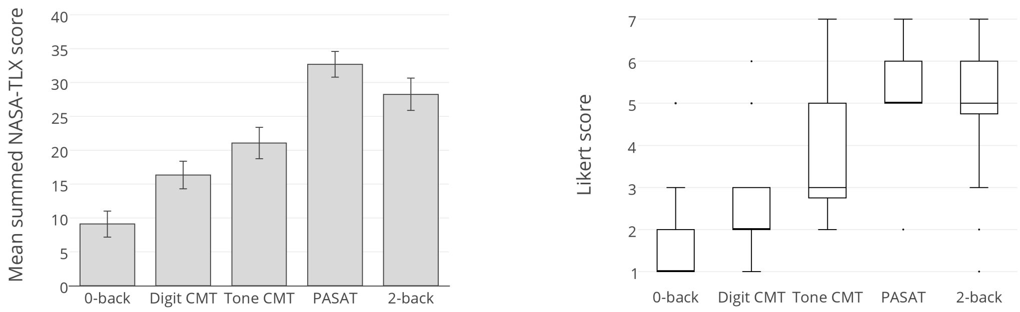
A further Friedman test showed that there was also a significant effect of task type on response time data ($\chi^2(4) = 63.42$, $p < .001$). Post-hoc testing showed that the differences in response times were statistically significant between all tasks except for PASAT vs 2-back (see Table 7.3). In terms of the variability in results, 2-back had the most variation in response times (S.D. = 1.23 ms), whereas the other tasks all provided a more stable response time across participants (S.D. $\leq$ 0.60 ms in all cases).

Table 7.3 p-values derived from Wilcoxon signed rank tests for differences in response time between the different task types. Significant results at the $\alpha = .05$ level (after applying a Bonferroni correction) are highlighted (*).

	0-back	dCMT	tCMT	PASAT
dCMT	<.001*	N/A	N/A	N/A
tCMT	<.001*	<.001*	N/A	N/A
PASAT	<.001*	.001*	.001*	N/A
2-back	<.001*	<.001*	.002*	.443

7.4.2.2 Subjective measures

Subjective scores on the difficulty of the chosen tasks were also collected (see Figure 7.2). PASAT was rated as the most demanding task followed in order of decreasing difficulty by 2-back, tCMT, dCMT and 0-back. Friedman tests showed that task type had an effect on both NASA-TLX ($\chi^2(4) = 66.88$, $p < .001$) and Likert data ($\chi^2(4) = 70.96$, $p < .001$). The differences in post-hoc pairwise comparisons between all tasks were found to be significant for both NASA-TLX and Likert scores, except for 2-back vs PASAT, though this comparison tended strongly towards significance for both NASA-TLX and Likert data (see Table 7.4 and Table 7.5).



(a) NASA-TLX scores

(b) Likert scores

Figure 7.2 Mean summed NASA-TLX scores (± 1 standard error), and box plots for Likert scores, on each auditory task. For the box-plot, bars show the 95% confidence intervals, boxes depict interquartile ranges, and the line therein shows the median. Outliers are shown as dots.

Table 7.4 p-values derived from Wilcoxon signed rank tests for differences in summed NASA-TLX scores across the different task types. Significant results at the $\alpha = .05$ level (after applying a Bonferroni correction) are highlighted (*).

	0-back	dCMT	tCMT	PASAT
dCMT	<.001*	N/A	N/A	N/A
tCMT	<.001*	.002*	N/A	N/A
PASAT	<.001*	<.001*	<.001*	N/A
2-back	<.001*	<.001*	.002*	.093

Table 7.5 p-values derived from Wilcoxon signed rank tests for differences in Likert scores across the different task types. Significant results at the $\alpha = .05$ level (after applying a Bonferroni correction) are highlighted (*).

	0-back	dCMT	tCMT	PASAT
dCMT	<.001*	N/A	N/A	N/A
tCMT	<.001*	.005*	N/A	N/A
PASAT	<.001*	<.001*	<.001*	N/A
2-back	<.001*	<.001*	.004*	.009

7.4.2.3 Difficulty Hierarchy

The aim of this experiment was to derive a relative hierarchy of task difficulty. Thus, the ease of performing each task in relation to others across dependent variables was derived from the pairwise comparisons performed between each task type. Where there was no statistically significant difference between the performance or perceived difficulty of a task, a joint ranking was given. A ranking of 1st denotes that the task was easiest or best performed, a ranking of 2nd, that the task was second easiest or best performed, and so forth. Table 7.6 shows the ranking of each outcome measure in relation to others.

Table 7.6 The ranking of each task type in relation to others across dependent variables. A ranking of 1st denotes that the task was easiest or best performed.

	Accuracy	**Reaction time**	**NASA-TLX score**	**Likert score**	**Overall**
0-back	1st	1st	1st	1st	1st
dCMT	1st	2nd	2nd	2nd	2nd
tCMT	2nd	3rd	3rd	3rd	3rd
PASAT	2nd	4th	4th	4th	4th
2-back	3rd	4th	4th	4th	4th

7.4.3 Discussion

The aim of this experiment was to investigate whether a set of five auditory tasks differed from each other in terms of accuracy, response time, and subjective difficulty. This was undertaken in order to derive a task hierarchy, so that tasks of 'low', 'medium' and 'high' difficulty could be identified for further testing in Experiment B, using a SimHL.

In this regard, the study has been successful; given the statistically significant differences that have arisen across dependent variables, a general order of task difficulty was established. Despite this, it was not possible to order PASAT and 2-back in terms of their relative difficulty. Although 2-back was less accurately performed, response times were similar between the tasks, and ratings suggested that participants found the PASAT more difficult. Thus it is unclear whether it is PASAT or 2-back which was more challenging. Whilst other tasks are equal in terms of their accuracy (i.e. 0-back vs dCMT; tCMT vs PASAT), the other dependent variables measured follow a clear pattern, showing response times which became slower in line with reports of more task difficulty. This is not the case for PASAT vs 2-back, and so these tasks were considered as being inextricable in terms of difficulty. The order of task difficulty generally reflects the hypothesised difficulty of each task presented during the methods section of this chapter.

Although analysis of this experiment has allowed for the derivation of a general hierarchy of task difficulty, this does not take in to account intricacies associated with the responses to each task. A key consideration that has arisen from the results is that some tasks appear much more variable for some dependent variables than do others. A prime example of this is the variability shown for accuracy and response time on the 2-back task. The standard deviation for these measures appears a lot higher than was noted across the majority of other tasks. This is an important consideration, given that these tasks are being considered for application in dual-task experimental paradigms, and thus require a stable and predictable level of demand. It is this variability which may, in fact, have given rise to the lack of statistical significance between the accuracy rates of tCMT (which was also variable) and 2-back, and the reaction times of PASAT and 2-back, despite mean data showing 2-back as the least accurately and most slowly performed task. Another task which appears to show a high degree of variability in outcomes is the tCMT. This task, whilst stable in terms of response time, appears to be variable in terms of its accuracy and difficulty rating. Thus, like the 2-back, it appears less applicable for dual-task research.

The remaining three tasks (0-back, dCMT, and PASAT) all appear to be stable across all dependent variables. In the case of PASAT, this may have been due to the increased number of responses that were required for this task. All tasks, except PASAT, required only one participant response per trial (at the end of the stimulus list) leading to a total number of ten responses. In contrast, PASAT involved ten answers per digit list, and meant that participants were giving one-hundred answers in total for this particular task. This greater number of responses for PASAT may have led to a better estimate of the mean and a smaller standard error. Incorrect responses on the 2-back may have skewed the mean value more than they would on the PASAT, as there were fewer responses given overall. Thus it is considered that altering the response paradigm of tasks such that participants had to give ten answers per trial (and $\approx$ 100 in total) would allow for a more stable measurement of reaction times and accuracy rates.

This argument does not apply to self-reports of difficulty associated with each task however. Each task has an identical amount of data for both NASA-TLX and Likert variables, though more variability is apparent for tCMT in its Likert scores, suggesting that participants disagree with each other in terms of how much difficulty they experienced on this task. One consideration for these self-reports of difficulty, however, is the greater number of required answers on PASAT. This may have led participants to feel that they were exerting more effort in this task. Perhaps if other tasks had incorporated a greater number of responses there may have been a feeling amongst participants that they were more demanding. Thus the case to equate the number of responses required in future work is also considered applicable in this regard.

The purpose of this study was to identify three tasks of ‘low’, ‘medium’, and ‘high’ difficulty to take forward to Experiment B. This study has provided a clear hierarchy of task difficulty, which can be used to select tasks fitting this criterion. Taking in to account that accuracy and response time was most variable for 2-back, and accuracy and self-reported difficulty was variable for tCMT, these tasks were considered problematic for Experiment B. Stable responses were considered more desirable as they allowed for a more accurate comparison across experimental conditions.

The three tasks with least variability were 0-back, dCMT, and PASAT, and these three tasks could also be successfully classified as ‘low’, ‘medium’, and ‘high’ difficulty, as they differed significantly from each other in a hierarchical manner in terms of accuracy, response time, NASA-TLX score, and Likert score. Thus, these were the three tasks which were used in Experiment B.

7.5 Experiment B

7.5.1 Method

A large proportion of the methodology for Experiment B matched that used in Experiment A, besides the alterations noted below.

7.5.1.1 Participants

Twenty-seven, young, normally hearing participants (18♀/9♂, mean age = 21.85 ± 3.47 years) were recruited via advertisement at the University of Leeds.

7.5.1.2 Materials

This experiment was designed to assess the effect of SimHL on the performance of three different auditory tasks. Participants were asked to complete the three auditory tasks under three different listening conditions: (1) no hearing loss, (2) simulated mild hearing loss, and (3) simulated moderate hearing loss. The derivation of these conditions is discussed below.

Hearing loss conditions

In driving and hearing loss literature, there is some evidence that the severity of hearing loss is correlated with accident risk (Picard et al., 2008), and that milder degrees of hearing loss do not significantly affect driving ability/safety (Ivers et al., 1999; Hickson et al., 2010). Furthermore, in the experiment investigating the effect of auditory distraction on the UFOV test described in Chapter 5, the inclusion of a large proportion of those with a mild hearing loss was identified as a potential reason for the lack of statistical significance between experimental groups. This evidence questions the disproportionate effect of hearing loss on task performance in those with a mild hearing loss, and suggests that those with a moderate or severe hearing loss might be most affected. However, this hypothesis cannot be explicitly inferred from past data. Accordingly, in this experiment, a range of hearing losses were studied to assess whether certain degrees of hearing impairment had an effect on cognitive tasks. These findings would then inform the methodology used in Chapter 8 to assesses the effect of SimHL on driving performance.

Research performed in this area has mainly focused on drivers with an age-related hearing loss (Ivers et al., 1999; Gilhotra et al., 2001; Unsworth et al., 2007; Hickson et al., 2010; Thorslund et al., 2013a,b,c; Green et al., 2013; Thorslund et al., 2014), and it is through this work that a disproportionate effect of auditory distraction on driving skills has been suggested. Furthermore, recruitment for prior experiments described in this thesis resulted in older samples (see Chapter 4 and Chapter 5), even though this particular demographic was not purposively sought.

Accordingly, the configurations of hearing loss studied were selected to reflect age-related hearing loss (Gates and Mills, 2005). As the method of SimHL used cannot accurately emulate hearing loss of a severe or profound nature, only mild and moderate hearing loss conditions were tested. Although these two conditions had to represent ecologically valid degrees of hearing loss, there also had to be a clear distinction between the two, so that a continuum of hearing loss severity could be studied. Levels of SimHL were based on an epidemiological study of hearing thresholds in the older population (Cruickshanks et al., 1998). The data presented by Cruickshanks et al. (1998) details the mean absolute thresholds (with standard deviation) measured in a large sample (n = 3,753) of males and females for different age groups: 48–59 years, 60–69 years, 70–79 years, and 80–92 years. This allowed for the derivation of a range within which hearing thresholds are likely to fall for individuals aged 48–92 years (see Figure 7.3). The range is reflective of age-related hearing loss, exhibiting a greater reduction in hearing thresholds, and, most likely, corresponding widening of auditory filters, at higher frequencies.

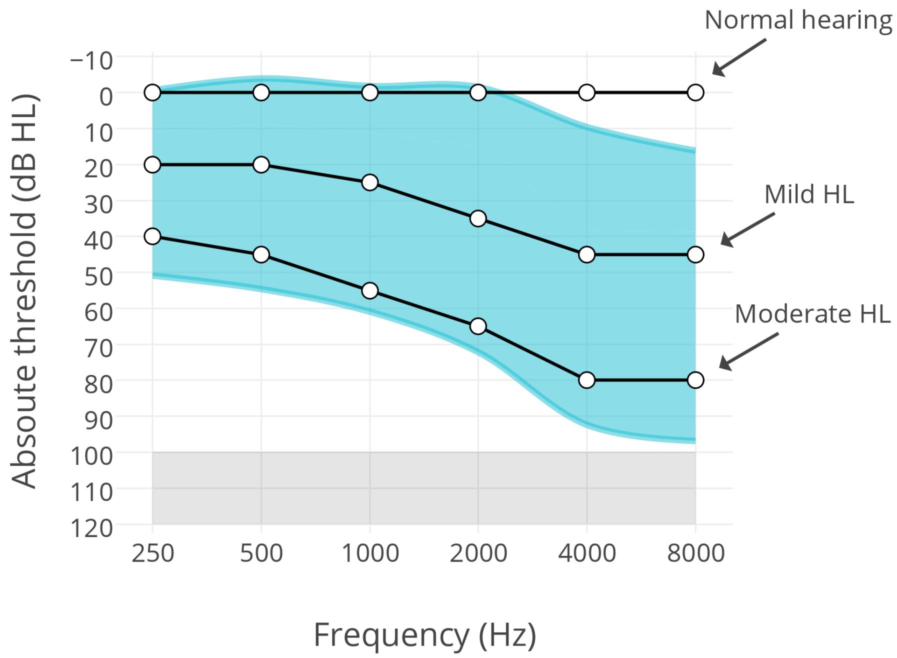


Figure 7.3 The range within which absolute hearing thresholds are likely to fall for individuals aged 48–92 years, according to data produced by Cruickshanks et al. (1998). Superimposed are the three audiograms used to simulate hearing loss for the listening conditions (no hearing loss, mild hearing loss, and moderate hearing loss).

The levels of hearing loss chosen for simulation attempted to replicate this reduction in high-frequency thresholds, as well as reflecting thresholds which spanned the entire identified range. The resulting audiograms which were simulated are superimposed over this range in Figure 7.3. The no hearing loss (control) condition does not reflect this reduction in thresholds at higher frequencies, because this condition was used to evaluate the performance of tasks without any influence of the SimHL. Thus the control condition was set to a flat 0 dB hearing loss, so that no DSP would be applied to the stimuli.

Audio files of individual digits were processed using the method described in Chapter 6 at an input level of 60 dB (reflecting the level at which they would be presented - a normal level of conversational speech; Skinner et al., 1997). These variables were used to provide digit lists for the SimHL experimental conditions.

Auditory tasks

Three of the tasks studied in Experiment A were used in this second experiment: 0-back, dCMT, and PASAT. However, some minor changes to task response parameters were made. Results from Experiment A showed that differences in the number of responses between tasks may have led to an increased perception of workload, and an increase in the spread of dependent variables (e.g. accuracy and response time). Accordingly, increasing the number of participant responses during each task, was considered to have the benefit of providing a more stable estimate of accuracy and response time data. It also helped to equate the number of responses given, such that participants were not experiencing a difference in perceived difficulty simply as a result differences of the response requirements from different tasks. Thus 0-back and dCMT were adapted in the following manner:

0-back required participants to respond after every digit presentation, for example:

Stimulus:	8		7		1		4	
Correct response:		8		7		1		4

dCMT required participants to respond *each time* they heard a target digit, by 'counting along' with the stimulus list using the keyboard number pad (i.e. after the first occurrence press one, after the second occurrence press 2 etc). For example:

Target digit: 4

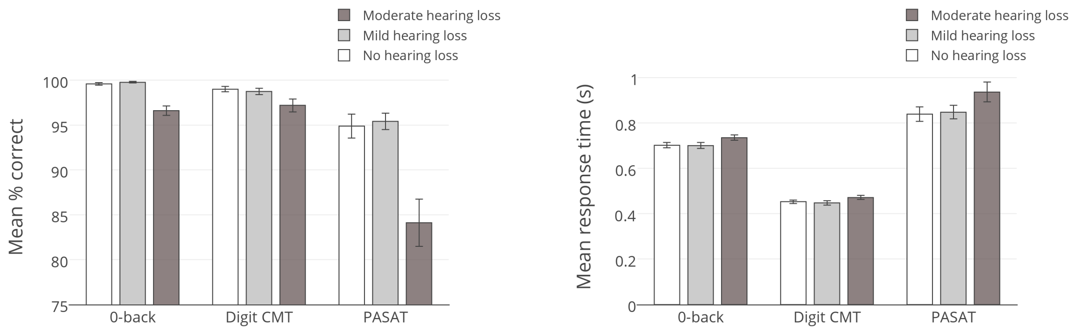
Stimulus:	8	4	7	4	9	4
Correct response:		1		2		3

These alterations were not considered likely to alter the task difficulty that had been established during Experiment A, as the hypothesised reason for their difficulty was not manipulated. 0-back still required only the most recent digit to be held in memory, it just required a response to be made more often than previously. dCMT also remained a similar task - the amount of information held in memory was still the same; participants still had to remember the target digit and the number of times that it had already occurred. Furthermore, it was previously discussed that interference between these two pieces of information may lead to disruption in rehearsal processes, causing confusion between the target digit and number of target occurrences. Even after the task response manipulation, this possibility would still be present.

7.5.2 Results

7.5.2.1 Baseline task performance

The mean accuracy rates for tasks under each auditory condition are shown in Figure 7.4. A Friedman test again showed an effect of task type on accuracy ($\chi^2(2) = 33.78$, $p < .001$). Post-hoc comparisons exhibited that under normally hearing (control) conditions, as in Experiment A, there was no difference in accuracy between the 0-back and dCMT, although the comparison did tend towards significance ($p = .057$). The PASAT was, again, less accurately performed than the 0-back ($p = < .001$) and the dCMT ($p = < .001$).



(a) Accuracy (b) Response time

Figure 7.4 Mean percent correct scores and response times (± 1 standard error) to each auditory task under each listening condition.

A Friedman test also showed that reaction times differed between the tasks ($\chi^2(2) = 48.67$, $p < .001$). In Experiment A, the dCMT was performed significantly slower than the 0-back, but the opposite trend was found in this experiment; with the dCMT being performed faster than the 0-back ($p < .001$). PASAT was performed significantly slower than the other two tasks ($p < .001$ in both cases).

Friedman tests showed that self-reported difficulty differed between auditory tasks for both Likert ($\chi^2(2) = 46.54$, $p < .001$) and NASA-TLX ($\chi^2(2) = 37.85$, $p < .001$) data. Post-hoc comparisons showed that PASAT was perceived as the most difficult task by participants, rated as harder than both the 0-back ($p < .001$) and dCMT ($p <.001$) on both NASA-TLX and Likert scores. dCMT was also, again, rated as being more difficult than the 0-back for both NASA-TLX ($p = .004$) and Likert ($p = .001$) data. Thus, under baseline (normally hearing) conditions, the task rankings (derived in the same manner as Experiment A) are shown in Table 7.7.

Table 7.7 The ranking of each task type in relation to others across dependent variables. A ranking of 1^{st} denotes that the task was easiest or best performed.

	Accuracy	Reaction time	NASA-TLX score	Likert score	Overall
0-back	1^{st}	2^{nd}	1^{st}	1^{st}	1^{st}
dCMT	1^{st}	1^{st}	2^{nd}	2^{nd}	1^{st}
PASAT	2^{nd}	3^{rd}	3^{rd}	3^{rd}	2^{nd}

7.5.2.2 Effect of SimHL on performance

Objective measures

Comparisons between the objective dependent variables were made within tasks between auditory conditions. Friedman tests showed a significant effect of auditory condition on the accuracy of the 0-back ($\chi^2(2) = 69.88$, $p < .001$) and PASAT ($\chi^2(2) = 24.804$, $p < .001$), whereas the differences in dCMT accuracy as a result of auditory condition only tended towards significance ($\chi^2(2) = 5.494$, $p = .064$). Post-hoc pairwise comparisons using Wilcoxon signed rank tests and the Bonferroni correction exhibited that it was the scores under moderate hearing loss conditions that were responsible for these significant and near-significant results; there were no significant differences between the scores in the normal hearing and mild hearing loss conditions (see Table 7.8). Indeed, for each task the greatest reduction in accuracy occurred when the task was performed under a simulated moderate hearing loss, and there was no effect of simulated mild hearing loss on any of the three tasks (see Figure 7.4).

The reduction in accuracy is most clearly shown in the case of PASAT, where the accuracy rate under the moderate hearing loss condition is 84%, as opposed to 95% in both the no hearing loss and mild hearing loss conditions. For the 0-back task, accuracy was 97% in the moderate hearing loss condition vs 100% in the no hearing loss and mild

Table 7.8 p-values derived from Wilcoxon signed rank tests on the accuracy and response time measures made in this experiment. Significant differences, after using the Bonferroni correction, are highlighted (*).

	0-back	dCMT	PASAT
Accuracy			
No hearing loss vs mild hearing loss	.232	.357	.896
No hearing loss vs moderate hearing loss	<.001*	.026*	<.001*
Mild hearing loss vs moderate hearing loss	<.001*	.043	<.001*
Response time			
No hearing loss vs mild hearing loss	.614	.313	.631
No hearing loss vs moderate hearing loss	<.001*	<.001*	<.001*
Mild hearing loss vs moderate hearing loss	.002*	.010*	<.001*

hearing loss conditions, and on dCMT the accuracy rate was 97% compared to 99% in the other two auditory conditions.

In order to establish which tasks were most associated with the biggest effect of SimHL, the calculation of effect sizes for each pairwise comparison was considered. However, there appeared to be a ceiling effect under baseline conditions for accuracy on the 0-back and dCMT tasks (99.5% and 99.0% respectively), both of these tasks showed very little variation under baseline conditions (S.D. of 0.75% and 1.57% respectively). This is in contrast to baseline data for PASAT, which was less accurate (95%) and more variable (S.D. = 6.87%). As such, effect size data may be misreprasentative, as these ceiling effects may have reduced standard deviation under baseline conditions. Accordingly, the effect size of SimHL across tasks was analysed by inspecting the individual raw difference in accuracy between no hearing loss and moderate hearing loss conditions.

A Friedman test on the individual raw difference scores in accuracy between normal hearing and moderate hearing loss suggested that there was a significant difference between task types ($\chi^2(2) = 15.61$, $p < .001$). Post-hoc pairwise comparisons using Wilcoxon Signed rank tests exhibited that this was because of the difference in accuracy reductions as a result of SimHL on PASAT, but not the 0-back or dCMT (see Table 7.9). This suggests that the reduction in performance as a result of moderate hearing loss is significantly greater on the PASAT task than either of the other two tasks studied.

Comparisons were also made for response times across the three auditory conditions (see Figure 7.4). The longest response time in each task occurred under conditions of moderate hearing loss, and there is little difference between response times recorded in the normal hearing and mild hearing loss conditions. Friedman tests showed that significant differences in the reaction times to PASAT ($\chi^2(2) = 18.07$, $p < .001$), 0-back ($\chi^2(2) = 14.00$, $p = .001$) and dCMT ($\chi^2(2) = 21.63$, $p < .001$) occurred as a result of auditory task condition. Post-hoc pairwise comparisons using Wilcoxon signed rank tests showed that these differences occurred as a result of the increase in reaction time brought about by simulated moderate hearing loss. Again there were no differences in reaction time brought about as a result of mild hearing loss (see Table 7.8).

Although there is a significant difference between response times recorded in the moderate hearing loss and the other two auditory conditions across all task types, there

Table 7.9 p-values derived from Wilcoxon signed rank tests on the individual differences between the normal hearing and moderate hearing loss conditions for accuracy and response time measures made in this experiment. Significant differences, after using the Bonferroni correction, are highlighted (*).

	0-back vs dCMT	0-back vs PASAT	dCMT vs PASAT
Accuracy	.071	.004*	.001*
Response time	.072	.034	.010*

appears to be a greater effect for the PASAT, compared to the other two tasks. Although calculated effect sizes reflect PASAT (r = .67) as being more affected by moderate hearing loss than 0-back (r =.58) or dCMT (r =.49), these estimates may, again inflate effect size for the 0-back and dCMT, given their small degree of variation under normal hearing conditions (S.D. of .06 ms and .04 ms respectively) in comparison to PASAT (S.D. = .17 ms). This difference in variation was also apparent for the moderate hearing loss condition in which standard deviations were, again, smaller for 0-back and dCMT (.06 ms and .05 ms respectively) than they were for PASAT (.23 ms). Accordingly the same approach to analysing the effect of moderate hearing loss across task types was taken for reaction time data as was used for accuracy data.

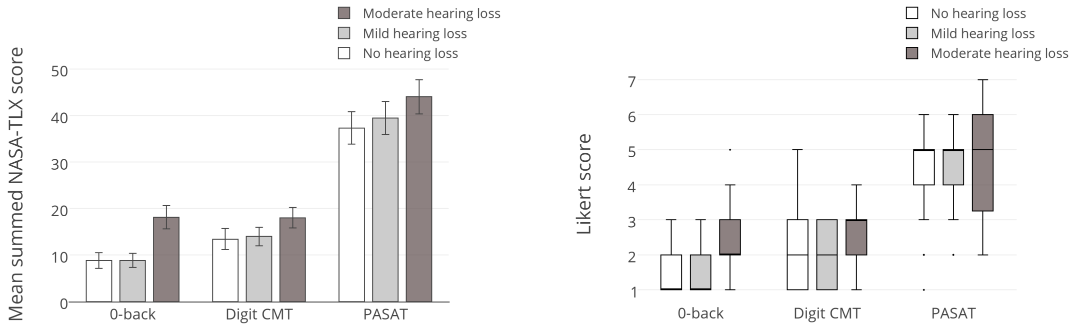
Individual raw difference values between the no hearing loss and moderate hearing loss conditions were calculated for interpretation. Pairwise comparisons highlighted that the effect of moderate hearing loss on the reaction times to PASAT was significantly greater than on the dCMT, and the comparison between PASAT and 0-back tended towards significance (see Table 7.9). This suggests that decrements to reaction times as a result of moderate hearing loss are also the greatest on the PASAT task.

Subjective measures

The mean overall summed NASA-TLX scores are shown in Figure 7.5. Comparisons were made between auditory conditions within each individual task for NASA-TLX and Likert scores. Friedman tests showed that alterations in the perception of task difficulty, as measured using the NASA-TLX, occurred as a result of auditory condition for dCMT ($\chi^2(2) = 11.06$, p = .003), 0-back ($\chi^2(2) = 29.15$, p < .001), and PASAT ($\chi^2(2) = 7.15$, p = .028). Likewise, Likert scores also showed a significant alteration in the perception of task difficulty as a result of auditory condition for 0-back ($\chi^2(2) = 30.91$, p < .001) and dCMT ($\chi^2(2) = 11.62$, p = .003). However, no such difference was found when using Likert score as the metric for perceived difficulty of PASAT ($\chi^2(2) = 4.03$, p = .133).

Post-hoc pairwise comparisons with Wilcoxon signed-rank tests showed that these significant differences occurred as a result of the perceived difficulty in the moderate hearing loss condition (see Table 7.10). When using NASA-TLX score as the metric for perceived difficulty, the performance of each task with a moderate SimHL significantly increased the perception of task difficulty over and above that experienced with no hearing loss. Moderate hearing loss also significantly raised the perceived difficulty of tasks compared to mild hearing loss, although this trend only tended towards significance for PASAT. In line with the objective measurements, NASA-TLX results suggested that mild hearing loss did not significantly raise the difficulty of any given task above that experienced under the control condition of no hearing loss.

Box plots of the Likert scores are shown in Figure 7.5. The plots exhibit an increase in perceived difficulty during the moderate hearing loss condition compared to the mild and no hearing loss conditions for 0-back and dCMT. Indeed, for these two task types, median



(a) NASA-TLX scores (b) Likert scores

Figure 7.5 Mean summed NASA-TLX scores (± 1 standard error), and box-plots for Likert scores, on each auditory task under each auditory condition. For the box-plot, Bars show the 95% confidence intervals, boxes depict interquartile ranges, and the line therein shows the median. Outliers are shown as dots.

Table 7.10 p-values derived from Wilcoxon signed rank tests on the NASA-TLX and Likert self-report measures of task difficulty made in this experiment. Significant differences, after using the Bonferroni correction, are highlighted (*).

	0-back	dCMT	PASAT
NASA-TLX			
No hearing loss vs mild hearing loss	.764	.875	.167
No hearing loss vs moderate hearing loss	<.001*	.017*	.003*
Mild hearing loss vs moderate hearing loss	<.001*	.005*	.042
Likert score			
No hearing loss vs mild hearing loss	.567	.658	.559
No hearing loss vs moderate hearing loss	<.001*	.076	.244
Mild hearing loss vs moderate hearing loss	<.001*	.001*	.077

values for the mild and no hearing loss conditions were comparable (0-back median = 1; dCMT median = 2), and increased for the moderate hearing loss condition (0-back median = 2 dCMT median = 3). This is not the case for PASAT which had a stable median (5) across all of the auditory conditions in this experiment. However, Likert scores suggest that the perception of difficulty associated with PASAT became more variable in the moderate hearing loss condition. This was not the case for any of the other tasks, suggesting that the performance of this task in the moderate hearing loss condition was more troublesome for some participants than others.

Post-hoc pairwise comparisons using Wilcoxon signed-rank tests were used to establish any significant differences in the Likert scores of auditory conditions for each individual task. There were no significant differences in the perception of difficulty between normal hearing and moderate hearing loss conditions for PASAT ($p = .244$) or dCMT ($p = .076$). However, the significant difference between these two auditory conditions on 0-back remained ($p < .001$), and the difference in the perception of difficulty between mild and moderate hearing loss conditions remained for 0-back ($p < .001$) and dCMT ($p < .001$). The difference between mild and moderate hearing loss conditions was also absent for PASAT ($p = .077$).

The magnitude of the increased perception of difficulty as a result of hearing loss was also analysed for each task, in order to investigate whether there was a difference across different tasks. Again, the calculation of effect size was not considered applicable, given that there was a floor effect on the 0-back task, whereby the majority of participants consistently rated this task as very easy under no hearing loss conditions, resulting in a very low degree of variability for both NASA-TLX and Likert data. Accordingly analysis on the raw difference values between the moderate and no hearing loss conditions was carried out. However, Friedman tests showed that there were no significant differences in these raw difference values across task type for either NASA-TLX ($\chi^2(2) = 2.89$, $p = .236$) or Likert ($\chi^2(2) = 3.89$, $p = .143$) data. This suggests that the increase in perceived difficulty as a result of moderate hearing loss is stable across tasks of varying difficulty.

7.5.3 Discussion

Experiment B assessed the effect of different degrees of SimHL on auditory tasks of varied difficulty. This information was considered valuable in predicting the effect that different types of auditory task might have on the performance of driving in the hearing impaired demographic. In order to establish the effect of hearing loss across task difficulties, it was first necessary to evaluate whether the previously noted hierarchy in task difficulty remained in this study.

7.5.3.1 Baseline task performance

In this experiment, the original hierarchy of task difficulty was not replicated completely. However, as was the case in Experiment A, the accuracy of PASAT was the lowest of the three tasks studied, its response times were longest, and its perceived difficulty was highest for both NASA-TLX and Likert scores. This task was, therefore, still considered as reflecting the highest degree of difficulty. The relationship of dependent variables between the 0-back and dCMT largely remained the same, with a difference between accuracy rates which tended towards significance, and a significantly higher perception of difficulty for the dCMT across NASA-TLX and Likert data. However, an alteration in the ranking of response times was noted, whereby the 0-back was performed more slowly than dCMT; whereas the opposite had been true in Experiment A. The most likely reason for this was the alteration in response paradigm between Experiment A and Experiment B for these two tasks.

A plausible explanation is as follows: Experiment A highlighted that a response paradigm incorporating more responses was preferable in providing a more stable estimate of mean values, and to make perceived demands more comparable between different tasks. Accordingly, the 0-back and dCMT were adapted so that participants had to respond throughout the stimulus list. Responses were made on the number pad of a computer keyboard, and as such a fraction of the response time measured consisted of the physical response (pressing a key). In the case of the 0-back, the exact response was not known in advance; it depended upon the random digit which was presented. Accordingly, once a digit was heard, the participant may have moved his/her finger to the relevant key, and pressed. However, for the dCMT the specific response was known in advance; participants were required to 'count along' the number of targets which they heard, thus all answers were consecutive, ascending numbers. Therefore, it is possible that participants had already moved their finger to the relevant key to provide their next response, allowing for shorter response times compared to 0-back.

Therefore, it is considered that the difference in response times to dCMT between Experiments A and B were not as a result of a reduction in task difficulty. Regardless, because of the inconsistencies in the ranking of 0-back and dCMT across dependent variables, it was not considered possible to state whether 0-back or dCMT was the more difficult task in Experiment B. Thus, the effect of SimHL can only be considered in terms of its effect on two levels of task difficulty: 0-back/dCMT vs PASAT.

7.5.3.2 Differences in task performance as a result of SimHL

Objective measures showed that moderate SimHL significantly increased the difficulty of all three tasks over and above that experienced when the same tasks were undertaken with a mild SimHL or normal hearing. Mild SimHL does not appear to show any difference in terms of performance when compared against normal hearing. This suggests that moderate hearing loss has the capacity to affect auditory task performance, and could therefore have a disproportionate impact on other concurrently performed tasks, such as driving. This does not appear to be a consideration for mild hearing loss, which had little bearing on auditory task performance. However, these results were obtained in single task conditions, and it might be that more challenging dual-task conditions reveal performance costs for mild hearing loss as well.

It is argued that an effect of moderate hearing loss on auditory task performance was not simply due to an inability to hear or understand auditory stimuli in the moderate hearing loss condition. An accuracy rate of 97% was recorded for the moderate hearing loss condition of the 0-back task, which required participants to simply shadow the stimulus digit list. This would suggest that, on average, at least 97% of the stimuli were at an audible level for participants and without excess distortion causing unintelligibility. Thus it is argued that the performance decrements noted were most likely associated with an increase in the effort exerted to understand the aurally presented numbers.

The results of this experiment mirror those of past work using participants with a 'real' hearing loss (Rabbitt, 1991; McCoy et al., 2005). However, this experiment used a SimHL, suggesting that the peripheral representation of a sound source is, at least in part, responsible for an increase in the listening effort requirements on auditory tasks. The ability to separate the effect of peripheral hearing loss from other co-existing factors on driving has been questioned in this thesis. However, this experiment has removed the influence of co-existing factors, and as such suggests that simulated psychoacoustic phenomena associated with SNHL (i.e. threshold elevation, loudness recruitment, and reduced frequency selectivity) have the potential to engage cognitive resources to a disproportionate extent, potentially impacting on other concurrent tasks (e.g. driving).

The fact that only an effect of moderate hearing loss on task performance was found in this experiment is of practical importance, as it suggests that mild hearing loss may not be problematic in terms of its effect on listening effort and, thus, other concurrently performed operations. This finding has been replicated by Rabbitt (1991), who found a disproportionate effect of hearing loss on encoding operations for participants with average hearing thresholds of 35–50 dB HL, a level close to the criteria used in this study to classify moderate hearing impairment ($\geq$ 40 dB HL; British Society of Audiology, 2011). However, (McCoy et al., 2005) found that hearing losses of 25 dB HL and greater were associated with processing decrements, which questions Rabbitt (1991) and the results of this experiment.

This discrepancy may have been due to the differences in the manners by which hearing loss was classified. McCoy et al. (2005) measured hearing impairment by taking the mean threshold at three discreet frequencies (1, 2 and 4 kHz), whereas Rabbitt (1991) took an average over the frequency range 300–10,000 Hz. This extended higher frequency range in the study of Rabbitt (1991) is likely to have incorporated thresholds which were raised to a greater extent than those at mid- and low-range frequencies (Gates and Mills, 2005), and thus may have positively skewed the average thresholds of participants who had milder hearing losses at the frequencies used by McCoy et al. (2005).

However, the frequencies used to calculate hearing loss severity in this study (the mean of thresholds at 500, 1000, 2000 and 4000 Hz; as per the British Society of Audiology, 2011) are comparable to those used by (McCoy et al., 2005). The argument for using these discreet frequencies is that they are considered highly important for speech recognition (Humes, 1996). Therefore, the difference in outcomes between this experiment and the work of McCoy et al. (2005) might be explained by the sensory-cognitive interaction theory (Baldwin, 2002).

Baldwin and Ash (2011) showed that whilst younger adults were affected by a reduction in stimulus presentation level, older adults were affected to a greater extent. This led them to conclude that peripheral and central issues impact speech understanding in older adults; because working memory skills are reduced in this demographic, they are less able to compensate for reductions in the clarity of auditory stimulation. Thus there appears to be a synergistic effect of age and hearing loss on the performance of auditory cognitive tasks.

McCoy et al. (2005) studied an older sample than was used in this experiment (mean age 72.9 years vs 21.9 years). Therefore, according to the theory discussed by Baldwin (2002), McCoy et al.'s (2005) sample were less equipped to compensate for a reduction in stimulus presentation level. Baldwin and Ash (2011) found a linear decrease in performance as presentation level decreased (in increments of 5 dB), but also that effect size of reducing presentation level was much greater in their older sample. Thus it is argued that even small reductions in the presentation level of stimuli may have a profound effect on the performance of the older demographic, hence supporting the finding of McCoy et al. (2005) that their older mildly hearing impaired sample showed a significant reduction in auditory task performance. However, in the current study the effect of mild hearing loss was negligible, it was only once the SimHL reached a greater level (moderate hearing loss) that the younger sample started to exhibit auditory task decrements.

The difficulty of the auditory task had a bearing on the effect size of simulated moderate hearing loss, such that the most difficult task suffered from a greater reduction in accuracy and increase in reaction time as a result of SimHL than did any of the other tasks studied. No such distinction was apparent between the two other tasks (0-back and target digit). This suggests that SimHL may have an effect on all auditory-based tasks, but that the most difficult auditory tasks are disproportionately affected by hearing losses of a moderate nature. Participants also reported perceiving a greater degree of difficulty whilst under conditions of moderate SimHL. However, this increase in difficulty did not appear to differ across tasks. This suggests that, although performance decrements as a result of hearing loss are tied to the difficulty of auditory tasks, this is not apparent to participants themselves. It should be noted, however, that an inability to successfully perform introspection as to the demand of certain tasks was raised in Chapter 4. The finding here that self-reports of difficulty to not entirely corroborate the increase of demand associated with a moderate hearing loss validates the decision to use more objective methodologies further.

7.6 Study direction and limitations

Though the SimHL used in this experiment has differentiated the effect of peripheral hearing loss, some thought should still be given to the complications that co-existing factors might present. No comparison was made between young and older participants, as it was not the aim of this experiment, thus the influence of a sensory-cognitive interaction (Baldwin, 2002) across task difficulties cannot be derived from this experiment. This would be of interest in quantifying the extent to which hearing loss and co-existing factors each affect task performance. This is an important consideration because the combination of these two factors is a true reflection for the majority of hearing impaired drivers, who are older.

Furthermore, whilst the study has used two varied levels of SimHL they are both reflective of a single type of hearing loss. It would have been of interest to examine the effect of a more severe level of hearing loss in order to establish whether the effect size of auditory task degradation increases with the severity of hearing loss. However, this was not possible given that the method of hearing loss simulation cannot accurately emulate hearing loss levels of $\geq$ 90 dB. Furthermore, the investigation of different configurations of hearing loss would also have been of interest (e.g. a noise-induced hearing loss, given the findings of Barreto et al., 1997 and Picard et al., 2008).

The purpose of this study was to establish how SimHL affected the performance of auditory tasks in order to predict how their performance might impact on driving. Whilst an effect of hearing loss on task performance has been shown, the experiment has not assessed how these tasks are performed as part of a dual-task paradigm. Thus, it is unclear whether there will be any extraneous effect of performing these tasks in a SimHL condition whilst dual-tasking. However, it might be argued that single-task performance should be easier than dual-task performance as it does not incorporate any extraneous processing demands or the coordination of resources. Accordingly, the increased difficulty of these tasks as a result of hearing loss may be exacerbated when under dual-task conditions, as well as reducing the performance of the concurrent task.

The experiment described in the following chapter investigated the effect of these auditory tasks in a dual-task paradigm; specifically whilst driving. Indeed it was the purpose of this study to establish the effect of different degrees of SimHL on these tasks to be able to predict the influence they might have on driving performance; thus the results were used to inform the experimental design. Because no effect of mild hearing loss on the performance of auditory tasks was found in the current experiment, it was hypothesised that listening effort demands associated with this level of hearing loss would not be raised sufficiently to result in dual-task decrements in young participants. Moderate hearing loss, on the other hand, appeared to require a greater degree of explicit processing compared to a no hearing loss condition. As such, moderate hearing loss was selected as the only alternative auditory condition in the study described in Chapter 8.

The next study also required the employment of two tasks, distinct in their demands. The decision was to use the dCMT and PASAT. PASAT was chosen, because it was clearly a more difficult task than the other two used in Experiment B. The decision between 0-back and dCMT was, however, more problematic. Task response metrics were considered to be slightly in favour of dCMT. Although dCMT showed a very high degree of accuracy and a low level of self-reported difficulty, it did not exhibit the strong ceiling and floor effects (on accuracy and self-reported difficulty, respectively) that 0-back did under the no hearing loss condition in both Experiments A and B. It was considered that floor and ceiling effects may be problematic for statistical testing performed on 0-back, given that baseline data would exhibit little to no variability, potentially inflating effect sizes. In addition to this reasoning, dCMT has been used during past driver safety research, albeit in a different format, and affected certain driving outcomes (Jamson and Merat, 2005; Engström et al., 2005b).

Accordingly, in order to investigate the effect of a concurrent auditory task on driving performance in the presence of a SimHL, dCMT and PASAT were chosen as two tasks of distinct (low and high) difficulty, and the moderate hearing loss condition was chosen as the only listening condition (besides a control), given that a SimHL of this degree is thought to be required in order to raise listening effort demands.

7.7 Conclusions

The aim of this two-part study was to establish a hierarchy of difficulty for a set of auditory tasks, and to then investigate how different levels of SimHL affected the performance of a selection of these tasks. This was undertaken in order to identify tasks for application in a driving simulator study assessing the effect of auditory task engagement on driving, and whether a disproportionate effect of SimHL was apparent.

Experiment A identified a hierarchy of difficulty in five auditory tasks, and allowed tasks of low-, medium- and high- difficulty forward to Experiment B. Experiment B assessed the effect of simulating two levels of hearing loss on the performance of the selected tasks. Simulated moderate hearing loss significantly reduced the accuracies, and increased the response times and perceived difficulties of each task tested. Furthermore, the negative effect of moderate hearing loss on task performance was greater for more difficult tasks. Conversely, simulated mild hearing loss showed no effects on task performance.

Given that a SimHL was used in this study, the source of this performance decrement is likely to be the degradation in the perceptual representation of sound stimuli, rather than any other age-related confound. This is something which has been queried in prior discourse. This finding has important ramifications in terms of how peripheral hearing loss might affect performance in more ecologically valid situations. Performance on more challenging everyday tasks is likely to be less accurate and slower for people with a moderate SNHL, and it is also likely to be perceived as more difficult by that individual. Furthermore, if a task is being performed concurrently with another, moderate hearing loss is likely to cause a disproportionate disruption on one, or both tasks. In the context of this thesis, this may mean that the performance of an auditory task whilst driving is an unsafe practice for those with a moderate hearing impairment.

To this end, the final experiment described in this thesis will investigate the effect of simulated moderate hearing loss on driving performance in the presence of auditory tasks of differing difficulty. The current two part experiment has identified that this level of hearing loss is most likely to cause disturbances to driving under this condition, it has also identified two suitable auditory tasks for use in the following experiment (dCMT and PASAT).

Chapter 8

The Effect of Simulated Hearing Loss on the Performance of Aurally Presented Cognitive Tasks whilst Driving

8.1 Introduction

The majority of work reported in this thesis has focused on the potential for hearing impairment to cause issues for driving whilst under conditions of auditory task engagement. It has done so using self-reported data (see Chapter 4) or abstract experimental paradigms investigating effects of hearing loss on task performance (see Chapter 5 and Chapter 7). Now that a valid method of differentiating peripheral hearing loss from other co-existing factors has been identified (see Chapter 6), this study will investigate the effect of peripheral hearing loss on driving in a more ecologically valid manner, by applying an experimental paradigm in a high-fidelity driving simulator.

Research suggests that a greater perceptual effort associated with listening to an auditory signal in the hearing impaired presents a dual-task cost for skills relevant to driving (Hickson et al., 2010). This argument has been explained in the context of an ELU model, which proposes that a more explicit processing strategy will be employed when an auditory signal is mismatched with phonological representations in long-term memory; something which is likely to happen more often in hearing impaired individuals (see Chapter 3). This explicit processing strategy is derived from a structure similar to the central executive described in Baddeley's Working Memory model (1974), which is responsible for attention switching between the visuospatial sketchpad and phonological loop. Thus it was reasoned that attention switching would be less efficient in those with a hearing loss, as a result of a disproportionate strain on the central executive. This would then be problematic for hearing impaired drivers in a dual-task set-up, when driving is concurrent with an auditory task (see Chapter 2).

Data from the study reported in Chapter 7 suggests that SimHL does, indeed, reduce performance on auditory tasks. Therefore, it is likely that tasks performed under SimHL conditions would have more of an effect on driving than those which are performed under normally hearing conditions. This is proposed to arise (at least in part) as a result of peripheral distortion to a sound source. The assumption that this disruption is due to the peripheral representation of a sound source is important because it is unclear how, and to what extent, factors co-existing with hearing impairment might affect cognitive performance (see e.g. Baldwin, 2002). This idea was considered particularly pertinent given there was a significant difference in the reading span of hearing impaired and normally hearing individuals in Chapter 5, thus suggesting that the two groups have a baseline difference in some Working Memory abilities.

Further to this, previously described findings of Thorslund et al. (2013a,b, 2014) suggest that a behavioural adaptation to driving takes place over time as a result of hearing loss. It is, therefore, unclear whether behavioural changes may have been one of these co-existing factors responsible for previously reported results investigating the effect of auditory distraction on driving behaviour (e.g. Hickson et al., 2010).

The interaction between auditory distraction and adaptive driving behaviour in the hearing impaired demographic, and their effect on driving performance is likely to be complex. Medeiros-Ward et al. (2014) propose that driving is coordinated by a hierarchical control network. In line with Fodor (1983), they argue that automatic, encapsulated aspects of driving operate outside of awareness, whereas processes under attentional control are easily brought in to conscious awareness. Medeiros-Ward et al. (2014) suggest that, as more attention is allocated to attentional control tasks, their performance will increase. On the other hand, when more attention is allocated to automatic, encapsulated tasks, their performance will actually decrease. Thus the authors argue that auditory task engagement whilst driving will lead to some performance decrements, whilst “improving” other aspects of driving. This theory explains past experimental findings which have exhibited a degradation in certain aspects of driving whilst concurrent demanding auditory tasks are performed. For example, longer reaction times to critical events (Lamble et al., 1999; Strayer et al., 2003), but an ‘improvement’ in lane keeping (Brookhuis et al., 1991; Jamson and Merat, 2005; Engström et al., 2005b). This is explained because steering is considered an automated aspect of driving (Michon, 1985), and as such is will not be affected by the diversion of cognitive resources to the secondary task. However, an alternative explanation, backed by a considerable literature, is that gaze concentration to the road centre is increased by extraneous cognitive load (e.g. Nunes and Recarte, 2002; Engström et al., 2005b; Jamson and Merat, 2005; Victor et al., 2005; Harbluk et al., 2007), and as drivers ‘steer where they look’ (Wilkie et al., 2010), this naturally leads to an improvement in peoples’ propensity for steady lane-keeping.

Because hearing loss increases the degree of workload required to perform an auditory task (Rabbitt, 1991), it is hypothesised that performing a difficult auditory task during driving will exacerbate the decrement in attentionally-controlled aspects of driving, such as reactions to critical events, whilst leading to a further 'improvement' of the encapsulated aspects, such as lateral vehicle control. The current experiment, therefore, investigated this hypothesis by asking participants to perform two auditory tasks (the dCMT and PASAT) whilst completing a short drive in the UoLDS. To assess the effect of hearing loss on driving performance, in this dual-task setting the two tasks were presented either at normal hearing levels or a simulated moderate hearing loss condition. As outlined in Chapter 7, these two auditory tasks imposed different levels of cognitive demand, and the simulated moderate hearing loss provided a listening condition which increased cognitive workload. Thus the effect of hearing loss on driving performance in the presence of an auditory task could be evaluated for auditory tasks of varied difficulties.

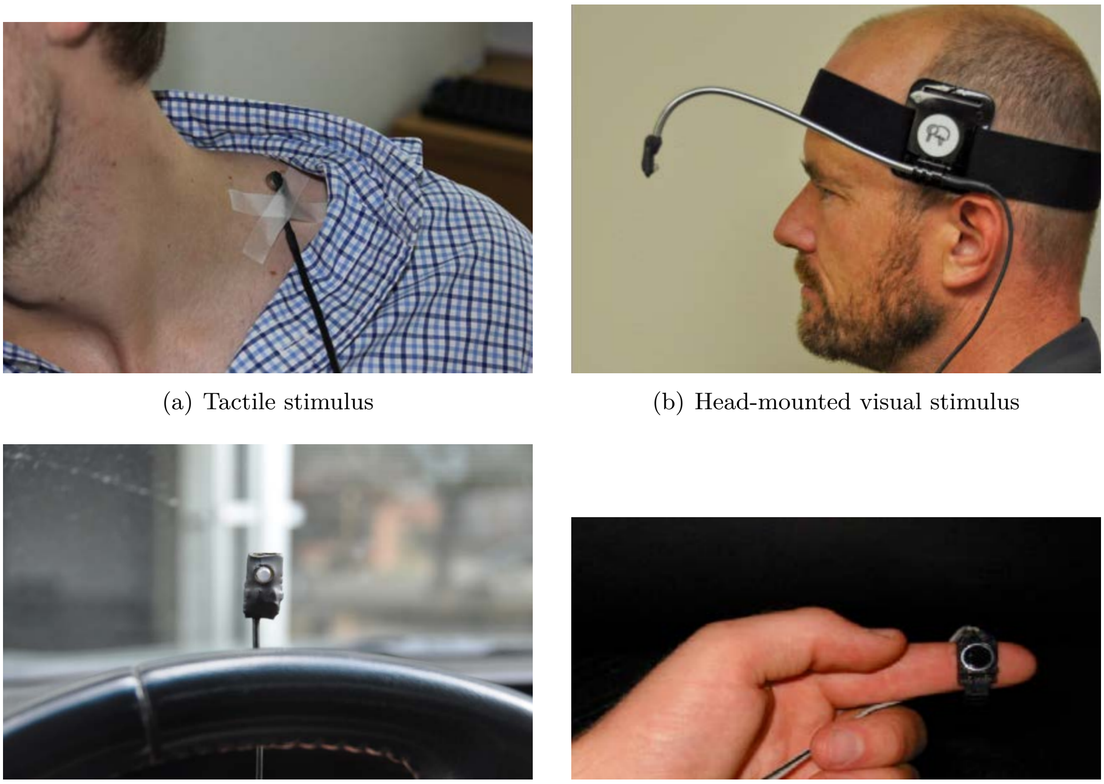
To assess whether SimHL raises the cognitive workload of drivers over and above that during normally hearing conditions, a visual version of the Detection Response Task (DRT) was also incorporated at designated sections in the experiment. The DRT is described in the next section.

8.1.1 The DRT

The DRT has evolved from a measure known as the Peripheral Detection Task (PDT), which was based on original work carried out by Miura (1986), and was more formally developed by van Winsum et al. (1999). The DRT is regarded as a promising measure of cognitive load and its effects on attentional control and functions (McGehee, 2014). It has been developed primarily to assess the demands associated with specific secondary tasks in the driving domain. The DRT involves the repeated presentation of a single stimulus which recurs with temporal uncertainty, requiring a response via a button attached to the index finger (see Figure 8.1). The stimulus presented is either visual (an LED), sound-based, or tactile (McGehee, 2014; see Figure 8.1). Each stimulus presentation has an epoch within which a response must be given, or a missed response is recorded and the DRT continues with the presentation of the following stimulus. The DRT can, therefore, produce data on 'hit rate' and response time and is analysed on these two measures under the premise that the greater the level of cognitive load, the longer the response time and the lower the hit rate.

The DRT is currently being developed by a working group with a view to present an ISO standard regarding its presentation and response parameters (ISO, TBA). A pre-draft ballot has produced a set of suggested stimulus parameters, which are shown for a single Stimulus Cycle Period (SCP) in Figure 8.2. A series of these SCPs, each lasting from 3–5 seconds, are presented to the participant under various experimental conditions.

The work described in this chapter only used the DRT as a visually-oriented task, which is henceforth referred to as the Visual Detection Response Task (vDRT). In the vDRT, a light stimulus is presented at a single point in a subject's peripheral vision, either via a



(a) Tactile stimulus

(b) Head-mounted visual stimulus

(c) Remote visual stimulus

(d) Response button

Figure 8.1 Different apparatus involved with the DRT. Source: McGehee (2014).

remotely mounted Light Emitting Diode (LED) or a head mounted LED (see Figure 8.1). The head mounted version holds the advantage that it will always occur in the same position in the participant's vision, whereas the position of a remotely mounted LED in vision will be dependent on the position of the subject's head.

8.1.1.1 Development of the DRT

Miura (1986) investigated the effect of driving task demand on the detection of an array of lights projected onto a vehicle windscreen (e.g. see Figure 8.3). He found that response time to the light stimuli increased with driving demand (which was indexed as an increase in traffic density). In addition, he found that an increase in driving demand decreased the response eccentricity (the distance between the gaze fixation and the stimulus). Miura (1986) interpreted this pattern of results as a reduction in the driver's functional visual field; because subjects were less able to detect stimuli in their peripheral vision, they had to look more directly at light array in order to respond to a stimulus.

The PDT aimed to exploit this narrowing of the visual field to obtain a method which was sensitive to workload, but did not interfere with concurrent tasks (Victor et al., 2008). van Winsum et al. (1999) formally developed the method using a PDT paradigm in which they presented light targets in the upper-left visual field with temporal

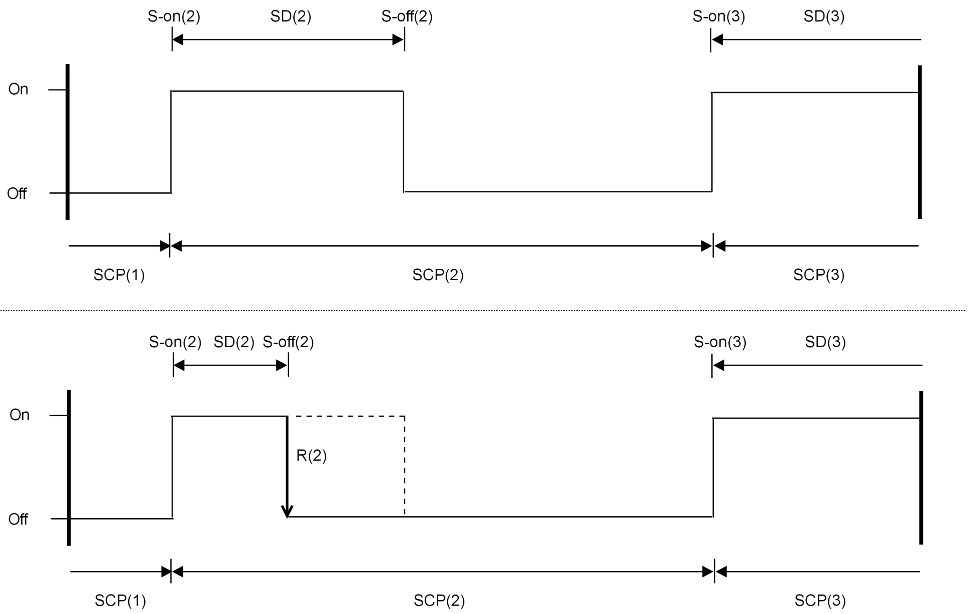


Figure 8.2 The presentation paradigm of a single DRT stimulus cycle. Adapted from McGehee (2014). The top panel shows a SCP in which the subject does not respond, and the bottom panel shows an instance where the subject does respond.

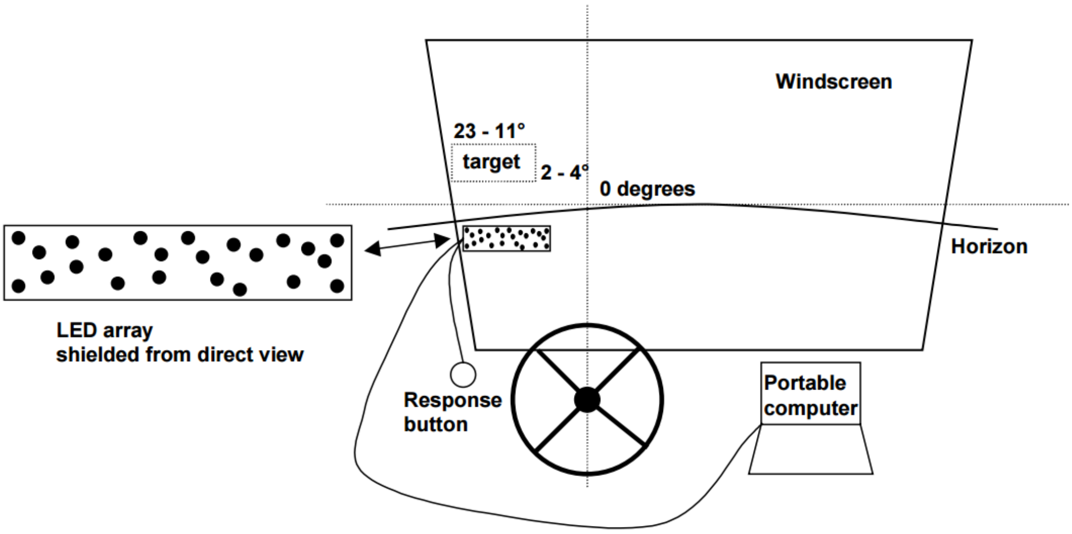


Figure 8.3 An example experimental setup showing the PDT task incorporating an array of LEDs which are projected on to the windscreen. Source: (Olsson and Burns, 2000).

and spatial uncertainty; the stimulus presentation region spanned 11–23° vertically and 2–4° horizontally, and stimuli were presented randomly at intervals of between 3–5 seconds.

Although van Winsum et al. (1999) showed that their version of the PDT was sensitive to workload (responses were slower during high demand traffic situations), in contrast to the work of Miura (1986), they found no effect of eccentricity, with detection performance being the same regardless of stimulus position.

A number of other studies have also shown that the horizontal angle of the PDT stimulus did not have any bearing on the results obtained (Martens and Van Winsum, 2000; Nunes and Recarte, 2002). Because of this, it is thought the PDT actually measures a general, amodal interference in attention selection, rather than a modality-specific visual perceptual narrowing (van Winsum et al., 1999; Merat and Jamson, 2008; Victor et al., 2008).

As such, the PDT has been adapted to present a stimulus at a single location, rather than as part of an array, which has the advantage of providing a pure measure of general attentional interference, rather than being contaminated by modality-specific factors, such as visual eccentricity (Victor et al., 2008). Accordingly, the DRT can be presented in a variety of modalities; visual, auditory, and tactile. Early work showed that there was no difference in response parameters between different presentation modalities (Engström et al., 2005a; Merat and Jamson, 2008), supporting the general attention interference theory.

8.1.1.2 Considerations for the DRT

Although the purpose of the DRT is to measure the cognitive workload associated with performing concurrent tasks whilst driving, it is a task in its own right. However, it is unclear whether the DRT is an unobtrusive method of assessment. Anecdotally, Olsson and Burns (2000) noted from their position in the passenger seat of the car, that there was no degradation in driving performance as a result of *PDT* performance. All of their participants also anecdotally reported that the PDT was acceptable to be performed simultaneously whilst driving. Merat and Jamson (2008) also used the DRT in a driving simulator study and noted that its performance whilst driving resulted in no significant effect on the measures of vehicle control such as: speed, headway, standard deviation of lane position, even in the presence of an additional cognitive task (counting backwards in multiples of seven). Thus it would appear that vehicular control aspects of driving remain unaffected by the simultaneous performance of the DRT.

Some studies have, however, exhibited that eye movement behaviour can be altered by the inclusion of the PDT, in that the stimuli are frequently fixated upon (Miura, 1986). Recarte and Nunes (2003) noted a higher dispersion of spatial gaze when their visual task (analogous to the PDT) was performed, and argued that this reflected their participants glancing to look for, and identify, visual targets. However, the DRT differs from the PDT in that it only incorporates a single stimulus location. It is unknown whether this adaptation leads to a reduction in such visual search for stimuli. Given these findings, it is an important consideration in experiments using the DRT that eye movement behaviour might be altered to a certain extent. Because eye movements were also recorded in the current experiment, they were analysed whilst the vDRT was absent and present in order to counter this potential confound.

It should also be noted that, although primarily considered a metric of workload (McGehee, 2014), the visual version of the DRT may also be reflective of hazard perception. This is because salient DRT stimuli are presented in the periphery of vision, where a number of hazards (such as pedestrians) or information (such as road signs) that require expedited action from the driver also occur. As such there is a functional correspondence that lends construct validity to this method of workload assessment (van Winsum et al., 1999). Indeed, data pertaining to the PDT version of the task collected by Olsson and Burns (2000) supports this inference, with a number of participants reporting false-hits whilst confusing external events such as traffic lights with the PDT stimuli. The DRT may also, therefore, exhibit drivers' ability to detect hazards during periods of workload also.

8.2 Study aims and hypotheses

The aim of this study was to assess the effect of SimHL on driving performance, cognitive workload and eye movements whilst performing a cognitively engaging auditory task. Participants were asked to drive a simulator and perform two auditory tasks of variable demand, presented with and without a SimHL.

A specific set of changes in driving behaviour were hypothesised to arise as a result of auditory task engagement whilst driving. These behaviours were in line with past research findings and are summarised in Table 8.1. It was hypothesised that, as a result of the auditory task being presented in a SimHL condition, these changes in driving behaviour would be even more marked as the demand of the auditory task would be raised as a result of the attenuation and distortion to auditory stimuli provided by the SimHL.

8.3 Method

8.3.1 Participants

36 young, normally-hearing participants (16♀; 20♂) were recruited from the UoLDS participant database to take part in this study. The sample was aged between 20–40 years and had a mean age of 28.3 (S.D. = 5.7) years. This age range was selected given that some authors have suggested cognitive decline may start at ages as early as 45 years (Singh-Manoux et al., 2012).

Participants had between 1–22 years of driving experience, with a mean of 9.5 years (S.D. = 6.3 years), and drove on average 6,900 miles per year (S.D. = 4,400 miles). Participants were reimbursed £15 for taking part in the experiment, and were screened for normal hearing (absolute thresholds of $\leq$ 20 dB HL at frequencies of 0.25, 0.5, 1, 2, 4 and 8 kHz in both ears) using pure tone audiometry.

Table 8.1 The hypothesised changes to dependent variables as a result of auditory task engagement in the current study.

Change in driving behaviour as a result of auditory task engagement	Related dependent variables	Evidence
Reduced visual scanning	· Increase in the proportion of time looking at the road centre · Increase in gaze concentration around the road centre	A perceptual narrowing/cognitive tunnelling effect has been suggested by previous work, whereby drivers spend more time focussed on the road centre under conditions of auditory task engagement (Jamson and Merat, 2005; Engström et al., 2005b; Victor et al., 2005).
Reduction in vDRT performance	· Decreased vDRT hit-rate · Increased vDRT reaction times	The vDRT measures cognitive workload. The performance of an auditory task will increase the cognitive workload experienced by participants, given that they are multi-tasking rather than driving in a single-task paradigm.
"Improvement" in lateral vehicle control	· Reduced standard deviation of lane position · Increased minimum time to line crossing	The performance of an auditory task whilst driving has been shown to improve lateral vehicle control, as indexed by the standard deviation of lane position, and minimum time to line crossing (Brookhuis et al., 1991; Jamson and Merat, 2005).
Altered longitudinal vehicle control	· Decreased driving speed · Increased headway	Studies have shown that, during auditory task engagement, travelling speed is reduced (Haigney et al., 2000; Rakauskas et al., 2004; Jamson and Merat, 2005), and headway is increased (Haigney et al., 2000). This is perhaps in order to provide a larger safety margin (Haigney et al., 2000).

8.3.2 Materials

8.3.2.1 The driving simulator

This study was conducted on the UoLDS, which is a second-generation, moving-base, high fidelity driving simulator (see Figure 8.4). The simulator vehicle (a 2005 Jaguar S-type) is suspended inside a projection dome offering a near seamless total horizontal field of view of 250°. The forward vertical field of view is 45°, and the 60° rear channel can be viewed through the vehicle's rear-view mirror. Images on liquid crystal displays built into the wing mirrors also offer information on the simulated environment for the driver.

The car is a right-hand drive vehicle, and its controls function as they would in a fully-

Figure 8.4 The UoLDS projection dome and motion system shown from the outside.

operational vehicle. Participants view the simulated environment through the windscreen and windows of the vehicle, as well as via the rear-view and wing mirrors (see Figure 8.5). Participants have full control of the vehicle's longitudinal and lateral motion. The vehicle uses an automatic transmission and so participants are not required to interact with the gear lever once the car is in motion.

Figure 8.5 The University of Leeds Driving Simulator shown from inside the vehicle cab.

The simulation is run on a network of local PCs (see Figure 8.6). The vehicle's Control Area Network transmits information about driver control of the vehicle to each node of the managing PC network, where it is assessed for relevance. This information is fed to a vehicle dynamics model, which simulates realistic driving cues such as the visual dashboard display, tactile cues and auditory stimuli (delivered via an 80 watt 4.1 sound system). This results in an ecologically valid simulation of various sensory components of the driving environment.

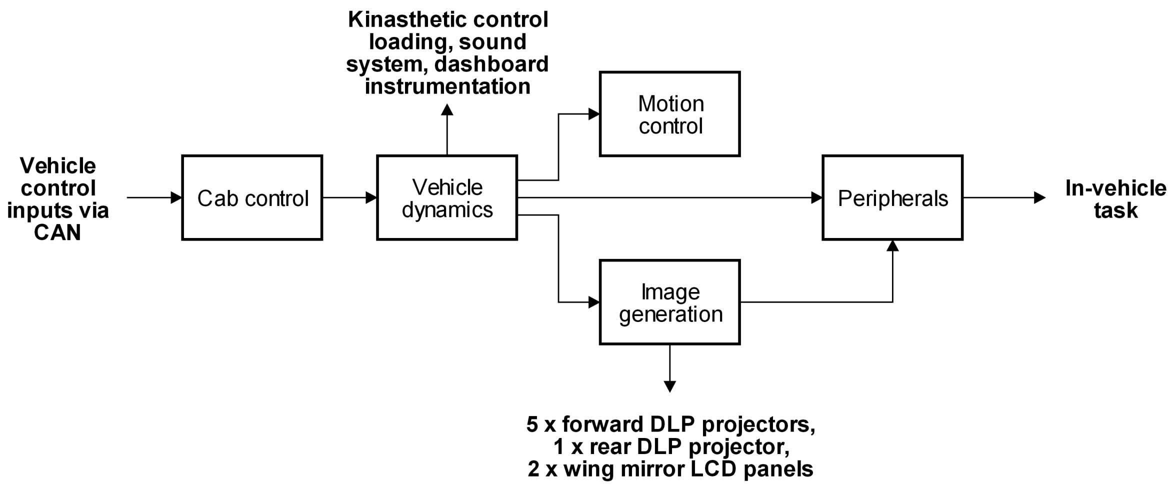


Figure 8.6 A flow diagram of the UoLDS computer network.

The projection dome is four metres in diameter and creates an immersive driving environment by reducing interference from external auditory and visual stimuli. Images generated are rendered at 60 frames per second and are presented over eight channels to create a real-time, fully textured three-dimensional graphical scene of the virtual world. Six of these channels are projected onto the inner surface of the dome, three forward facing (resolution 1920×1200; pixel density 2.1 arcmin per pixel), two side facing (resolution 1920×1200; pixel density 4.1 arcmin per pixel), and one rear facing (resolution 1024×768; pixel density 4.1 arcmin per pixel). All channels are frame locked in order to avoid inconsistencies arising in the image. The composite image is corrected and colour balanced prior to display. The 7" liquid crystal display wing mirrors use a resolution of 800 pixels.

Also visible in Figure 8.4 is the eight degree-of-freedom motion system which is responsible for moving the dome and vehicle cab to simulate the linear and rotational accelerations of the vehicle. This is controlled via a dedicated PC which sends information to the motion system in a timely fashion over Ethernet.

8.3.2.2 The driving environment

The simulated scene was based on the UK road system, with participants required to drive on the left hand side of the road. For the entirety of the drive the road was a single carriageway which proceeded through a village setting, with a speed limit of 40 mph, onto a rural road of 60 mph speed limit. This format was repeated four times for each of the experimental drives undertaken; thus a depiction of an entire drive is shown in Figure 8.7, and there are example screenshots of the driving environment shown in Figure 8.8. The road consisted of straight and curved sections (see Figure 8.7). The curved sections comprised a gently winding road with alternating left and right turns. Besides the curvature of the road, all other driving conditions remained identical to the straight road condition. Whilst driving the course, participants were required to perform a number of tasks (auditory and visual). The experiment required the performance of these tasks at various points during the drive; sometimes in isolation, and sometimes simultaneously. Each of the tasks are described below.

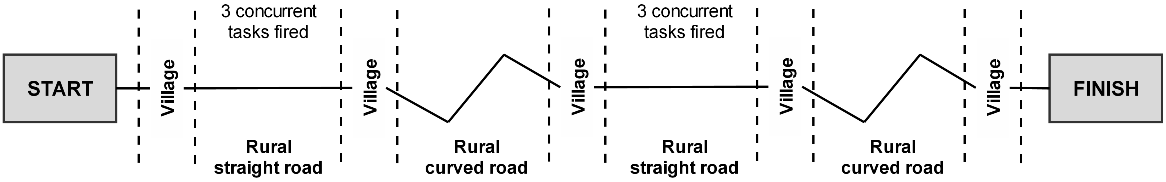
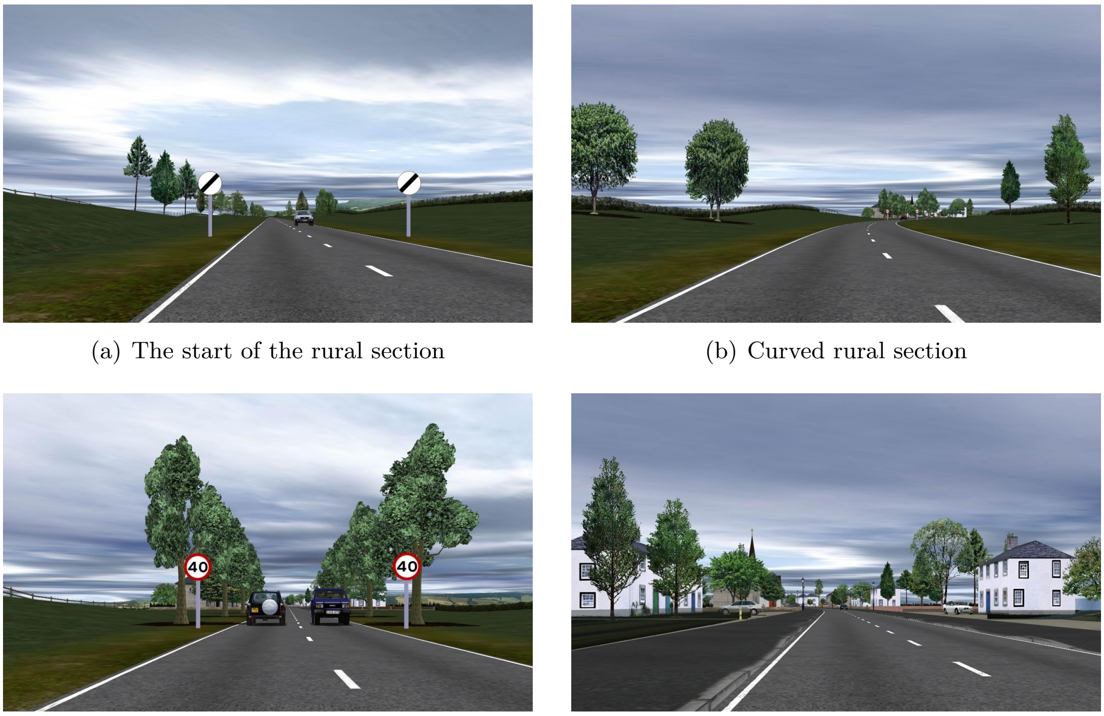


Figure 8.7 A depiction of one of the experimental drives that participants undertook in this study. The order of the conditions being presented was counterbalanced and no tasks were presented whilst driving in the village.



(a) The start of the rural section (b) Curved rural section

(c) Straight rural section (d) End of the rural section

Figure 8.8 Screenshots of the driving scene in this experiment.

8.3.2.3 Auditory tasks

The dCMT and PASAT were selected for inclusion in this study, based on the findings of the study presented in Chapter 7, with dCMT regarded as an ‘easy’ task, and PASAT as a ‘difficult’ task. The task presentation paradigms were very similar to those reported in Chapter 7; however there were some minor changes. The PASAT was adapted slightly so that in the current study it was system-paced, as opposed to self-paced. This change was made for two main reasons:

1. There were a number of set 30 second epochs within which the PASAT would be presented during the experimental drives. This epoch was stable across participants, so that there was an identical amount of driving, eye tracking and vDRT data for each participant under each condition. Using a self-paced PASAT task would have resulted in variable epochs, leading to inconsistencies in the amount of data between and within each participant.

2. Responses to auditory tasks were given vocally in this study, as opposed to manually on a computer keyboard number pad. It was, therefore, not possible to present a stimulus upon submission of a response. As such, the stimuli had to flow at a pre-defined rate. The change was not considered problematic; the original decision to use a self-paced presentation rate was because there was a focus on recording reaction time data. This was not the case in this study, in which only accuracy on, and adherence to, the auditory tasks was analysed.

Because the PASAT was a system-paced task, a suitable presentation rate for stimuli had to be considered. This decision was based on normative data presented in Chapter 7. Data from these experiments showed that mean response times plus standard error to PASAT were consistently under two seconds. Thus it was considered that participants should be able to perform the majority of sums presented at a pace of one digit every two seconds. In order to coincide with this, the dCMT was also presented at this pace. If a stimulus number was missed by the participant they were instructed to simply ignore that number and continue listening to the list, counting targets as they would have done without the mistake.

For the dCMT, participants were, again, required to only respond at the end of the digit list. There was very little difference in accuracy rates, or perceived difficulty, as a result of the ‘counting along’ alteration used in Experiment B of Chapter 7. Requiring one response at the end of the list reduced the chance of participants vocalising their answer over stimuli and masking them so that they were inaudible.

Stimuli were played using the car speakers, which had been calibrated to provide an accurate presentation level of 80 dB(A). The calibration process was as follows. A sound level meter was attached to a tripod placed on the driver’s seat of the car, with the microphone positioned at a representative level of a driver’s ear. A calibration speech-shaped noise, corresponding to the amplitude of the waveforms of the normal hearing and simulated moderate hearing loss conditions, was then played and the volume of the car speaker system was manipulated until a reading of 80 dB(A) was obtained.

The experiment described in Chapter 7 used a stimulus presentation level of 60 dB(A). The choice of 80 dB(A) as a presentation level in this study was deemed necessary as it provided audibility of stimuli over and above background road and vehicle noise. During pilot work, the background vehicle noise in the simulator cabin was measured at a level of 77 dB(A), thus it was considered that auditory stimuli played at 60 dB(A) would be largely masked. Further pilot work was performed in which a 28 year old male participant with normal hearing was asked to shadow number lists in the simulated moderate hearing loss condition, presented at levels of 60–80 dB(A) in increments of 5 dB(A). The participant reported difficulties in perceiving the sound source at any presentation level other than 80 dB(A). Thus to ensure audibility of stimuli, this presentation level was chosen.

Answers to the auditory tasks were recorded via a digital Dictaphone with a lapel microphone attachment. Participants were requested to clearly vocalise responses to each auditory task to ensure that the microphone picked up their responses to the individual trials. The digit presentations in each auditory task were also software-recorded so that an overall accuracy score for each trial could be derived.

The auditory tasks were presented in one of three listening conditions: (1) no sound (baseline), (2) normal hearing, and (3) simulated moderate hearing loss (henceforth referred to as 'SimHL'). Given the findings presented in Chapter 7, that performance on these auditory tasks did not differ significantly from normal hearing for a mild hearing loss, and previous experimental results which suggest the same trend (Hickson et al., 2010), mild hearing loss was not included in this study. The magnitude and configuration of the moderate hearing loss was kept the same as for the previous experiments (see Figure 8.9), given that it produced a significant effect on performance, and is representative of what might be expected of an age-related decline in hearing.

8.3.2.4 The vDRT

This experiment also used the vDRT to assess the effect of auditory task engagement on the workload experienced by subjects whilst driving.

The specific version of vDRT used was head-mounted, and consisted of a red LED suspended on a headset worn by the participant at an angle of approximately 20° to the left and 10° above the participants left eye (McGehee, 2014; see Figure 8.10). The LED illuminated at intervals of between 3–5 seconds, requiring a response from the participant. The presentation paradigm was summarised earlier in Figure 8.2, which shows the time periods associated with different stages of the vDRT presentation. The maximum value for the stimulus duration (SD) was set as one second.

Participants responded using a button placed on their thumb, such that it could be pressed against the steering wheel without having any influence on participants' ability to manipulate the vehicle controls. Where the vDRT was presented simultaneously with a

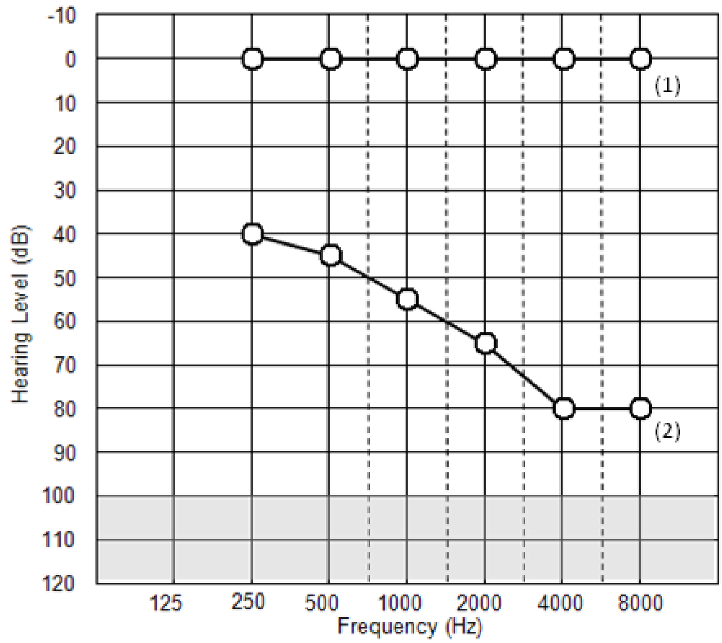


Figure 8.9 The two hearing loss conditions used in this study: (1) normal hearing; (2) moderate hearing loss.

Figure 8.10 A participant pictured whilst completing his practice drive. The picture shows him wearing the vDRT headset and response button which is positioned ready to respond by pushing it against the steering wheel.

listening task, vDRT trials began 15 seconds prior to the digit list, and continued until 15 seconds after the digit list had finished. This ensured that participants were given chance to perform the tasks reliably, without having to start numerous tasks at the same time. Furthermore, it was considered that after 15 seconds of vDRT performance, participants were adequately engaged to provide a stable measure of the effect of driving and/or auditory task on the performance of the vDRT. Analysis was only performed on the 30 second epoch where the two tasks overlapped.

8.3.3 Procedure

Upon attendance at the driving simulator, participants were welcomed to the facility and were given an information sheet explaining the purpose of the study and what would be required of them. Participants were left to read the information sheet and were asked if they had any questions regarding the protocol, prior to signing their consent to participate. Once registered for the study, participants were asked to provide information about their age, driving experience, and annual mileage.

Once this process was completed, participants were shown the setup of the equipment in order to understand where they would be driving and how to enter/exit the simulator vehicle and projection dome. If any questions arose the experimenter was on hand to provide answers. Following this familiarisation period, subjects were provided with a practice session (described in the following section). Upon successful completion of the practice session, participants performed two experimental drives (lasting approximately thirty minutes each) separated by a brief rest period.

Ethical approval was granted for this study by the University of Leeds ESSL, Environment and LUBS (AREA) Faculty Research Ethics Committee (reference: LTTRAN-048), and participants were required to sign informed consent prior to participating.

8.3.3.1 Practice session

The function of the practice session was to allow participants to familiarise themselves with the apparatus, and the tasks which would be used in the experiment.

Participants were fully briefed on the operation of the simulator and were asked to familiarise themselves with the vehicle. This included changing the position of the seat to obtain a comfortable driving position, and testing the vDRT response button in order to establish it could be pressed successfully with ease at every attempt. The experimenter fitted the head mounted LED to the participant, and adjusted the head strap so that it was comfortable.

Participants were then given fifteen vDRT presentations in isolation (i.e. without any driving task) to ensure successful understanding of the task. Two digit lists for each type of auditory task were then played over the car speakers, and the participant was asked to complete them in order to ensure understanding. Again this was performed in isolation (i.e. without any driving task). Two more lists for each task were then played, but under the moderate hearing loss condition. Again the participant was asked to respond in order to ensure audibility and understanding. In no case was the auditory task too quiet to hear, and as such participants were able to complete the listening tasks with a high level of success, regardless of the listening condition.

Participants were then provided with a practice drive. For the practice drive, the experimenter was seated in the vehicle with the participant in order to instruct, and answer any questions which arose. To begin with, there was a ten minute section of road in which no extraneous tasks were presented. As such, the participant was given ample opportunity to become used to the vehicle and driving environment. This section concluded with the participant drawing up behind a parked car at a set of traffic lights. It was stressed that they were to try and follow this vehicle and try to maintain a stable headway, without overtaking, regardless of task engagement. There was no following distance specified, rather participants were told to "follow at a distance with which they felt comfortable, and would adopt during normal everyday driving".

For the remainder of the practice drive, the participant was told to observe this vehicle following behaviour, and that a number of tasks would start at random intervals. For the practice drive the experimenter pointed out when a task was about to begin, and informed the participant what type of auditory task he/she should perform. In the practice session all auditory tasks were presented simultaneously with the vDRT under normally hearing and SimHL conditions. This decision was taken as it was considered the most complex task type, and so if participants were able to perform this condition successfully it was thought that they would also be able to perform all others. This approach also limited fatigue by keeping the session as short as possible. In its entirety, the practice session lasted approximately 25 minutes and the road length was 20km.

8.3.3.2 Experimental drive

Once the practice session was complete, and the experimenter was satisfied that the participant understood the experimental protocol, subjects were asked to complete two experimental drives in the vehicle on their own.

Prior to beginning each 60km drive participants were informed about the listening task they would perform for the proceeding drive, this was counterbalanced across drivers in order to avoid any order effects. Participants were given a break between the two experimental drives in order to reduce fatigue whilst driving.

The drive began with the participant pulling away and reaching the target speed. After a short free drive they stopped at a set of traffic lights, where the lead vehicle was stationary. The lead vehicle then pulled away and kept a consistent speed (governed by the speed limit imposed) ahead of the participant for the remainder of the drive (see Figure 8.11). A constant contra flow of traffic was present in order to make it difficult for the participant to attempt to overtake the lead vehicle, and as such they were consistently bound by the behaviour of the vehicle that they were following.

Figure 8.11 The typical driving scene from this experiment showing the vehicle that participants were asked to follow at a set distance.

8.3.3.3 Experimental design

In this experiment, only straight sections of road were analysed for clarity. Accordingly, this resulted in a $2\times3\times2$ within-subjects experimental design incorporating the factors: auditory task type (PASAT vs dCMT), listening condition (no sound, normal hearing, SimHL), vDRT presence (yes vs no). Thus, a schematic diagram of all experimental conditions is shown in Figure 8.12. The 'no sound' condition was a baseline against which the effect of auditory tasks in the normal hearing and SimHL conditions could be compared. As such, it was possible to establish the effect of an increasing difficulty of auditory task engagement on dependent variables. Because of the experimental design, there was a 'no sound' condition under both the dCMT and PASAT, as shown in Figure 8.12. These conditions actually reflected baseline performance in two separate drives, because, for clarity, participants performed two separate experimental drives and only one single auditory task type per drive, i.e. were instructed to perform PASAT for the entirety of their first drive and dCMT for the second drive, or vice versa. The implications of these duplicated experimental conditions for statistical analysis are addressed later in subsection 8.3.5.

Within each drive, conditions were counterbalanced using the Latin square method, and the drive order was also counterbalanced between participants in order to negate any order effects which may have arisen. During periods of rural driving, simultaneous tasks were fired for the participant to perform whilst continuing along the road. Participants were asked to focus equal attention on their performance of all tasks undertaken (driving, auditory and visual). Each task section lasted thirty seconds, and was followed by an interval, again of thirty seconds, before the next task was presented. This led to three task conditions performed per rural driving section, thus in a whole drive six task conditions were performed.

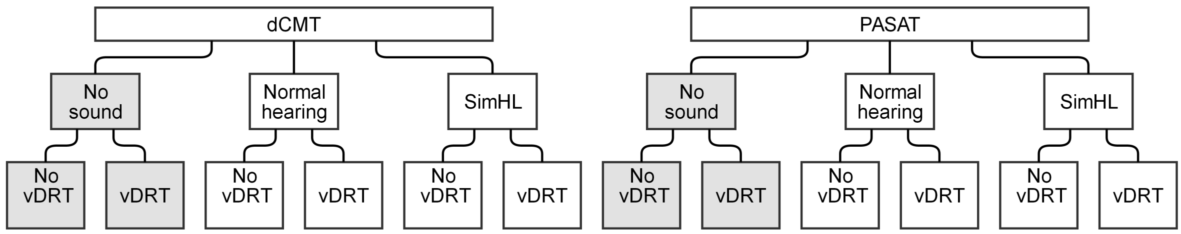


Figure 8.12 A schematic diagram of all experimental conditions undertaken by participants. Each participant undertook two drives; one in which PASAT was performed the other in which dCMT was performed. The shaded conditions essentially highlight a duplication.

8.3.4 Derivation of dependent variables

Data for a number of dependent variables was collected during this experiment from a number of sources. These are described in detail below.

8.3.4.1 Driving performance

Data on lateral and longitudinal position of the simulated vehicle, and its position in relation to other vehicles on the road, was recorded at a resolution of 60 Hz. For each condition, the data from each variable was identified as a 28 second period corresponding to the time between the first number presented in an auditory task, and the beep to signal the end of that list (see Figure 8.13). Thus measurements were reflective of vehicle control whilst the participant was fully engaged in performing the auditory task. A number of dependent variables were derived from the simulator and used for analysis in this study; these measures were based around those used in previous literature for the measurement of cognitive workload and its effect on driving (see e.g. Roskam et al., 2002; Knappe et al., 2007). A description of how each measure was calculated is given below.

1. **Speed**. Instantaneous speed values were derived for each participant. Minimum, maximum, mean and standard deviation values were then established for each participant during each of these periods.

2. **Headway** (i.e. the distance in time separating the participant and lead vehicles). Instantaneous headway values were recorded for each participant, and minimum, maximum, mean and standard deviation values were derived during each experimental condition. This gave an idea about the distance at which participants were following the lead vehicle, but also their ability to maintain a steady distance.

3. **Standard Deviation of Lane Position (SDLP)**. This was calculated using the position of the centre of the car in the lane in relation to the left-hand lane edge. Instantaneous position values were isolated for each condition, and a standard deviation was calculated to give a measure of the stability of the vehicle within its lane of travel.

4. **Minimum Time to Line Crossing (TTLC)**. This is a measure, for a given point in time, which specifies how long it would take for the vehicle to cross a lane boundary while maintaining its current course (Knappe et al., 2007). Thus using this measure will provide similar information as the SDLP, but puts it into a more applicable context by providing a point of reference (the lane edge).

5. **High Frequency Component of Steering Angle (HFC)**. This measure provides information about the amount of high frequency steering which occurs; reflecting steering corrections (Merat and Jamson, 2013). The steering wheel angle signal is filtered using a low-pass 2nd order Butterworth filter with a cut-off frequency of 0.6 Hz to eliminate noise. A signal is obtained (S_{all}), which is then filtered again using a low-cut 2nd order Butterworth filter with a cut-off frequency of 0.3 Hz. This produces a second signal (S_{high}) which reflects the high frequency component of the steering behaviour. The respective powers of S_{all} and S_{high} are then derived, and a ratio of these two numbers is calculated to provide the HFC. The greater the value of HFC, the more corrective movements which have been made using the steering wheel.

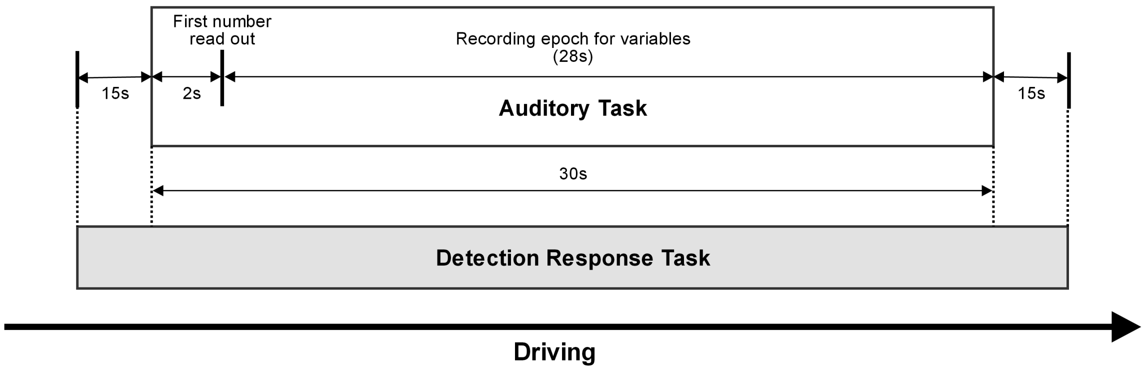


Figure 8.13 The recording epoch in relation to concurrent tasks for driving simulator, eye tracking, and vDRT measurements in each respective condition.

8.3.4.2 Eye tracking

In the same manner as for vehicular control variables, eye tracking data for each condition was isolated as 28 seconds which corresponded to the period shown in Figure 8.13. The eye tracking equipment used (SeeingMachines faceLAB v5) gives a measure of the quality of each observation it makes ranging from 0–3 (the higher the number, the better the quality). For these calculations, all data with a quality of less than 3 was discarded in order to ensure an accurate representation of eye movement behaviour. In cases where this resulted in less than 75% of the data being present in individual conditions (21/28 seconds), the participant was discounted from analyses using that condition. Two dependent variables were derived from the eye tracking data:

1. **Percent Road Centre (PRC)**; the proportion of time spent looking at the centre of the road. Pitch and yaw angles were taken as the average of data recorded from the left and right eyes. PRC was calculated by first rounding all instantaneous pitch and yaw gaze angles for the whole drive to the nearest whole number and finding the mode value of each. The mode gaze angle was assumed to be the road centre, as it is considered that this is the area in the driving scene people will look at most of the time (Ahlstrom et al., 2009).

   Within each condition, instantaneous yaw and pitch angles were then subtracted from the respective mode values in order to give a set of data centred on zero (i.e. their distance from the mode gaze). The road centre region was defined as a 6° circle surrounding the road centre, as has been the case for previous work using the same driving simulator (Jamson et al., 2011, 2013). The number of observations occurring within this region was then found, giving the percentage of observations occurring in the road centre region as a proportion of the total number of observations. A similar methodological approach has been described previously by Ahlstrom et al. (2009).

2. The **gaze concentration** around the road centre was defined as the standard deviation of linear distances in a given epoch from the assumed road centre. The road centre was established as above, taking the mode pitch and yaw angles for the entire drive. Instantaneous pitch and yaw angles were then subtracted from these values to centre the data set around zero (i.e. the distance from the road centre). Linear distances from the road centre were then calculated for each instantaneous observation. The standard deviation of these values was then calculated to give a gaze concentration for each experimental condition. Thus the higher the value, the less concentrated the gaze behaviour.

8.3.4.3 Detection Response Task

As can be seen in Figure 8.13, when present, the vDRT started prior to the auditory task commencing, and carried on past the completion of the auditory task. The rationale for including the vDRT was to investigate the effect of auditory task engagement on cognitive workload. Thus it was necessary to isolate just the vDRT responses which had been recorded during the 28 second window of auditory task engagement. Once this had been done for each condition, the variables of interest could be calculated:

1. The **hit-rate** of responses in each experimental condition (i.e. how many correct responses were given as a proportion of the number of stimulus presentations).

2. The mean **response time** for correct responses in each experimental condition.

8.3.4.4 Auditory tasks

Finally, auditory task responses resulted in two variables:

1. The **accuracy** of responses given in each experimental condition (i.e. how many answers were correct as a proportion of the number of stimuli).

2. Participants' **adherence** to the task, by counting the number of responses given (regardless of whether they were correct) as a proportion of the number of stimuli.

8.3.5 Statistical analysis

Prior to analysis, Shapiro-Wilk tests were used to establish the normality of each variables' distribution; where a non-normal distribution was noted, equivalent non-parametric testing was carried out. The experimental design used necessitated a number of comparisons to be made in order to answer the research questions posed. Because there was a duplication of 'no sound' conditions, and the fact that these did not reflect a level of auditory task difficulty (because they essentially presented no auditory task), performing a simple 2 (PASAT, dCMT) × 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA was not considered applicable. Accordingly, in order to investigate differences arising between dependent variables as a result of different auditory task types (dCMT vs. PASAT), a 2 (PASAT, dCMT) × 2 (normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA was performed on each dependent variable (see Figure 8.14).

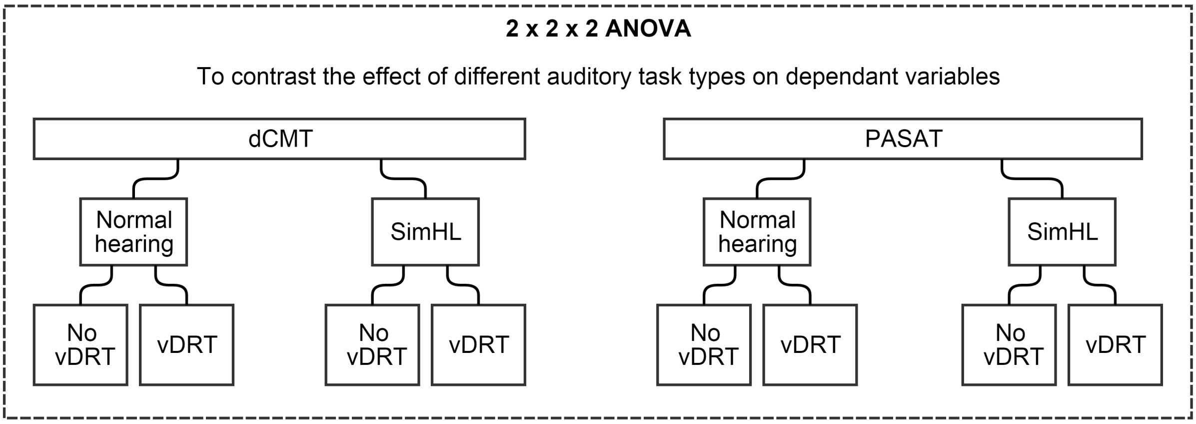


Figure 8.14 A depiction of the two ANOVAs used to investigate the effect of auditory task type on driving performance.

In order to test for differences in dependent variables as a result of different listening conditions (no sound vs. normal hearing vs. SimHL), two separate repeated measures ANOVAs of the same design were run on dCMT and PASAT drives respectively. These ANOVAs were a 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) design. Because no comparison was being made between conditions within dCMT and PASAT, no duplication occurred (see Figure 8.15).

Where applicable, Mauchly's test was carried out in order to establish whether the assumption of sphericity had been violated. Where this was the case the Greenhouse-Geisser estimates of sphericity were used in cases where $\epsilon < .75$, and the Hyuhn-Feldt estimates of

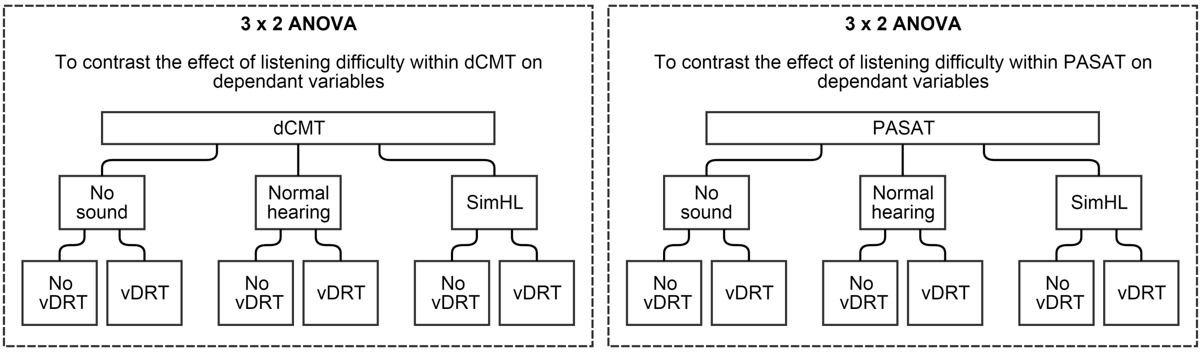


Figure 8.15 A depiction of the two ANOVAs used to investigate the effect of different listening conditions on driving performance.

sphericity were used in cases where $\epsilon > .75$ (Field, 2013). In cases of a significant result on ANOVA testing, post-hoc pairwise comparisons were carried out using the Bonferroni correction to account for the increased possibility of type I errors occurring in the analysis (Field, 2013).

8.4 Results

Analysis of the results is presented in this section under the four main headings: (1) Driving behaviour; (2) Eye tracking; (3) Detection Response Task; and (4) Auditory tasks.

8.4.1 Driving behaviour

8.4.1.1 Longitudinal vehicle control

Speed

A 3 (no sound, normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA was performed for each of mean, maximum, minimum and standard deviation of speed data recorded during the performance of dCMT. No main effects of hearing loss condition, or vDRT presence were shown in any of the analyses. No significant interactions were observed. Thus, the performance of vDRT did not have an effect on driving speed, nor did hearing loss have an effect on driving speed during the performance of dCMT.

A 3 (no sound, normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA was performed for each of mean, maximum, minimum and standard deviation of speed data recorded during the performance of PASAT. No main effects of listening condition, or vDRT presence were shown in any of these analyses. No significant interactions were observed. Thus, suggesting that the performance of vDRT did not have an effect on driving speed, nor did hearing loss have an effect on driving speed during the performance of PASAT.

A 2 (dCMT, PASAT) $\times$ 2 (normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA was performed on each of mean, maximum, minimum and standard deviation of speed data. No main effects of auditory task type, listening condition, or vDRT presence were shown in any of the analyses. No significant interactions were observed. There was no difference, therefore, in driving speeds between driving and performing dCMT or driving and performing PASAT.

Headway

A 3 (no sound, normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA was performed on each of mean, maximum, minimum and standard deviation of headway data recorded during the performance of dCMT. For mean, minimum, and standard deviation of headway data, no main effects of listening condition, or vDRT presence were shown in any of the analyses. No significant interactions were observed. However, a 3 (no sound, normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA of *maximum* headway data recorded during the performance of dCMT showed a main effect of listening condition ($F(1.7,59.4) = 3.68$, $p = .038$). Post-hoc pairwise comparisons, however, showed no significant differences between the three listening conditions (no sound, normal hearing and SimHL). Thus, the performance of vDRT did not have an effect on headway, nor did SimHL have an effect, over and above that of the normal hearing condition, on headway during the performance of dCMT.

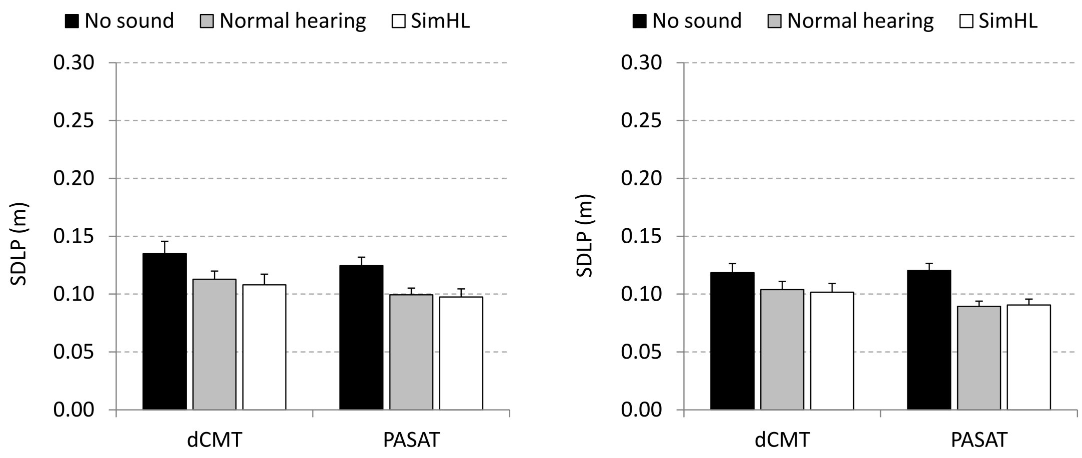
A 3 (no sound, normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA was performed on each of mean, maximum, minimum and standard deviation of headway data recorded during the performance of PASAT. No main effects of listening condition, or vDRT presence were shown in any of the analyses. No significant interactions were observed. Thus, the performance of vDRT did not have an effect on headway, nor did the SimHL condition have a greater effect than the normal hearing condition on headway during the performance of PASAT.

A 2 (dCMT, PASAT) $\times$ 2 (normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA was performed on each of mean, maximum, minimum and standard deviation of headway data. No main effects of task type, hearing loss condition, or vDRT presence were shown for mean, maximum, or minimum headway data. No significant interactions were observed. However, a 2 (dCMT, PASAT) $\times$ 2 (normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA of *standard deviation* of headway showed a main effect of task type ($F(1,35) = 4.40$, $p = .043$). Post-hoc analysis confirmed that headway was more variable during the performance of PASAT ($M = 4.94$ s) than it was during dCMT performance ($M = 4.05$ s).

8.4.1.2 Lateral vehicle control

Standard deviation of lane position

The mean SDLP for each experimental condition is shown in Figure 8.16. A 3 (no sound, normal hearing, SimHL) $\times$ 2 (no vDRT, vDRT) repeated measures ANOVA of SDLP data recorded during the performance of dCMT showed a main effect of listening condition (F(2,70) = 4.75, p = .012). Post-hoc analysis confirmed that lane position was less variable when dCMT was present. During the no sound condition SDLP was greater (M = .13 m) than it was during the normal hearing condition (M = .11 m; p = .055), and was significantly greater than in the SimHL condition (M = .13 m; p = .023). No significant difference was found between the normal hearing and SimHL conditions (p = 1.00). No main effect of vDRT presence was found, nor were any significant interactions observed.



(a) vDRT absent (b) vDRT present

Figure 8.16 The mean SDLP (±SE) under different study conditions.

A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of SDLP data recorded during the performance of PASAT showed a main effect of listening condition (F(2,70) = 19.04, p < .001). Post-hoc analysis confirmed that lane position was less variable when PASAT was present. During the no sound condition SDLP was significantly greater (M = .12 m) than it was during the normally hearing (M = .09 m; p < .001), and SimHL conditions (M = .09; p < .001). No significant difference was found between the normal hearing and SimHL condition (p = 1.00). No main effect of vDRT presence was found, nor were any significant interactions observed.

A 2 (dCMT, PASAT) × 2 (normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of SDLP showed a main effect of task type (F(1,35) = 6.10, p = .019). Post-hoc analysis confirmed that lane variation was higher during the performance of dCMT (M = .11 m) than it was during the performance of PASAT (M = .09 m). A main effect of vDRT presence also tended towards significance (F(1,35) = 4.01, p = .053), with post-hoc analysis showing that lane position was more variable when the vDRT was absent (M = .104 m), as opposed to when it was present (M = .096 m). No significant interactions were observed.

Minimum time to line crossing

A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of TTLC data recorded during the performance of dCMT showed no main effect of listening condition or vDRT presence, nor were any significant interactions observed.

Likewise, a 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of TTLC data recorded during the performance of PASAT showed no main effect of listening condition or vDRT presence, nor were any significant interactions observed.

A 2 (dCMT, PASAT) × 2 (normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of TTLC data showed no main effect of auditory task type, listening condition or vDRT presence, nor were any significant interactions observed.

High frequency component of steering

A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of HFC data recorded during the performance of dCMT showed no main effect of listening condition or vDRT presence, nor were any significant interactions observed.

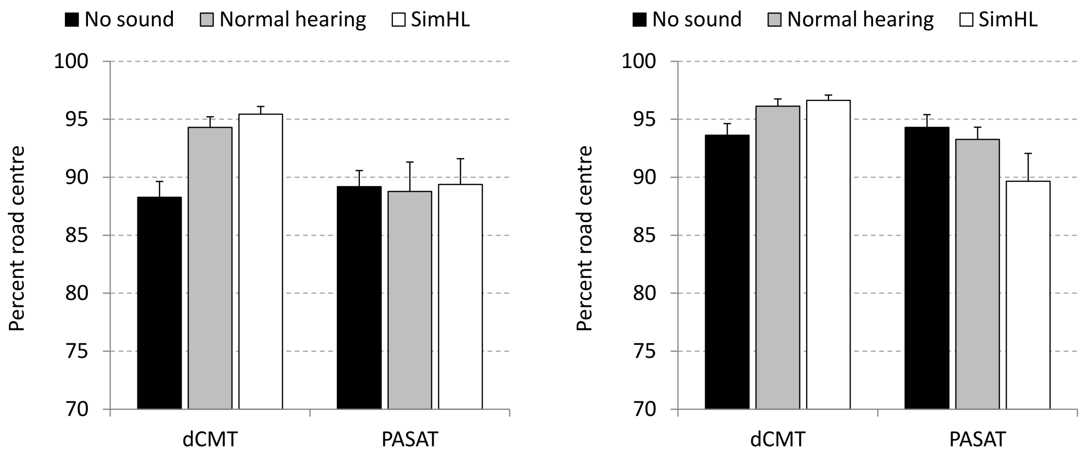
Likewise, a 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of HFC data recorded during the performance of PASAT showed no main effect of listening condition or vDRT presence, nor were any significant interactions observed.

A 2 (dCMT, PASAT) × 2 (normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of HFC data showed no main effect of auditory task type, hearing loss condition or vDRT presence, nor were any significant interactions observed.

8.4.2 Eye tracking data

Percent road centre

Mean PRC values are shown in Figure 8.17. A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of PRC data recorded during the performance of dCMT showed a main effect of listening condition ($F(1.4,47.9) = 21.48$, $p < .001$). Post-hoc analysis confirmed that PRC was higher when dCMT was being performed. PRC was significantly lower in the no sound condition ($M = 90.95\%$) than it was in the normally hearing ($M = 95.22\%$; $p < .001$) or SimHL ($M = 96.03\%$) conditions. However, the normally hearing and SimHL conditions did not significantly differ from each other ($p = .364$). A main effect of vDRT presence was also observed ($F(1.4,47.9) = 21.48$, $p < .001$), with post-hoc testing showing that PRC was higher when the vDRT was present ($M = 95.46\%$) as opposed to absent ($M = 92.67\%$). An interaction between listening condition and vDRT presence was also observed ($F(1.8,61.1) = 21.48$, $p = .001$). Post-hoc paired t-tests suggested that this was because, as the listening difficulty of dCMT decreased, the effect size associated with the increase in PRC grew. That is to say, the increase in PRC as a result of vDRT presence was greater for the no sound condition (M = 5.35%), t(35) = 5.28; $p < .001$, than it was for the normal hearing condition (M = 1.83%), t(35) = 2.58; p = .019, and to an even greater extent than the SimHL condition (M = 1.19%), t(35) = 2.15; p = .039.



(a) vDRT absent (b) vDRT present

Figure 8.17 The mean PRC (±SE) under different study conditions.

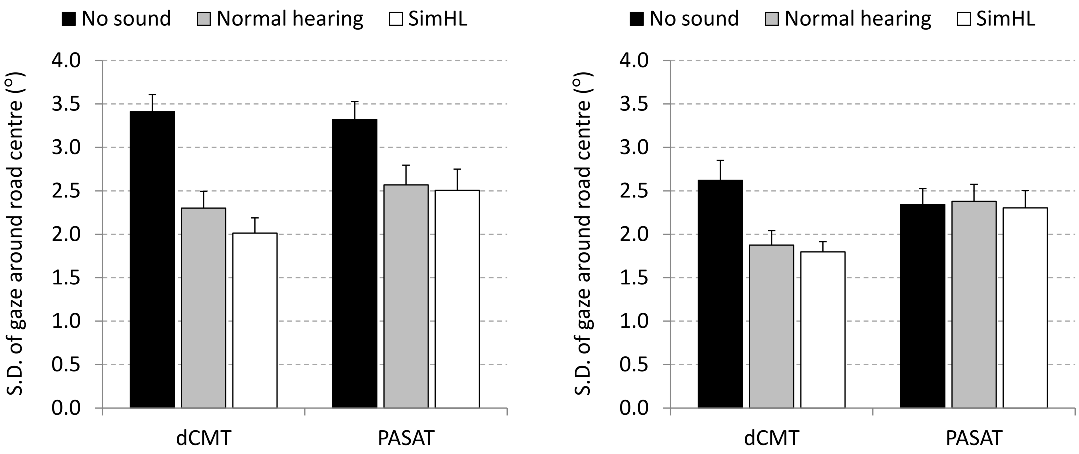
A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of PRC data recorded during the performance of PASAT showed a main effect of vDRT presence (F(1,35) = 27.87, $p < .001$), with post-hoc testing showing that PRC was higher when the vDRT was present (M = 92.41%) as opposed to absent (M = 89.11%). No main effect of listening condition was observed, nor was an interaction between listening condition and vDRT presence.

A 2 (dCMT, PASAT) × 2 (normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of PRC data showed a main effect of auditory task type (F(1,35) = 12.77, p = .001). Post-hoc analysis showed that PRC was higher when dCMT was being performed (M = 95.62%) than it was during PASAT performance (M = 90.27%). A main effect of vDRT presence was also observed (F(1,35) = 21.42, $p < .001$). Post-hoc analysis showed that PRC was higher when the vDRT was present (M = 93.92) than it was when the vDRT was absent (M = 91.97). No significant interactions were observed.

Gaze concentration

Gaze concentration to the road centre is shown in Figure 8.18. A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of gaze concentration data recorded during the performance of dCMT showed a main effect of listening condition (F(1.8,61.5) = 29.58, $p < .001$). Post-hoc analysis confirmed that gaze was less variable when dCMT was being performed. Gaze variability was significantly higher in the no sound condition (M = 3.02°) than it was in the normally hearing (M = 2.09°; $p < .001$)

or SimHL conditions (M = 1.91°; $p < .001$). However, the normally hearing and SimHL conditions did not significantly differ from each other (p = .558). A main effect of vDRT presence was also observed ($F(1,35) = 40.00$, $p < .001$), with post-hoc testing showing that gaze was less variable when the vDRT was present (M = 2.10°) as opposed to absent (M = 2.58°). An interaction between listening condition and vDRT presence was also observed ($F(2,70) = 4.04$, $p = .022$). In concurrence with PRC data, post-hoc t-tests suggested that this was because a progressive decrease in listening difficulty resulted in an increase in gaze variation as a result of the vDRT being present. The decrease in gaze concentration as a result of vDRT presence was greater for the no sound condition (M = .79°), $t(35) = 5.19$; $p < .001$, than it was for the normal hearing condition (M = .43°), $t(35) = 3.03$; $p = .005$, and to an even greater extent than the SimHL condition (M = .22°), $t(35) = 1.72$; $p = .094$.



(a) vDRT absent (b) vDRT present

Figure 8.18 The mean gaze concentration (±SE) under different study conditions.

A 3 (no sound, normal hearing, SimHL) × 2 (no vDRT, vDRT) repeated measures ANOVA of gaze concentration data recorded during the performance of PASAT showed a main effect of vDRT presence ($F(1,35) = 28.35$, $p < .001$), with post-hoc testing showing that gaze was less variable when the vDRT was present (M = 2.34°) as opposed to absent (M = 2.80°). No main effect of listening condition was apparent, although the ANOVA did tend towards significance ($F(1.4,47.7) = 3.11$, $p = .072$). An interaction between listening condition and vDRT presence was also observed ($F(1.7,60.9) = 6.72$, $p = .003$). As previously, post-hoc t-tests suggested that this was because a progressive decrease in listening difficulty resulted in greater decreases in gaze variation as a result of the vDRT being present. The decrease in gaze concentration as a result of vDRT presence was greater for the no sound condition (M = .98°), $t(35) = 4.67$; $p < .001$, than it was for the normal hearing condition (M = .19°), $t(35) = 1.42$; $p = .164$, and to an even greater extent than the SimHL condition (M = .20°), $t(35) = 1.37$; $p = .179$.

A 2 (dCMT, PASAT) × 2 (normal hearing, dCMT) × 2 (no vDRT, vDRT) repeated measures ANOVA of gaze concentration data showed a main effect of auditory task type ($F(1,35) = 6.29$, $p = .017$). Post-hoc analysis showed that gaze was more variable when PASAT was being performed ($M = 2.44°$) than it was during dCMT performance ($M = 1.20°$). A main effect of vDRT presence was also observed ($F(1,35) = 16.36$, $p < .001$). Post-hoc analysis showed that gaze was more variable when the vDRT was absent ($M = 2.35°$) than it was when the vDRT was present ($M = 2.09°$). No significant interactions were observed.

8.4.3 Visual Detection Response Task

Hit rate

The hit rates on vDRT are shown across experimental conditions in Figure 8.19. Shapiro-Wilk tests showed that vDRT accuracy data was not normally distributed, as such equivalent non-parametric statistical testing was employed for this dependent variable. A Friedman test performed on the three listening conditions in dCMT drives showed a significant difference in vDRT hit rates ($\chi^2(2) = 11.09,\ p < .001$). Subsequent Wilcoxon signed rank tests showed that vDRT hit rates were lower when dCMT was being performed. There was a significant difference in hit rates between the no sound and normal hearing conditions ($Z = -2.99$, $p = .003$), and the no sound and SimHL conditions ($Z = -1.96$, $p = .050$). However, the normal hearing and SimHL conditions did not significantly differ from each other ($p = .868$).

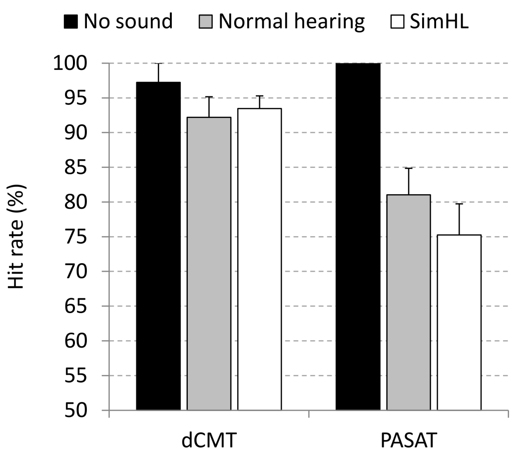


Figure 8.19 The mean hit-rate (±SE) on the vDRT for each experimental condition.

A Friedman test performed on the three listening conditions in PASAT drives showed a significant difference in vDRT hit rates ($\chi^2(2) = 31.66$, $p < .001$). Subsequent Wilcoxon signed rank tests showed that vDRT hit rates were lower when PASAT was being performed. There was a significant difference in hit rates between the no sound and normal hearing conditions ($Z = -3.74$, $p < .001$), and the no sound and SimHL conditions ($Z = -4.20$, p

$< .001$). However, again the normal hearing and SimHL conditions did not significantly differ from each other (p = .113).

A Friedman test performed between matched PASAT and dCMT experimental conditions showed a significant difference in vDRT hit rates ($\chi^2(3) = 21.72,\ p < .001$). Subsequent Wilcoxon signed rank tests showed that vDRT hit rates were lower when PASAT was being performed than when dCMT was being performed. Hit rates were significantly lower during PASAT for both the normal hearing (Z = -2.78, p = .005), and SimHL (Z = -3.32, p = .001) conditions.

Response time

Unlike hit rate data, vDRT response times conformed to a normal distribution, thus parametric testing was carried out for this variable. A one-way ANOVA showed a significant difference in vDRT response times between listening conditions during dCMT drives (F(1.7,58.8) = 67.98, p < .001). Post-hoc analysis showed that response times were slower when the dCMT was present (either in the normal hearing or SimHL condition). When no task was present, response times to vDRT were faster in the no sound condition (M = 303.92 ms) than they were during the performance of dCMT in the normal hearing (M = 433.13 ms, p < .001), or SimHL (M = 445.02 ms; p < .001) conditions. However, the normally hearing and SimHL conditions did not differ from each other (p = 1.00).

A one-way ANOVA showed a significant difference in vDRT response times between listening conditions during PASAT drives (F(2,70) = 63.57, p < .001). Post-hoc analysis showed that response times were slower during the performance of PASAT (regardless of whether it was presented in the normal hearing or SimHL condition). When no task was present, response times to vDRT were faster (M = 294.56 ms) than they were during the performance of PASAT in the normally hearing (M = 464.36 ms, p < .001), or SimHL condition (M = 449.26 ms; p < .001). However, the normally hearing and SimHL conditions did not differ from each other (p = 1.00).

A 2 (dCMT, PASAT) × 2 (normal hearing) repeated measures ANOVA of vDRT response time data showed no significant main effects or interactions.

Multivariate analysis

There was some evidence of the SimHL reducing vDRT hit-rate during the performance of PASAT, however this reduction was not significantly different from the hit-rate obtained during the normally hearing condition. In order to investigate whether SimHL might affect vDRT hit-rate and response time to a statistically significant extent when taken together, a MANOVA was run with both hit-rate and response time as dependent variables, and listening condition as the independent variable. No significant effect of listening condition was found (p = .57), reiterating that SimHL does not affect performance on vDRT.

8.4.4 Auditory tasks

Accuracy

Shapiro-Wilk tests exhibited that data regarding the accuracy on PASAT was not normally distributed, and in the case of dCMT data was non-parametric, thus non-parametric statistical testing was employed to analyse auditory task accuracy data. Response paradigms were different between PASAT and dCMT, so their respective results were not contrasted.

A Friedman test performed on the four conditions in dCMT drives was not statistically significant, thus no further testing was carried out on data regarding the accuracy of dCMT. The mean accuracy for PASAT in each relevant experimental condition is thus shown in Figure 8.20.

A Friedman test performed on the four conditions in PASAT drives showed a significant difference in PASAT accuracy across experimental conditions $(\chi^2(3) = 10.02,\ p = .018)$. Subsequent Wilcoxon signed rank tests showed that PASAT accuracy was lower in the SimHL condition, but only when vDRT was absent. Pairwise comparisons between the no vDRT and vDRT conditions *within* normally hearing and SimHL conditions revealed no significant differences. Pairwise comparisons *between* normal hearing and SimHL conditions, however, showed a significant difference in the case of the vDRT absent condition (Z = -2.86, p = .004).

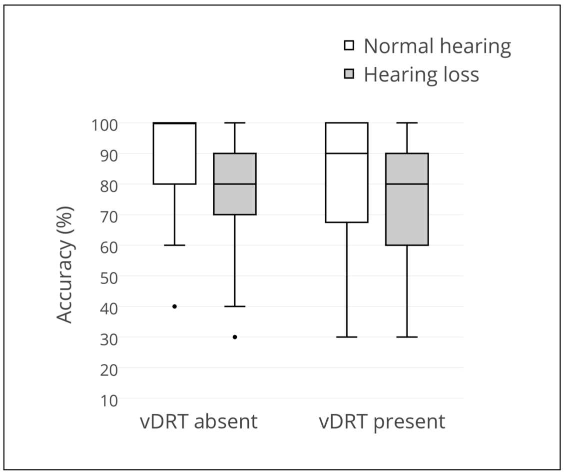


Figure 8.20 Auditory task accuracies for answers given to PASAT with and without the vDRT.

Adherence

In terms of the number of answers given to the auditory tasks, no participant missed an answer to dCMT under any experimental condition, thus it was considered that engagement in this task was optimal. Shapiro-Wilk tests showed that adherence data for PASAT was not normally distributed, and so non-parametric statistical analysis was used. Adherence to PASAT is summarised in Figure 8.21.

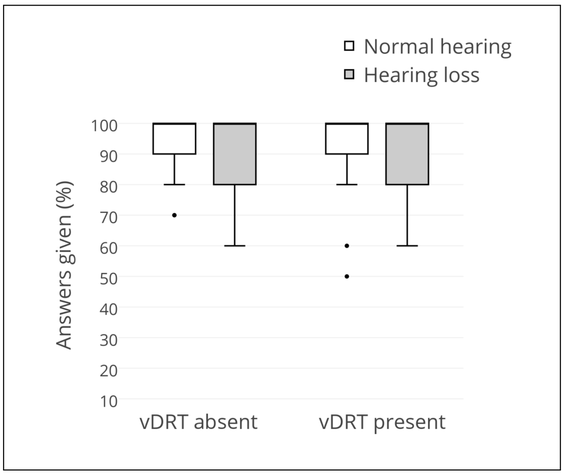


Figure 8.21 Auditory task adherence for answers given to PASAT with and without the vDRT.

A Friedman test performed on the four conditions in PASAT drives was not statistically significant. Thus, the number of answers being given to PASAT across experimental conditions were considered comparable. Accordingly, no further statistical testing on adherence to PASAT was carried out.

8.4.5 Summary

A summary of the statistically significant results which have arisen in this study are shown in Table 8.2, and are discussed in the following section with a particular focus on the most relevant to this thesis; the influence of SimHL on driving.

8.5 Discussion

This study investigated the influence of two cognitively engaging auditory tasks, which have already been shown to vary in the demand they impose (see Chapter 7), on driving performance, eye movements and cognitive load whilst driving. The main aim was to establish if the inclusion of a SimHL on auditory stimuli increased the difficulty of auditory tasks sufficiently to affect driving performance measures, eye movement behaviour, or vDRT performance. In this section the results in relation to the effect of SimHL will primarily be discussed. The effect of vDRT performance and the difference between auditory task types will be given less attention, given that they were not the main focus of this study.

8.5.1 Driving performance measures

No extraneous effect of SimHL on any of the measures of longitudinal or lateral vehicle control used in this experiment was observed. This suggests that SimHL did not raise the demands of the auditory task sufficiently to have an effect on measures of driving performance. This finding does not support the hypothesis that hearing impaired individuals

Table 8.2 Significant main effects and interactions suggested from the analysis of this experiment.

Dependent variable		Significant findings
Speed	·	No effect observed
Headway	·	More variable during PASAT than dCMT
SDLP	· ·	Less SDLP during PASAT than dCMT Greater SDLP when no auditory task is being performed
Minimum TTLC	·	No effect observed
HFC	·	No effect observed
PRC	· · · ·	Less when no auditory task is being performed Greater during dCMT Greater during vDRT During dCMT: increase as a result of vDRT presence greater with decreasing listening difficulty
Gaze concentration	· · · ·	Less when no auditory task is being performed Less for PASAT than dCMT Less for vDRT absent During both dCMT and PASAT: increase as a result of vDRT presence greater with decreasing listening difficulty
vDRT	· · ·	Lower hit rate when an auditory task is being performed Lower hit rate for PASAT than dCMT Longer response time when an auditory task is being performed
Auditory task	·	Less accurate in SimHL condition when vDRT absent

are disproportionately affected, in terms of their driving performance, whilst driving under conditions of auditory task load. However, there are a number of factors which are important in the analysis of this experiment, and these require careful consideration before inferences are made.

Longitudinal vehicle control

It was hypothesised that speed would be disproportionately reduced by the presentation of an auditory task in the SimHL condition, because past work has found a reduction in travelling speed during periods of high cognitive load imposed by auditory tasks (Lansdown et al., 2004; Jamson and Merat, 2005; Lewis-Evans et al., 2011). As cognitive load was hypothesised to be greater under the SimHL condition, it was thought that driving speeds would be slowest under the SimHL condition. The fact that this has not been shown, questions whether peripheral hearing impairment causes enough of a cognitive load to have an effect on driving behaviour of this type.

Likewise, it was considered that headway would follow a similar pattern, with an increased following distance during the SimHL condition, given that past work has shown participants adopt an increased headway during auditory task engagement (Strayer and Drew, 2004; Jamson and Merat, 2005). However, this study showed that headway was not significantly affected by the presentation of auditory tasks in the SimHL condition. Whilst there was some evidence that the performance of PASAT increased the variability of headway when under normally hearing conditions, there was no effect when this task was presented in the SimHL condition.

Small headways have been associated with an increased crash risk (Evans and Wasielewski, 1982; Risto and Martens, 2014). Alm and Nilsson (1995), therefore argue that longer following distances can be associated with an increased 'safety buffer', as they give drivers more time to react to sudden changes in behaviour of the lead vehicle. The authors suggest that drivers may be aware of dangers associated with performing secondary tasks whilst driving (e.g. a delay in detecting salient visual information; Strayer et al., 2003), and increase headway in order to account for this. Similarly, Jamson and Merat (2005) explain slower driving speeds during task engagement (Brown et al., 1969; Haigney et al., 2000; Strayer and Drew, 2004; Rakauskas et al., 2004; Jamson and Merat, 2005) as a simplification of the primary driving task in order to 'free-up' resources for the performance of a secondary task. The fact that participants' longitudinal vehicle control was not disproportionately affected by auditory tasks presented in the SimHL condition, suggests that they perceived no extraneous demand as a result of stimulus clarity, and did not alter their speed or headway accordingly.

Thorslund et al. (2013b) argue that changes in driving speeds of *hearing impaired* drivers are also undertaken in order to provide an increased 'safety buffer'. The fact that this study has shown no such behaviour as a result of SimHL suggests that factors outside of peripheral hearing loss have an effect on hearing impaired drivers' longitudinal vehicle control. Given that Thorslund et al.'s (2013b) sample had a mean age of over 60 years, the different results exhibited in this study lead to the suggestion that factors co-existing with hearing loss (e.g. age-related cognitive decline) may raise the cognitive workload requirements of performing a task whilst driving, and this may lead to an increased 'safety buffer' being adopted by slowing driving speeds and maintaining an increased headway. However, it is not clear from the results of Thorslund et al. (2013a,b) whether this adaptation to driving speed occurs simply in situations where participants are engaged with a secondary task, or whether hearing impaired drivers have developed a slower driving speed more generally. The authors have found a slower driving speed during periods of secondary task engagement (Thorslund et al., 2013b), and during the absence of a secondary task (Thorslund et al., 2013a).

Although Hickson et al. (2010) did not find an effect of hearing loss on driving speed in their experiment, this result does not contradict the assertion that adaptive driving behaviour is responsible for changes in the speed choice of hearing impaired drivers. The authors did not incorporate any interaction with other vehicles in their experiment, thus an increased 'safety buffer' would not have been required. It could, therefore, be that the increased propensity of slower driving speed in hearing impaired noted by Thorslund et al. (2013a,b) is only apparent during driving environments where other vehicles or obstacles are present.

Lateral Vehicle Control

Lateral vehicle control was hypothesised to be 'improved' by the performance of an auditory task, and the addition of a SimHL was hypothesised to further 'improve' this aspect of driving performance. Previous work has exhibited a decrease in SDLP as a result of auditory task engagement (Brookhuis et al., 1991; Engström et al., 2005b; Jamson and Merat, 2005). Thus, lateral vehicle control appears to be an 'encapsulated' part of driving, as described by Medeiros-Ward et al. (2014). Accordingly, a diversion of attention away from this task would actually lead to its improvement. As SimHL was hypothesised to disproportionately increase cognitive load on the auditory task, the allocation of more attention away from the driving task should have resulted in a more marked improvement in lane-keeping ability.

The current study showed less lateral deviation of the vehicle during auditory task engagement, and this increased when the type of auditory task being performed was made more challenging (e.g. PASAT was performed as opposed to dCMT). However, there was no extraneous increase in lane-keeping ability as a result of SimHL, again suggesting that the demand imposed as a result of SimHL was not significantly increased. By Medeiros-Ward et al.'s (2014) reasoning, it would, therefore, appear that SimHL did not require the allocation of more attention to the auditory task, and so there was no difference in SDLP noted between the SimHL and normally hearing conditions.

Minimum TTLC and HFC were also used as measures of lateral vehicle control in this study. However, no significant differences in these dependent variables were found as a result of auditory task engagement. This was expected given that they are measuring similar constructs to SDLP. Accordingly, it would appear that, whilst the driver is able to maintain a more stable position within the lane of travel during auditory task engagement, this does not arise as a result of more corrective steering wheel manoeuvres, nor does it result in a significantly decreased risk of crossing the road marking into the next lane.

There is no prior evidence to suggest that lane-keeping is improved for hearing impaired individuals during auditory task engagement, it is simply a hypothesis based on past experimental findings in normally hearing individuals (Brookhuis et al., 1991; Engström et al., 2005b; Jamson and Merat, 2005). However, it might be that an effect was absent in this study as a result of using a young, normally hearing sample. Again, factors which co-exist with hearing loss may be responsible for an increased cognitive demand of performing auditory tasks whilst driving. The use of a young, normally hearing sample in this study may have removed these co-existing factors and reduced the extraneous demand that hearing loss and these extraneous factors together pose for auditory task performance.

Contrary to the findings in the current study with regard to speed and headway, the absence of an increased lane-keeping ability cannot be simply explained by an adapted driving style in response to a long-standing hearing loss. Because lateral vehicle control is thought to be an encapsulated, automatic component of driving (Medeiros-Ward et al., 2014) it is likely to be made worse by directed attentional control from the driver. Therefore, whilst alterations in longitudinal vehicle control may arise from behavioural changes in the hearing impaired demographic, it is not considered that lateral aspects of vehicle control can be altered as a result of goal-directed behaviour. Thus, the absence of adaptive driving behaviour which is exhibited by 'real' hearing impaired drivers (e.g. slower driving speeds; Thorslund et al., 2013a,b) in this young, normally-hearing sample does not explain the absence of the hypothesised changes in lateral vehicle control under SimHL conditions.

8.5.2 Eye movement behaviour

In this study it was hypothesised that PRC would be greater when auditory tasks were presented in the SimHL condition, and that gaze concentration to the road centre would also be increased. This is because previous work has shown that engagement in auditory tasks decreases the spread of visual search, increasing PRC in normally hearing individuals (Victor et al., 2005; Engström et al., 2005b; Victor et al., 2008). The extra demand imposed on the auditory task by SimHL was hypothesised to make this trend more marked, and show a further reduction in visual search and an increase in PRC from the normal hearing condition. A trend of this type would explain Hickson et al.'s (2010) findings of a reduction in road sign recognition (visual information which was presented in the periphery).

PRC and gaze concentration were significantly increased by the addition of an auditory task, and this trend became more marked as a result of increasing the demand of the type of auditory task being performed (e.g. PRC was increased to a greater extent during PASAT than it was during dCMT). However, there was no extraneous effect of SimHL noted on either dependent variable. In the context of SDLP results, this is unsurprising. A decrease in SDLP as a result of auditory task engagement whilst driving (e.g. Brookhuis et al., 1991) has been explained through an increase in gaze concentration to the road centre (Engström et al., 2005b). This pattern of eye movement behaviour is thought to arise because the most likely area in which an obstacle will arise whilst driving is in the forward position (Jamson and Merat, 2005). It is argued that the increased gaze to the road centre gives a superior perception of the roadway, in turn leading to improved lane-keeping (Jamson and Merat, 2005). Because, improved lane-keeping as a result of SimHL was not apparent in this study, it follows that PRC and gaze concentration were also comparable between normally hearing and SimHL conditions.

Although no previous study has explicitly investigated the effect of *auditory distraction* on eye movements whilst driving in the hearing impaired demographic, some research has noted that eye movement behaviour is altered during normal driving in these individuals. Importantly these findings have arisen from studies either using no task secondary to driving (Thorslund et al., 2013a), or a secondary visual task (Thorslund et al., 2014).

However, manipulations in eye movement behaviour noted by Thorslund et al. (2013b, 2014) were explained by hearing impaired drivers adopting a more careful approach to driving. The authors noted that hearing impaired drivers adopt an increased propensity for using their rear and side view mirrors. They envisaged that this type of behaviour occurred as an acclimatisation effect, stating that hearing impaired drivers may be less aware of their surroundings whilst driving, and accordingly compensate by increasing their visual scanning of the surrounding environment. Again, this type of behaviour is unlikely to have been observed in this experiment, in a young, normally hearing sample who have been suddenly presented with a SimHL.

The changes to eye movement behaviour that were expected in this study were different from the type of adaptive eye movement behaviour Thorslund et al. (2013a) observed. Instead, alterations were expected as a direct consequence of engaging with an auditory task. Both of these underlying reasons for altered eye movement behaviour in hearing impaired drivers can explain the results of Hickson et al. (2010). The authors did not measure eye movements during their experiment, and explain their finding as a reduction in the functional visual field as a result of a disproportionate increase in cognitive workload. It is, however, not possible to infer if this is correct through the data they collected. Their results could, in addition to a visual field reduction or adapted driving style, also be explained by a failure of general attention selection, rather than a specific perceptual narrowing (Victor et al., 2008). This was expected in this study, and was measured by using the vDRT during auditory task engagement.

The current experiment did not assess a visual field reduction in hearing impaired drivers whilst engaging in an auditory task, but the possibility that perceptual narrowing may be affected by hearing loss (Hickson et al., 2010) should not be discounted. Indeed, the study described in Chapter 5 hinted that the performance of UFOV, which measures visual processing efficiency in the functional visual field, might be reduced in ‘real’ hearing impaired individuals whilst they perform an auditory task. Further research using a task such as the PDT, which can measure visual responses at varied eccentricities, may be applicable in this regard. What the results of the current study do suggest, however, is that SimHL did not increase the cognitive demands of driving with an auditory task over and above those imposed during the normal hearing condition.

8.5.3 Visual Detection Response Task performance

vDRT performance also supported the finding that SimHL does not raise cognitive workload of driving whilst performing an auditory task over and above a normal hearing condition. The vDRT was included in this study as a sensitive measure of cognitive workload, and was seen as an applicable manner in which to test the inference that cognitive load would be higher under SimHL conditions. The vDRT is hypothesised to measure general attentional control (Victor et al., 2008), providing an indirect measure of a reduction in attention switching ability between the visuospatial sketchpad and phonological loop. This was hypothesised to occur more often in hearing impaired individuals (see Chapter 3).

It was expected that SimHL would make auditory information less distinct, engaging the central executive more, and thus reducing the ability to switch between the phonological loop (for the performance of the auditory task) and the visuospatial sketchpad (for the performance of the vDRT and driving). By this reasoning, vDRT hit rate should have decreased and response time increased during auditory task engagement with a SimHL. Hit rate and response time to the vDRT was negatively affected by the concurrent performance of an auditory task, and increasing the difficulty of the task type being performed resulted in further decrements (e.g. response times were slower and hit rates higher during PASAT). However, the addition of a SimHL on either auditory task type had no extraneous affect on either hit rate or response time.

This finding suggests that cognitive workload was no greater as a result of performing auditory tasks in the SimHL condition whilst driving. Again, this reiterates the suggestion that the peripheral representation of a sound source does not disproportionately increase cognitive load. Instead, factors which co-exist and interact with hearing loss, or an adaptive driving style, are likely to be responsible for previous experimental findings exhibiting driving changes as a result of hearing loss.

In fact, if the vDRT were being undertaken by a driver with an actual hearing loss, performance could be subject to complications arising as a result of an adaptive driving style. Thorslund et al. (2013b) cite a withdrawal from secondary task engagement in hearing impaired drivers as part of their hypothesised adaptive driving style. Thus, it is considered that an increase in cognitive load experienced by those with actual hearing impairment may lead them to shed performance of secondary tasks (e.g. the vDRT) whilst driving. Thus the measurement of vDRT performance whilst driving in those with an actual hearing loss would be of interest.

One interesting trend arose, in that during the performance of PASAT, SimHL tended to reduce the hit-rate achieved by participants. This trend was not significant, but does raise questions over whether there may have been a small effect of SimHL on the performance of vDRT. This was the only measure used in this study which showed a trend of being affected by SimHL. Therefore, there is a possibility that peripheral hearing loss might lead to an increase in cognitive workload whilst an auditory task is being undertaken. Likewise, if the vDRT is considered as a metric of peripheral hazard detection (as was discussed earlier), this may suggest that some hazards are seen less often as a result of hearing impairment during the performance of an auditory task. Although this cannot be inferred from the current data, given the lack of statistical significance, this possibility should not be discounted. This is particularly true, because it ties in with the results of Hickson et al. (2010), who found a reduced propensity of their hearing impaired drivers in noticing peripheral road signs during auditory task engagement.

It should also be noted that a main effect of vDRT presence on gaze concentration and PRC was found. This is an important methodological consideration for future work in the area, because it exhibits that vDRT is not a completely unobtrusive measure of workload. This concurs with the interaction that was also present between listening condition and vDRT absence for PASAT accuracy, suggesting that vDRT has a bearing on the performance of independent variables. In fact, the significant interactions between listening condition and vDRT presence for PRC and gaze concentration data are considered artefacts, and have not, therefore, been analysed in any further detail. The increase in gaze concentration as a result of vDRT being present was shown to become greater with decreasing listening difficulty. However, closer inspection of the results suggests that this had occurred simply because there was a hierarchy of differences in eye movement behaviour as a result of listening difficulty, which was then masked by vDRT causing a similar pattern of eye movement behaviour across listening conditions. This gave the false impression that vDRT presence and listening condition had interacted, whereas listening condition was the independent variable responsible for the statistical significance. Statistical outcomes such as these highlight the caution that should be exercised when using vDRT in experimental studies of this type.

Prior to the performance of this study, it was considered that undertaking the vDRT might alter eye movement behaviour, as past work using the similar PDT task resulted in participants fixating on visual stimuli presented in the periphery of vision (Miura, 1986). Accordingly, the experimental design accounted for this possibility, so that eye movement behaviour could be analysed independently of vDRT presence. Thus, this effect of vDRT on dependent variables associated with eye movement behaviour did not have a impact on analyses concerned with answering the research questions posed.

8.5.4 Auditory task performance

dCMT and PASAT results were analysed in this study to check whether participants had withdrawn from performing the auditory tasks in order to simplify the driving task. This would have reduced the cognitive workload imposed by the SimHL and was, as such, not desirable in answering the research questions posed. There was, however, no evidence to suggest that this was the case. There was no significant difference between the number of answers given to either auditory task in the normal hearing and SimHL conditions.

However, when the vDRT was absent, PASAT accuracy was significantly decreased during the SimHL condition. The absence of a reduction in PASAT accuracy in the SimHL condition during the presence of the vDRT requires explanation. It may have been that during what were effectively *triple* task conditions (driving, auditory task, and vDRT), a raised cognitive workload led to task performance being highly variable, reducing the power of the statistical analysis undertaken. Indeed, the standard deviation of auditory task accuracy during PASAT trials with vDRT present was greater (S.D. = 6.0) than it was when the vDRT was absent (S.D. = 4.6).

The finding of a lower PASAT accuracy in the SimHL condition raises two important possibilities:

1. A dual-task cost as a result of performing PASAT in the SimHL condition whilst driving was observed, and accordingly auditory task performance was reduced.

2. Participants managed their cognitive load in order to maintain driving performance by decreasing attention to the performance of auditory tasks once demand reached a certain level.

The adherence data for the auditory tasks suggests that it is the first of these two possibilities which is most likely. Furthermore, whilst the second of these two suggestions can explain why driving performance decrements as a result of SimHL were not observed in some instances, it cannot for others. PASAT was the only task which was affected by SimHL in terms of its accuracy, dCMT was not. Some dependent variables were affected to a greater extent by dCMT than PASAT (PRC and gaze concentration), and others were still affected by the performance of dCMT even if not to a greater extent than PASAT (SDLP and vDRT). SimHL is thought to raise the processing demands required to complete the dCMT task successfully (see Chapter 7). Thus, because participants engaged in this task regardless of the listening condition, its performance in the SimHL should have resulted in some driving behaviour changes, but did not.

Accordingly, it was concluded that participants did not simply withdraw from performing the PASAT under difficult listening conditions in order to maintain driving performance. Rather, it is argued that a dual-task cost was observed, such that when the listening task became more difficult (as a result of SimHL), the cognitive demands imposed by undertaking the auditory task whilst driving were sufficient to cause a disruption on performance of the auditory task. Whilst the auditory task appeared sensitive to this increased cognitive load, measures of driving performance and the vDRT did not.

Hickson et al. (2010) is the only other study which has investigated the effect of auditory distraction whilst driving in hearing impaired individuals. They employed a task very similar to PASAT, whereby participants were presented with two numbers in the auditory modality, and had to add them together. Data regarding the accuracy on this auditory task during driving was presented, and suggested that there was no significant difference in the number of answers being given, or the accuracy on sums, between normally hearing and hearing impaired participants. However, their presentation rate for stimuli was 3.5 seconds, compared to the 2 seconds used in this study, thus giving participants extra time in order to be able to formulate a response. It should be noted that this difference in presentation rate was also more likely to make the task in the current study more challenging, yet a significant effect on driving as a result of SimHL was still not found. This further compounds the inference that factors co-existing with hearing loss which were present in the experiment of Hickson et al. (2010) are likely to be mostly responsible for driving performance decrements.

8.5.5 General considerations

The results of this study suggest that hearing loss does not disproportionately affect driving performance whilst a concurrent auditory task is being undertaken. An ecologically valid SimHL (see Chapter 6) has been applied and compared against a normal hearing condition in a simulated driving environment whilst performing an auditory task, and no difference in any of the dependent variables used has been observed. Previous research which has found an effect of hearing loss on driving contradicts these results (Hickson et al., 2010) and prompts considerations regarding the reasons for no effect of SimHL being observed in this experiment. Given the methodology used, a number of explanations for the differences in outcomes against previous research can be suggested:

1. Aspects of SNHL not emulated by the SimHL are responsible for driving decrements.
2. Factors which co-exist with SNHL are, at least in part, responsible for driving decrements.
3. An adapted driving style, which has been developed over a long period of time is responsible for certain observations regarding driving performance.

These factors are all feasible, and it is entirely possible that they may all (or a number of them) account for the lack of an effect of SimHL on dependent variables in this experiment.

However, it is considered that the SimHL used replicates the most troublesome aspects of SNHL for speech understanding (Moore, 2007), and in an ecologically valid and accurate manner, as has been suggested by the work described in Chapter 6. Thus it was considered that the SimHL used provided a fair approximation of actual hearing loss, and was applicable for use in the current study. However, the possibility that it has not captured all pertinent aspects of SNHL should not be discounted, and further research with young individuals with an actual hearing impairment should be undertaken in order to expand the research findings presented here.

However, in support of the hearing loss simulation, the experiments described in Chapter 7 showed that listening effort demands imposed by a moderate SimHL caused auditory tasks of all difficulties to be more poorly performed than they were under normally hearing conditions. This suggests that cognitive workload is higher as a result of performing an auditory task in the presence of a moderate SimHL.

One difference in the presentation paradigm of auditory tasks in this study should, however, be pointed out. Whereas in the previous study auditory stimuli were processed at an input level of 60 dB, in this experiment they were processed at a reference level of 80 dB. The reason for this change was to provide audibility of the auditory tasks. Furthermore, in each case the selected levels were considered ecologically valid in terms of the environments in which they were being presented; a normal conversational level of speech equates to 60 dB (Skinner et al., 1997), and the background level of noise in car cabins is such that it would require an increase in this level in order to ensure audibility (Wang and Wang, 2012).

The change to input level would have had no effect on the spectral smearing portion of the SimHL and would, therefore, not have changed the clarity of the auditory signal. It would, however, have made subtle changes to the loudness recruitment portion of the SimHL. These changes may have restored some of the loudness relationships between phonemes which were absent at a 60 dB input level, potentially reducing the amount of explicit processing required in order to perform the auditory task. However, an increase in explicit processing would still be expected as a result of just the spectral smearing paradigm, as stimuli were being presented in a background noise (Baer and Moore, 1993). Accordingly, an effect on experimental outcomes would still have been expected. Future work should, however, assess whether different presentation levels of auditory stimuli have an effect on driving under the same experimental conditions.

Besides limitations of the hearing loss simulation, the two possibilities for differences in experimental outcomes between the current study and past research are that differences in driving in hearing impaired individuals may occur as a result of adaptive driving behaviour which is developed over time, or that factors which co-exist with hearing loss are responsible (at least in part) for driving decrements. These two suggestions can feasibly both occur simultaneously, in fact they can both explain outcomes in previous research. This study employed a SimHL in young, normally-hearing participants, whereas previous study investigated older individuals with a 'real' SNHL (Hickson et al., 2010). SimHL was used in order to isolate the effect of sensory acuity as a result of hearing impairment from other age-related factors which co-exist with hearing loss. The difference in outcomes appears to suggest that it is co-existing factors, present in the study of Hickson et al. (2010), but not in this study, which are mostly responsible for noted driving decrements whilst concurrently performing an auditory task in those with a hearing loss.

Thorslund et al. (2013a,b, 2014) did not investigate the effect of auditory distraction on driving, but did assess the driving of those with an actual hearing loss. This work was carried out with an older demographic, primarily experiencing acquired hearing losses, and also found alterations in driving outcomes. In these experiments no auditory distraction (and thus increase in cognitive load as a result of listening effort) was present, and so the research group argue that these outcomes have been observed as a result of adaptive driving behaviour. Something which, the authors argue, has been adopted in response to a lack of situation awareness whilst driving. This adaptive driving behaviour would certainly not have been present in the sample used in this study, and so might be a further reason why changes in driving performance were not observed under SimHL conditions.

8.5.6 Study limitations

This study has investigated the effect of hearing loss on driving under one specific set of circumstances. This approach was taken in order to ensure experimental control, and has resulted in a number of important outcomes, which enhance knowledge regarding the effect of hearing loss on driving performance. However, its findings should not necessarily be considered as transferable to *all* driving situations.

The experiment was run in a simulator, and the environment consisted of a single carriageway road and a car-following scenario. Hickson et al. (2010) found their results during a field trial, meaning that discrepancies between simulator and 'real world' driving might justify differences in experimental outcomes. Furthermore, the complexity of the driving scenario was not considered to be significantly challenging.

A wide variety of driving scenarios were not covered in this experiment (e.g. complex manoeuvres, driving in heavy traffic, motorway driving). SimHL could have an effect on the dependent variables used in this experiment during more visually demanding situations, though it is not possible to say whether this is the case from the design of this study. If the visual demand of the driving task is increased, disproportionate central executive engagement with auditory operations may have more of a negative effect on the efficiency with which visual processes can be carried out. The study of Hickson et al. (2010) did not incorporate any other traffic, but it did present participants with a number of tasks they had to complete whilst driving, some of which were visual in nature (e.g. road sign recognition, perception of obstacles). Thus, the difference in findings noted here may have been as a result of a lower primary driving demand. Further research employing the experimental paradigm used here, but in environments with different driving demands, would, therefore, be of interest in the development of knowledge in this area.

Furthermore, only a single degree and configuration of hearing loss has been investigated. A moderate SimHL was chosen for investigation, given that this level of impairment has affected driving performance in past study (Hickson et al., 2010). The configuration of the SimHL condition was chosen to be reflective of age-related hearing loss (Gates and Mills, 2005), and will have, therefore, provided similar perceptual consequences as have been apparent in previous work, given that an elderly sample was studied (Hickson et al., 2010). Without investigating different hearing loss severities and types, it is not possible to say whether SimHLs of greater magnitudes would produce an effect on driving performance. According to the ELU model, the greater the degree of hearing loss, the greater the amount of explicit processing required, and the greater the effect on concurrently performed tasks. Investigation of greater hearing loss severities was not possible using the type of SimHL employed in this experiment. Future work investigating more severe SimHL would be of interest in the development of work in this area.

8.6 Conclusions

It was hypothesised that a SimHL would cause an increase in the listening effort required to perform aurally presented tasks. This increased listening effort was postulated to manifest in an exacerbation of driving performance changes which occur as a result of auditory task performance. This study has not presented evidence to support this hypothesis. No difference in measures of longitudinal or lateral vehicle control, eye movement behaviour, or cognitive workload were apparent between normal hearing and SimHL conditions. These outcomes remained regardless of the difficulty of the auditory task being undertaken. However, there is some evidence that auditory task performance whilst driving might suffer as a result of hearing loss. Thus, research into the applicability of in-car systems which make use of auditory information for hearing impaired individuals is considered important.

A failure to observe these hypothesised outcomes has led to the conclusion that a facet of hearing impairment not captured by the SimHL used is responsible for previously noted changes in driving behaviour. These factors have been identified as: (1) physiological aspects of SNHL which the SimHL did not address, (2) complications which co-exist with hearing loss, such as age-related changes in cognitive function, and (3) the development of 'coping strategies' in hearing impaired drivers in order to negate these driving performance decrements. Further work is required in order to establish to what extent each of these issues plays a part in driving performance alterations. Thus, the results of this study present novel information regarding the effect of hearing impairment on driving and related tasks, though they should not be considered entirely conclusive. Rather, they raise important questions which require further investigation. The most pertinent questions which arise are discussed in the final chapter of this thesis (see Chapter 9).

Chapter 9

Final Discussion and Recommendations

In this chapter, the results obtained from the programme of research reported in this thesis are discussed in relation to the research questions posed in Chapter 2 (see Table 2.4). The implications of the research are also discussed, and recommendations made regarding the direction of future research.

9.1 Main findings

Eight specific research questions were posed for investigation in Chapter 2, and the series of experiments reported in this thesis have answered these, as follows:

1. **Is hearing impairment seen as a cause of any problems for driving by people with a hearing loss?**

2. **Do people with a hearing loss report any alterations to their own driving behaviour?**

3. **Is there a difference between self-reported and pure tone audiometry measures of hearing loss in terms of their affect on experienced driving problems?**

These questions were all addressed by the study described in Chapter 4, which found that hearing impaired individuals did not see hearing loss as a cause of any driving problems. Although some respondents did suggest that hearing loss might present a problem for driving generally, this was certainly not the majority view, nor was there a consensus regarding specific manners in which this might be the case. Accordingly, the study also showed no significant alterations in driving behaviour in hearing impaired individuals, except for some reporting that they drive more slowly than a comparable normally hearing group. This finding concurred with past research in the area (Picard et al., 2008; Thorslund et al., 2013a,b), and suggested that hearing impaired drivers might alter their driving speed in order to account for driving decrements. Although it should be considered that this may simply have been due to a general increase in speed limit compliance over time.

Furthermore, it was shown that self-reported hearing loss was a better predictor of reports of driving difficulties/behaviour changes than pure tone audiometry data. This suggested that *functional hearing ability* (the extent to which somebody struggles with their auditory impairment) governs the extent to which somebody experiences driving problems as a result of hearing loss, rather than an individual's auditory sensitivity. This did not entirely agree with recent hypotheses regarding why hearing loss affects driving, because auditory sensitivity has previously been considered the most important factor (Hickson et al., 2010). Thus, questions were raised about the influence of other factors which are linked to functional hearing ability (e.g. cognitive skills; Salonen et al., 2011).

Given the disconnect between reports of hearing loss affecting driving and changes in driving speed, there was some concern that introspection had not been possible to establish what effect hearing loss was having on driving. i.e. although past driving decrements had been shown in hearing impaired individuals (Hickson et al., 2010), this happened subconsciously and therefore respondents were unaware and unable to report the behaviour. Another possible explanation for this was that those who self-reported a hearing loss were simply more likely to self-report other problems (e.g. experiencing an affect of their hearing loss on driving), hence the association between self-reports of driving difficulty/behaviour frequency and hearing loss.

Because of the uncertainty regarding the efficacy of self-reports, a more objective course of research was implemented in order to identify whether hearing loss was subconsciously presenting problems for driving performance. Chapter 4 did not present any specific driving concerns for investigation, given that the majority of hearing impaired respondents had indicated no effect of hearing loss on driving. Accordingly, findings from previous research informed the direction of the first objective study. Past evidence had suggested that hearing impaired individuals were less visually aware than their hearing counterparts whilst concurrently performing an auditory task and driving (Hickson et al., 2010). This was an interesting finding because it concurred with research showing an effect of auditory distraction whilst driving on failures of visual attention (e.g. Strayer et al., 2003) and alterations in eye movement behaviour (e.g. Victor et al., 2005). Therefore, it was considered that visual attention may be one of the manners in which hearing impairment presented problems for driving performance in the presence of a concurrent auditory task. Accordingly, the next research question posed was:

4. **Does hearing impairment disproportionately alter visual processing efficiency during auditory task engagement?**

The study described in Chapter 5 investigated this possibility in a laboratory setting. In line with previous work (Wood et al., 2006), the results showed that visual processing within the useful field of view is significantly less efficient when a concurrent auditory task is being undertaken. The results also suggested that this effect was more pronounced in hearing impaired individuals, but the results did not reach statistical significance.

Interestingly, some other differences between normally hearing and hearing impaired individuals arose, although they were not expected. For example, hearing impaired participants appeared to have poorer Working Memory abilities than their hearing counterparts; a reading span task was significantly more poorly performed by the hearing impaired sample. Furthermore, the results hinted that hearing impaired individuals performed a rhyme task more poorly than their hearing counterparts, and were also worse at performing the divided attention subtest of UFOV in the absence of any auditory task. These results were curious, because the only variation expected between the hearing impaired and normally hearing individuals was a difference in outcomes as a result of auditory task engagement.

This evidence, arising from Chapter 5, highlighted concerns that the only difference between hearing impaired and normally hearing individuals was not auditory perception. Rather, poorer Working Memory abilities, which data suggested were more prevalent in hearing impaired individuals, were suggested as having an effect on study outcomes. This potential reliance on factors extraneous to hearing loss was of particular concern, because hearing loss is an age-related sensory impairment (Davis, 1995), and as such brings with it a range of other age-related considerations. An important example being cognitive decline (Salthouse, 1991), a factor which becomes even more pertinent in light of the issue that hearing loss might be associated with cognitive decline (see Chapter 3). Such examples of discrepancies in the baseline abilities of hearing impaired and normally hearing individuals may go some way towards explaining why past research investigating the effect of hearing loss on driving has reached mixed outcomes. For example, past work has given contradictory conclusions in terms of road traffic accident rates (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008 vs. McCloskey et al., 1994; Sims et al., 2000; Green et al., 2013), and has shown visual distraction to affect hearing impaired individuals to a greater extent than normally hearing drivers (Thorslund et al., 2013b, 2014) when it should not, according to the hypothesis of other authors (Hickson et al., 2010).

This problem led to the identification of a method which could control for these extraneous variables which were potentially having an effect on study outcomes. A method of simulating hearing loss in young, normally hearing individuals was identified and tested, and showed that hearing loss could be administered in an accurate and ecologically valid manner (see Chapter 6). Applying this simulation allowed for a within-subjects experimental design to be used so that the only difference between experimental conditions would be auditory perception. However, it was unclear whether a simulation of hearing loss would result in increased listening effort, as is hypothesised to occur in individuals with an actual hearing loss (Rabbitt, 1991). In order to test this assumption, the next research question posed was:

5. **Is the performance of auditory-based cognitively demanding tasks made more difficult by sound distortion representative of hearing loss?**

The study described in Chapter 7 tested whether this SimHL resulted in performance decrements on auditory-based cognitive tasks. The results showed that tasks of varied difficulty were negatively affected by the inclusion of a SimHL, thus suggesting that auditory sensitivity has the capacity to affect cognitive performance as a result of perceptual difficulties. This finding concurred with the hypothesis of past work that sound distortion has a downstream effect on cognitive processes (e.g. Rabbitt, 1991).

Hickson et al. (2010) had previously extended this thinking to show that the effect of increased listening effort in hearing impaired individuals impacts on driving performance. However, their findings arose from a sample of older adults, which would have incorporated the extraneous factors suggested in Chapter 5. Accordingly, it was questioned whether SimHL would show an effect on driving performance in the presence of an auditory task. This would establish the extent to which hearing loss *alone* affected driving performance, and so the next research questions addressed were:

6. **Does the distortion to sound brought about by hearing impairment at a *peripheral level* have the capacity to affect driving performance when a simultaneous auditory task is present?**

7. **What are the measurable vehicle control and behavioural correlates of this effect on driving performance?**

8. **Do people limit engagement in secondary tasks in order to maintain successful driving performance?**

The study reported in Chapter 8 confirmed that auditory task engagement whilst driving leads to a previously observed set of driving performance outcomes (see Chapter 2). However, it was shown that this trend did not become more marked as a result of SimHL. Therefore, the data gathered suggested no vehicle control or behavioural correlates which are affected by peripheral hearing loss when driving and concurrently performing an auditory task. There was also little tangible suggestion that this observation had arisen as a result of withdrawal from auditory task performance in order to maintain driving performance.

Therefore, this work has suggested that mild or moderate, age-related hearing loss *in its own right* does not have the capacity to impair driving performance to a disproportionate extent as a result of auditory distraction. This is contrary to past work which has observed an effect of hearing loss on driving; whether it be implied by road traffic accident rates (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008), or as a result of measured driving performance (Hickson et al., 2010; Thorslund et al., 2013a,b, 2014). Given that these studies all used participants with actual hearing loss, and did not extensively control for cognitive abilities, it can be concluded that cognitive factors are (at least in part) responsible for driving decrements in the hearing impaired.

Furthermore, some of the studies which have found an effect of hearing loss on driving safety have been carried out in specific demographic groups, which may have confounded their outcomes. Both Barreto et al. (1997) and Picard et al. (2008) studied individuals with noise-induced hearing losses who worked in noisy, industrial environments. It is considered that those who develop a significant noise-induced hearing loss in such an environment may have undertaken risky behaviour such as neglecting to wear hearing protection provided by their employer. Behaviour of this type may predispose other risky behaviour which is linked with road traffic accident frequency, such as speeding (Aarts and Van Schagen, 2006). Likewise, pre-existing cognitive impairments resulting in individuals not understanding the importance of hearing protection may also have led to the development of a noise-induced hearing loss. These potential confounds highlight the possibility that other factors tied to hearing loss may have inflated the effect found on driving performance in previous studies.

It is important to note, however, that the potential susceptibility of past work to the influence of these co-existing factors does not render it flawed. In fact, quite the opposite - the work is highly valuable because it provides an ecologically valid view of driving in the hearing impaired demographic. Given the link between hearing loss and age (Davis, 1995), those with a hearing loss will often exhibit age-related information processing declines which may cause driving performance decrements, and as such the cumulative effect of *all* of these factors should (and appears to be) reflected in experimental data. However, whilst this ecological approach to research in this area can say something about the driving performance of hearing impaired individuals, it cannot explicitly say anything about driving performance considerations *as a direct result* of hearing impairment. This distinction is highly important because the latter provides information about why driving performance decrements occur, how they might be remedied, behaviours which may exacerbate these problems, and suitable procedures for identifying drivers who are at-risk. It is this information which the work described in this thesis has begun to unravel.

Thus, this programme of novel research has significantly contributed to evidence needed to answer the overarching research question posed by this thesis: “does hearing impairment affect driving performance?” The message arising from prior research is that auditory distraction does have an effect on hearing impaired drivers’ performance (Hickson et al., 2010). However, the work described in this thesis has shown that damage to the peripheral auditory system (in line with with mild or moderate, age-related hearing loss) in isolation is not likely to be responsible for significant changes in the measures of driving performance which were recorded in this programme of research. It should, however, be noted that the driving and auditory tasks employed in the final investigation described in this thesis were of low complexity. The use of either more complex driving situations (e.g. traversing intersections, lane changing tasks etc) or more complex auditory processing tasks (e.g. sentence or prose processing) may have revealed significant impacts of SimHL on driving.

Thus, further research is required before the above suggestions can be more definitively proven. Further, since severe hearing loss could not be adequately simulated, it was not examined in the studies described in this thesis. Therefore, no strong conclusions regarding the effect of severe hearing impairment on driving performance can be made.

Given the discrepancy between the findings of the research described in this thesis, and that which has been previously performed, it appears that the presence of other co-existing factors, such as age-related changes in cognitive function, may have the capacity to interact with hearing loss and potentially affect driving performance. This consideration has been brought to light by the findings of this programme of research. However, the extent to which these co-existing factors influence and interact with driving performance cannot be explicitly inferred from my studies. This is because the focus of this work was to extract the influence of *peripheral hearing loss alone* on driving, rather than investigate the effect of other co-existing factors.

9.2 Real-world application

The primary concern of this line of research is road safety; i.e. the consideration that hearing impaired individuals may be less safe drivers than normally hearing individuals. This was one of the main motivations for my research, given that some authors have hypothesised a decrease in driver safety for this demographic (Barreto et al., 1997; Ivers et al., 1999; Picard et al., 2008; Hickson et al., 2010), and that certain licensing authorities do not allow people with a severe hearing impairment to drive, under the perception that their (and others') safety is affected by this impairment (World Federation of the Deaf and the Swedish National Association of the Deaf, 2008). In contrast to these opinions, the work reported in this thesis suggests that hearing loss *alone* does not predispose a driver to be more affected by auditory distraction, and is thus not necessarily any less a safe driver than a normally hearing individual in this regard. Therefore, the sentiments of Hickson et al. (2010) that hearing impaired individuals should limit their engagement with in-vehicle devices whilst driving appears to be an overly-simplistic one. The implication of my work is that other co-existing factors must be considered alongside hearing loss in order to gauge potential driving performance decrements.

A great deal of attention has been paid to identifying at-risk drivers in terms of visual sensory impairment (see e.g. Anstey et al., 2005 for a review), and there are strict sensory criteria that must be met for an individual to be granted a driver's licence. Currently, no such licensing criteria exist for hearing impaired individuals in the United Kingdom. However, objective hearing tests are required by certain licensing authorities (e.g. Australia) to ensure their commercial drivers meet a minimum hearing standard. Because the work presented in this thesis has shown no extra effect of auditory distraction on the driving of hearing impaired individuals as a result of hearing loss *alone*, tests of hearing sensitivity used in isolation are unlikely to predict driving decrements as a result of auditory distraction. Much like evidence regarding visual sensory problems and driving, the effect of hearing loss on driving appears to be reliant on higher-order cognitive processes which are not specifically targeted by objective measures of sensory functioning (e.g. pure tone audiometry, or static visual acuity for a visual parallel). Thus, any assessment to be developed in this regard must reflect higher-order cognitive capabilities, much like UFOV has attempted to achieve in the realms of assessment in terms of visual function. Of course, an extension to UFOV incorporating auditory distraction would require validation.

However, it would appear that the main focus of licensing authorities with regard to hearing loss is the inability to hear acoustic information in the car, rather than an additional effect of auditory distraction. It is difficult to comment on this aspect of the research topic, because this project did not aim to investigate the effect of unheard auditory information in the driving environment. An absence or attenuation of auditory cues in the driving environment may cause problems for the hearing impaired, but this is an intuitively predicted issue, and one which could be remedied by adaptive mechanisms such as an improvement in visual processing ability (Bavelier et al., 2000, 2006). This problem may also be improved through the use of hearing aids. Indeed, the Australian licensing authority themselves allow the use of hearing aids in order to allow an individual to meet their minimum hearing requirements for the issue of a commercial license.

Hearing aids may also be applicable in minimising the effect of auditory distraction, as they are thought to reduce listening effort (Sarampalis et al., 2009). However, this should be considered carefully because emerging evidence suggests that the benefit derived from hearing aids is linked to Working Memory abilities, such that those with better cognitive abilities will derive more benefit from hearing instruments (Lunner et al., 2009; Rudner et al., 2011). This is concerning because an assertion arising from the work reported in this thesis is that cognitive skills interact with hearing loss to produce an effect on driving performance; thus those with lesser cognitive abilities will be the ones who experience problems with their driving, as well as being those who do not gain optimal benefit from hearing instruments. Furthermore, the efficacy and acceptance of hearing aid use in the car has been previously considered a concern (McCloskey et al., 1994), particularly as the acoustic environment is not particularly favourable for their success (with high levels of background noise and an inability to face the speaker). Indeed, this was mentioned anecdotally by audiological clinicians in my study reported in Chapter 4.

Chapter 4, however, also showed a very positive attitude from hearing impaired individuals about the use and benefit of hearing aids during driving. Contrary to the perceptions of clinicians, patients reported using their hearing aids more often whilst driving than during everyday situations and noted no negative impact of their hearing instruments on driving performance. Audiologists often inform patients of acoustic environments in which hearing aids may or may not be beneficial, managing patient expectations of hearing instruments in order to maximise the benefit from rehabilitation (Knudsen et al., 2010). A preconception that hearing aids would not work well whilst driving may, therefore, lead to inaccurate use of hearing aids by patients, and should be reconsidered in light of the findings reported in Chapter 4.

However, the commonly held view that hearing loss does not affect driving (see Chapter 4) tends to suggest that employing rehabilitative measures aimed at improving the driving performance of hearing impaired individuals may be difficult. This is because those with a hearing loss will not wish to employ a measure aimed at improving something which is not perceived as a problem in the first instance. Thus, a challenge which faces clinicians is how hearing impaired individuals can be persuaded to accept advice with regard to improving driving performance.

Another potential manner in which the effects of hearing loss on driving performance can be counteracted is by adopting a driving style accounting for driving performance shortcomings. It is suggested that adaptive driving behaviour is undertaken in those with a hearing loss (Thorslund et al., 2013a,b, 2014), though it is uncertain whether this driving behaviour is as a result of hearing loss, co-existing factors, or an amalgamation of the two. What *is* clear, from the results presented in Chapter 4, is that this phenomenon is likely to be of a subconscious nature; hearing impaired individuals do not see hearing impairment as a barrier for successful driving performance, and so why would they adapt their driving behaviour accordingly? Despite this rationale, there have been multiple observations of differences between the behaviour of hearing impaired and normally hearing individuals, even in the absence of auditory distraction. This adaptive behaviour is likely to have been developed over a prolonged period of hearing loss, and would therefore not have been observed in Chapter 8 which involved participants who did not have a hearing loss. Indeed, no behaviour comparable to that noted by Thorslund et al. (2013a,b, 2014) was observed in the work described in this thesis, suggesting that alterations in driving behaviour do not arise as an instantaneous reaction to hearing loss.

The finding in Chapter 4 that hearing impaired individuals reported a slower driving speed is applicable in this regard. A slower driving speed is one of the adaptive behaviours which Thorslund et al. (2013a,b) argue they have observed in hearing impaired individuals. This is corroborated by the data that I collected using the DBQ in a sample who largely had an acquired, age-related hearing loss. It follows that this adaptive driving style is present in individuals who experience hearing loss over a long period, but not in those who have a sudden hearing loss, given that SimHL resulted in no alteration in driving speed in a normally hearing sample (see Chapter 8).

9.3 Contribution to the field

Investigating the effect of hearing loss on driving is a complex problem. The research presented in this thesis has suggested that there are a range of potential issues, which can be confounded by a number of different parameters related to hearing loss (e.g. hearing loss severity and type), but also by cognitive abilities. Furthermore there is little experimental evidence in the area, and research to date has not reached a consensus (see Chapter 2). It is important to note that my work does not describe the effect of all aspects of hearing loss on driving performance, and that other factors (i.e. audibility) may also play a role. Further work is required to understand the exact contribution of these factors, although a summary of my proposition is given in Figure 9.1.

The work described in this thesis suggests that hearing loss is likely to be a consideration for auditory distraction in the driving domain *only* when it is paired with co-existing factors such as age-related cognitive decline. Accordingly, the schematic makes a primary distinction between younger and older hearing impaired individuals, because these co-existing factors (e.g. cognitive decline) are more likely to occur in older adults. Of course, the distinction between 'young' and 'old' is not unambiguous, and the schematic should not be considered in this way. Instead, the influence of cognitive factors is likely to increase with age in a continuous fashion, though for ease of understanding the schematic has been presented making a clear categorical distinction between the two. Because, younger hearing impaired individuals are less likely to exhibit cognitive deficits, they are shown as mostly being subject to lack of audibility issues whilst driving, whereas older hearing impaired individuals may also experience a disproportionate effect of auditory distraction, as suggested by Hickson et al. (2010). The aim of this work was not, however, to establish whether co-existing factors act alone, or in conjunction with hearing loss, to cause driving decrements in the elderly. Thus, the schematic does not specify the exact origin of the disproportionate effect of auditory distraction in the older hearing impaired demographic.

Two potential barriers to successful driving performance in hearing impaired individuals were identified in Chapter 2 (reduced audibility and increased effect of auditory distraction). In this schematic, they are both hypothesised to lead to an effect on driving performance. However, there is no evidence to suggest that reduced audibility has a *direct* effect on driving performance, this has simply been hypothesised by some authors (Coppin and Peck, 1963, 1965; Slawinski and MacNeil, 2002). In contrast, there *is* evidence for a disproportionate effect of distraction in hearing impaired drivers, whether it be as a result of auditory (Hickson et al., 2010) or visual (Thorslund et al., 2013b, 2014) task engagement. There is also evidence that adaptive driving behaviour is undertaken in hearing impaired individuals in order to negate driving performance decrements (Thorslund et al., 2013a,b, 2014). These changes in driving behaviour also have the capacity to alter driving performance. Thus, the use of a neutral term ('effect on driving performance') as an outcome for the schematic is deliberate, because adaptive behaviour countering any negative effects may well result in a positive influence on driving performance.

I envisage this schematic as a common framework for future research in this area. The uncertain relationships between particular nodes (highlighted by the use of a broken line), are key areas that require further research in order to build a more complete picture of how hearing loss interacts with driving performance. This serves as a common baseline from which researchers can work - a tool which is not currently available in this area.

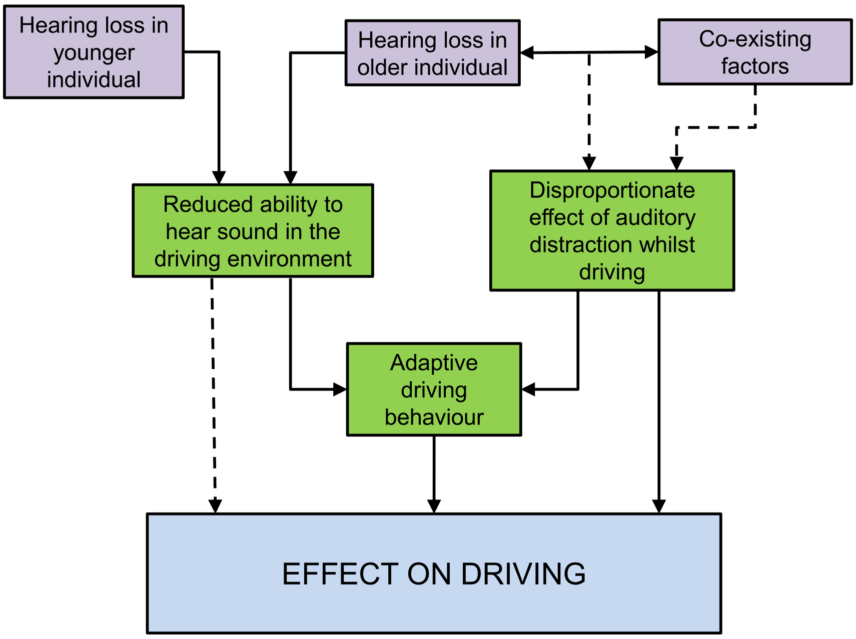


Figure 9.1 A preliminary schematic which explains how hearing impairment might affect driving performance. Aspects of the model substantiated by work described in this thesis and published research are shown with solid lines, whereas those which have simply been hypothesised by authors are shown with broken lines.

9.4 Further research

This research has generated a number of questions, and some limitations have been highlighted. Accordingly, further study is required in order to carry the investigation of this topic forward. I would argue that there are three pertinent areas for further research in this novel area, which have arisen as a result of my studies:

1. **The investigation of the effect of SimHL on driving whilst under auditory task conditions in a wider variety of driving environments.**
   The research described in this thesis has taken a novel approach to investigate the effect of hearing loss on driving. However, this is a vast topic and driving is a highly complex task (Groeger, 2000). The work described in this thesis has identified some interesting and important trends. However, it is not exhaustive - it has investigated a specific driving situation within a specific environment, and has used a specific set of dependent variables as a measure of driving performance. It would be beneficial to extend the work in some manners in order to provide further data regarding the effect of different levels of SimHL on driving performance.

   For example, the dependent variables measured in my driving simulator study were specific to driving behaviour that had been affected as a result of auditory task engagement in normally hearing individuals (e.g. PRC, SDLP). However, a propensity for visual information to be less efficiently processed in the hearing impaired demographic has been suggested by past work (Hickson et al., 2010) and work undertaken in this thesis (see Chapter 5). Whilst the experiment described in Chapter 8 looked at eye movement behaviour and reactions to visual stimuli, it did not evaluate subjects' ability to perceive and manipulate visual information whilst driving during auditory task engagement. Therefore, the use of other objective measures related to driving performance, such as the recognition of road signs, might be useful in identifying other specific problems that arise as a result of SimHL. Again, this will go some way towards confirming that hearing loss *alone* does not affect driving performance, and will inform on the 'effect on driving' portion of the schematic which I have proposed.

2. **Establishing the extent to which co-existing factors account for driving decrements in hearing impaired individuals.**
   Another consideration for the work described in this thesis is that it has only measured driving performance in younger, normally-hearing individuals. The evidence suggests that the cognitive capabilities of this group of individuals are sufficient to be able to deal with a degraded auditory input, thus hearing loss does not have an effect on the driving of this demographic. However, it is unknown how this transfers to the older demographic, and the relative influence that co-existing factors and hearing loss have on driving performance in this group of individuals. To investigate this, driving performance during auditory task engagement could be compared between a large sample of age-matched normally hearing and hearing impaired older adults. However, recruitment for a study of this type might be challenging, and so the extent to which older and younger normally hearing individuals are affected by SimHL could also be compared to inform on the same consideration.

   Furthermore, it should be considered that a SimHL has been used as part of work described in this thesis. Evidence suggested that this method provided a reasonable approximation of actual hearing loss (see Chapter 6). However, the method of simulation used cannot, and did not, emulate *every* aspect of SNHL and so there is a possibility that factors associated with hearing loss outside of those simulated might have an effect on driving performance. It would, therefore, be of interest to observe the effect of auditory distraction on the driving performance of young hearing impaired individuals, in order to inform on this prospect.

3. **Investigating the best manner of reducing auditory distraction in hearing impaired drivers.**
   The work described in this thesis has suggested that co-existing factors must be present for hearing loss to affect driving as a result of auditory distraction. However, a majority of hearing impaired individuals will have some age-related cognitive decline, given the association between hearing loss and age (Davis, 1995). Accordingly, there is a need to investigate how the additional effect of hearing loss on driving performance

in the presence of an auditory task can be remedied. The use of hearing aids in the car has already been discussed in this chapter, but despite the positive view of their use whilst driving held by hearing impaired individuals, their efficacy is unproven, and some concerns have been raised (e.g. their success being reliant on Working Memory abilities). Accordingly research should focus on establishing if hearing aids are of benefit in reducing auditory distraction during driving in a more objective manner, because there is currently no data available on this. If it transpires that hearing aids do not help to decrease auditory distraction in hearing impaired drivers, other rehabilitative measures should be considered, for example improving the acoustic environment in vehicles, using assistive listening devices such as loop-systems, or discouraging engagement with auditory tasks whilst driving.

9.5 Dissemination

It is now my intention to further disseminate the findings from this course of research. You will see in the following 'publications' section of this thesis that I have already begun to publicise my work through conference presentations and publication in academic journals. However, I also feel that it is important to engage practitioners and clinicians in the dissemination of this work, given that the outcomes are highly relevant to a specific patient group. Accordingly, I have arranged a visit to University Hospitals North Staffordshire NHS Trust in order to present the findings of the questionnaire study reported in Chapter 4. I also hope to be able to arrange further presentations at some of the other sites involved in data collection for this project. As I continue research in this area, I would like to maintain this method of dissemination; the work has been carried out in order to inform clinicians about, what I believe, is a very important, applicable, and novel topic.

9.6 Conclusion

Hearing is an important sensory modality for driving. A range of information in the driving environment can be portrayed acoustically; we can hear sirens of emergency service vehicles or can have our attention drawn to an impending collision by the piercing sound of a horn. We can hear mechanical sounds of our vehicle which inform on its health or current speed, and can converse with other road users or policemen in the case of an emergency situation arising.

Not having access to this information might be problematic, but there are mechanisms in place which can ameliorate these potential problems. A hearing impaired individual can wear hearing aids, visual awareness can increase over time, and an individual can adapt his/her driving behaviour in order to accommodate a lack of information. What these changes cannot alter, however, is the distortion to sound that SNHL presents. Past authors have suggested that this aspect of hearing loss might make audible auditory information in the car more distracting for hearing impaired individuals.

Work described in this thesis has, however, shown this not to be the case when the influence of hearing loss on driving is isolated from other co-existing factors. Thus, it is suggested that hearing loss *alone* is not responsible for driving decrements as a result of auditory distraction, rather it is as a result of synergy between hearing loss and these co-existing factors, or directly because of the co-existing factors. This inference needs to be confirmed through the performance of similar research on the effects of real and simulated hearing loss, but varying the driving demand, degree of hearing loss and type of measures used to indicate driving performance. However, this initial conclusion has allowed for the development of a preliminary schematic of how hearing loss affects driving. This schematic can be used as a framework to inform continuing research in the area, and it is hoped that, as more research becomes available, this schematic will evolve until a thorough understanding of the topic is reached.

Research in the immediate future should focus on identifying the specific factors co-existing with hearing loss which present problems for driving, and whether/the extent to which they interact with hearing loss to cause driving decrements. Attention should also be paid to establishing the effect of missed auditory information as a result of hearing loss on driving performance. The generation of this data will allow for the development of the schematic proposed in this chapter, and will contribute greatly towards our understanding of how hearing loss affects driving generally, allowing sensible, evidence-based policy decisions to be made.

Publications

Journal articles (published)

Herbert, N. C., Thyer, N. J., Isherwood, S. J. & Merat, N. 2016. The Effect of Auditory Distraction on the Useful Field of View in Hearing Impaired Individuals and its Implications for Driving. *Cognition, Technology & Work*, 18(2), p393–402.

Thorslund, B., Peters, B., Herbert, N., Holmqvist, K., Lidestam, B., Black, A. & Lyxell, B. 2013. Hearing loss and a supportive tactile signal in a navigation system: effects on driving behavior and eye movements. *Journal of Eye Movement Research*, 6(5), p1–9.

Journal articles (under review)

Herbert, N. C., Thyer, N. J., Isherwood, S. J. & Merat, N. The Effect of a Simulated Hearing Loss on Performance of an Auditory Memory Task in Driving. *Submitted to Transportation Research Part F: Traffic Psychology.*

Journal articles (in preparation)

Herbert, N. C., Thyer, N. J., Isherwood, S. J. & Merat, N. Self-Reported Driving Behaviours in Hearing Impaired Individuals. *For submission to International Journal of Audiology.*

Conference presentations

Herbert, N. C., Merat, N., Thyer, N. J. & Isherwood, S. J. 2014. Comparing Performance on a Number of Auditory Memory Tasks: Implications for How Auditory Information is Perceived in Vehicles. *The 5th International Conference on Applied Human Factors & Ergonomics, 19th–23rd July 2014, Krakow, Poland.*

Herbert, N. C., Merat, N., Thyer, N. J. & Isherwood, S. J. 2012. Is the 'Useful Field of View' Affected by Hearing Impairment? *The 5th International Conference on Traffic & Transport Psychology, 29–31st August 2012, Groningen, Netherlands.*

Herbert, N. C. & Merat, N. 2011. Deafness and its Relevance to the Driving Task. *The British Academy of Audiology Annual Conference, 8–11th November, Llandudno, UK.*

Herbert, N. C. & Merat, N. 2011. Deafness and its Relevance to the Driving Task. *Human Factors and Ergonomics Society European Chapter Conference, 19–21st October 2011, Leeds, UK.*

References

Aarts, L. and Van Schagen, I. (2006). Driving Speed and the Risk of Road Crashes: a Review. *Accident Analysis & Prevention*, 38(2):215–224.

Åberg, L. and Rimmö, P.-A. (1998). Dimensions of Aberrant Driver Behaviour. *Ergonomics*, 41(1):39–56.

af Wåhlberg, A., Dorn, L., and Kline, T. (2011). The Manchester Driver Behaviour Questionnaire as a Predictor of Road Traffic Accidents. *Theoretical Issues in Ergonomics Science*, 12(1):66–86.

Ahlstrom, C., Kircher, K., and Kircher, A. (2009). Considerations When Calculating Percent Road Centre from Eye Movement Data in Driver Distraction Monitoring. In *Proceedings of the Fifth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, pages 132–139.

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(S2):S53–S71.

Akeroyd, M. A., Foreman, K., and Holman, J. A. (2014). Estimates of the Number of Adults in England, Wales, and Scotland with a Hearing Loss. *International Journal of Audiology*, 53(1):60–61.

Allinson, P. D. (2001). Logistic Regression Using the SAS System: Theory and Application. In Meyer, D. E. and Kornblum, S., editors, *Attention and Performance XIV*, pages 183–218. MIT Press.

Allport, A. (1980). Patterns and Actions: Cognitive Mechanisms are Content-Specific. In Claxton, G., editor, *Cognitive Psychology: New Directions*, pages 26–64. Routledge and Kegan Paul.

Allport, A., Meyer, D., and Kornblum, S. (1993). Attention and Control: Have We Been Asking the Wrong Questions? A critical review of twenty-five years. In Meyer, D. E. and Kornblum, S., editors, *Attention and Performance XIV*, pages 183–218. MIT Press.

Allport, D. A., Antonis, B., and Reynolds, P. (1972). On the Division of Attention: A Disproof of the Single Channel Hypothesis. *The Quarterly Journal of Experimental Psychology*, 24(2):225–235.

Alm, H. and Nilsson, L. (1994). Changes in Driver Behaviour as a Function of Handsfree Mobile Phones - a Simulator Study. *Accident Analysis and Prevention*, 26(4):441–451.

Alm, H. and Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident Analysis and Prevention*, 27(5):707–715.

American Speech-Language-Hearing Association (1988). Guidelines for determining threshold level for speech. *ASHA*, 30(3):85–89.

Andersson, U. (2002). Deterioration of the Phonological Processing Skills in Adults with an Acquired Severe Hearing Loss. *European Journal of Cognitive Psychology*, 14(3):335–352.

ANSI (1997). *American National Standard Methods for Calculation of the Speech Intelligibility Index*.

Anstey, K. J., Wood, J., Lord, S., and Walker, J. G. (2005). Cognitive, Sensory and Physical Factors Enabling Driving Safety in Older Adults. *Clinical Psychology Review*, 25(1):45–65.

Arlinger, S. (2003). Negative Consequences of Uncorrected Hearing Loss: A Review. *International Journal of Audiology*, 42:2S17–2S20.

Atchley, P. and Dressel, J. (2004). Conversation Limits the Functional Field of View. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 46(4):664–673.

Austroads and the National Transport Commission Australia (2014). Assessing Fitness to Drive for Commercial and Private Vehicle Drivers. Online. Available from: https://www.onlinepublications.austroads.com.au/items/AP-G56-13. [Last accessed: 08/01/2016].

Baddeley, A. (1992). Working Memory. *Science*, 255(5044):556–559.

Baddeley, A. (2000). The Episodic Buffer: A New Component of Working Memory? *Trends in Cognitive Sciences*, 4(11):417–423.

Baddeley, A. (2003). Working Memory: Looking Back and Looking Forward. *Nature Reviews. Neuroscience*, 4(10):829–839.

Baddeley, A., Logie, R., Bressi, S., Sala, S. D., and Spinnler, H. (1986). Dementia and Working Memory. *The Quarterly Journal of Experimental Psychology*, 38(4):603–618.

Baddeley, A. D. (1997). *Human Memory: Theory and Practice*. Psychology Press.

Baddeley, A. D. (2002). Is Working Memory Still Working? *European Psychologist*, 7(2):85–97.

Baddeley, A. D. and Hitch, G. (1974). Working Memory. *Psychology of Learning and Motivation*, 8:47–89.

Baer, T. and Moore, B. C. (1993). Effects of Spectral Smearing on the Intelligibility of Sentences in Noise. *The Journal of the Acoustical Society of America*, 94(3):1229–1241.

Baer, T. and Moore, B. C. (1994). Effects of Spectral Smearing on the Intelligibility of Sentences in the Presence of Interfering Speech. *The Journal of the Acoustical Society of America*, 95(4):2277–2280.

Baldwin, C. L. (2002). Designing in-Vehicle Technologies for Older Drivers: Application of Sensory-Cognitive Interaction Theory. *Theoretical Issues in Ergonomics Science*, 3(4):307–329.

Baldwin, C. L. (2007). Cognitive Implications of Facilitating Echoic Persistence. *Memory and Cognition*, 35(4):774–780.

Baldwin, C. L. and Ash, I. K. (2011). Impact of Sensory Acuity on Auditory Working Memory Span in Young and Older Adults. *Psychology and Aging*, 26(1):85.

Baldwin, C. L. and Schieber, F. (1995). Dual Task Assessment of Age Differences in Mental Workload with Implications for Driving. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 39(2), pages 167–171.

Baldwin, C. L. and Struckman-Johnson, D. (2002). Impact of Speech Presentation Level on Cognitive Task Performance: Implications for Auditory Display Design. *Ergonomics*, 45(1):61–74.

Ball, K., Edwards, J. D., and Ross, L. A. (2007). The Impact of Speed of Processing Training On Cognitive and Everyday Functions. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 62(Special Issue 1):19–31.

Ball, K. and Owsley, C. (1991). Identifying Correlates of Accident Involvement for the Older Driver. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 33(5):583–595.

Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., and Bruni, J. R. (1993). Visual Attention Problems as a Predictor of Vehicle Crashes in Older Drivers. *Investigative Ophthalmology and Visual Science*, 34(11):3110–3123.

Ball, K., Owsley, C., Stalvey, B., Roenker, D. L., Sloane, M. E., and Graves, M. (1998). Driving Avoidance and Functional Impairment in Older Drivers. *Accident Analysis and Prevention*, 30(3):313–322.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., and Griggs, D. S. (1988). Age and Visual Search: Expanding the Useful Field of View. *Journal of the Optical Society of America A: Optics and Image Science*, 5(12):2210–2219.

Ball, K. K., Roenker, D. L., Wadley, V. G., Edwards, J. D., Roth, D. L., McGwin, G., Raleigh, R., Joyce, J. J., Cissell, G. M., and Dube, T. (2006). Can High-Risk Older Drivers be Identified Through Performance-Based Measures in a Department of Motor Vehicles Setting? *Journal of the American Geriatrics Society*, 54(1):77–84.

Balota, D. A. and Chumbley, J. I. (1984). Are Lexical Decisions a Good Measure of Lexical Access? The Role of Word Frequency in the Neglected Decision Stage. *Journal of Experimental Psychology: Human Perception and Performance*, 10(3):340–357.

Baltes, P. B. and Lindenberger, U. (1997). Emergence of a Powerful Connection Between Sensory and Cognitive Functions Across the Adult Life Span: A New Window to the Study of Cognitive Aging? *Psychology and Aging*, 12(1):12–21.

Barreto, S., Swerdlow, A., Smith, P., and Higgins, C. (1997). Risk of Death From Motor-Vehicle Injury in Brazilian Steelworkers: A Nested Case-Control Study. *International Journal of Epidemiology*, 26(4):814–821.

Barreto, S., Swerdlow, A., Smith, P., Higgins, C., and Andrade, A. (1996). Mortality From Injuries and Other Causes in a Cohort of 21,800 Brazilian Steel Workers. *Occupational and Environmental Medicine*, 53(5):343–350.

Başkent, D., Eiler, C. L., and Edwards, B. (2010). Phonemic Restoration by Hearing-Impaired Listeners with Mild to Moderate Sensorineural Hearing Loss. *Hearing Research*, 260(1):54–62.

Bavelier, D., Dye, M. W., and Hauser, P. C. (2006). Do Deaf Individuals See Better? *Trends in Cognitive Sciences*, 10(11):512–518.

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G., and Neville, H. (2000). Visual Attention to the Periphery is Enhanced in Congenitally Deaf Individuals. *The Journal of Neuroscience*, 20(17):RC93.

Bellinger, D. B., Budde, B. M., Machida, M., Richardson, G. B., and Berg, W. P. (2009). The Effect of Cellular Telephone Conversation and Music Listening on Response Time in Braking. *Transportation Research Part F: Traffic Psychology and Behaviour*, 12(6):441–451.

Bendixen, A., Schröger, E., and Winkler, I. (2009). I Heard That Coming: Event-related Potential Evidence for Stimulus-driven Prediction in the Auditory System. *The Journal of Neuroscience*, 29(26):8447–8451.

Bener, A., Özkan, T., and Lajunen, T. (2008). The Driver Behaviour Questionnaire in Arab Gulf Countries: Qatar and United Arab Emirates. *Accident Analysis and Prevention*, 40(4):1411–1417.

Bentley, S. A., LeBlanc, R. P., Nicolela, M. T., and Chauhan, B. C. (2012). Validity, Reliability, and Repeatability of the Useful Field of View Test in Persons with Normal Vision and Patients with Glaucoma. *Investigative ophthalmology and visual science*, 53(11):6763–6769.

Besner, D. (1987). Phonology, Lexical Access in Reading, and Articulatory Suppression: A Critical Review. *The Quarterly Journal of Experimental Psychology*, 39(3):467–478.

Bess, F. H., Humes, L., and Towsend, T. (1995). *Audiology: The Fundamentals*. Williams and Wilkins Baltimore, MD.

Boothroyd, A. (1968). Developments in Speech Audiometry. *British Journal of Audiology*, 2(1):3–10.

Borg, E., Bergkvist, C., Olsson, I.-S., Wikström, C., and Borg, B. (2008). Communication as an Ecological System. *International Journal of Audiology*, 47(S2):S131–S138.

Bosworth, R. G. and Dobkins, K. R. (2002). Visual Field Asymmetries for Motion Processing in Deaf and Hearing Signers. *Brain and Cognition*, 49(1):170–181.

Boufous, S., Ivers, R., Senserrick, T., Stevenson, M., Norton, R., and Williamson, A. (2010). Accuracy of Self-Report of On-Road Crashes and Traffic Offences in a Cohort of Young Drivers: The DRIVE Study. *Injury Prevention*, 16(4):275–277.

Bradley, J. V. (1958). Complete Counterbalancing of Immediate Sequential Effects in a Latin Square Design. *Journal of The American Statistical Association*, 53(282):525–528.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4):433–436.

Brant, R. (1990). Assessing Proportionality in the Proportional Odds Model for Ordinal Logistic Regression. *Biometrics*, 46(4):1171–1178.

Bregman, A. S. (1994). *Auditory Scene Analysis: The Perceptual Organization of Sound*. MIT press.

Breitmeyer, B. and Ogmen, H. (2006). *Visual Masking: Time Slices Through Conscious and Unconscious Vision*. Oxford University Press.

British Society of Audiology (2011). Recommended Procedure: Pure-Tone Air-Conduction and Bone-Conduction Threshold Audiometry with and Without Masking. Online. Available from: http://www.thebsa.org.uk/wp-content/uploads/2014/04/BSA_RP_PTA_FINAL_24Sept11_MinorAmend06Feb12.pdf. [Last accessed: 27/09/2015].

Broadbent, D. (1958). *Perception and Communication*. Pergamon.

Bronkhorst, A. W. (2000). The Cocktail Party Phenomenon: A Review of Research on Speech Intelligibility in Multiple-Talker Conditions. *Acta Acustica united with Acustica*, 86(1):117–128.

Brookhuis, K. A., de Vries, G., and de Waard, D. (1991). The Effects of Mobile Telephoning on Driving Performance. *Accident Analysis and Prevention*, 23(4):309–316.

Brown, I., Tickner, A., and Simmonds, D. (1969). Interference Between Concurrent Tasks of Driving and Telephoning. *Journal of Applied Psychology*, 53(5):419.

Brownell, W. E. (1990). Outer Hair Cell Electromotility and Otoacoustic Emissions. *Ear and Hearing*, 11(2):82.

Burch, S. (2004). *Signs of Resistance: American Deaf Cultural History, 1900 to World War II.* NYU Press.

Burg, F. D., Stock, M. S., Light, W. O., and Douglass, J. M. (1970). Licensing the Deaf Driver. *Archives of Otolaryngology*, 91(3):289–290.

Cacciatore, F., Napoli, C., Abete, P., Marciano, E., Triassi, M., and Rengo, F. (1999). Quality of Life Determinants and Hearing Function in an Elderly Population: Osservatorio Geriatrico Campano Study Group. *Gerontology*, 45(6):323–328.

Cattell, R. B. (1987). *Intelligence: Its Structure, Growth and Action.* Elsevier.

Cepeda, N. J., Kramer, A. F., and Gonzalez de Sather, J. (2001). Changes in Executive Control across the life span: Examination of task-switching performance. *Developmental Psychology*, 37(5):715.

Cherry, E. C. (1953). Some Experiments On the Recognition of Speech, with One and with Two Ears. *The Journal of the Acoustical Society of America*, 25(5):975–979.

Child, D. (2006). *The Essentials of Factor Analysis.* Continuum.

Chiras, D. D. (2013). *Human Biology.* Jones and Bartlett Publishers.

Chung, J. H., Des Roches, C. M., Meunier, J., and Eavey, R. D. (2005). Evaluation of Noise-Induced Hearing Loss in Young People Using a Web-Based Survey Technique. *Pediatrics*, 115(4):861–867.

Classon, E., Rudner, M., and Rönnberg, J. (2013). Working Memory Compensates for hearing related phonological processing deficit. *Journal of Communication Disorders*, 46(1):17–29.

Clay, O. J., Wadley, V. G., Edwards, J. D., Roth, D. L., Roenker, D. L., and Ball, K. K. (2005). Cumulative Meta-Analysis of the Relationship Between Useful Field of View and Driving Performance in Older Adults: Current and Future Implications. *Optometry and Vision Science*, 82(8):724–731.

Clogg, C. C. and Shihadeh, E. S. (1994). *Statistical Models for Ordinal Variables.* Sage Publications Inc.

Collins, J. G. (1997). Prevalence of Selected Chronic Conditions: United States, 1990-1992. *Vital and (H]ealth Statistics. Series 10, Data from the National Health Survey*, 194:1–89.

Conrad, R. and Hull, A. J. (1964). Information, Acoustic Confusion and Memory Span. *British Journal of Psychology*, 55(4):429–432.

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., and Engle, R. W. (2005). Working Memory Span Tasks: A Methodological Review and User's Guide. *Psychonomic bulletin and review*, 12(5):769–786.

Cooper, J. M., Medeiros-Ward, N., and Strayer, D. L. (2013). The impact of Eye Movements and cognitive workload on lateral position variability in driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 55(5):1001–1014.

Coppin, R. S. and Peck, R. C. (1963). The Totally Deaf Driver in California, Part I. Technical report, California Department of Motor Vehicles.

Coppin, R. S. and Peck, R. C. (1965). The Totally Deaf Driver in California. *Highway Research Record*, 79:35–44.

Cord, M. T., Surr, R. K., Walden, B. E., and Olson, L. (2002). Performance of Directional Microphone Hearing Aids in Everyday Life. *Journal of the American Academy of Audiology*, 13(6):295–307.

Cornsweet, T. N. (1962). The Staircase-Method in Psychophysics. *The American Journal of Psychology*, 75(3):485–491.

Costello, A. and Osborne, J. (2005). Best Practices in Exploratory Factor Analysis: Four Recommendations for Getting the Most From Your Analysis. *Practical Assessesment, Research and Evaluation*, 10(7):1–9.

Cox, R., Alexander, G., Taylor, I., and Gray, G. (1996). Benefit Acclimatization in Elderly Hearing Aid Users. *Journal of the American Academy of Audiology*, 7(6):428–441.

Cox, R. M. (2005). Evidence-Based Practice in Provision of Amplification. *Journal of the American Academy of Audiology*, 16(7):419–438.

Craik, F. I. (1977). Age Differences in Human Memory. In Birren, J. E. and Schaie, K. W., editors, *Handbook of the Psychology of Aging*, pages 384–420. Van Nostrand Reinhold.

Craik, F. I. (1994). Memory Changes in Normal Aging. *Current Directions in Psychological Science*, 3(5):155–158.

Craik, F. I. (2000). Age-related Changes in Human Memory. In Park, D. and Schwarz, N., editors, *Cognitive Aging: A Primer*, pages 75–92. Psychology Press.

Craik, F. I. (2007). The Role of Cognition in Age-Related Hearing Loss. *Journal of the American Academy of Audiology*, 18(7):539–547.

Crandell, C., Mills, T. L., and Gauthier, R. (2004). Knowledge, Behaviors, and Attitudes About Hearing Loss and Hearing Protection Among Racial/Ethnically Diverse Young Adults. *Journal of the National Medical Association*, 96(2):176.

Cruickshanks, K. J., Wiley, T. L., Tweed, T. S., Klein, B. E., Klein, R., Mares-Perlman, J. A., and Nondahl, D. M. (1998). Prevalence of Hearing Loss in Older Adults in Beaver Dam, Wisconsin the Epidemiology of Hearing Loss Study. *American Journal of Epidemiology*, 148(9):879–886.

Davis, A. (1995). *Hearing in Adults: The Prevalence and Distribution of Hearing Impairment and Reported Hearing Disability in the MRC Institute of Hearing Research's National Study of Hearing.* Whurr.

Davison, P. A. (1985). Inter-relationships Between British Drivers' Visual Abilities, Age and Road Accident Histories. *Ophthalmic and Physiological Optics*, 5(2):195–204.

de Lorenzo, R. A. and Eilers, M. A. (1991). Lights and Siren: A Review of Emergency Vehicle Warning Systems. *Annals of Emergency Medicine*, 20(12):1331–1335.

de Rammelaere, S., Stuyven, E., and Vandierendonck, A. (2001). Verifying Simple Arithmetic Sums and Products: Are the Phonological Loop and the Central Executive Involved? *Memory and Cognition*, 29(2):267–273.

de Waard, D., Edlinger, K., and Brookhuis, K. (2011). Effects of Listening to Music, and of Using a Handheld and Handsfree Telephone on Cycling Behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, 14(6):626–637.

de Winter, J. and Dodou, D. (2010). The Driver Behaviour Questionnaire as a Predictor of Accidents: A Meta-Analysis. *Journal of Safety Research*, 41(6):463–470.

DeLucia, P. R., Kathryn Bleckley, M., Meyer, L. E., and Bush, J. M. (2003). Judgments About Collision in Younger and Older Drivers. *Transportation Research Part F: Traffic Psychology and Behaviour*, 6(1):63–80.

Department for Transport (2014). Reported Road Casualties in Great Britain: Main Results 2013. Technical report, Office for National Statistics.

Deutsch, J. A. and Deutsch, D. (1963). Attention: Some Theoretical Considerations. *Psychological Review*, 70(1):80–90.

Diehr, M. C., Heaton, R. K., Miller, W., and Grant, I. (1998). The Paced Auditory Serial Addition Task (PASAT): Norms for Age, Education, and Ethnicity. *Assessment*, 5(4):375–387.

Dillon, H. (2001). *Hearing Aids.* Thieme.

Dingus, T. A., Klauer, S., Neale, V., Petersen, A., Lee, S., Sudweeks, J., Perez, M., Hankey, J., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z., Jermeland, J., and Knipling, R. (2006). The 100-car naturalistic driving study, phase II-results of the 100-car field experiment. Technical report, National Highways Traffic Safety Administration.

Downs, D. W. (1982). Effects of Hearing Aid Use on Speech Discrimination and Listening Effort. *Journal of Speech and Hearing Disorders*, 47(2):189–193.

Drews, F. A., Pasupathi, M., and Strayer, D. L. (2008). Passenger and Cell Phone Conversations in Simulated Driving. *Journal of Experimental Psychology: Applied*, 14(4):392.

Driver and Vehicle Licensing Agency (2012). AUD1 Online: Confidential Medical Information. Online. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/320704/AUD1.pdf. [Last accessed: 08/01/2016].

Dubno, J. R. and Schaefer, A. B. (1992). Comparison of Frequency Selectivity and Consonant Recognition Among Hearing-Impaired and Masked Normal-Hearing Listeners. *The Journal of the Acoustical Society of America*, 91(4):2110–2121.

Duchnowski, P. and Zurek, P. M. (1995). Villchur Revisited: Another Look at Automatic Gain Control Simulation of Recruiting Hearing Loss. *The Journal of the Acoustical Society of America*, 98(6):3170–3181.

Edwards, B. (2007). The Future of Hearing Aid Technology. *Trends in Amplification*, 11(1):31–46.

Edwards, J. D., Ross, L. A., Wadley, V. G., Clay, O. J., Crowe, M., Roenker, D. L., and Ball, K. K. (2006). The Useful Field of View Test: Normative Data for Older Adults. *Archives of Clinical Neuropsychology*, 21(4):275–286.

Edwards, J. D., Vance, D. E., Wadley, V. G., Cissell, G. M., Roenker, D. L., and Ball, K. K. (2005). Reliability and Validity of Useful Field of View Test Scores As Administered by Personal Computer. *Journal of Clinical and Experimental Neuropsychology*, 27(5):529–543.

Edwards, W. (2010). *Motor Learning and Control: From Theory to Practice.* Cengage Learning.

Eisele, G., Wolff, K., Alt, N., and Hüser, M. (2005). Application of Vehicle Interior Noise Simulation (VINS) for NVH Analysis of a Passenger Car. Technical report, SAE Technical Paper.

Elander, J., West, R., and French, D. (1993). Behavioral Correlates of Individual Differences in Road-Traffic Crash Risk: An Examination of Methods and Findings. *Psychological Bulletin*, 113(2):279.

Endsley, M. R. (1988). Design and Evaluation for Situation Awareness Enhancement. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 32(2), pages 97–101. SAGE Publications.

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1):32–64.

Endsley, M. R. (2000). Theoretical Underpinnings of Situation Awareness: A Critical Review. In R., E. M., editor, *Situation Awareness Analysis and Measurement*, pages 3–32. Lawrence Erlbaum Associates.

Engle, R. W. (2002). Working Memory Capacity as Executive Attention. *Current Directions in Psychological Science*, 11(1):19–23.

Engström, J. (2011). *Understanding Attention Selection in Driving: From Limited Capacity to Adaptive Behaviour.* PhD thesis, Chalmers University of Technology.

Engström, J., Åberg, N., Johansson, E., and Hammarbäck, J. (2005a). Comparison Between Visual and Tactile Signal Detection Tasks Applied to the Safety Assessment of in-Vehicle Information Systems. In *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, pages 232–239.

Engström, J., Johansson, E., and Östlund, J. (2005b). Effects of Visual and Cognitive Load in Real and Simulated Motorway Driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2):97–120.

Evans, L. (1970). Speed Estimation from a Moving Automobile. *Ergonomics*, 13(2):219–230.

Evans, L. and Wasielewski, P. (1982). Do accident-involved drivers exhibit riskier everyday driving behavior? *Accident Analysis and Prevention*, 14(1):57–64.

Eysenck, M. W. (2000). *Cognitive Psychology: A Student's Handbook.* Taylor and Francis.

Fabry, D. A. and Van Tasell, D. J. (1986). Masked and Filtered Simulation of Hearing Loss: Effects on Consonant Recognition. *Journal of Speech and Hearing Research*, 29(2):170–178.

Farrand, P. and McKenna, F. P. (2001). Risk Perception in Novice Drivers: The Relationship Between Questionnaire Measures and Response Latency. *Transportation Research Part F: Traffic Psychology and Behaviour*, 4(3):201–212.

Faulkner, A., Rosen, S., and Moore, B. C. (1990). Residual Frequency Selectivity in the Profoundly Hearing-Impaired Listener. *British Journal of Audiology*, 24(6):381–392.

Festen, J. M. and Plomp, R. (1990). Effects of Fluctuating Noise and Interfering Speech On the Speech-Reception Threshold for Impaired and Normal Hearing. *The Journal of the Acoustical Society of America*, 88(4):1725–1736.

Field, A. (2013). *Discovering Statistics Using IBM SPSS Statistics*. Sage.

Findlay, J. M. and Gilchrist, I. D. (2003). *Active Vision: The Psychology of Looking and Seeing*. Oxford University Press.

Finesilver, S. G. (1962). They Can't Hear, but They Get the Message. *California News*, 77(8):1–5.

Fisher, D. L. and Strayer, D. L. (2014). Modeling Situation Awareness and Crash Risk. *Annals of Advances in Automotive Medicine*, 58:33–39.

Fitzgibbons, P. J. and Wightman, F. L. (1982). Gap detection in Normal and Hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 72(3):761–765.

Fodor, J. A. (1983). *The Modularity of Mind: An Essay on Faculty Psychology*. MIT press.

Foo, C., Rudner, M., Rönnberg, J., and Lunner, T. (2007). Recognition of Speech in Noise with New Hearing Instrument Compression Release Settings Requires Explicit Cognitive Storage and Processing Capacity. *Journal of the American Academy of Audiology*, 18(7):618–631.

Freeman, J. E., Wishart, D. E., Davey, J. D., Rowland, B. D., and Williams, R. (2009). Utilising the Driver Behaviour Questionnaire in an Australian Organisational Fleet Setting: Can it Identify Risky Drivers? *Journal of the Australasian College of Road Safety*, 20(2):38–45.

Fritz, J. B., Elhilali, M., David, S. V., and Shamma, S. A. (2007). Auditory Attention—Focusing the Searchlight on Sound. *Current Opinion in Neurobiology*, 17(4):437–455.

Gallo, J. J., Rebok, G. W., and Lesikar, S. E. (1999). The Driving Habits of Adults Aged 60 Years and Older. *Journal of the American Geriatrics Society*, 47(3):335–341.

Gatehouse, S. (1993). Role of Perceptual Acclimatization in the Selection of Frequency Responses for Hearing Aids. *Journal of the American Academy of Audiology*, 4(5):296–306.

Gates, G. A. and Mills, J. H. (2005). Presbycusis. *The Lancet*, 366(9491):1111–1120.

Gathercole, S. E. and Baddeley, A. D. (1993). *Working Memory and Language.* Lawrence Erlbaum Associates.

Gelfand, S. A. (2009). *Essentials of Audiology.* Thieme.

Gherri, E. and Eimer, M. (2011). Active Listening Impairs Visual Perception and Selectivity: An ERP Study of Auditory Dual-Task Costs on Visual Attention. *Journal of Cognitive Neuroscience*, 23(4):832–844.

Gilhotra, J. S., Mitchell, P., Ivers, R., and Cumming, R. G. (2001). Impaired Vision and Other Factors Associated with Driving Cessation in the Elderly: The Blue Mountains Eye Study. *Clinical and Experimental Ophthalmology*, 29(3):104–107.

Glasberg, B. R. and Moore, B. C. (1992). Effects of Envelope Fluctuations on Gap Detection. *Hearing Research*, 64(1):81–92.

Goode, K. T., Ball, K. K., Sloane, M., Roenker, D. L., Roth, D. L., Myers, R. S., and Owsley, C. (1998). Useful Field of View and Other Neurocognitive Indicators of Crash Risk in Older Adults. *Journal of Clinical Psychology in Medical Settings*, 5(4):425–440.

Goode, R. L. (1986). Middle Ear Function, Biologic Variation, and Otosurgical Alchemy: Can We Turn Tin Ears Into Gold? *Archives of Otolaryngology–Head and Neck Surgery*, 112(9):923–924.

Gordon, A. and Zillmer, E. (1997). Integrating the MMPI and Neuropsychology: A Survey of NAN Membership. *Archives of Clinical Neuropsychology*, 12(4):325–326.

Gosselin, P. A. and Gagné, J.-P. (2010). Use of a Dual-Task Paradigm to Measure Listening Effort. *Canadian Journal of Speech-Language Pathology and Audiology*, 34(1):43–51.

Graham, J. and Baguley, D. (2009). *Ballantyne's Deafness.* John Wiley and Sons.

Grattan, E. and Jeffcoate, G. (1968). Medical Factors and Road Accidents. *BMJ: British Medical Journal*, 1(5584):75–79.

Green, K. A., McGwin, G., and Owsley, C. (2013). Associations Between Visual, Hearing, and Dual Sensory Impairments and History of Motor Vehicle Collision Involvement of Older Drivers. *Journal of the American Geriatrics Society*, 61(2):252–257.

Gresset, J. A. and Meyer, F. M. (1994). Risk of Accidents Among Elderly Car Drivers with Visual Acuity Equal to 6/12 or 6/15 and Lack of Binocular Vision. *Ophthalmic and Physiological Optics*, 14(1):33–37.

Groeger, J. A. (2000). *Understanding Driving: Applying Cognitive Psychology to a Complex Everyday Task.* Psychology Press.

Groeger, J. A. and Brown, I. (1989). Assessing One's Own and Others' Driving Ability: Influences of Sex, Age, and Experience. *Accident Analysis and Prevention*, 21(2):155–168.

Gronwall, D. and Sampson, H. (1974). *The Psychological Effects of Concussion.* Oxford University Press.

Gronwall, D. and Wrightson, P. (1974). Delayed Recovery of Intellectual Function After Minor Head Injury. *The Lancet*, 304(7881):605–609.

Gugerty, L. J. (1997). Situation Awareness During Driving: Explicit and Implicit Knowledge in Dynamic Spatial Memory. *Journal of Experimental Psychology: Applied*, 3(1):42–66.

Guo, M., Jensen, S. H., and Jensen, J. (2012). Novel Acoustic Feedback Cancellation Approaches in Hearing Aid Applications Using Probe Noise and Probe Noise Enhancement. *IEEE Transactions on Acoustics Speech and Signal Processing*, 20(9):2549–2563.

Gussekloo, J., de Craen, A. J., Oduber, C., van Boxtel, M. P., and Westendorp, R. G. (2005). Sensory Impairment and Cognitive Functioning in Oldest-old Subjects: The Leiden 85+ Study. *The American Journal of Geriatric Psychiatry*, 13(9):781–786.

Haigney, D., Taylor, R., and Westerman, S. (2000). Concurrent Mobile (Cellular) Phone Use and Driving Performance: Task Demand Characteristics and Compensatory Processes. *Transportation Research Part F: Traffic Psychology and Behaviour*, 3(3):113–121.

Hakamies-Blomqvist, L. and Wahlström, B. (1998). Why Do Older Drivers Give Up Driving? *Accident Analysis and Prevention*, 30(3):305–312.

Hällgren, M., Johansson, M., Larsby, B., and Arlinger, S. (1998). Dichotic Speech Tests. *Scandinavian Audiology*, 27(4):35–39.

Hällgren, M., Larsby, B., Lyxell, B., and Arlinger, S. (2001). Cognitive Effects in Dichotic Speech Testing in Elderly Persons. *Ear and Hearing*, 22(2):120–129.

Halpern, A. R., Zatorre, R. J., Bouffard, M., and Johnson, J. A. (2004). Behavioral and Neural Correlates of Perceived and Imagined Musical Timbre. *Neuropsychologia*, 42(9):1281–1292.

Halpin, C. and Rauch, S. D. (2009). Article Commentary: Hearing Aids and Cochlear Damage: The Case Against Fitting the Pure Tone Audiogram. *Otolaryngology–Head and Neck Surgery*, 140(5):629–632.

Hancock, P., Lesch, M., and Simmons, L. (2003). The Distraction Effects of Phone Use During a Crucial Driving Maneuver. *Accident Analysis and Prevention*, 35(4):501–514.

Harbluk, J. L., Noy, Y. I., Trbovich, P. L., and Eizenman, M. (2007). An On-Road Assessment of Cognitive Distraction: Impacts on Drivers' Visual Behavior and Braking Performance. *Accident Analysis and Prevention*, 39(2):372–379.

Hart, S. G. (2006). NASA-Task Load Index (NASA-TLX); 20 Years Later. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 50(9), pages 904–908.

Hart, S. G. and Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, 52:139–183.

Haualand, H. and Allen, C. (2009). *Deaf People and Human Rights*. Available from: http://www.wfdeaf.org/wp-content/uploads/2011/06/Deaf-People-and-Human-Rights-Report.pdf. [Last accessed: 23/09/2015].

Hellier, E., Naweed, A., Walker, G., Husband, P., and Edworthy, J. (2011). The Influence of Auditory Feedback on Speed Choice, Violations and Comfort in a Driving Simulation Game. *Transportation Research Part F: Traffic Psychology and Behaviour*, 14(6):591–599.

Henderson, R. L. and Burg, A. (1973). The Role of Vision and Audition in Truck and Bus Driving. Technical report, National Highway Traffic Safety Administation.

Henderson, R. L. and Burg, A. (1974). *Vision and Audition in Driving*. System Development Corporation.

Hickman, J. S., Hanowski, R. J., and Bocanegra, J. (2010). Distraction in Commercial Trucks and Buses: Assessing Prevalence and Risk in Conjunction with Crashes and Near-crashes. Technical report, Federal Motor Carrier Safety Administration.

Hickson, L., Wood, J., Chaparro, A., Lacherez, P., and Marszalek, R. (2010). Hearing Impairment Affects Older People's Ability to Drive in the Presence of Distracters. *Journal of the American Geriatrics Society*, 58(6):1097–1103.

Ho, C. and Spence, C. (2012). *The Multisensory Driver: Implications for Ergonomic Car Interface Design*. Ashgate Publishing.

Ho, C., Tan, H. Z., and Spence, C. (2006). The Differential Effect of Vibrotactile and Auditory Cues on Visual Spatial Attention. *Ergonomics*, 49(7):724–738.

Hofstetter, H. (1976). Visual Acuity and Highway Accidents. *Journal of the American Optometric Association*, 47(7):887–893.

Hole, G. (2007). *The Psychology of Driving*. Psychology Press.

Holland, C. A. and Rabbitt, P. (1992). People's Awareness of Their Age-Related Sensory and Cognitive Deficits and the Implications for Road Safety. *Applied Cognitive Psychology*, 6(3):217–231.

Hood, J. (1984). Speech Discrimination in Bilateral and Unilateral Hearing Loss Due to Meniere's Disease. *British Journal of Audiology*, 18(3):173–177.

Horberry, T., Anderson, J., Regan, M. A., Triggs, T. J., and Brown, J. (2006). Driver Distraction: The Effects of Concurrent in-Vehicle Tasks, Road Environment Complexity and Age on Driving Performance. *Accident Analysis and Prevention*, 38(1):185–191.

Hornsby, B. W. (2013). The Effects of Hearing Aid Use On Listening Effort and Mental Fatigue Associated with Sustained Speech Processing Demands. *Ear and Hearing*, 34(5):523–534.

Horowitz, S. S. (2012). *The Universal Sense: How Hearing Shapes the Mind*. Bloomsbury Publishing.

Horrey, W. J. and Wickens, C. D. (2006). Examining the Impact of Cell Phone Conversations on Driving Using Meta-Analytic Techniques. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 48(1):196–205.

Horswill, M. S. and McKenna, F. P. (1999). The Development, Validation, and Application of a Video-Based Technique for Measuring an Everyday Risk-Taking Behavior: Drivers' Speed Choice. *Journal of Applied Psychology*, 84(6):977–985.

Horswill, M. S. and Plooy, A. M. (2008). Auditory Feedback Influences Perceived Driving Speeds. *Perception*, 37(7):1037–1043.

Horswill, M. S., Waylen, A. E., and Tofield, M. I. (2004). Drivers' Ratings of Different Components of Their Own Driving Skill: A Greater Illusion of Superiority for Skills That Relate to Accident Involvement. *Journal of Applied Social Psychology*, 34(1):177–195.

Humes, L. E. (1996). Speech Understanding in the Elderly. *Journal of the American Academy of Audiology*, 7(3):161–167.

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(7):590–603.

Humes, L. E., Dirks, D. D., Bell, T. S., and Kincaid, G. E. (1987). Recognition of Nonsense Syllables by Hearing-Impaired Listeners and by Noise-Masked Normal Hearers. *The Journal of the Acoustical Society of America*, 81(3):765–773.

Humes, L. E., Dubno, J. R., Gordon-Salant, S., Lister, J. J., Cacace, A. T., Cruickshanks, K. J., Gates, G. A., Wilson, R. H., and Wingfield, A. (2012). Central Presbycusis: A Review and Evaluation of the Evidence. *Journal of the American Academy of Audiology*, 23(8):635–666.

Humphries, D. (1987). Three South African Studies on the Relation Between Road Accidents and Drivers Vision. *Ophthalmic and Physiological Optics*, 7(1):73–79.

Hutcheson, G. D. and Sofroniou, N. (1999). *The Multivariate Social Scientist: Introductory Statistics Using Generalized Linear Models*. Sage.

Irwin, R. and Purdy, S. C. (1982). The Minimum Detectable Duration of Auditory Signals for Normal and Hearing-impaired Listeners. *The Journal of the Acoustical Society of America*, 71(4):967–974.

ISO (TBA). Detection-Response Task (DRT) for Assessing Attentional Effects of Cognitive Load in Driving. ISO 17488, International Organization for Standardization, Geneva, Switzerland.

Ivers, R. Q., Mitchell, P., and Cumming, R. G. (1999). Sensory Impairment and Driving: The Blue Mountains Eye Study. *American Journal of Public Health*, 89(1):85–87.

Jamson, A. H., Merat, N., Carsten, O. M., and Lai, F. C. (2013). Behavioural Changes in Drivers Experiencing Highly-Automated Vehicle Control in Varying Traffic Conditions. *Transportation Research Part C: Emerging Technologies*, 30:116–125.

Jamson, H., Merat, N., Carsten, O., and Lai, F. (2011). Fully-Automated Driving: The Road to Future Vehicles. In *Proceedings of the Sixth International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*.

Jamson, H. A. and Merat, N. (2005). Surrogate in-Vehicle Information Systems and Driver Behaviour: Effects of Visual and Cognitive Load in Simulated Rural Driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2):79–96.

Jenstad, L. and Moon, J. (2011). Systematic Review of Barriers and Facilitators to Hearing Aid Uptake in Older Adults. *Audiology Research*, 1(1):25.

Johansson, K., Bronge, L., Lundberg, C., Persson, A., Seideman, M., and Viitanen, M. (1996). Can a Physician Recognize an Older Driver with Increased Crash Risk Potential? *Journal of the American Geriatrics Society*, 44(10):1198–1204.

Kahneman, D. (1973). *Attention and Effort*. Prentice Hall.

Katz, J. and Smith, P. S. (1991). The Staggered Spondaic Word Test. *Annals of the New York Academy of Sciences*, 620(1):233–251.

Kidd Jr, G., Mason, C. R., and Feth, L. L. (1984). Temporal Integration of Forward Masking in Listeners having Sensorineural Hearing Loss. *The Journal of the Acoustical Society of America*, 75(3):937–944.

Killion, M. C. (1978). Revised Estimate of Minimum Audible Pressure: Where is the "Missing 6 dB"? *The Journal of the Acoustical Society of America*, 63(5):1501–1508.

Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., and Banerjee, S. (2004). Development of a Quick Speech-in-Noise Test for Measuring Signal-to-Noise Ratio Loss in Normal-Hearing and Hearing-Impaired Listeners. *The Journal of the Acoustical Society of America*, 116(4):2395–2405.

Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., and Broussard, C. (2007). What's New in Psychtoolbox-3. *Perception*, 36(14):1–1.

Klingberg, T. (2010). Training and Plasticity of Working Memory. *Trends in Cognitive Sciences*, 14(7):317–324.

Knappe, G., Keinath, A., and Bengler, K. (2007). Driving Simulator as an Evaluation Tool - Assessment of the Influence of Field of View and Secondary Tasks on Lane Keeping and Steering Performance. Technical report, Friedrich Alexander Universit´at Erlangen and BMW Group Forschung und Technik.

Knudsen, L. V., Öberg, M., Nielsen, C., Naylor, G., and Kramer, S. E. (2010). Factors Influencing Help Seeking, Hearing Aid Uptake, Hearing Aid Use and Satisfaction with Hearing Aids: A Review of the Literature. *Trends in Amplification*, 14(3):127–154.

Kochhann, R., Varela, J. S., de Macedo Lisboa, C. S., and Chaves, M. L. F. (2010). The mini mental state examination review of cutoff points adjusted for schooling in a large southern brazilian sample. *Demntia and Neurophsycholigia*, 4(5):35–41.

Kochkin, S. (1992). MarkeTrak III Identifies Key Factors in Determining Consumer Satisfaction. *Hearing Journal*, 45:39–39.

Kosnik, W. D., Sekuler, R., and Kline, D. W. (1990). Self-Reported Visual Problems of Older Drivers. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 32(5):597–608.

Kramer, A. F., Wiegmann, D. A., and Kirlik, A. (2006). *Attention: From Theory to Practice*. Oxford University Press.

Kramer, S. E., Kapteyn, T. S., Festen, J. M., and Kuik, D. J. (1997). Assessing Aspects of Auditory Handicap by Means of Pupil Dilatation. *International Journal of Audiology*, 36(3):155–164.

Krejcie, R. V. and Morgan, D. W. (1970). Determining Sample Size for Research Activities. *Educational and Psychological Measurement*, 30(3):607–610.

Laberge, J., Scialfa, C., White, C., and Caird, J. (2004). Effects of Passenger and Cellular Phone Conversations on Driver Distraction. *Transportation Research Record: Journal of the Transportation Research Board*, 1899(1):109–116.

Lajunen, T., Corry, A., Summala, H., and Hartley, L. (1997). Impression Management and Self-Deception in Traffic Behaviour Inventories. *Personality and Individual Differences*, 22(3):341–353.

Lajunen, T., Parker, D., and Stradling, S. G. (1998). Dimensions of Driver Anger, Aggressive and Highway Code Violations and Their Mediation by Safety Orientation in UK Drivers. *Transportation Research Part F: Traffic Psychology and Behaviour*, 1(2):107–121.

Lajunen, T., Parker, D., and Summala, H. (2004). The Manchester Driver Behaviour Questionnaire: A Cross-Cultural Study. *Accident Analysis and Prevention*, 36(2):231–238.

Lajunen, T. and Summala, H. (2003). Can we Trust Self-Reports of Driving? Effects of Impression Management on Driver Behaviour Questionnaire Responses. *Transportation Research Part F: Traffic Psychology and Behaviour*, 6(2):97–107.

Lamble, D., Kauranen, T., Laakso, M., and Summala, H. (1999). Cognitive Load and Detection Thresholds in Car Following Situations: Safety Implications for Using Mobile (Cellular) Telephones While Driving. *Accident Analysis and Prevention*, 31(6):617–623.

Lance, C. E., Butts, M. M., and Michels, L. C. (2006). The Sources of Four Commonly Reported Cutoff Criteria: What Did They Really Say? *Organizational Research Methods*, 9(2):202–220.

Langford, J., Methorst, R., and Hakamies-Blomqvist, L. (2006). Older Drivers Do Not Have a High Crash Risk—A Replication of Low Mileage Bias. *Accident Analysis and Prevention*, 38(3):574–578.

Lansdown, T. C., Brook-Carter, N., and Kersloot, T. (2004). Distraction From Multiple in-Vehicle Secondary Tasks: Vehicle Performance and Mental Workload Implications. *Ergonomics*, 47(1):91–104.

Laplante-Lévesque, A., Hickson, L., and Worrall, L. (2010). Rehabilitation of Older Adults with Hearing Impairment: A Critical Review. *Journal of Aging and Health*, 22(2):143–153.

Larsby, B., Hällgren, M., Lyxell, B., and Arlinger, S. (2005). Cognitive Performance and Perceived Effort in Speech Processing Tasks: Effects of Different Noise Backgrounds in Normal-Hearing and Hearing-Impaired Subjects. *International Journal of Audiology*, 44(3):131–143.

Lavie, N. (1995). Perceptual Load as a Necessary Condition for Selective Attention. *Journal of Experimental Psychology: Human Perception and Performance*, 21(3):451.

Lavie, N. (2005). Distracted and Confused?: Selective Attention Under Load. *Trends in Cognitive Sciences*, 9(2):75–82.

Lawton, R., Parker, D., Manstead, A. S., and Stradling, S. G. (1997). The Role of Affect in Predicting Social Behaviors: The Case of Road Traffic Violations. *Journal of Applied Social Psychology*, 27(14):1258–1276.

Lewis-Evans, B., De Waard, D., and Brookhuis, K. A. (2011). Speed Maintenance Under Cognitive Load–Implications for Theories of Driver Behaviour. *Accident Analysis and Prevention*, 43(4):1497–1507.

Li, K. Z. and Lindenberger, U. (2002). Relations between Aging Sensory/Sensorimotor and Cognitive Functions. *Neuroscience and Biobehavioral Reviews*, 26(7):777–783.

Lichtenstein, M. J., Bess, F. H., and Logan, S. A. (1988). Validation of Screening Tools for Identifying Hearing-Impaired Elderly in Primary Care. *The Journal of the American Medical Association*, 259(19):2875–2878.

Likert, R. (1932). A Technique for the Measurement of Attitudes. *Archives of Psychology*, 140:44–60.

Lindeman, M. and Verkasalo, M. (1995). Personality, Situation, and Positive–Negative Asymmetry in Socially Desirable Responding. *European Journal of Personality*, 9(2):125–134.

Lindenberger, U. and Baltes, P. B. (1994). Sensory Functioning and Intelligence in Old Age: A Strong Connection. *Psychology and Aging*, 9(3):339–355.

Lindenberger, U. and Baltes, P. B. (1997). Intellectual Functioning in Old and Very Old Age: Cross-Sectional Results from the Berlin Aging Study. *Psychology and Aging*, 12(3):410–432.

Lindenberger, U., Mayr, U., and Kliegl, R. (1993). Speed and Intelligence in Old Age. *Psychology and Aging*, 8(2):207–220.

Litwin, M. S. (1995). *How to Measure Survey Reliability and Validity*. Sage.

Liu, Y.-C. (2001). Comparative Study of the Effects of Auditory, Visual and Multimodality Displays on Drivers' Performance in Advanced Traveller Information Systems. *Ergonomics*, 44(4):425–442.

Lobley, K. J., Baddeley, A. D., and Gathercole, S. E. (2005). Phonological Similarity Effects in Verbal Complex Span. *The Quarterly Journal of Experimental Psychology Section A*, 58(8):1462–1478.

Logan, G. D. and Crump, M. J. (2009). The Left Hand Doesn't Know What the Right Hand is Doing: The Disruptive Effects of Attention to the Hands in Skilled Typewriting. *Psychological Science*, 20(10):1296–1300.

Loughlin, P. J. and Tacer, B. (1996). On the Amplitude-and Frequency-Modulation Decomposition of Signals. *The Journal of the Acoustical Society of America*, 100(3):1594–1601.

Lund, N. (2002). *Attention and Pattern Recognition*. Routledge.

Lunner, T. (2003). Cognitive Function in Relation to Hearing Aid Use. *International Journal of Audiology*, 42:S49–S58.

Lunner, T., Rudner, M., and Rönnberg, J. (2009). Cognition and Hearing Aids. *Scandinavian Journal of Psychology*, 50(5):395–403.

Lunner, T. and Sundewall-Thorén, E. (2007). Interactions Between Cognition, Compression, and Listening Conditions: Effects on Speech-in-Noise Performance in a Two-Channel Hearing Aid. *Journal of the American Academy of Audiology*, 18(7):604–617.

Lyxell, B., Andersson, J., Andersson, U., Arlinger, S., Bredberg, G., and Harder, H. (1998). Phonological Representation and Speech Understanding with Cochlear Implants in Deafened Adults. *Scandinavian Journal of Psychology*, 39(3):175–179.

Lyxell, B., Andersson, U., Borg, E., and Ohlsson, I.-S. (2003). Working-memory Capacity and Phonological Processing in Deafened Adults and Individuals with a Severe Hearing Impairment. *International Journal of Audiology*, 42(S1):S86–S89.

Lyxell, B. and Rönnberg, J. (1989). Information-Processing Skill and Speech-Reading. *British Journal of Audiology*, 23(4):339–347.

Marottoli, R. and Drickamer, M. (1993). Psychomotor Mobility and the Elderly Driver. *Clinics in Geriatric Medicine*, 9(2):403–411.

Marottoli, R. A., Cooney, L. M., Wagner, D. R., Doucette, J., and Tinetti, M. E. (1994). Predictors of Automobile Crashes and Moving Violations Among Elderly Drivers. *Annals of Internal Medicine*, 121(11):842–846.

Marottoli, R. A., Richardson, E. D., Stowe, M. H., Miller, E. G., Brass, L. M., Cooney Jr, L. M., and Tinetti, M. E. (1998). Development of a Test Battery to Identify Older Drivers at Risk for Self-Reported Adverse Driving Events. *Journal of the American Geriatrics Society*, 46(5):562–568.

Martens, M. and Van Winsum, W. (2000). *Measuring Distraction: The Peripheral Detection Task*. TNO Human Factors.

Martin, J. S. and Jerger, J. F. (2005). Some Effects of Aging on Central Auditory Processing. *Journal of Rehabilitation Research and Development*, 42(4):25.

Martin, M. (1987). *Practical Aspects of Audiology: Speech Audiometry*. Whurr, London.

MATLAB (2010). Version 7.10.0 (R2010a).

Matthews, M. L. and Cousins, L. R. (1980). The Influence of Vehicle Type on the Estimation of Velocity While Driving. *Ergonomics*, 23(12):1151–1160.

Mayer, C. (2007). What Really Matters in the Early Literacy Development of Deaf Children. *Journal of Deaf Studies and Deaf Education*, 12(4):411–431.

McCarley, J. S., Vais, M., Pringle, H., Kramer, A. F., Irwin, D. E., and Strayer, D. L. (2004). Conversation Disrupts change detection in complex traffic scenes. *Human Factors*, 46(3):424–436.

McCloskey, L. W., Koepsell, T. D., Wolf, M. E., and Buchner, D. M. (1994). Motor Vehicle Collision Injuries and Sensory Impairments of Older Drivers. *Age and Ageing*, 23(4):267–273.

McCoy, S. L., Tun, P. A., Cox, L. C., Colangelo, M., Stewart, R. A., and Wingfield, A. (2005). Hearing Loss and Perceptual Effort: Downstream Effects on Older Adults' Memory for Speech. *The Quarterly Journal of Experimental Psychology Section A*, 58(1):22–33.

McDowd, J. and Shaw, R. (2000). Attention and Aging: A Functional Perspective. In Craik, F. I. and Salthouse, T. A., editors, *The Handbook of Aging and Cognition*. Lawrence Erlbaum.

McEvoy, S. P., Stevenson, M. R., McCartt, A. T., Woodward, M., Haworth, C., Palamara, P., and Cercarelli, R. (2005). Role of Mobile Phones in Motor Vehicle Crashes Resulting in Hospital Attendance: A Case-Crossover Study. *British Medical Journal*, 331(7514):428–433.

McFarland, R. and Moore, R. (1955). Human Variables in Motor Vehicle Accidents: A Review of the Literature. Technical report, Harvard School of Public Health.

McGehee, D. V. (2014). Visual and Cognitive Distraction Metrics in the Age of the Smart Phone: A Basic Review. *Annals of Advances in Automotive Medicine*, 58:15–23.

McGwin Jr, G., Owsley, C., and Ball, K. (1998). Identifying Crash Involvement Among Older Drivers: Agreement Between Self-Report and State Records. *Accident Analysis and Prevention*, 30(6):781–791.

McKenna, F. P. (2007). Do Attitudes and Intentions Change Across a Speed Awareness Workshop? In *17th Seminar Proceedings: Behavioural Research in Road Safety*, pages 265–276.

McKnight, A. J. and McKnight, A. S. (1993). The Effect of Cellular Phone Use Upon Driver Attention. *Accident Analysis and Prevention*, 25(3):259–265.

McManus, B., Cox, M. K., Vance, D. E., and Stavrinos, D. (2015). Predicting Motor Vehicle Collisions in a Driving Simulator in Young Adults Using the Useful Field of View Assessment. *Traffic Injury Prevention*, 16(8):818–823.

Medeiros-Ward, N., Cooper, J. M., and Strayer, D. L. (2014). Hierarchical Control and Driving. *Journal of Experimental Psychology: General*, 143(3):953–958.

Merat, N. and Jamson, A. (2007). Multisensory signal detection: How does driving and IVIS management affect performance. In *Proceedings of the 4th International Driving Symposium on Human Factors in Driver Assessement, Training and Vehicle Design*, pages 351–357.

Merat, N. and Jamson, A. H. (2005). Shut Up I'm Driving! Is Talking to an Inconsiderate Passenger the Same as Talking On a Mobile Telephone. In *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, pages 426–432.

Merat, N. and Jamson, A. H. (2008). The Effect of Stimulus Modality on Signal Detection: Implications for Assessing the Safety of in-Vehicle Technology. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 50(1):145–158.

Merat, N. and Jamson, A. H. (2013). The Effect of Three Low-Cost Engineering Treatments on Driver Fatigue: A Driving Simulator Study. *Accident Analysis and Prevention*, 50:8–15.

Merat, N. and Jamson, H. (2011). A Driving Simulator Study to Examine the Role of Vehicle Acoustics on Drivers' Speed Perception. In *Proceedings of the sixth international symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, pages 226–232.

Metropolitan Police (2014). Metropolitan Police Response to a Freedom of Information Request. Available from: http://www.met.police.uk/foi/pdfs/disclosure_2014/June_2014/2014060000016.pdf. [Last accessed: 20/01/2015].

Metz, B., Landau, A., and Hargutt, V. (2015). Frequency and Impact of Hands-Free Telephoning while Driving - Results from Naturalistic Driving Data. *Transportation Research Part F: Traffic Psychology and Behaviour*, 29:1–13.

Michon, J. A. (1985). A critical view of driver behavior models: what do we know, what should we do? In Evans, L. and Schwing, R. C., editors, *Human behavior and traffic safety*, pages 485–524. Springer.

Miura, T. (1986). Coping with Situational Demands: A Study of Eye Movements and Peripheral Vision Performance. In Gale, A., Brown, I., Haselgrave, C., Smith, P., and Taylor, S., editors, *Proceedings of Vision in Vehicles*. Elsevier, Amsterdam.

Miyazaki, S. and Ishida, A. (1987). Traffic-Alarm Sound Monitor for Aurally Handicapped Drivers. *Medical and Biological Engineering and Computing*, 25(1):68–74.

Moore, B. and Glasberg, B. (1997). A Model of Loudness Perception Applied to Cochlear Hearing Loss. *Auditory Neuroscience*, 3(3):289–311.

Moore, B. C. (1996). Perceptual Consequences of Cochlear Hearing Loss and Their Implications for the Design of Hearing Aids. *Ear and Hearing*, 17(2):133–161.

Moore, B. C. (2001). Dead Regions in the Cochlea: Diagnosis, Perceptual Consequences, and Implications for the Fitting of Hearing Aids. *Trends in Amplification*, 5(1):1–34.

Moore, B. C. (2003a). *An Introduction to the Psychology of Hearing*. Academic Press.

Moore, B. C. (2003b). Speech Processing for the Hearing-Impaired: Successes, Failures, and Implications for Speech Mechanisms. *Speech Communication*, 41(1):81–91.

Moore, B. C. (2007). *Cochlear Hearing Loss: Physiological, Psychological and Technical Issues*. John Wiley and Sons.

Moore, B. C. (2008). The Role of Temporal Fine Structure Processing in Pitch Perception, Masking, and Speech Perception for Normal-Hearing and Hearing-Impaired People. *Journal of the Association for Research in Otolaryngology*, 9(4):399–406.

Moore, B. C. (2012). *An introduction to the psychology of hearing*. Brill.

Moore, B. C. and Glasberg, B. R. (1983). Suggested Formulae for Calculating Auditory-Filter Bandwidths and Excitation Patterns. *The Journal of the Acoustical Society of America*, 74(3):750–753.

Moore, B. C. and Glasberg, B. R. (1993). Simulation of the Effects of Loudness Recruitment and Threshold Elevation on the Intelligibility of Speech in Quiet and in a Background of Speech. *The Journal of the Acoustical Society of America*, 94(4):2050–2062.

Moore, B. C. and Glasberg, B. R. (2004). A Revised Model of Loudness Perception Applied to Cochlear Hearing Loss. *Hearing Research*, 188(1):70–88.

Moore, B. C., Glasberg, B. R., and Stone, M. A. (1991). Optimization of a Slow-Acting Automatic Gain Control System for Use in Hearing Aids. *British Journal of Audiology*, 25(3):171–182.

Moore, B. C., Glasberg, B. R., and Vickers, D. A. (1995). Simulation of the Effects of Loudness Recruitment on the Intelligibility of Speech in Noise. *British Journal of Audiology*, 29(3):131–143.

Moore, B. C., Glasberg, B. R., and Vickers, D. A. (1999). Further Evaluation of a Model of Loudness Perception Applied to Cochlear Hearing Loss. *The Journal of the Acoustical Society of America*, 106(2):898–907.

Moore, B. C., Johnson, J. S., Clark, T. M., and Pluvinage, V. (1992). Evaluation of a Dual-Channel Full Dynamic Range Compression System for People with Sensorineural Hearing Loss. *Ear and Hearing*, 13(5):349–370.

Moore, B. C., Vickers, D. A., Glasberg, B. R., and Baer, T. (1997). Comparison of Real and Simulated Hearing Impairment in Subjects with Unilateral and Bilateral Cochlear Hearing Loss. *British Journal of Audiology*, 31(4):227–245.

Mueller, H. G. and Powers, T. A. (2001). Consideration of Auditory Acclimatization in the Prescriptive Fitting of Hearing Aids. *Seminars in Hearing*, 22(2):103–124.

Murnane, O. and Turner, C. W. (1991). Growth of Masking in Sensorineural Hearing Loss. *International Journal of Audiology*, 30(5):275–285.

Murphy, D. R., Craik, F. I., Li, K. Z., and Schneider, B. A. (2000). Comparing the Effects of Aging and Background Noise of Short-Term Memory Performance. *Psychology and Aging*, 15(2):323–334.

Murphy, S., Fraenkel, N., and Dalton, P. (2013). Perceptual Load does not Modulate Auditory Distractor Processing. *Cognition*, 129(2):345–355.

Myers, R. S., Ball, K. K., Kalina, T. D., Roth, D. L., and Goode, K. T. (2000). Relation of Useful Field of View and Other Screening Tests to On-Road Driving Performance. *Perceptual and Motor Skills*, 91(1):279–290.

Nachmias, J. and Steinman, R. M. (1965). An Experimental Comparison of the Method of Limits and the Double Staircase-Method. *The American Journal of Psychology*, 78(1):112–115.

Nagelkerke, N. J. (1991). A Note on a General Definition of the Coefficient of Determination. *Biometrika*, 78(3):691–692.

Naramura, H., Nakanishi, N., Tatara, K., Ishiyama, M., Shiraishi, H., and Yamamoto, A. (1999). Physical and Mental Correlates of Hearing Impairment in the Elderly in Japan. *International Journal of Audiology*, 38(1):24–29.

Navon, D. and Gopher, D. (1979). On the Economy of the Human-Processing System. *Psychological Review*, 86(3):214–255.

Nederhof, A. J. (1985). Methods of Coping with Social Desirability Bias: A Review. *European Journal of Social Psychology*, 15(3):263–280.

Neisser, U. (1976). *Cognition and Reality: Principles and Implications of Cognitive Psychology.* W. H. Freeman.

Nejime, Y. and Moore, B. C. (1997). Simulation of the Effect of Threshold Elevation and Loudness Recruitment Combined with Reduced Frequency Selectivity on the Intelligibility of Speech in Noise. *The Journal of the Acoustical Society of America*, 102(1):603–615.

Newman, C. W., Weinstein, B. E., Jacobson, G. P., and Hug, G. A. (1990). The Hearing Handicap Inventory for Adults: Psychometric Adequacy and Audiometric Correlates. *Ear and Hearing*, 11(6):430–433.

Newman, C. W., Weinstein, B. E., Jacobson, G. P., and Hug, G. A. (1991). Test-Retest Reliability of the Hearing Handicap Inventory for Adults. *Ear and Hearing*, 12(5):355–357.

Niskar, A. S., Kieszak, S. M., Holmes, A. E., Esteban, E., Rubin, C., and Brody, D. J. (2001). Estimated Prevalence of Noise-Induced Hearing Threshold Shifts Among Children 6 to 19 Years of Age: The Third National Health and Nutrition Examination Survey, 1988–1994, United States. *Pediatrics*, 108(1):40–43.

Noble, W. (2006). Bilateral Hearing Aids: A Review of Self-Reports of Benefit in Comparison with Unilateral Fitting. *International Journal of Audiology*, 45(S1):63–71.

Nondahl, D. M., Cruickshanks, K. J., Wiley, T. L., Tweed, T. S., Klein, R., and Klein, B. E. K. (1998). Accuracy of Self-Reported Hearing Loss. *International Journal of Audiology*, 37(5):295–301.

Norman, L. (1962). Driving and Medical Fitness. *The Journal of the Royal Institute of Public Health and Hygiene*, 25:288–292.

Nunes, L. and Recarte, M. A. (2002). Cognitive Demands of Hands-Free-Phone Conversation While Driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 5(2):133–144.

Ohene-Djan, J., Hersh, M., and Naqvi, S. (2010). Investigating Road Safety Issues and Deaf People in the United Kingdom: An Empirical Study and Recommendations for Good Practice. *Journal of Prevention and Intervention in the Community*, 38(4):290–305.

Olson, R. L., Hanowski, R. J., Hickman, J. S., and Bocanegra, J. L. (2009). Driver distraction in commercial vehicle operations. Technical report, Federal Motor Carrier Safety Administration.

Olsson, S. and Burns, P. (2000). Measuring Driver Visual Distraction with a Peripheral Detection Task. Technical report, National Highway Traffic Safety Administration.

Owsley, C. (1994). Vision and Driving in the Elderly. *Optometry and Vision Science*, 71(12):727–735.

Owsley, C., Ball, K., McGwin Jr, G., Sloane, M. E., Roenker, D. L., White, M. F., and Overley, E. T. (1998). Visual Processing Impairment and Risk of Motor Vehicle Crash Among Older Adults. *The Journal of the American Medical Association*, 279(14):1083–1088.

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., and Bruni, J. R. (1991). Visual/Cognitive Correlates of Vehicle Accidents in Older Drivers. *Psychology and Aging*, 6(3):403.

Owsley, C. and McGwin Jr, G. (1999). Vision Impairment and Driving. *Survey of Ophthalmology*, 43(6):535–550.

Oxford Dictionaries (2012). *Oxford English Dictionary*. Oxford University Press.

Özkan, T. and Lajunen, T. (2005). A New Addition to DBQ: Positive Driver Behaviours Scale. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(4):355–368.

Özkan, T., Lajunen, T., Chliaoutakis, J. E., Parker, D., and Summala, H. (2006a). Cross-Cultural Differences in Driving Behaviours: A Comparison of Six Countries. *Transportation Research Part F: Traffic Psychology and Behaviour*, 9(3):227–242.

Özkan, T., Lajunen, T., and Summala, H. (2006b). Driver Behaviour Questionnaire: A Follow-Up Study. *Accident Analysis and Prevention*, 38(2):386–395.

Parker, D., Lajunen, T., and Stradling, S. (1998). Attitudinal Predictors of Interpersonally Aggressive Violations On the Road. *Transportation Research Part F: Traffic Psychology and Behaviour*, 1(1):11–24.

Parker, D., McDonald, L., Rabbitt, P., and Sutcliffe, P. (2000). Elderly Drivers and Their Accidents: The Aging Driver Questionnaire. *Accident Analysis and Prevention*, 32(6):751–759.

Parker, D., Reason, J. T., Manstead, A. S., and Stradling, S. G. (1995a). Driving Errors, Driving Violations and Accident Involvement. *Ergonomics*, 38(5):1036–1048.

Parker, D., West, R., Stradling, S., and Manstead, A. S. (1995b). Behavioural Characteristics and Involvement in Different Types of Traffic Accident. *Accident Analysis and Prevention*, 27(4):571–581.

Pashler, H. (1994). Dual-Task Interference in Simple Tasks: Data and Theory. *Psychological Bulletin*, 116(2):220.

Patrick, D. L. and Deyo, R. A. (1989). Generic and Disease-Specific Measures in Assessing Health Status and Quality of Life. *Medical Care*, 27(Suppliment 3):S217–S232.

Paulhus, D. L. (1991). Measurement and Control of Response Bias. In Robinson, J., Shaver, P., and Wrightsman, L., editors, *Measures of Personality and Social Psychological Attitudes: Volume 1: Measures of Social Psychological Attitudes Series*, pages 17–59. Academic Press.

Pelli, D. G. (1997). The VideoToolbox Software for Visual Psychophysics: Transforming Numbers Into Movies. *Spatial Vision*, 10(4):437–442.

Persson, D. (1993). The Elderly Driver: Deciding When to Stop. *The Gerontologist*, 33(1):88–91.

Peters, R. W., Moore, B. C., and Baer, T. (1998). Speech Reception Thresholds in Noise with and Without Spectral and Temporal Dips for Hearing-Impaired and Normally Hearing People. *The Journal of the Acoustical Society of America*, 103(1):577–587.

Phillips, D. (1987). Stimulus Intensity and Loudness Recruitment: Neural Correlates. *The Journal of the Acoustical Society of America*, 82(1):1–12.

Picard, M., Girard, S. A., Courteau, M., Leroux, T., Larocque, R., Turcotte, F., Lavoie, M., and Simard, M. (2008). Could Driving Safety be Compromised by Noise Exposure at Work and Noise-Induced Hearing Loss? *Traffic Injury Prevention*, 9(5):489–499.

Pichora-Fuller, M. K. (1996). Working Memory and Speechreading. In Stork, D. G. and Hennecke, M. E., editors, *Speechreading by Humans and Machines*, pages 257–274. Springer.

Pichora-Fuller, M. K., Schneider, B. A., and Daneman, M. (1995). How Young and Old Adults Listen to and Remember Speech in Noise. *The Journal of the Acoustical Society of America*, 97(1):593–608.

Pickles, J. O. (2012). *An Introduction to the Physiology of Hearing*. Brill.

Plomp, R. (1986). A Signal-to-Noise Ratio Model for the Speech-Reception Threshold of the Hearing Impaired. *Journal of Speech, Language, and Hearing Research*, 29(2):146–154.

Plomp, R. (1988). The Negative Effect of Amplitude Compression in Multichannel Hearing Aids in the Light of the Modulation-Transfer Function. *The Journal of the Acoustical Society of America*, 83(6):2322–2327.

Poeppel, D., Idsardi, W. J., and van Wassenhove, V. (2008). Speech Perception at the Interface of Neurobiology and Linguistics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1493):1071–1086.

Pomplun, M., Reingold, E. M., and Shen, J. (2001). Investigating the Visual Span in Comparative Search: The Effects of Task Difficulty and Divided Attention. *Cognition*, 81(2):B57–B67.

Pöysti, L., Rajalin, S., and Summala, H. (2005). Factors Influencing the Use of Cellular (Mobile) Phone During Driving and Hazards While Using it. *Accident Analysis and Prevention*, 37(1):47–51.

Quinn, G. P. and Keough, M. J. (2002). *Experimental Design and Data Analysis for Biologists*. Cambridge University Press.

Rabbitt, P. (1991). Mild Hearing Loss Can Cause Apparent Memory Failures Which Increase with Age and Reduce with IQ. *Acta Oto-Laryngologica*, 111(S476):167–176.

Rabbitt, P. M. (1968). Channel-Capacity, Intelligibility and Immediate Memory. *The Quarterly Journal of Experimental Psychology*, 20(3):241–248.

Rabinowitz, P. M. (2000). Noise-Induced Hearing Loss. *American Family Physician*, 61(9):2759–2760.

Rakauskas, M. E., Gugerty, L. J., and Ward, N. J. (2004). Effects of Naturalistic Cell Phone Conversations on Driving Performance. *Journal of Safety Research*, 35(4):453–464.

Raphael, L. J. and Isenberg, D. (1980). Acoustic Cues for a Fricative-Affricate Contrast in Word-Final Position. *Journal of Phonetics*, 8(4):397–405.

Rawool, V. W. (2006). The Effects of Hearing Loss on Temporal Processing. *Hearing Review*, 13(6):42.

Reason, J., Manstead, A., Stradling, S., Baxter, J., and Campbell, K. (1990). Errors and Violations On the Roads: A Real Distinction? *Ergonomics*, 33(10-11):1315–1332.

Recarte, M. A. and Nunes, L. M. (2003). Mental Workload While Driving: Effects on Visual Search, Discrimination, and Decision Making. *Journal of Experimental Psychology: Applied*, 9(2):119–137.

Redelmeier, D. A. and Tibshirani, R. J. (1997). Association Between Cellular-Telephone Calls and Motor Vehicle Collisions. *New England Journal of Medicine*, 336(7):453–458.

Reimer, B. (2009). Impact of Cognitive Task Complexity on Drivers' Visual Tunneling. *Transportation Research Record: Journal of the Transportation Research Board*, 2138(1):13–19.

Retchin, S. M. and Anapolle, J. (1993). An Overview of the Older Driver. *Clinics in Geriatric Medicine*, 9(2):279–296.

Richard, C. M., Wright, R. D., Ee, C., Prime, S. L., Shimizu, Y., and Vavrik, J. (2002). Effect of a Concurrent Auditory Task on Visual Search Performance in a Driving-Related Image-Flicker Task. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 44(1):108–119.

Richards, E., Bennett, P. J., and Sekuler, A. B. (2006). Age Related Differences in Learning with the Useful Field of View. *Vision Research*, 46(25):4217–4231.

Ricketts, T. A. (2001). Directional Hearing Aids. *Trends in Amplification*, 5(4):139–176.

Rimmö, P.-A. (2002). Aberrant Driving Behaviour: Homogeneity of a Four-Factor Structure in Samples Differing in Age and Gender. *Ergonomics*, 45(8):569–582.

Rimmö, P.-A. and Åberg, L. (1999). On the Distinction Between Violations and Errors: Sensation Seeking Associations. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2(3):151–166.

Risto, M. and Martens, M. H. (2014). Supporting Driver Headway Choice: The Effects of Discrete Headway Feedback when Following Headway Instructions. *Applied Ergonomics*, 45(4):1167–1173.

Roman, D. D., Edwall, G. E., Buchanan, R. J., and Patton, J. H. (1991). Extended Norms for the Paced Auditory Serial Addition Task. *The Clinical Neuropsychologist*, 5(1):33–40.

Ronnberg, 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:S68–S76.

Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B., Dahlström, Ö., Signoret, C., Stenfelt, S., Pichora-Fuller, M. K., et al. (2013). The Ease of Language Understanding (ELU) Model: Theoretical, Empirical, and Clinical Advances. *Frontiers in Systems Neuroscience*, 7(31):1–17.

Rönnberg, J., Rudner, M., Foo, C., and Lunner, T. (2008). Cognition Counts: A Working Memory System for Ease of Language Understanding (ELU). *International Journal of Audiology*, 47(S2):S99–S105.

Rosen, S. and Howell, P. (2011). *Signals and Systems for Speech and Hearing*. Brill.

Roskam, A., Brookhuis, K., de Waard, D., Carsten, O., Read, L., Jamson, S., Ostlund, J., Bolling, A., Nilsson, L., Antilla, V., Hoedemaker, M., W, J., J, H., Johansson, E., Tevell, M., Fowkes, M., Engstr'́om, J., and Victor, T. (2002). Development of Experimental Protocol. Deliverable 1. eu project HASTE, project number GRD1/2000/25361. Available from: http://www.its.leeds.ac.uk/projects/haste/HASTE%20Deliverable%201%20v1.1.pdf. [Last accessed: 27/09/2015].

Roth, T. N., Hanebuth, D., and Probst, R. (2011). Prevalence of Age-Related Hearing Loss in Europe: A Review. *European Archives of Oto-Rhino-Laryngology*, 268(8):1101–1107.

Royan, J., Tombaugh, T., Rees, L., and Francis, M. (2004). The Adjusting-Paced Serial Addition Test (Adjusting-PSAT): Thresholds for Speed of Information Processing

As a Function of Stimulus Modality and Problem Complexity. *Archives of Clinical Neuropsychology*, 19(1):131–143.

Roydhouse, N. (1967). Deafness and Driving. *The New Zealand Medical Journal*, 66(425):878–881.

Rudner, M., Rönnberg, J., and Lunner, T. (2011). Working Memory Supports Llistening in Noise for Persons with Hearing Impairment. *Journal of the American Academy of Audiology*, 22(3):156–167.

Salonen, J., Johansson, R., Karjalainen, S., Vahlberg, T., and Isoaho, R. (2011). Relationship Between Self-Reported Hearing and Measured Hearing Impairment in an Elderly Population in Finland. *International Journal of Audiology*, 50(5):297–302.

Salthouse, T. (2000). *A Theory of Cognitive Aging*. Elsevier.

Salthouse, T. A. (1991). Mediation of Adult Age Differences in Cognition by Reductions in Working Memory and Speed of Processing. *Psychological Science*, 2(3):179–183.

Salthouse, T. A. (1994). The Aging of Working Memory. *Neuropsychology*, 8(4):535–543.

Salthouse, T. A. and Hedden, T. (2002). Interpreting Reaction Time Measures in Between-Group Comparisons. *Journal of Clinical and Experimental Neuropsychology*, 24(7):858–872.

Sampson, H. (1956). Pacing and Performance on a Serial Addition Task. *Canadian Journal of Psychology*, 10(4):219–225.

Sanders, A. F. (1970). Some Aspects of the Selective Process in the Functional Visual Field. *Ergonomics*, 13(1):101–117.

Sarampalis, A., Kalluri, S., Edwards, B., and Hafter, E. (2009). Objective Measures of Listening Effort: Effects of Background Noise and Noise Reduction. *Journal of Speech, Language, and Hearing Research*, 52(5):1230–1240.

Schein, J. D. (1968). *The Deaf Community: Studies in the Social Psychology of Deafness*. Gallaudet College Press.

Seitz, K. and Schumann-Hengsteler, R. (2002). Phonological Loop and Central Executive Processes in Mental Addition and Multiplication. *Psychologische Beitrage*, 44(2):275–302.

Sekuler, B., Bennett, P. J., and Mortimer Mamelak, A. (2000). Effects of Aging on the Useful Field of View. *Experimental Aging Research*, 26(2):103–120.

Sekuler, R. and Ball, K. (1986). Visual Localization: Age and Practice. *Journal of the Optical Society of America A, Optics and Image Science*, 3(6):864–867.

Selander, H., Lee, H. C., Johansson, K., and Falkmer, T. (2011). Older Drivers: On-Road and Off-Road Test Results. *Accident Analysis and Prevention*, 43(4):1348–1354.

Shaffer, J. P. (1995). Multiple Hypothesis Testing. *Annual Review of Psychology*, 46(1):561–584.

Shaffer, L. H. (1975). Multiple attention in continuous verbal tasks. In Rabbitt, P. and Dornič, S., editors, *Attention and Performance V*, pages 157–167. Academic Press.

Shannon, R. V., Zeng, F.-G., Kamath, V., Wygonski, J., and Ekelid, M. (1995). Speech Recognition with Primarily Temporal Cues. *Science*, 270(5234):303–304.

Shaw, E. (1974). Transformation of Sound Pressure Level From the Free Field to the Eardrum in the Horizontal Plane. *The Journal of the Acoustical Society of America*, 56(6):1848–1861.

Shinn-Cunningham, B. G. and Best, V. (2008). Selective Attention in Normal and Impaired Hearing. *Trends in Amplification*, 12(4):283–299.

Simon, H. J. and Yund, E. W. (1993). Frequency Discrimination in Listeners with Sensorineural Hearing Loss. *Ear and Hearing*, 14(3):190–201.

Sims, R. V., McGwin Jr, G., Allman, R. M., Ball, K., and Owsley, C. (2000). Exploratory Study of Incident Vehicle Crashes Among Older Drivers. *Journals of Gerontology-Biological Sciences and Medical Sciences*, 55(1):M22.

Sindhusake, D., Mitchell, P., Smith, W., Golding, M., Newall, P., Hartley, D., and Rubin, G. (2001). Validation of Self-Reported Hearing Loss. The Blue Mountains Hearing Study. *International Journal of Epidemiology*, 30(6):1371–1378.

Singh-Manoux, A., Kivimaki, M., Glymour, M. M., Elbaz, A., Berr, C., Ebmeier, K. P., Ferrie, J. E., Dugravot, A., et al. (2012). Timing of Onset of Cognitive Decline: Results from Whitehall II Prospective Cohort Study. *British Medical Journal*, 344:1–8.

Sivak, M. et al. (1996). The Information That Drivers Use: Is It Indeed 90% Visual? *Perception*, 25(9):1081–1090.

Skinner, M. W., Holden, L. K., Holden, T. A., Demorest, M. E., and Fourakis, M. S. (1997). Speech Recognition at Simulated Soft, Conversational, and Raised-to-Loud Vocal Efforts by Adults with Cochlear Implants. *The Journal of the Acoustical Society of America*, 101(6):3766–3782.

Slawinski, E. B. and MacNeil, J. F. (2002). Age, Music, and Driving Performance. *Psychomusicology: Music, Mind and Brain*, 18(1):123–131.

Smeds, K. (2004). Is Normal or Less Than Normal Overall Loudness Preferred by First-Time Hearing Aid Users? *Ear and Hearing*, 25(2):159–172.

Snyder, J. S., Gregg, M. K., Weintraub, D. M., and Alain, C. (2012). Attention, Awareness, and the Perception of Auditory Scenes. *Frontiers in psychology*, 3(15):1–17.

Songer, T. J. (1993). Hearing Disorders and Commercial Motor Vehicle Drivers. Technical report, Federal Highway Administration, Office of Motor Carriers.

Spelke, E., Hirst, W., and Neisser, U. (1976). Skills of divided attention. *Cognition*, 4(3):215–230.

Spence, C. and Driver, J. (2004). *Crossmodal Space and Crossmodal Attention*. Oxford University Press.

Stach, B. (2008). *Clinical Audiology: An Introduction*. Cengage Learning.

Steinhardt, D. A. and Wishart, D. E. (2006). Driver and Rider Licensing Provisions for Clients Who Are d/Deaf. *Journal of the Australasian College of Road Safety*, 17(3):34–39.

Stelmachowicz, P. G., Lewis, D. E., Larson, L. L., and Jesteadt, W. (1987). Growth of Masking as a Measure of Response Growth in Hearing-Impaired Listeners. *The Journal of the Acoustical Society of America*, 81(6):1881–1887.

Stenfelt, S. and Rönnberg, J. (2009). The Signal-Cognition Interface: Interactions Between Degraded Auditory Signals and Cognitive Processes. *Scandinavian Journal of Psychology*, 50(5):385–393.

Stephens, D. and Zhao, F. (1996). Hearing Impairment: Special Needs of the Elderly. *Folia Phoniatrica et Logopaedica*, 48(3):137–142.

Stevens, S. and Guirao, M. (1967). Loudness Functions Under Inhibition. *Perception and Psychophysics*, 2(10):459–465.

Stickney, G., Nie, K., Kong, Y.-Y., Chen, H., and Zeng, F.-G. (2004). Temporal Fine Structure: The Missing Component in Speech Processing Algorithms. In *International Congress Series*, volume 1273, pages 23–26. Elsevier.

Stradling, S. G., Parker, D., Lajunen, T., Meadows, M. L., and Xiel, C. Q. (2000). Normal Behavior and Traffic Safety: Violations, Errors, Lapses and Crashes. In von Holst, H., Nygren, A., and Andersson, A. E., editors, *Transportation, Traffic Safety and Health—Human Behavior*, pages 279–295. Springer.

Strayer, D. L. and Drew, F. A. (2004). Profiles in Driver Distraction: Effects of Cell Phone Conversations On Younger and Older Drivers. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 46(4):640–649.

Strayer, D. L., Drews, F. A., and Johnston, W. A. (2003). Cell Phone-Induced Failures of Visual Attention During Simulated Driving. *Journal of Experimental Psychology: Applied*, 9(1):23–32.

Strayer, D. L. and Johnston, W. A. (2001). Driven to Distraction: Dual-Task Studies of Simulated Driving and Conversing On a Cellular Telephone. *Psychological science*, 12(6):462–466.

Studebaker, G. A., Sherbecoe, R. L., McDaniel, D. M., and Gwaltney, C. A. (1999). Monosyllabic Word Recognition at Higher-than-Normal Speech and Noise Levels. *The Journal of the Acoustical Society of America*, 105(4):2431–2444.

Stutts, J. C., Stewart, J. R., and Martell, C. (1998). Cognitive Test Performance and Crash Risk in an Older Driver Population. *Accident Analysis and Prevention*, 30(3):337–346.

Sümer, N. (2003). Personality and Behavioral Predictors of Traffic Accidents: Testing a Contextual Mediated Model. *Accident Analysis and Prevention*, 35(6):949–964.

Szklo, M. and Nieto, F. J. (2012). *Epidemiology: Beyond the Basics*. Jones and Bartlett Publishers.

Tabachnick, B. G. and Fidell, L. S. (2013). *Using Multivariate Statistics*. Pearson.

Tabak, J. (2006). *Significant Gestures: A History of American Sign Language*. Greenwood Publishing Group.

Tambs, K. (2004). Moderate Effects of Hearing Loss on Mental Health and Subjective Well-Being: Results From the Nord-Trøndelag Hearing Loss Study. *Psychosomatic Medicine*, 66(5):776–782.

ter Keurs, M., Festen, J. M., and Plomp, R. (1992). Effect of Spectral Envelope Smearing on Speech Reception. I. *The Journal of the Acoustical Society of America*, 91(5):2872–2880.

ter Keurs, M., Festen, J. M., and Plomp, R. (1993). Effect of Spectral Envelope Smearing on Speech Reception. II. *The Journal of the Acoustical Society of America*, 93(3):1547–1552.

Thorslund, B., Ahlström, C., Peters, B., Eriksson, O., Lidestam, B., and Lyxell, B. (2014). Cognitive Workload and Visual Behavior in Elderly Drivers with Hearing Loss. *European Transport Research Review*, 6:377–385.

Thorslund, B., Peters, B., Herbert, N., Holmqvist, K., Lidestam, B., Black, A., and Lyxell, B. (2013a). Hearing Loss and a Supportive Tactile Signal in a Navigation System: Effects on Driving Behavior and Eye Movements. *Journal of Eye Movement Research*, 6(5):1–9.

Thorslund, B., Peters, B., Lidestam, B., and Lyxell, B. (2013b). Cognitive Workload and Driving Behavior in Persons with Hearing Loss. *Transportation Research Part F: Traffic Psychology and Behaviour*, 21:113–121.

Thorslund, B., Peters, B., Lyxell, B., and Lidestam, B. (2013c). The Influence of Hearing Loss On Transport Safety and Mobility. *European Transport Research Review*, 5(3):117–127.

Törnros, J. E. and Bolling, A. K. (2005). Mobile Phone Use—Effects of Handheld and Handsfree Phones On Driving Performance. *Accident Analysis and Prevention*, 37(5):902–909.

Treisman, A. M. (1960). Contextual Cues in Selective Listening. *Quarterly Journal of Experimental Psychology*, 12(4):242–248.

Uhlmann, R. F., Larson, E. B., Rees, T. S., Koepsell, T. D., and Duckert, L. G. (1989). Relationship of Hearing Impairment to Dementia and Cognitive Dysfunction in Older Adults. *Journal of the American Medical Association*, 261(13):1916–1919.

Underwood, G., Chapman, P., Bowden, K., and Crundall, D. (2002). Visual Search While Driving: Skill and Awareness During Inspection of the Scene. *Transportation Research Part F: Traffic Psychology and Behaviour*, 5(2):87–97.

Unsworth, C. A., Wells, Y., Browning, C., Thomas, S. A., and Kendig, H. (2007). To Continue, Modify or Relinquish Driving: Findings from a Longitudinal Study of Healthy Ageing. *Gerontology*, 53(6):423–431.

Van Boxtel, M., Ten Tusscher, M., Metsemakers, J., Willems, B., and Jolles, J. (2001). Visual Determinants of Reduced Performance on the Stroop Color-word Test in Normal Aging Individuals. *Journal of Clinical and Experimental Neuropsychology*, 23(5):620–627.

Van der Hulst, M., Rothengatter, T., and Meijman, T. (1998). Strategic Adaptations to Lack of Preview in Driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 1(1):59–75.

van Winsum, W., Martens, M., and Herland, L. (1999). The Effects of Speech Versus Tactile Driver Support Messages On Workload Driver Behaviour and User Acceptance: TNO-Report, TM-99-C043. Technical report, TNO Human Factors Research Institute.

Veltman, J. and Gaillard, A. (1998). Physiological Workload Reactions to Increasing Levels of Task Difficulty. *Ergonomics*, 41(5):656–669.

Ventry, I. and Weinstein, B. (1983). Identification of Elderly People with Hearing Problems. *ASHA*, 25(7):37–42.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., and Cerella, J. (2003). Aging and Dual-Task Performance: A Meta-Analysis. *Psychology and Aging*, 18(3):443.

Victor, T., Dozza, M., Bärgman, J., Boda, C.-N., Engström, J., Flannagan, C., Lee, J. D., and Markkula, G. (2015). Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk. Technical report, Transportation Research Board.

Victor, T. W., Engström, J., and Harbluk, J. L. (2008). Distraction Assessment Methods Based On Visual Behavior and Event Detection. In Regan, M. A., Lee, J. D., and Young,

K. L., editors, *Driver Distraction: Theory, Effects, and Mitigation*, pages 135–165. CRC Press.

Victor, T. W., Harbluk, J. L., and Engström, J. A. (2005). Sensitivity of Eye-Movement Measures to In-Vehicle Task Difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2):167–190.

Visual Awareness Inc. (2003). *UFOV User's Guide.*

Voxeo Corporation (2013). *Pre-Recorded Audio Files.* Available from: http://evolution.voxeo.com/library/audio/prompts/numbers/index.jsp. [Last accessed: 18/11/2013].

Wagner, T. (1962). Licensing Restrictions and the Deaf Driver. In Finesilver, S. G., editor, *National Symposium on the Deaf Driving and Employability*, pages 118–127. US Department of Health, Education and Welfare.

Walker, G. H., Stanton, N. A., and Young, M. S. (2001). Hierarchical Task Analysis of Driving: A New Research Tool. In *Proceedings of the Annual Conference of the Ergonomics Society, Cirencester, April 2001*, pages 435–440. Taylor and Francis.

Walker, G. H., Stanton, N. A., and Young, M. S. (2006). The Ironies of Vehicle Feedback in Car Design. *Ergonomics*, 49(2):161–179.

Walker, G. H., Stanton, N. A., and Young, M. S. (2008). Feedback and Driver Situation Awareness (SA): A Comparison of SA Measures and Contexts. *Transportation Research Part F: Traffic Psychology and Behaviour*, 11(4):282–299.

Wang, E. Y.-N. and Wang, E. M.-Y. (2012). In-Car Sound Analysis and Driving Speed Estimation Using Sounds with Different Frequencies as Cues. *International Journal of Industrial Ergonomics*, 42(1):34–40.

Warren, R. M. (1982). *Auditory Perception: A New Synthesis.* Elsevier.

Warren, R. M. et al. (1970). Perceptual Restoration of Missing Speech Sounds. *Science*, 167(3917):392–393.

Weinstein, B. (1986). Validity of a Screening Protocol for Identifying Elderly People with Hearing Problems. *ASHA*, 28(5):41–45.

Weinstein, B. E., Spitzer, J. B., and Ventry, I. M. (1986). Test-Retest Reliability of the Hearing Handicap Inventory for the Elderly. *Ear and Hearing*, 7(5):295–299.

Weinstein, B. E. and Ventry, I. M. (1983). Audiometric Correlates of the Hearing Handicap Inventory for the Elderly. *Journal of Speech and Hearing Disorders*, 48(4):379–384.

West, R., French, D., Kemp, R., and Elander, J. (1993). Direct Observation of Driving, Self Reports of Driver Behaviour, and Accident Involvement. *Ergonomics*, 36(5):557–567.

Wickens, C. D. (1984). Processing Resources in Attention. In Parasuraman, R. and Davies, D., editors, *Varieties of Attention*. Academic Press, New York.

Wickens, C. D. (2002). Multiple Resources and Performance Prediction. *Theoretical Issues in Ergonomics Science*, 3(2):159–177.

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 50(3):449–455.

Wilkie, R., Kountouriotis, G., Merat, N., and Wann, J. (2010). Using Vision to Control Locomotion: Looking where you want to go. *Experimental Brain Research*, 204(4):539–547.

Willott, J. F. (1996). Physiological Plasticity in the Auditory System and its Possible Relevance to Hearing Aid Use, Deprivation Effects, and Acclimatization. *Ear and Hearing*, 17(Suppl. 3):66S–77S.

Wingfield, A., Tun, P. A., and 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(3):144–148.

Winkler, I. and Cowan, N. (2004). From Sensory to Long-Term Memory: Evidence from Auditory Memory Reactivation Studies. *Experimental Psychology*, 51(3):1–17.

Wiseman, E. and Souder, E. (1996). The Older Driver: A Handy Tool to Assess Competence Behind the Wheel. *Geriatrics*, 51(7):36–8.

Withaar, F. K., Brouwer, W. H., and Van Zomeren, A. H. (2000). Fitness to Drive in Older Drivers with Cognitive Impairment. *Journal of the International Neuropsychological Society*, 6(4):480–490.

Wood, J., Chaparro, A., Hickson, L., Thyer, N., Carter, P., Hancock, J., Hoe, A., Le, I., Sahetapy, L., and Ybarzabal, F. (2006). The Effect of Auditory and Visual Distracters on the Useful Field of View: Implications for the Driving Task. *Investigative Ophthalmology and Visual Science*, 47(10):4646–4650.

Wood, J. M. (2002). Age and Visual Impairment Decrease Driving Performance as Measured on a Closed-Road Circuit. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 44(3):482–494.

World Federation of the Deaf and the Swedish National Association of the Deaf (2008). *Global Survey Reports 1–7 by the World Federation of the Deaf and the Swedish National Association of the Deaf, 2008*. Available from: http://wfdeaf.org/our-work/development-cooperation/project. [Last accessed: 27/09/2015].

World Health Organization (1980). *International Classification of Impairments, Disabilities, and Handicaps: A Manual of Classification Relating to the Consequences of Disease, Published in Accordance with Resolution WHA29. 35 of the Twenty-Ninth World Health Assembly, May 1976*. Available from: http://apps.who.int/iris/bitstream/10665/41003/1/9241541261_eng.pdf. [Last accessed: 23/09/2015].

World Health Organization (2000). *ICIDH-2: International Classification of Functioning, Disability and Health: Prefinal Draft Full Version*. Available from: http://www.sustainable-design.ie/arch/ICIDH-2Final.pdf. [Last accessed: 23/09/2015].

World Health Organization (2015). *Deafness and Hearing Loss*. Available from: http://www.who.int/mediacentre/factsheets/fs300/en/. [Last accessed: 23/09/2015].

Yanz, J. L. (2002). Cochlear Dead Regions and Practical Implications for High Frequency Amplification. *Hearing Review*, 9(4):58–63.

Yost, W. (2000). *Fundamentals of Hearing an Introduction*. Academic Press.

Young, K., Regan, M., and Hammer, M. (2007). Driver distraction: A review of the literature. technical report 206. Technical report, Monash University, Accident Research Centre, Victoria, Australia.

Ysander, L. (1966). The Safety of Drivers with Chronic Disease. *British Journal of Industrial Medicine*, 23(1):28–36.

Zekveld, A. A., Kramer, S. E., and Festen, J. M. (2011). Cognitive Load During Speech Perception in Noise: The Influence of Age, Hearing Loss, and Cognition On the Pupil Response. *Ear and Hearing*, 32(4):498–510.

Zurek, P. and Delhorne, L. (1987). Consonant Reception in Noise by Listeners with Mild and Moderate Sensorineural Hearing Impairment. *The Journal of the Acoustical Society of America*, 82(5):1548–1559.

Appendix

The questions administered to participants in Chapter 4

Section A: Demographic information

General

1. Age:
2. Gender:
3. Occupation:

Driving

4. For how long have you held your driver's licence?
5. Did you have to perform an official test to initially obtain your driver's licence?
6. Have you ever been a professional driver?
7. Approximately how many miles do you drive in a year?
8. Do you tend to avoid driving on certain types of road, or at certain times during the day (if so please give details)?
9. Over the past three years, has the amount you drive increased, decreased, or stayed the same?
10. How many times in the past five years have you been crashed into by another drivers' vehicle whilst driving?
11. How many times in the past five years have you crashed your car into another vehicle whilst driving?
12. How many times in the past year have you almost been involved in an accident?

Section B: Driver Behaviour Questionnaire (Parker et al., 2000 version)

Please rate the extent to which the following situations arise during your driving from 1–6, with 1 denoting that it never happens and 6 denoting that it always happens:

1. Attempt to drive away from traffic lights in too high a gear
2. Forget where you left your car in a car park
3. Become impatient with a slow driver in the outer lane and overtake on the inside
4. Drive especially close to the car in front as a signal to its driver to go faster or get out of the way
5. Switch on one thing, such as the headlights, when you meant to switch on something else such as the wipers
6. Realize that you have no recollection of the road along which you have just been travelling
7. Intending to drive to destination A, you suddenly notice that you are on the road to destination B, perhaps because B is your more usual destination
8. Cross a junction knowing the traffic lights have already turned against you
9. Angered by another driver's behaviour, you give chase with the intention of giving him/her a piece of your mind
10. Disregard the speed limits late at night or early on in the morning
11. On turning left, nearly hit a cyclist who has come up on your inside
12. Queuing to turn left onto main road, you pay such close attention to the main stream of traffic that you nearly hit the car in front
13. Drive even though you realize that you may be over the legal blood alcohol limit
14. Have an aversion to a particular class of road user, and indicate your hostility by whatever means you can
15. Underestimate the speed of an oncoming vehicle when overtaking
16. Hit something when reversing that you had not previously seen
17. Get into the wrong lane approaching a roundabout or a junction
18. Misread signs and take the wrong turning off a roundabout
19. Miss give way signs and narrowly avoid colliding with traffic having right of way
20. Fail to check your rear-view mirror before pulling out, changing lanes, turning, etc.
21. Attempt to overtake someone you had not noticed to be signalling a right turn
22. Fail to notice pedestrians crossing on turning into a side road
23. Get involved in unofficial 'races' with other drivers
24. Brake too quickly on a slippery road, or steer the wrong way into a skid

Section C: The Driving and Hearing Loss Questionnaire

Please rate the extent to which you agree with each of the following situations from 1–5, with 1 denoting that you strongly disagree, and 5 denoting that you strongly agree:

1. I have considered limiting the amount I drive because of my hearing loss
2. I think that hearing loss presents some problems for driving
3. I feel that my hearing loss sometimes makes driving more difficult for me
4. I think that sounds from the surrounding environment are important for safe driving
5. Working out the direction from which emergency services vehicles are approaching is difficult because of my hearing loss
6. Having the stereo on whilst I drive has a negative effect on my driving
7. I find it difficult to hear sounds produced by electronic devices in my car (e.g. satellite navigation instructions, parking sensors etc)
8. My hearing loss sometimes makes it difficult for me to judge how fast I am driving
9. When I am talking to people in my car I find it difficult to concentrate on the road
10. When I am paying attention to sounds produced by electronic devices in the car I find driving more difficult (e.g. satellite navigation instructions)
11. Being able to hear when emergency services vehicles are near is difficult for me
12. I have a problem hearing what passengers say whilst I'm driving my car
13. I feel that because of my hearing loss I am sometimes less aware of what is going on around me when I am driving
14. I find that talking on a hands-free mobile phone whilst I drive is very difficult because of my hearing loss
15. I think that sounds from the engine of the car are important for safe driving
16. My hearing loss makes me worry about parking my vehicle in close proximity to other obstacles (e.g. other cars, fences, walls etc)
17. I feel that some in-car electronic devices which make use of sound are not accessible to me
18. My hearing aid(s) do not allow me to communicate more easily with passengers in the car whilst I am driving
19. Wearing my hearing aid(s) whilst driving makes sounds uncomfortably loud
20. My hearing aid(s) do not improve my ability to drive
21. My hearing aid(s) do not make me feel more aware of my surroundings whilst driving
22. I feel that wearing my hearing aid(s) disorientates me whilst driving
23. Using my hearing aid(s) does not allow me to use devices in my car more easily

Section D: Hearing information

General

1. For how long have you had a hearing loss?
2. Do you own a hearing aid?
3. For how long have you owned your hearing aid(s)?
4. Do you ever use your hearing aid(s)?
5. How often do you usually wear your hearing aid(s)?
6. How often do you usually wear your hearing aid(s) whilst driving?

HHIE-S (Ventry and Weinstein, 1983)

Please answer 'yes', 'sometimes', or 'no' for each of the following questions:

1. Does a hearing problem cause you to feel embarrassed when you meet new people?
2. Does a hearing problem cause you to feel frustrated when talking to members of your own family?
3. Do you have difficulty hearing/understanding co-workers, clients or customers?
4. Do you feel handicapped by a hearing problem?
5. Does a hearing problem cause you difficulty when visiting friends, relatives or neighbours?
6. Does a hearing problem cause you difficulty in the cinema or theatre?
7. Does a hearing problem cause you to have arguments with family members?
8. Does a hearing problem cause you difficulty when listening to TV or radio?
9. Do you feel that any difficulty with your hearing limits or hampers your personal or social life?
10. Does a hearing problem cause you difficulty when in a restaurant with relatives or friends?