THE EFFECTS OF AGE, SIMULATED VISION IMPAIRMENT, AND DISTRACTION ON HAZARD DETECTION WHILE DRIVING

A thesis presented to the graduate faculty of
New England College of Optometry in partial fulfilment
of the requirements for the degree of Master of Science

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ABSTRACT

Purpose

Driving is crucial for maintaining independence in older age, but age-related vision impairments (VI) and in-vehicle auditory distractions may impair driving safety. However, the nature in which VI and auditory distraction interact to affect hazard detection while driving has yet to be fully understood. The goal of this thesis project was, therefore, to assess the effects of age, central vision loss (CVL), auditory distractions, and their interactions, on detection of pedestrian hazards within the safe environment of a driving simulator.

Methods

We first developed a pedestrian hazard detection paradigm in which participants drove along highway routes and pressed the horn whenever they saw a pedestrian. Pedestrians ran toward the road on a collision course with the approaching vehicle. Detection performance was quantified in terms of reaction times (RT) and safe detection rates (whether or not the participant would have had sufficient time to safely brake before reaching the collision point). A pilot study (16 normally-sighted participants, three older) was then conducted to evaluate potential auditory distraction tasks. An auditory book task was determined to be the most appropriate as it was distracting enough for both age groups, required constant engagement, and resembled a task that drivers encounter in the real world. Participants listened to audiobook excerpts while driving and repeated out loud target words whenever they were heard. Next, we conducted the main study

(32 normally-sighted subjects, 16 older) using the pedestrian detection paradigm, auditory distraction task and a simulation of central VI (simVI) achieved with diffusing filters that reduced VA to 20/80 (within the range for a restricted license in MA) and reduced contrast sensitivity (CS) by 0.35 log units. Participants completed four drives, two with the auditory task, and two with simVI. Lastly, as a follow up to our main study, we conducted a small study with four subjects with real CVL to evaluate the feasibility of implementing our paradigm to examine the effects of auditory distraction on drivers with real CVL.

Results

In the main study, simVI had a greater effect on RT (660 ms increase) than age (350 ms increase) and distraction (160 ms increase), and had a greater effect on older than younger participants (828 ms and 492 ms increase, respectively). SimVI decreased safe response rates from 94.7% to 78.3%. Distraction did not, however, affect safety because older participants drove more slowly when distracted (but did not drive more slowly with simVI). Our final study confirmed that the paradigm was suitable for participants with real CVL, and distraction again increased RTs. However, only one real CVL participant decreased their speed when driving with distraction.

Conclusions

In the main study, simVI increased response times to a much greater extent in older than younger participants, despite similar levels of VA and CS reductions. Neither older nor younger participants adapted their speed in response to simVI, resulting in unsafe detections. However, older participants appeared to compensate for the auditory distraction by driving more slowly, possibly perceiving a greater threat to their driving safety from the auditory distraction than from the simVI. We extended prior research by not only evaluating detection rates and response times,

but also evaluating the safety of responses in a paradigm where participants could modify their driving behaviors to compensate for vision impairment or distraction. Findings from participants with simVI and real CVL underline the importance of this approach which flexibly allows participants to modify their driving behaviors.

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CHAPTER 1 – GENERAL INTRODUCTION

Driving is vital in maintaining one's independence and quality of life in the United States, especially with increasing age (Karthaus & Falkenstein, 2016). In 2016, 41.7 million of the licensed drivers in the United States were 65 years or older, accounting for 18.8% of all licensed drivers (U. S. Department of Transportation, 2017), compared to 15% in 2006 (National Highway Traffic Safety Administration, 2015). The increase of drivers in this age group has far outpaced those who are in their teens or early adulthood (U. S. Department of Transportation, 2017). In general, older drivers have been found to drive safely in routine traffic situations and practice safer driving habits than young drivers, such as not speeding or overtaking other vehicles (Merat, Anttila, & Luoma, 2005). This may be due to the fact that younger drivers are less experienced and are more likely to overestimate their driving abilities. However, a common finding is that older drivers respond more slowly to hazards when driving than younger individuals (Fildes et al., 2007) and older drivers are more frequently involved in motor vehicle collisions (Wood, 2002). It is possible that both age-related degradations of vision (Keltner & Johnson, 1987; Owsley & McGwin, 2010; Wood, 2002) and cognitive resources (Mathias & Lucas, 2009) may impair the ability of older drivers to respond to hazards in a timely manner, which may put them at increased risk for crashes. In addition, auditory distractions are becoming increasingly more common in today's driving environment (Strayer et al., 2017) and may adversely affect hazard detection. Therefore, an important question is how impairments in vision interact with auditory distraction to affect hazard detection in both older and younger drivers.

Drivers often devote a portion of their attention resources to auditory activities such as communicating with passengers, listening to an audiobook, or interacting with in-vehicle navigation and assistance systems. Mental effort is required to engage in these activities, which decreases the amount of cognitive resources available to be devoted to the driving task which could have a negative impact on driving performance (Strayer et al., 2017). However, the nature in which vision impairment (VI) and auditory distraction interact to affect hazard detection while driving has yet to be fully understood. The goal of this thesis project is, therefore, to assess the effects of age, central vision loss (CVL) and auditory distractions, and their interactions, on detection of moving pedestrian hazards.

1.1 Central vision loss (CVL) and driving

Vision is considered to be the most important sensory modality for driving (Hills, 1980). Therefore, having impaired vision may adversely affect driving safety (DeCarlo et al., 2003; Owsley, 2010). Age-related eye conditions involving CVL, such as cataracts or age-related macular degeneration (AMD), result in reduced visual acuity (VA) and contrast sensitivity (CS). Nevertheless, it is possible for people with VA outside the typical 0.3 logMAR (20/40 Snellen) requirement for an unrestricted license to continue to drive legally on a restricted license (Peli & Peli, 2002). For example, in Massachusetts (MA), VA can be as low as 0.54 logMAR (20/70 Snellen) for a restricted license, or 0.7 logMAR (20/100 Snellen) if driving with a bioptic telescope (American Association of Motor Vehicle Administrators). In addition, some people continue to drive illegally when their VA is outside the legal requirement (DeCarlo et al., 2003). However, prior research suggests that impairments in VA and CS, in particular, may adversely affect hazard detection. Drivers with CVL (mainly from

AMD) had slower responses to pedestrian hazards than age-matched normally-sighted drivers in a driving simulator (Owsley et al., 2001). In many cases, their responses were so delayed that a collision could not have been avoided. Similarly, drivers with CVL (from cataracts) were more likely to have a history of at-fault crashes in the prior five years than drivers without CVL (Owsley et al., 2001). Simulated VA and CS impairments have been reported to impair responses to hazards in a number of situations, including video-based hazard perception tests (Lee et al., 2016; Marrington, Horswill, & Wood, 2008), driving simulator hazard detection tasks (Lehsing et al., 2019; Swan et al., 2019), and on closed-road driving courses (Wood, Chaparro, & Hickson, 2009). A number of studies have demonstrated that changes in CS have a greater impact on hazard detection than changes in VA (Owsley et al., 2001; Swan et al., 2019; Wood, 2002; Wood, Chaparro, & Hickson, 2009). For instance, Marrington et al. (2008) showed that drivers with simulated cataracts had a delayed hazard detection time by 350 ms, even if the resulting VA with simulated cataracts met the minimum vision requirements for driving. This is of particular interest given that licensing authorities impose minimum requirements for VA but not CS.

1.2 Cognitive resources, distraction and driving

Driving is cognitively as well as visually demanding. Cognitive resources are finite and have to be divided across a multitude of tasks when driving including lane keeping, hazard detection, and interacting with information and assistance systems. Aging contributes to a decline in the total available pool of cognitive resources, which means there are fewer resources to divide among concurrent tasks. Thus, older drivers may be less able to allocate cognitive resources in a timely manner (Belbase & Sanzenbacher, 2017; Karthaus &

Falkenstein, 2016). Working memory stores overlapping and competing information, such as processing of prior events that has been interrupted by newer processing, so that the older process can be resumed, if needed (Miller, Galanter, & Pribram, 1962). Working memory also allows for different processing to be buffered and coordinated so multiple behavioral goals can be accomplished (Baddeley & Hitch, 1974). However, there is a limit to the amount of information that can be retained in working memory. When multiple tasks must be performed at the same time, which is often the case when driving, there is competition for cognitive resources. Two stimuli of the same modality (visual, auditory, or tactile) result in greater competition for resources than two stimuli of different modalities. Moreover, visual stimuli have been found to dominate information processing unless specific, non-visually related behavioral goals exist (Scalf et al., 2013). Cross modal interference is also possible, where auditory distraction may affect one's performance on a visual task. Savage et al. (2013) found that even the act of contemplating a previous conversation can have negative effects on how a concurrent visual task is performed.

Higher-level executive functions, which are thought to mediate the allocation of attention resources to lower-level functions such as attention selectivity and task switching, are also affected by distraction (Karthaus & Falkenstein, 2016). Since cognitive resources are limited (Hahn, Wild-Wall, & Falkenstein, 2011), older people may experience difficulty processing concurrent tasks and filtering out irrelevant information. This can result in cognitive resources being allocated to the wrong tasks at crucial moments in time (Charness & Bosman, 1992). Therefore, age-related declines in cognitive resources may reduce one's ability to detect hazards and drive safely (Strayer & Drews, 2004; Wood, Chaparro, &

Hickson, 2009). An important question to be addressed in this thesis is how impairments in vision interact with auditory distraction to affect hazard detection in both older and younger drivers.

1.3 Auditory distractions when driving

Auditory distractions are becoming increasingly more common in today's driving environment (Strayer et al., 2017) and can distract a driver from tasks specifically related to driving (Courage et al., 2015). This issue is of special interest as many new car models have built-in assistance systems to help with navigation and collision avoidance that use auditory interfaces (Strayer et al., 2017). Engagement in auditory activities such as listening to an audio book or holding a cell-phone conversation decreases the amount of cognitive resources available for driving tasks and may impair driving performance (Strayer et al., 2017). However, little is known about how VI and auditory distraction interact to affect detection of hazards. It is likely that more cognitive resources are needed to process visual information when the incoming visual signal is degraded (as with CVL) than when it is not degraded. Previous studies have shown that reduced CS and luminance result in longer fixation durations, suggesting that subjects required a longer time and took more resources to process visual information when it was degraded (Bowers & Reid, 1997). This effect is likely greater in an older driver with recently acquired CVL who is still adapting to their vision loss. They may need to allocate more cognitive resources to seeing and interpreting degraded visual inputs, which in turn will reduce resources available for driving tasks or coping with auditory distractions. Thus, the combined negative effects of VI and distraction on hazard detection may be greater in older than younger drivers.

1.4 Prior studies of the effects of vision impairment (VI) and distraction

There have been very few prior studies investigating the effects of VI and distraction on performance of driving-related tasks (Lee et al., 2016; Wood, Chaparro, & Hickson, 2009). Two main studies are discussed below.

Lee et al. (2016) examined the effects of simulated reduced VA (using positive sphere lenses) and auditory distraction on hazard perception performance of older and younger drivers. The auditory distraction task involved determining whether a given navigation instruction was logical or impossible to follow according to the road layout. Their results suggested that simulated VA loss, without a reduction in CS, and auditory distraction both led to an increase in reaction times (RTs) to hazards. Older drivers were more greatly distracted and responded more slowly to hazards than younger drivers. Lee and colleagues (2016) made use of a standard video-based hazard perception paradigm. This methodology involved watching a series of video clips but did not require subjects to be actively engaged in motor coordination tasks important for driving, such as steering or operating the brake and accelerator (Lee et al., 2016). In addition, their use of positive sphere lenses did not simulate the effects of reduced CS, which is often a result of many age-related ocular conditions and has been found to have greater negative effects on reaction times than a VA reduction alone (Swan et al., 2019).

Wood et al. (2009) conducted a study that examined the effects of CVL (simulated reduced VA and simulated cataracts with reduced VA and CS), age, and distraction on driving performance on a closed-road course (Wood, Chaparro, & Hickson, 2009). Distraction was created using a mental arithmetic task that was presented in either the visual

or auditory domain (reporting the sum of two numbers that were either presented on the dashboard or were played through speakers). The authors investigated the effects of these factors on road sign recognition and hazard avoidance. A key finding was that the combined adverse effects of visual distraction and simulated cataracts were significantly greater for older than younger subjects. However, the hazards along the driving course were large pieces of low contrast foam (Wood, Chaparro, & Hickson, 2009), which were stationary and did not pose real danger to the subjects. By comparison, in open-road driving, many hazards are moving and present real collision risks.

1.5 Driving simulators as a safe environment to evaluate hazard detection

Although open-road driving (i.e. driving a pre-determined route along public roads) has the greatest real-world validity for studying the effects of VI and distraction on driving, there are a number of disadvantages that need to be considered. In particular, there is no control over if, when or where a hazard might appear and little control over environmental conditions and the behavior of other traffic on the road. This means that one participant might experience multiple hazards while another might experience only one hazard. And, very importantly, there are significant safety concerns, making open-road courses less than ideal for systematic investigations of the effects of VI and distraction on hazard detection.

In contrast, a driving simulator provides a safe, controlled, realistic and replicable experimental environment in which to evaluate the effects of VI and distraction on detection of hazards (Bronstad et al., 2013; Alberti, Peli, & Bowers, 2014) while participants are actively engaged in controlling vehicle speed and steering. One potential way to compensate for VI, and/or auditory distraction would be to drive more slowly (as has been reported for

drivers with real CVL) (Bronstad et al., 2013). Thus, an important advantage of simulated driving tasks over video-based hazard perception tasks is that subjects are able to control the speed at which they drive and can therefore control the speed of incoming visual information. For these reasons, a driving simulator was used in this thesis project to investigate the effects of age, simVI and auditory distraction on detection of pedestrian hazards (Bronstad et al., 2013; Alberti, Peli, & Bowers, 2014) while driving.

1.6 Simulating central vision impairment (simVI)

As in many prior studies that investigated the effects of VI on driving (Lee et al, 2016; Marrington, Horswill, & Wood, 2008; Swan et al., 2019; Wood, Chaparro, & Hickson, 2009), we used a simulation of central VI. Simulated VI (simVI) ensures a relatively homogeneous degree of impairment, which can be difficult to achieve with a heterogeneous sample of people with real VI. We simulated a level of VI that was within the minimum requirements for a restricted license in MA (American Association of Motor Vehicle Administrators).

Two main methods of creating simVI have been used in previous studies investigating the effects of simVI on driving tasks: positive sphere lenses (Lee et al., 2016) and diffusing filters (Swan et al., 2019; Wood, Chaparro, & Hickson, 2009). While positive sphere lenses decrease VA only (Wood, Chaparro, & Hickson, 2009), diffusing filters decrease both VA and CS (Swan et al., 2019). Both reduced VA and reduced CS affect driving performance (Lee et al., 2016; Marrington, Horswill, & Wood, 2008; Wood, Chaparro, & Hickson, 2009, but reduced CS has a greater negative effect on hazard detection than reduced VA (Swan et al., 2019). Furthermore, in real CVL it is rare to have a reduction

in VA without an accompanying reduction in CS. Therefore, for the purpose of our study, we decided to use diffusing filters to simulate both a reduction in VA and a reduction in CS. We used Bangerter diffusing filters attached to the lenses of laboratory goggles. They reduced participants' VA and CS without reducing their binocular field of view. These filters have been used to simulate VI in a number of studies (Bowers et al., 2018; Hecht et al., 2015; Lehsing et al., 2019).

1.7 Overview of thesis project

In this thesis we investigated the effects of age, simVI and auditory distraction on detection of pedestrian hazards (Bronstad et al., 2013; Alberti, Peli, & Bowers, 2014) while driving in a simulator. We expected that each of these factors would increase RTs and that they might interact to further increase RTs. For example, any increases in RTs as a result of distraction or simVI might be greater in older than younger participants. If RTs are longer, it might be assumed that the responses would be less safe. However, if the subjects also compensated by driving more slowly, a longer RT would not necessarily be less safe than a shorter RT when driving more quickly. We, therefore, measured both RTs to the pedestrian hazards and the safety of the response (i.e., whether or not detection was made in enough time to avoid a collision given the speed and distance of the car to the pedestrian at the time of detection).

We first conducted a small-sample pilot study (Chapter 2) to establish our methodology and determine an appropriate auditory distraction task for both younger and older subjects. We then implemented the methodology in our main study (Chapter 3) where we included a greater number of subjects and tested the effects of age, simVI and audio distraction on a greater number of driving-related variables than in the pilot study. Finally,

we conducted a small proof-of-concept study (Chapter 4) to evaluate the feasibility of using our methodology to investigate the effects of auditory distraction in drivers with real CVL.

CHAPTER 2 – PILOT STUDY TO SELECT AN AUDITORY DISTRACTION TASK

2.1 Introduction

A pilot study was conducted as the first part of the thesis project to determine an appropriate auditory distraction task to be used in the main study. Our goal was to develop an auditory distraction task that would require constant engagement from the subject throughout a drive.

Auditory distraction tasks used in prior studies

A search of the literature identified several auditory distraction tasks that had been employed in previous studies, which examined the effects of distraction on driving. Each task had advantages and disadvantages (see Table 1 for a summary). Heenan (2014) included simulated hands-free cell phone conversations, during which participants were instructed to guess a particular item by asking 20 questions. The advantage of this task was that the act of talking or having a conversation while driving can be commonly found in real-world driving. However, multiple variables could affect the execution of the task, making it difficult to control. For instance, the quality of the questions each participant asked and the amount of time that each participant needed to complete the task may have varied greatly. Liang and Lee (2010) used audio clips with logical and illogical navigation instructions as a form of distraction. Instructions from navigation systems are commonly found and used in real world driving. However, in highway drives without intersections, as would be used in the driving simulator scenarios in this study, navigation instructions were unnecessary. Reimer et al. (2009) employed an auditory N-back task, a delayed recall task in which participants had to listen to a series of numbers and repeat out loud one of the numbers with varying levels of difficulty. Participants either repeated the numbers immediately after they were played,

repeated the numbers that were played two numbers earlier, or repeated the numbers three numbers earlier. This task provides a consistent level of engagement for subjects and is difficult enough to distract both younger and older participants. However, it is not found in a natural driving setting, and might be too difficult for some older participants to complete, especially with a concurrent driving task. Speckman-Collins et al. (2005) used an auditory sound/word matching task. Participants were instructed to press a button when they heard the same sound or word, from a sequence, that matched the experimenter's sample sound or word given at the beginning of each trial. Finally, Sonnleitner et al. (2012) used an audiobook task in which participants listened to excerpts while driving and had to report predetermined words in the excerpts by pressing a button every time they heard one of the predetermined words. People often listen to audiobooks when driving and it is a task that can require constant engagement from the driver. However, excerpts and predetermined words must be carefully selected to constantly engage the participant.

Table 1. Auditory distraction tasks that have been used in prior studies.

Authors	Distraction task used	Advantages	Disadvantages
Heenan (2014)	Simulated hands-free cell phone conversations (20 questions were asked by the participant to guess a particular item)	Task is commonly found in a real-world driving setting	Task requires additional experimenters during the study and is more difficult to control for variables
Liang & Lee (2010); Lee, Black, Lacherez, & Wood (2006)	Audio clips containing logical or illogical navigation instructions given a road layout	Task is commonly found in a real-world driving setting	Task does not apply to the highway settings in the current study where there are no intersections
Wood, Chaparro, & Hickson (2009)	Mental arithmetic task (reporting the sum of two numbers)	Task is easy to control and execute and it provides relatively consistent engagement from the driver	Not found in a natural driving setting
Reimer, Mehler, Coughlin, Godfrey, & Tan (2009)	N-back task	Consistent engagement of the cognitive system and difficult enough to distract all participants	Not found in a natural driving setting and may be too difficult for older participants to complete
Sonnleitner, Simon, Kincses, Buchner, & Schrauf (2012)	Audiobook excerpt (participants detected predetermined words by pressing on a button)	Task is commonly found in a real-world driving setting and it allows for constant engagement from the driver	Must carefully select for excerpts and words that constantly engage the participant and many drivers do not listen to audio books as intently as in this task
Speckman-Collins, Park, & Greer (2005)	Matching task	Task is easy to control and execute and it provides relatively consistent engagement from the driver	May be too easy and not employ much cognitive load and not found in a natural driving setting

Criteria for selecting auditory distraction task

Our three main criteria for choosing an auditory task were: 1) it should require constant cognitive engagement by the participant throughout the drive; 2) it should be ecologically valid, resembling (as close as possible) a task that drivers typically encounter in a car when driving in the real world; and 3) the task should be difficult enough to distract younger participants, but not be too difficult for older participants. Based on our review of the literature, and these criteria, we identified three potential tasks – an n-back-1 task, a category matching task, and an audiobook task – to try as potential auditory distraction tasks in the pilot study. All involved continuous performance and the recalling of words or numbers.

Pilot study aims

Our aims for the pilot study were to identify an appropriate auditory distraction task and establish our methodology for the main study.

2.2 Methods

Design

The effects of the three audio distraction tasks on detection performance were first examined in small group of younger participants to narrow the selection down to the two most promising tasks. These two tasks were then evaluated using a small group of younger (n = 3) and older (n = 3) participants in order to determine which of the two auditory tasks was the most suitable for both age groups.

Participants

A total of 16 participants (9 females, 7 males, age range 22-40 for young (n=13) and 60-84 for older subjects (n=3)) were recruited from the Schepens Eye Research Institute. Participants were English-speaking, current drivers with at least two years of driving experience. They had no adverse history of eye disease that might affect VA or visual fields. All participants were able to participate in a conversation without any hearing difficulties (without or with a hearing aid - as evaluated by the experimenter during the informed consent process). All participants' vision exceeded the requirements for an unrestricted license in Massachusetts (VA of at least 0.3 logMAR and a 120° visual field extent; American Association of Motor Vehicle Administrators). The average VA and CS of the younger participants were 0.0 logMAR and 1.77 log units, respectively, while those for older participants were 0.12 logMAR and 1.59 log units, respectively.

The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the institutional review board (IRB) at the Schepens Eye Research Institute. All participants received a full explanation of the experimental procedures, and read and signed an informed consent form prior to the start of the study.

Driving simulator and pedestrian detection task

A high-fidelity LE-1500 driving simulator (FAAC, Inc., Ann Arbor, MI) with five 42-inch liquid crystal display monitors (LG M4212C-BA, native resolution of 1366 x 768 pixels; 225° x 32° field of view) was used. The simulator included a motion-based seat, with three degrees of freedom in its movement (forward / backward; up / down; left / right), standard driving controls for an automatic transmission vehicle, and an interior dashboard modeled on

a Ford Crown Victoria (see Figure 1). Data from the driving simulator, including the participants' vehicle control inputs (steering, horn presses, braking, acceleration, etc.), and positional information of the vehicle and scripted entities in the world, were recorded at 30Hz throughout the drive.



Figure 1. LE-1500 driving simulator (FAAC, Inc., Ann Arbor, MI) used in this study. The auditory distraction task was delivered though a pair of speakers (Amazon *Basics A100* Multimedia Speakers, China) positioned to the left and right of the participant's seat (white circle). A video recorder (yellow circle; DVC, WEILIANTE Co., Ltd, China) was positioned above and behind the car seat to simultaneously record participants' repetition of target words in the auditory distraction task along with video of the central screens of the simulator (to facilitate scoring of auditory task performance for segments without and with pedestrians on the screen).

Scenarios and pedestrian events were created using the Scenario Toolbox (FAAC Inc., Version 3.9.4.25873) and were based on scenarios used in prior driving simulator studies of pedestrian detection by drivers with real VI (Alberti, Peli, Bowers, 2014; Bronstad et al., 2013). We used pedestrian hazards because they are one of the most vulnerable road users. Nearly 12,000 pedestrians were killed by motor vehicles in the United States in 2016 and 2017, the highest number in more than 25 years (Governors Highway Safety Association; 2018). A total of four rural highway scenarios (‘nh1aap,’ ‘nh1bap,’ ‘nh1cap,’ and ‘nh1dap’) were developed, each including oncoming traffic (average 16 vehicles, range 15-19) and 12 highly-salient, moving pedestrians (2.0 m tall, subtending 0.9° vertically when they first appeared, and all dressed in a white shirt and blue jeans, see Figure 2). The routes were along undivided highways (60 mph posted speed limit, equivalent to 97 kph) with a single lane in each direction, including long straight sections and long gentle curves without any sharp 90° turns (lessen the likelihood of simulator sickness), stop signs, traffic lights, or lead cars. The background scenery contained grassy hills with some trees (see Figure 1).



Figure 2. Screenshot of the running pedestrian as it appeared on the left (as in this example) or right side of the participant's travel lane.

Pedestrians appeared at pseudorandom intervals every 15 to 60 seconds. They appeared from either the left (n = 6) or right side (n = 6) of the road when the car was approximately 5 seconds away (if travelling at the set speed limit of 97 kph). Pedestrians were programmed to run at a constant velocity toward the road on a trajectory perpendicular to the subject's travel lane, as if to cross in front of the subject's vehicle. If the subject's vehicle was travelling at 97 kph, the pedestrian was on a direct collision course with the subject's vehicle (with a constant bearing angle between the vehicle and the pedestrian) and the two road users would have reached the collision point in the middle of the driving lane at the same time. If the participant drove more slowly than the speed limit, then the pedestrian would have reached the collision point before the car, but would still have appeared as a potential hazard (unless the participant drove extremely slowly). However, to avoid upset from actual collisions, the pedestrians were programmed to stop just before entering the participant's driving lane. We instructed subjects to drive as close to 97 kph (60 mph) as possible to ensure that the pedestrians were on a true collision course (a constant bearing angle) as well as to increase the difficulty of the driving task. The subject's task was to press the horn as soon as they perceived a pedestrian; they were not asked to make any judgments about the level of hazard posed by the running pedestrian.

Simulated central vision impairment (simVI) goggles

VI was simulated by fitting Bangerter diffusing filters (Fresnel Prism & Lens Co., Eden Prairie, MN) to both left and right lenses of a pair of laboratory safety goggles (Guardian Pro

Over-the Glass, Safety Glasses USA Inc., Three Rivers, MI). For the pilot study, 0.1 opacity filters were applied on the front surface of the safety goggles' lenses which reduced the VA of the young participants to 0.39 logMAR, on average. Participants always wore the simVI goggles over their habitual corrections for testing of their VA and CS, as well as for the drives in the simulator.

Auditory distraction tasks

As detailed in the introduction, three auditory distraction tasks were tested during this pilot study.

In the first task, the n-back-1 task, a series of pre-recorded numbers were played while the participants were driving. There was 2.5 seconds between each number. There was a total of five recordings and each contained a total of 20 numbers. Each of the recordings was played on loop, which lasted the entirety of a drive. The recordings were played in random order for the assigned drives. Participants were required to make a response after each number: they had to say out loud the number that was played prior to the current number (Jacola et al., 2014; Lezak et al., 2004). This meant that they had to remember the prior number while the current number was being played.

The second task, the category matching task, required the participant to listen to lists of five words played throughout the drive and state, at the end of each list, which word did not belong to the list. There was a total of five recordings and each contained 20 five-word sets. Each of the recordings was played on loop, in random order, for the assigned drives. In each recording, each word was played one second after another with four seconds in between each set for the participant to respond.

The last task was the audiobook task, in which the participant listened to an excerpt from a book throughout a drive and repeated out loud a set of predetermined words as soon as they were heard in the recording. Excerpts from the novel "Oryx and Crake" by Margaret Atwood were used for the pilot study and participants were instructed to repeat the words "Jimmy," "was," and "the." The time taken to complete each drive differed between participants (depending on their driving speed). As a consequence, the total number of target words presented by the end of each drive also varied across participants. Thus, one high frequency target word ("*the*") that was present throughout all three audiobook excerpts was chosen along with a one medium frequency word present throughout each excerpt ("*Jimmy,*" "*was"*).

Procedures

General procedures

Prior to driving in the simulator, participants' binocular distance VA was measured with a logMAR chart at 120 cm (Test Chart 2000 PRO, Hertfordshire, UK), which was similar to the distance between the car seat and the center monitor in the driving simulator. Participants' binocular letter CS was measured with the MARS letter contrast sensitivity chart at 50 cm (The Mars Perceptrix Corporation, Chappaqua, NY). Vision was measured under binocular viewing conditions because participants viewed binocularly while driving in the simulator. Each test was taken under standard illumination conditions. Each test was taken two times, once without the simVI goggles (either without or with the habitual correction, as appropriate for that viewing distance) and again with the addition of simVI goggles (which fitted over the top of participants' glasses, if worn). The filtered provided sufficient coverage for the

goggles and participants were unable to see around the filters given their field of view of the driving simulator. Participants were also asked to fill out a questionnaire regarding their driving history and demographics.

In the driving simulator, participants first completed an acclimatization drive in a highway scenario with no traffic or pedestrians. This drive allowed participants to become familiarized with the simulated vehicle, surroundings, and controls. A practice drive followed, which contained all the elements of the experimental drives including 10 pedestrian events and some oncoming traffic. Participants began the practice drive without any distraction or simVI and were instructed to press the horn as soon as a pedestrian was seen. After they had driven for about two minutes, they stopped the vehicle to put on the simVI goggles and wore them for the rest of the practice drive. After another two minutes of driving, they stopped the vehicle and were given instructions on the auditory task. Participants practiced performing the auditory task(s) that they were assigned to do without driving until they were sufficiently comfortable with it (them), after which they began driving again and completed the rest of the practice drive with the simVI and the auditory distraction task(s). For the n-back-1 and category matching tasks, the list of numbers or words played during the practice drive was selected randomly and was different from those played during the experimental drives. For the audiobook excerpt task, a passage from "Handmaid's Tale" by Margaret Atwood was played, and participants were instructed to repeat out loud the words "thing" and "it." During the practice drives we adjusted the volume of the audiobook task for each individual so that it was equally easy for the older and younger participants to hear above the simulator's engine noise.

Once participants were comfortable with driving while wearing simVI goggles and performing the auditory task, they began the experimental drives. Participants were instructed to press the horn as soon as they saw a pedestrian and to drive as close to 97 kph at all times, as long as it was safe to do so. This speed cap at 97 kph was implemented so that participants were not required to monitor their exact speed. To maintain a constant 97 kph, participants were only required to have their foot on the gas pedal and could take their foot off the gas pedal and engage the brake as needed to slow down (e.g. when going around curves). Participants had full control of vehicle steering. Each drive lasted approximately 8 to 10 minutes depending on the speed at which the participants drove. During the drives with auditory distraction, participants were told that their performance on both the driving and the auditory task were equally important and that performance on both tasks was being scored.

Determining which auditory distraction task to use

As a first step in determining which auditory distraction task to use, five young participants each completed experimental drives with and without the three distraction tasks (audiobook excerpt, category matching, n-back-1), both with and without simVI. The goal was to test the feasibility of administering each of the tasks and to determine which two of the three tasks might be the most suitable to use. As such, detection performance data were not analyzed for this first part of the pilot.

Having narrowed the choice to two of the tasks, three older and three younger participants then each drove six experimental drives with the following conditions: 1) no auditory task, normal vision, 2) auditory distraction task 1, normal vision, 3) auditory distraction task 2, no simVI, 4) no auditory task, simVI, 5) auditory distraction task 1, simVI,

and 6) auditory distraction task 2, simVI. As we developed only four experimental drives, two drives (selected at random) were repeated to provide the total six drives. As far as possible, the order of conditions and drives was counterbalanced across participants. For this second part of the pilot, reaction time (RT) was used as the performance measure for evaluating the effects of the distraction tasks on detection performance. RT was measured as the time between the pedestrian appearing and the horn-press response. (Additional measures of detection performance were used in the main study.)

2.3 Results

Auditory tasks

Feasibility testing confirmed that all three auditory distraction tasks could be easily administered and that young participants did not have any difficulties in performing the three tasks. Based on our observations during the pilot test drives and the participants' feedback, we concluded that the category matching task was too easy because the young participants were not distracted enough. However, both the audiobook and n-back-1 tasks seemed to be good candidates for the distraction task and were therefore evaluated in the second stage of the pilot testing with 3 younger and 3 older participants.

Analysis of the detection performance data from the second stage of the pilot testing revealed that the audiobook and n-back-1 tasks had little/ no effects on the median RTs of either the younger or older participants when driving without the simVI (Figures 3 and 4, "Normal vision"). When driving with simVI, the audiobook task increased median RT slightly in younger participants, while the n-back-1 task had no effect (Figure 3, "SimVI"). In older participants driving with simVI, median RTs were increased by both the audiobook and

n-back-1 tasks (Figure 4, “Sim VI”). However, the increase from the audiobook task (1117 ms) was greater than that from the n-back-1 task (633 ms). The older participants tended to give up on the n-back-1 task as they found it very difficult, which may explain why the audiobook task had a greater effect on their RTs than the n-back-1 task. The older participants reported that they preferred the audiobook task and they were all clearly engaged in the task during the experimental drives.

In general, older participants had a greater median RT than younger participants across all conditions (median increase of 342 ms), while simVI increased RTs in both age groups (median increase of 283 ms).

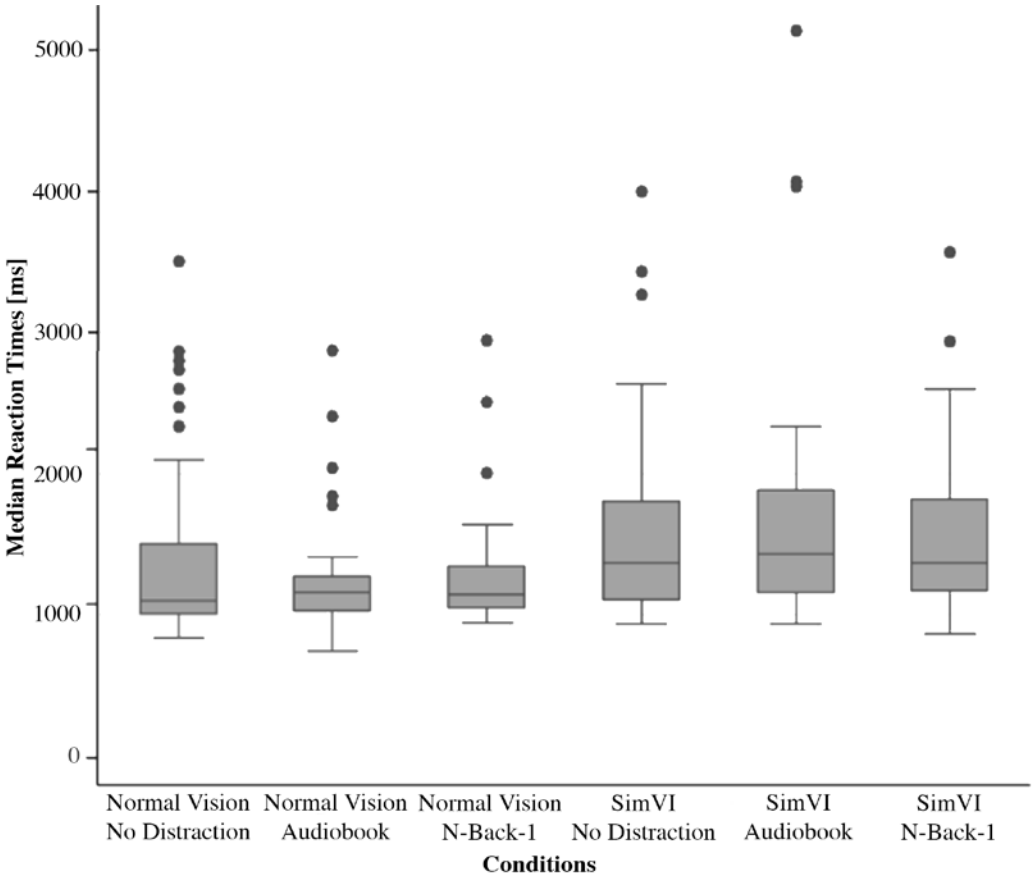


Figure 3 Median reaction time for young participants for each condition in the pilot study. The black lines in the middle of the boxes represent group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR.

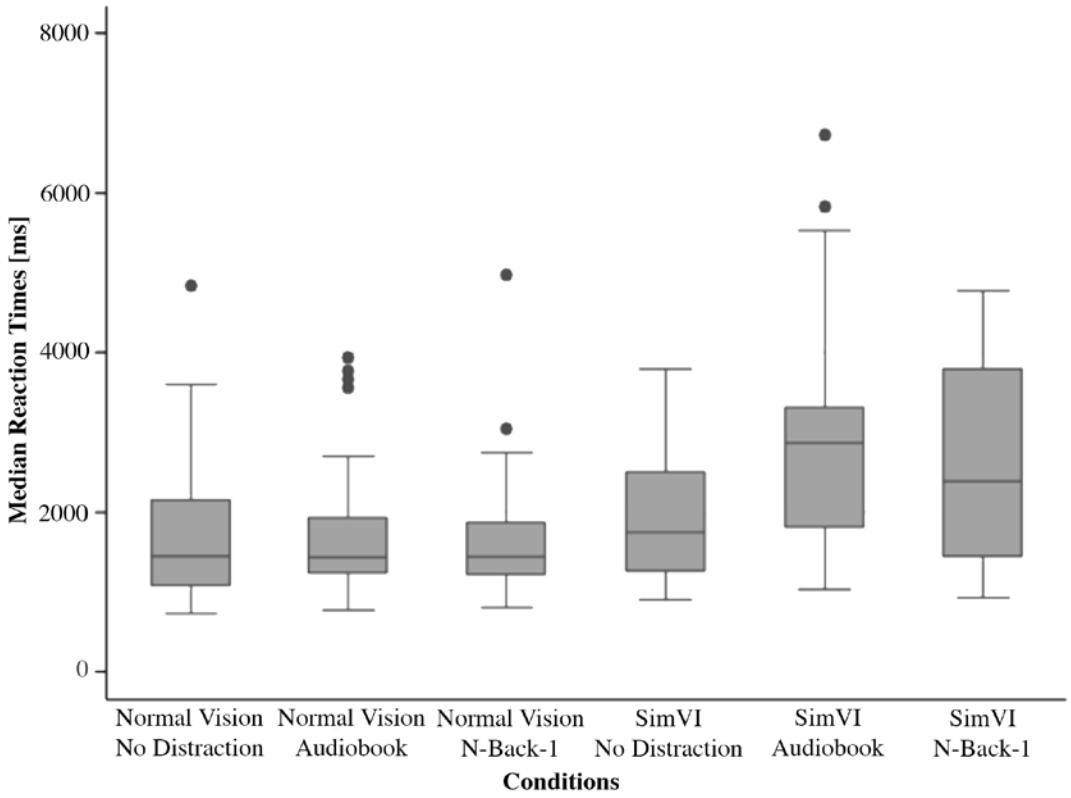


Figure 4. Median reaction time for older participants for each condition in the pilot study. The black lines in the middle of the boxes represent group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR.

Evaluating the four highway scenarios

Before starting the main study, we wanted to check that the detection task difficulty did not differ across the four highway scenarios. We used a linear mix model and evaluated whether there were any differences in RTs between the four highway scenarios using the data from the pilot study. Overall we found no significant effects of the drive scenarios on participants' RTs (nh1aap and nh1bap: β= -.98; SE= 9.71, t = -.10, P= .92; nh1aap and nh1cap: β= 9.22; SE= 9.43, t = .98, P= .34; nh1aap and nh1dap: β= 9.18; SE= 9.43, t = .97, P= .35; nh1bap and nh1cap: β= 10.2; SE= 9.71, t = 1.05, P= .31; nh1bap and nh1dap: β= 10.2; SE= 9.71, t = 1.05, P= .31; nh1cap and nh1dap: β= -.04; SE= 9.43, t = -.004, P= 1.0; Figure 5).

Figure 5. Average reaction time for each driving scenario for participants in the pilot study.

Error bars represent the SEM.

2.4 Discussion

The main aim of the pilot study was to identify an appropriate auditory distraction task for the main study. We tested three potential distraction tasks (audiobook excerpt, category matching, n-back-1). Based on participant feedback and the RT results, we chose the audiobook task as our distraction task for the main study.

Feedback from participants revealed that the category matching task was not sufficiently difficult for younger participants and did not require their constant attention. For instance, if the outlier was first or second in the list that was being played, participants did not have to listen to the last two words and could still complete the task correctly. In comparison, participants performing the n-back-1 and audiobook tasks reported being distracted by the audio task, especially when a pedestrian appeared on screen. Feedback from participants also revealed that the n-back-1 task was too difficult for some participants over 60 years old to complete. As a result, some participants gave up on doing the auditory n-back-1 task altogether. In comparison, both older and younger participants engaged in the audiobook task and none of them reported that it was too difficult. They also much preferred the audiobook task over the n-back task. Although n-back (Mehler, Reimer, & Dusek, 2011) tasks are commonly used as distraction tasks in driving research, they lack relevance and face validity. On the other hand, listening to an audiobook is something that people do when driving and is relevant to drivers of all ages. Furthermore, the audiobook task increased the

RTs of both younger and older participants to pedestrian hazards, while the n-back-task increased only the RTs of older participants (Figures 3 and 4).

For all these reasons, the audiobook excerpt task was considered the most appropriate to use in the main study and met our three criteria. It required constant engagement from participants as they had to listen closely for the target words in the excerpt played throughout the drive. It resembled a task that drivers might encounter when driving in the real world. And, it was of sufficient difficulty for younger and older participants; it was difficult enough for young participants and not too difficult for older participants to perform.

2.5 Conclusion

In this pilot study, we identified an auditory distraction task, the audiobook task, which met our three criteria and was suitable for older and younger participants. We demonstrated that the task increased RTs of older and younger participants, and that older age and simVI also increased RTs (as expected). Thus, we established our methodology and testing paradigm. We then implemented the paradigm in the main study (Chapter 3) to evaluate the effects of age, simVI and auditory distraction (audiobook task) in a larger group of participants with a broader range of performance measures.

CHAPTER 3 – MAIN STUDY

3.1 Introduction

In the main study for this thesis project we used the methodology that we developed in the pilot study and examined the effects of age, simVI (Bangerter diffusing filters), and distraction (audiobook excerpt task) on pedestrian detection performance of normally sighted younger and older participants. We simulated a level of reduced VA that was within the range for a restricted license in Massachussetts (Peli & Peli, 2002).

Our primary hypotheses were that age, simVI, and distraction would each adversely affect detection performance (increasing RTs and reducing safe detections) and that the three factors would interact to further impair detection performance. Specifically, we predicted that the effects of distraction and simVI would be greater when the two factors were combined and that both the effects of simVI and distraction would be greater for older than younger participants. In the pilot study we evaluated only RTs. In the main study we also evaluated the safety of detections because longer RTs are not necessarily unsafe (e.g., if the individual is driving slowly; see section 1.5).

While our main focus was on detection performance, we also evaluated vehicle control skills (vehicle speed and lane position). We expected that participants might compensate for simVI and/or auditory distraction by driving more slowly (as has been reported for drivers with real CVL; Coeckelbergh et al., 2002). We also expected that age (Doroudgar et al., 2017), simVI, and distraction might impair lane position control. When driving under difficult or unfamiliar conditions, as is the case with simVI and/or auditory distraction, participants might divert cognitive resources away from basic vehicle control

skills, which might result in more variable lane position. We therefore examined the effects of our main factors (age, simVI, and distraction) on vehicle speed, and lane position.

3.2 Methods

Design

The main study implemented a 2 (levels of age - younger vs. older) x 2 (levels of distraction - with vs. without distraction) x 2 (levels of simVI - with vs. without simVI) mixed design. The primary performance measures were split into two groups: 1) detection measures; 2) and vehicle control measures. Detection based measures included detection rates, RTs, and the rate of safe detections. Vehicle control measures included average lane position, the variability of lane position, and speed. In addition, we analyzed participants' performance on the audiobook task.

Participants

A total of 32 current drivers were recruited from the New England College of Optometry and a database of participants who had participated in prior studies at the Schepens Eye Research Institute. They were recruited in two groups: younger (n=16; age range 22-37 year) and older (n = 16; age range 60-82 years) (for details, see Table 2 in results). The inclusion and exclusion criteria for these participants were the same as for the pilot study. All participants' baseline vision exceeded the requirements for an unrestricted license in Massachusetts (VA of at least 20/40 and a 120° visual field extent; American Association of Motor Vehicle Administrators). The level of lens opacity among older participants was measured with a slit lamp (SL990 slit lamp; SCO Ophthalmic, Scandicci, Italy). The level of opacity was measured in accordance with the LOCS III grading system (Chylack et al., 1993), which was

on average trace to grade 1+ nuclear sclerotic, anterior cortical, and/or anterior subcapsular cataract. No participant had cataract grading worse than grade 2. Only one rater graded lens opacity. Two older participants were pseudophakes.

Materials

Driving simulator and pedestrian detection scenarios

The main study used the same driving simulator and pedestrian events as those used in the pilot study. Four drives were completed by each participant, one in each condition in counterbalanced order across participants.

Simulated vision impairment (simVI) goggles

The method of creating simVI was the same as used in the pilot study with Bangerter filters mounted on a pair of laboratory safety goggles that fitted over the participant's habitual correction (if worn for the study tests). For the main study, we used a 0.1 opacity (on the front surface) and a 0.4 opacity (on the back surface) Bangerter filter combination that in a prior study in our lab had reduced VA of young normally-sighted participants to about 0.6 logMAR (20/80; Swan et al., 2019), which is within the range for a restricted license in MA.

Our aim was to try to reduce the VA of older and younger participants by the same amount. Therefore, for each of the older participants in the main study, we verified that their binocular VA with the simVI goggles was within ± 0.1 logMAR of the average binocular VA of the younger participants with the simVI goggles (Table 2 - this was possible because the data for younger participants were collected before the data for older participants). There was only one older participant (the oldest) whose VA with the simVI goggles was outside ± 0.1 logMAR of the average of the younger participants. For this participant a different pair of

simVI goggles was used with a 0.1 opacity filter on the front surface of the lenses only, which reduced that participant's VA to 0.6 logMAR.

Auditory distraction task

The auditory distraction task was the same as the audiobook task implemented in the pilot study. We selected new audiobook excerpts in which the language was easy to understand and engaging, and likely to be of interest to both older and younger participants. Participants listened to professional recordings (read by Dan Stevens, 2009) of two short excerpts from the novel "*Boy*" by Roald Dahl during two of the four experimental drives. A third extract from "*The Hitchhiker*" by Roald Dahl was used during the practice drive. The reading difficulty of the audiobook excerpts were calculated using the "*Flesch Reading Ease Score (FRES)"* (www.readabilityformulas.com). The excerpts from "Boy" were considered fairly easy – easy to read (Excerpt 1 – 70.2 FRES – fairly easy to read; Excerpt 2 – 82.9 FRES – easy to read). Recordings were played through computer speakers (Amazon *Basics A100* Multimedia Speakers, China). Two comprehension questions were also asked at the end of each drive with distraction. This task ensured constant cognitive processing from the participants throughout the drives, as they had to listen to the content of the excerpts instead of merely listening out for the target words. Younger participants answered the questions correctly 74.2% of the time, while older participants were correct 62.1% of the time. Participants' responses on the audiobook task were video and sound recorded using a video recorder (DVC, WEILAND Co., Ltd, China), which was positioned above and behind the car seat (see Figure 1).

As was the case in the pilot study, the time taken to complete each drive differed between participants (depending on their driving speed). As a consequence, the total number of target words presented by the end of each drive also varied across participants. Thus, one high frequency target word ("*the*") that was present throughout all three audiobook excerpts was chosen along with a one medium frequency word present throughout each excerpt ("*school*", "*father*" or "*mother*"). The first excerpt (for experimental drives) was 10:48 minutes long, where "*the*" took up 5% (97 words) of the total word count and "*father*" took up 1% (21 words). The second excerpt (for experimental drives) was 10:29 minutes in length, where "*the*" took up 5% (93 words) and "*school*" 0.5% (13 words) of the total word count. The third excerpt for the practice drive was 11:47 minutes in length, where "*the*" took up 4% (82 words) and "*mother*" 2% (41 words) of the total word count.

Procedure

Prior to driving in the simulator, participants' binocular distance VA and CS were measured using the same tests as those used in the pilot study.

In the driving simulator, participants completed an acclimatization drive in a highway scenario, followed by a practice drive, similar to the pilot study. Then, participants completed four experimental drives, one in each of the four conditions. At the end of the experimental drives with auditory distraction, participants answered two comprehension questions based on the excerpt to which they had listened. The order of the conditions was counterbalanced across participants using a Latin Square Design. We employed this counterbalancing scheme in order to counteract any learning and adaptation effects that may have occurred during the

experiment. The order of the two audiobook excerpts was also counterbalanced across the two audiobook drives.

As in the pilot study, participants were instructed to obey all road regulations, to drive as close to 97 kph (60 mph) as possible while maintaining safe control of the vehicle and to press the horn as soon as they saw a pedestrian. We again implemented a speed cap at 97kph. To maintain a constant 97 kph, participants were only required to have their foot on the gas pedal and could take their foot off the gas pedal and engage the brake as needed to slow down. Participants had full control of vehicle steering. Each drive lasted approximately 8 to 10 minutes depending on the speed at which the participants drove. During the drives with auditory distraction, participants were told that their performance on both the driving and the auditory task were equally important and that performance on both tasks was being scored. These instructions were used to encourage participants to put effort into completing both tasks and not to prioritize one over the other.

Performance measures

Detection performance measures included detection rates (percent of total number of presented pedestrians that were detected), reaction times (RT, time from pedestrian appearance to the horn press response when detected), and safe response rates (percent of total number of presented pedestrians for which there was a safe response).

The safety of a response was calculated based on the deceleration (m/s^2) that would have been required to stop the vehicle before reaching the collision point with the pedestrian:

$$\text{Deceleration} = \frac{V_f^2 - V_h^2}{2D_h}$$

Where V_f is the final velocity that was fixed to be 0, V_h is the vehicle's velocity at the time of horn press, and D_h is the vehicle's distance to the collision point at the time of the horn-press. The collision point was the location where the front of the car would have intersected with the pedestrian, assuming that the pedestrian had continued on its trajectory. If the necessary deceleration to stop the car prior to the collision point was greater than -5 m/s^2 the detection was considered unsafe (Hupfer 1997). In addition, any event where there was no horn-press response (i.e., the pedestrian was not detected) was categorized as unsafe. The cut off of -5 m/s^2 was chosen because it is commonly considered to be an unsafe deceleration rate (Hupfer 1997). Decelerating at this rate would result in the driver either becoming a hazard to themselves (if the road conditions were wet or slippery) or to the driver in the car behind them.

Vehicle control measures were computed for two pre-defined straight road segments in each drive (Bowers et al., 2010). These segments were selected to be pedestrian-free because reaching to press the horn might affect vehicle control. Vehicle control measures included the vehicle's average speed, the lateral lane offset (the average position of the center of the car relative to the center of the travel lane, over each predetermined segment), and standard deviation of lane offset (the variability of the vehicle's lane offset). As simulator data were recorded at 30 Hz, a straight segment 200 m long driven at 97 kph (26.9 m/s) would have 223 samples from which each of the measures was computed.

Performance on the audiobook task was scored from the video recordings. The number of target words correctly repeated out loud was counted for the time between pedestrian events (when no pedestrian was in the scene) and the time during pedestrian

events (when the pedestrian was in the scene). In some cases, there were no target words during a pedestrian event because they were quite brief (e.g., 5 s). Therefore, the total number of words repeated across all pedestrian events was tallied for each participant for each drive and expressed as a percent of the total number of target words presented during pedestrian events in that drive. The percentage of words correctly repeated between pedestrian events was computed in a similar manner.

Statistical analyses

Prior to running our analyses, we excluded data where a participant had pressed the horn but it did not register due to mechanical issues. This removed a total of 12 trials, leaving a total of 1536 trials that went into our subsequent analyses.

We evaluated the effects of age (older vs. younger), distraction (with vs. without distraction), and simVI (with vs. without simVI goggles) on detection performance and vehicle control measures. Detection rates for older (average: 99.8%) and younger (average: 100%) participants were close to ceiling in all conditions (age: p=.23; distraction: p= .73; simVI; p= .37) and were therefore not analyzed further. One older participant did not detect one pedestrian in the audiobook condition, otherwise all pedestrians were detected by all participants. However, RTs and safety of the detections varied sufficiently across conditions and age groups for us to conduct statistical analyses. We also evaluated participants' audiobook task performance by comparing the effects of age and simVI on the rate of correctly repeated words between pedestrian events (when no pedestrian was in the scene) and during pedestrian events (when the pedestrian was in the scene).

Continuous measures for which the data were normally distributed (log10 RTs and lateral lane offset measures) were analyzed with Linear Mixed Models (LMMs) constructed in the R statistical programming environment. A log10 transformation was applied to normalize the raw RT data. We then winsorized our data by removing all outliers greater than ± three standard deviations from the mean (Wilcox, 2005). This removed only 0.3% of the total data. All analyses were performed on the transformed data; however, results are reported in milliseconds for ease of interpretation. Binomial outcome variables (safety of responses) were analyzed by means of Generalized Linear Mixed Models (GLMMs; R Core Team).

We assessed the overall effect of age (young or old), simVI (with and without goggles), and distraction (with and without the audiobook task) by entering these as fixed factors in our models. In order to examine the interaction of age with both distraction and simVI, we dummy coded simVI (0 – without goggles; 1 – with goggles) and distraction (0 – not distracted; 1 – distracted) variables. We also constructed random effects structures for participants (to account for any variability contributed by individual differences between our participants), unique pedestrian events (to remove any random variability contributed by the different pedestrian events and any variability contributed by learning / practice effects) and the participants' baseline CS (to remove any random variability contributed by the differences in baseline CS; Table 2). For lane offset measures, we included a random effects structure for each straight road segment instead of each pedestrian event (to remove any random variability caused by the different road segments). CS was included as a random factor, but VA was not, because prior studies found that CS (but not VA) was a strong

predictor of hazard response times (Owsley et al., 2001; Wood, 2002; Wood, Chaparro, & Hickson, 2009), and baseline CS differed significantly between the older and younger groups (Table 2).

For the random effects structure, we attempted to include random slopes and intercepts for all fixed effects and their interactions to produce a maximal random effects structure (Barr et al., 2013). However, maximal structure models often fail to converge. When these models did not converge, we first removed the computation of correlation parameters within the random effects structures. If further simplification was required for convergence, we first began by simplifying the pedestrian event / road segment term in the random effects structure, then the CS term, and finally, the participant term. First, we removed the interaction between age and distraction, then the interaction between distraction and simVI. If further simplification was required, we sequentially removed the age group, then distraction, and finally simVI from the random effects structures. The results we report in the following results section are for the most complex random effects structure for which the models converged. *P*-values for main effects were estimated by means of the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017). Any interactions between age, distraction, and simVI were computed by means of model comparisons. For each interaction, we compared a baseline model (with all interactions between the fixed factors removed) with the same model plus the interaction of interest by means of analyses of variance (ANOVAs). The resulting χ^2 values represented the significance of the interaction of interest.

The effects of age, simVI and distraction on measures that were not normally distributed (vehicle speed and word recall rates in the auditory task) were analyzed by means

of non-parametric tests. The effect of age group (young vs old; a binary factorial variable) was analyzed by means of an independent-samples Mann-Whitney U test. The effect of condition (within- participants factor with 4 levels) was analyzed by means of a Kruskal-Wallis rank sum test. The difference in audiobook recall rates between and during pedestrian events was analyzed by means of a paired-samples Wilcoxon Signed Rank Test.

3.3 Results

Sample characteristics

As planned, the older group differed significantly from the younger group in age but did not differ in the proportion of male participants (Table 2). The two groups also did not differ in the level of driving exposure in a typical week (number of days and total distance driven each week; Table 2). The baseline VA (without goggles) of the older group was on average 0.04 logMAR (i.e., 2 letters) worse than that of younger participants (Table 2). Although the difference was just statistically significant, it was not clinically meaningful. Thus, the two groups were reasonably well matched in terms of baseline VA. The difference in CS (without goggles) between the two groups was significant and slightly greater in magnitude, being 0.1 log units worse on average in the older group (Table 2). As such, baseline CS was included as a random factor in analyses (see Statistical Analysis section).

Table 2. Demographics, vision measures and driving exposure for study participants

	Younger (n=16)	**Older (n=16)**	***P*-value***
Demographics[#]			
Age [years]	27 *(6.7)*	67 *(4.9)*	<.001
Male [n]	7	8	
Vision measures[#]			
VA without goggles [logMAR]	.02 *(0.05)*	.06 *(0.09)*	.03
VA with goggles [logMAR]	.62 *(0.14)*	.58 *(0.14)*	.58
CS without goggles [logCS]	1.78 *(0.06)*	1.67 *(0.11)*	.001
CS with goggles [logCS]	1.43 *(0.08)*	1.33 *(0.11)*	.002
Driving exposure[†]			
Number of days driven in a week	3.5 *(.8 - 7)*	5 *(2.4 - 7)*	.97
Average travel distance per week [km]	64 *(28 - 209)*	*89 (46 - 227)*	.69

**P*-values are given for the difference between older and younger participants
[#] mean (SD)
[†]Median (IQR)

Effects of SimVI on VA and CS

The simVI goggles reduced binocular VA from about 0.0 to 0.6 logMAR in both age groups (Table 2). VA with the simVI goggles did not differ between the older and younger participants $F(1, 26)= .31$; $P= .58$, and the average change in VA with the simVI goggles also did not differ (older 0.52 and younger 0.60 logMAR change, $F(1,26)= 2.98$; $P= .1$). By comparison, there was a significant age group difference in CS with the goggles, $F(1,26)= 11.9$; $P= .002$ (Table 2). However, the average reduction in CS with the goggles did not differ significantly between the two age groups (older 0.35 and younger 0.35 log units change; $F(1,26)= .03$, $P= .86$).

Detection Performance Measures

Reaction Times

Age, β= .19; SE= .049, t = 3.96, P< .001, distraction, β= -.07; SE= .01, t= -6.02, P< .001, and simVI, β= -.03; SE= .01, t= -22.1, P< .001, each significantly increased participants' RTs (Figure 6). Collapsed across distraction and simVI conditions, average RTs of older participants (average: 1501 ms) were 350 ms slower than those of younger participants (average: 1151 ms). Collapsed across age and simVI conditions, distraction produced a 161 ms delay in RTs (average without distraction: 1327 ms, average with distraction: 1488 ms). Lastly, when collapsed across age and distraction conditions, simVI produced a 660 ms delay in RTs (average without simVI: 1327 ms, average with simVI: 1987 ms). We found a significant interaction between simVI and age ($\chi^2(1, 9)= 8.66$; P= .003). This interaction came about as the cost of simVI on older participants' RTs was 828 ms (average without simVI: 1501 ms, average with simVI: 2329 ms), whereas the cost of simVI on younger participants' RTs was only 492 ms (average without simVI: 1151 ms, average with simVI: 1643 ms). Thus, older participants incurred a cost to RTs which was 336 ms greater than younger participants when wearing simVI goggles.

Figure 6. Average reaction time for each condition plotted separately for older and younger participants. The y-axis is truncated at 800 ms. Error bars represent the SEM.

No significant interactions were found between distraction and simVI ($\chi^2(1, 9)= 1.77$; $P= .18$) or between distraction and age ($\chi^2(1, 9)= .011$; $P= .92$). However, we found a significant, but weak, three-way interaction between distraction, simVI, and age ($\chi^2(4, 12)= 10.49$; $P= .03$). Specifically, the cost of distraction was greater for older participants without than with the simVI goggles (146 ms vs. 165 ms increase in RT, respectively). However, but the opposite was true for younger participants (177 ms vs. 125 ms increase, respectively), where distraction produced a greater effect when they wore the simVI goggles. Given that

the difference between without and with the simVI goggles was only 21 ms for older participants and 52 ms for younger participants, this three-way interaction has little real-world significance.

Rate of safe detections

Simulated VI had a significant detrimental effect on safe detection rates (β= 1.13, SE= .12, z= 9.45, $P < .0001$; Figure 7). Collapsed across age and distraction conditions, simVI reduced safe detections by 16.4% (78.3% with, 94.7% without simVI). However, distraction (β= .18, SE= .11, z= 1.60, P= .11) and age (β= -.30, SE= .250, z= -1.19, P= .23) did not cause any significant changes in the rate of safe detections. No significant interactions were found between age and distraction ($\chi^2(1, 9)= .002$; P= .97), between age and simVI ($\chi^2(1, 9)= .206$; P= .65), or between distraction and simVI ($\chi^2(1, 9)= .011$; P= .92). There was also no significant three-way interaction between distraction, simVI, and age ($\chi^2(4, 12)= .825$; P= .94).

Figure 7. Percent of safe detections for each condition split by older and younger participants. Error bars represent the SEM.

Vehicle Control Measures

Average speed

Older participants drove more slowly than younger (averages 91.8 km/h and 98.6 km/h, respectively; W= 4944, P< .001; Figure 8). Collapsed across age, a Kruskal-Wallis test revealed that subjects drove more slowly when they were distracted ($\chi^2(1)$= 6.5; P= .01) but not when driving with simVI ($\chi^2(1)$= .19; P= .66). Next, we ran the same analyses for older and younger participants separately. We found that younger participants did not adjust their speed in response to either distraction ($\chi^2(1)$= 1.93; P= .16) or simVI ($\chi^2(1)$= 37; P= .54). In contrast to this, older participants did drive more slowly as a response to distraction ($\chi^2(1)$= 4.93; P= .03) but not in response to simVI ($\chi^2(1)$= .91; P= .34).

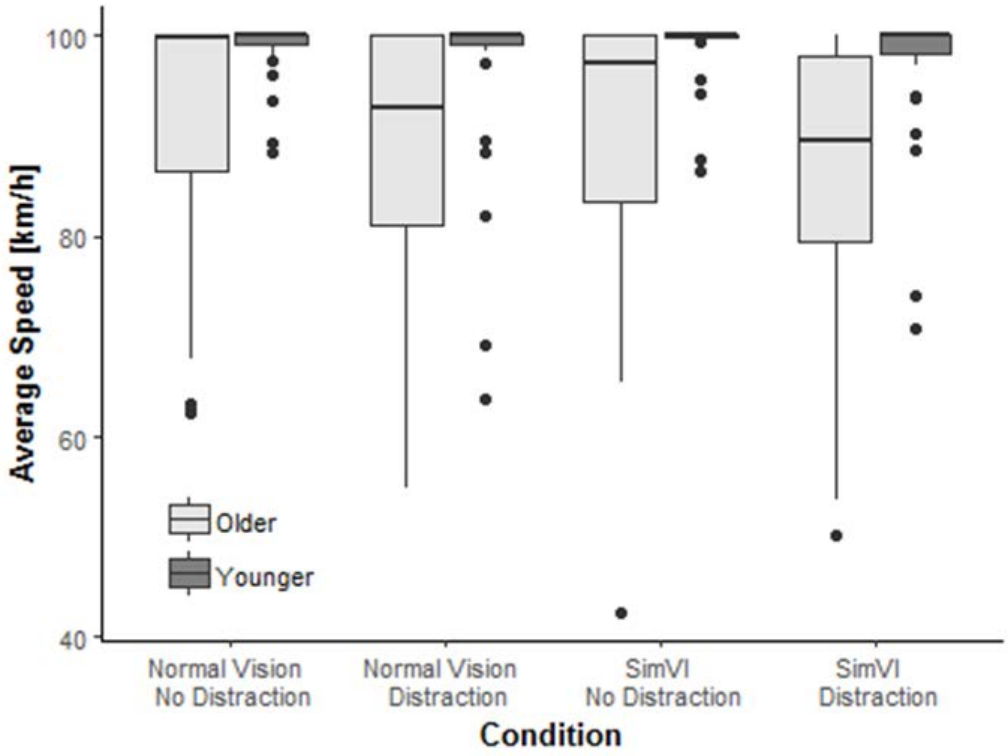


Figure 8. Boxplots for average vehicle speed of older and younger participants for each condition. Thick black line represents group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR (note: the y-axis has been truncated and runs from 40-100 km/h).

Average lateral lane offset

Younger participants' average lane position was significantly more to the right of the center of the travel lane than that of older participants (averages .56 m and .39 m, respectively, β= -.01, SE= .04, t= -2.37, P= .03; Figure 9). Distraction (β= -.01, SE= .02, t= -.51, P= .61) and simVI (β= .03, SE= .02, t= 1.68, P= .09) had no significant effects on average lane position.

No interactions were found between distraction and simVI ($\chi^2(1, 9)= 1.57$; $P= .21$), between distraction and age ($\chi^2(1, 9)= .61$; $P= .44$), or between simVI and age ($\chi^2(1, 9)= .83$; $P= .94$). There was also no significant three-way interaction between distraction, simVI, and age ($\chi^2(4, 12)= 3.01$; $P= .56$).

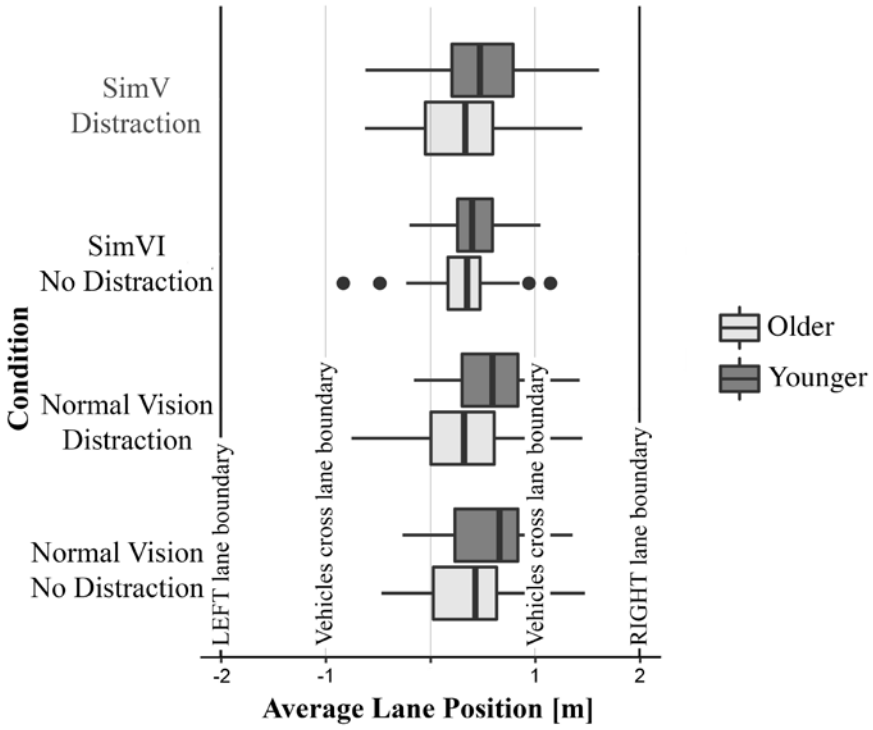


Figure 9. Boxplot of average lateral lane offset of older and younger participants for each condition. The travel lane was 4.0 m wide; 0 m marks the center of the lane. Vertical dashed lines represent the lateral lane offset at which the tires of the vehicle (1.92 m wide) would first cross the lane boundary. Thick black lines within the boxes represent group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR.

Standard deviation of lateral lane offset

We quantified participants' lane keeping variability by calculating the standard deviation (SD) of all lateral lane offsets for the two straight segments in the drives. Younger participants had a less variable lane position than older participants (averages: .212 m and .253 m, respectively; β= .024, SE= .01, t= 2.13, P= .04; Figure 10). However, distraction (β= .007, SE= .006, t= 1.08, P= .28) and simVI (β= .01, SE= .006, t= 1.56, P= .12) had no significant effects on variability of lateral lane offset. No interactions were found between distraction and simVI ($\chi^2(1, 9)$= .11; P= .746), between distraction and age ($\chi^2(1, 9)$= .117; P= .73), or between simVI and age ($\chi^2(1, 9)$= .1.27; P= .26). There was also no significant three-way interaction found between distraction, simVI, and age ($\chi^2(1, 12)$= 1.84; P= .77).

Figure 10. Standard deviation of lateral lane offset of older and younger participants for each condition. Error bars represent the SEM.

Word recall rates

When collapsing across age, word recall rates were significantly lower during pedestrian events (when the pedestrian was in the scene) as compared to the time between events when no pedestrian was on the screen (*V*= 162; *P*< .001; see Figure 11, left panel compared to right panel). Older participants recalled significantly fewer words than younger participants both during pedestrian events (24.9% vs. 38.9%; *W*= 221.5, *P*= .007; Figure 8 left) and between pedestrian events (34.7% vs. 52.9%; *W*= 148, *P*< .0001; Figure 11 right). Finally, wearing the simVI goggles did not significantly alter recall rates either during (*W*=.69; *P*= .41) or between pedestrian events (*W*= .95; *P*= .33).

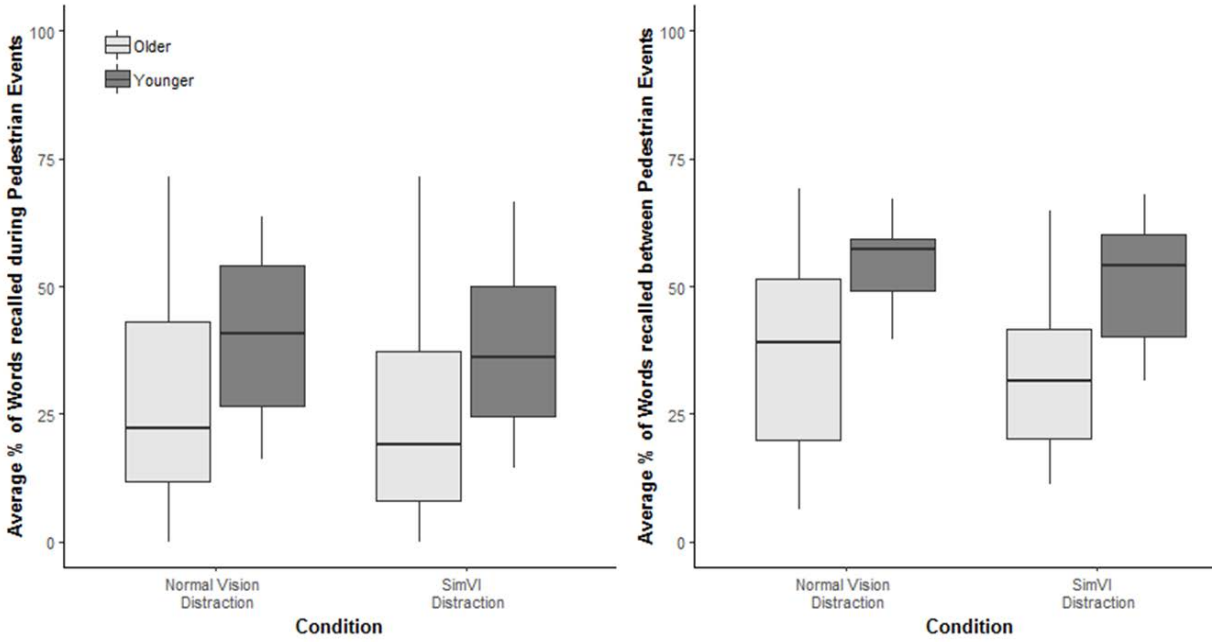


Figure 11. Boxplots of average percentage of words recalled both during pedestrian events (left) and between pedestrian events (right) plotted separately for older and younger participants. Rates were calculated by dividing the total number of words within

each segment by the amount of words each participant repeated within that segment. Thick black line represents group median; box extent represents the inter quartile range (IQR); and plot whiskers represent 1.5x IQR.

3.4 Discussion

We examined the effects of age, simulated central vision impairment (simVI), and auditory distraction (audiobook task) on participants' detection of moving pedestrian hazards as well as their lane keeping ability while driving in a simulator. Habitual VA without simVI differed slightly between younger and older participants; however, VA with simVI did not. Older participants had lower CS scores (0.1 log unit lower) both without and with simVI. However, the amount by which the filters reduced VA and CS (mean 0.57 logMAR and 0.35 log units, respectively) did not differ between the two age groups.

Detection rates were uniformly high (99.8-100%) and varied little with simVI, age, or distraction. However, each of these factors had a negative effect on RTs. SimVI had the greatest effect (660 ms RT increase), followed by age (350 ms increase), and then distraction (160 ms increase). Despite the increases in RTs, only simVI significantly reduced the rate of safe detections (the ability to stop in time to avoid a collision given the vehicle speed and distance). A significant interaction was found between age and simVI such that the increase in RT with simVI was greater for older than younger participants.

<u>Effects of age, simVI and distraction on detection rates</u>

It was not surprising that age, simVI, and distraction each had little effect on detection rates. The pedestrians were highly salient and the detection task itself was relatively

straightforward (‘press the horn when you see a pedestrian’). Participants were not required to make any judgments about whether or not a pedestrian was a hazard (they were all hazards). Comparably high detection rates were found in prior driving simulator studies for both normally sighted participants with simVI (Swan et al., 2019) and participants with real VI (mostly AMD; Bronstad et al., 2013; Bronstad et al., 2015) when performing a similar pedestrian detection task.

The effects of age on RTs and safe detection rates

Age had a significant effect on RTs, which was likely due to lower baseline CS scores in the older group and age-related reductions in psychomotor abilities (Hicks & Birren, 1970; Spirduso, 1980). Previous studies showed that CS scores were predictive of RTs in driving simulator pedestrian detection tasks (Swan et al., 2019). Thus, we accounted for any between- participants random variation in CS by including baseline CS as a random factor in our models. However, older participants were still found to have significantly longer RTs. The longer RTs in the older group were thus most likely due to reduced psychomotor abilities (Hicks & Birren, 1970; Spirduso, 1980), which can affect how quickly an intention can be turned into an action (i.e. the time between the intention to honk the horn and the physical pressing of it).

Interestingly, we found no significant effect of age on safe detection rates despite the longer RTs in the older group. The safety calculation took account of the speed and distance of the vehicle at the time of detection. Thus, while older participants had significantly longer RTs, they drove more slowly and, in turn, did not make more unsafe detections than younger subjects.

The effects of simVI on RTs and safe detection rates

SimVI also had a significant effect on RTs. The increase in RTs with simVI was expected, which was consistent with findings in previous driving simulator studies of normally-sighted subjects with simVI (Swan et al., 2019) and participants with real CVL (compared to controls without VI; Bronstad et al., 2013; Bronstad et al., 2015). In a prior study (Swan et al., 2019) where VA was matched between sphere lenses (decrease in VA only) and the diffusing filters (decrease in VA and CS), normally-sighted subjects were instructed to perform a similar pedestrian detection task. Participants' RTs were found to be much more increased when their VA and CS was reduced (using diffusing Bangerter filters, as used in the current study) as opposed to when only their VA was reduced (plus sphere lenses). Thus, the increase in RTs with simVI in the current study was most likely due to CS reduction from the diffusing filters rather than the reduction in VA.

The large increase in RTs due to simVI resulted in a significant decrease in safe detection rates (from 95% to 78%). This finding suggests that the level of simVI that we simulated could potentially have adverse consequences on driving safety in real world situations. However, contrary to expectations, participants did not drive more slowly with than without simVI; the longer RTs with the simVI were not offset by slower vehicle speeds.

The combined effects of simVI on RTs and safe detection rates

We found a significant interaction for RT between age and simVI. The increase in RTs with simVI was much greater for older than younger participants even though the amount of change in VA and CS from the simVI goggles did not differ for the two age groups. This is an interesting finding because it suggests that reactions to hazards by older drivers with

recent onset CVL may be delayed to a much greater extent than those of younger drivers with recent onset CVL. It is likely that older drivers are less able to compensate for their CVL than younger drivers as older adults have a smaller cognitive resource pool (Mathias & Lucas, 2009) than younger adults. The processing of visual information requires cognitive resources (Cavanagh, 2011); when wearing simVI goggles, more cognitive resources are likely employed to process the degraded visual scene (Henderson & Pierce, 2008). The combination of degraded visual information and the already reduced cognitive resource pool in older participants may have negatively affected their RTs to a greater extent than in younger participants.

In a previous study by Lee and colleagues (2016), older participants (without simVI) detected fewer hazards than younger participants but did not have longer RTs. In the current study, we found the opposite pattern of results where older participants were slower to react to hazards but they did not miss more of them. One reason for this may have been that our hazard pedestrians were identical to one another. During the drives, participants most likely would have simply pressed the horn as soon as they saw the pedestrian. In hazard perception videos of real-world driving scenes, such as those used by Lee et al. (2016) and Lacherez et al. (2019), the hazard targets were more varied and appeared in a wider range of situations. Detecting a hazard relies on knowing the rules of the road and the driving scene, which needs to be recalled and processed before a hazard judgment can be made. Therefore, the processing of potential hazards was harder in hazard perception videos than in our current driving simulator paradigm. This may explain why Lee and colleagues (2016) found an effect on detection rates but not on RTs whereas we found the opposite. Another consideration,

however, is that in the hazard perception task, participants were not able to adapt their driving behavior in any way because they were not performing any vehicle control tasks (Lee et al., 2016). Measuring RT alone provides limited information about how safe a detection might have been. By considering the speed of the driver, the speed of the hazard, and the distance of both road users from the collision point at the time of detection, we were able to calculate whether or not the driver could safely avoid the hazard (Hupfer, 1997). This is a more nuanced measure than RTs alone as it considers the various possible adaptive behaviors of the participants on the road, such as the speed of the vehicle.

The effects of distraction on RTs and safe detection rates

Auditory distraction had less of an effect on detection measures than either age or simVI. Distraction increased RTs slightly (160 ms) but had no significant effect on safe detection rates. Interestingly, older drivers drove more slowly when distracted but did not adapt their driving to simVI. Younger drivers did not drive more slowly either with simVI or with distraction. This raises an interesting question: how do people subjectively assess their driving abilities relative to their physical and visual abilities, and the cognitive distractions around them? In the current study, we found that both simVI and distraction negatively affected RTs, indicating that both factors had a detrimental effect on hazard detection. However, as older drivers only adapted their driving speed in response to distraction but not to simVI, we found that only simVI had a significant effect on the safety of our participants' responses. This suggested that older drivers were aware of the fact that the distraction from our audiobook task was having a detrimental effect on their driving performance, but may have underestimated how much a change in their VA and CS could affect their driving

performance. There is, however, evidence from survey studies that older drivers do self-restrict their driving after the onset of VI by avoiding difficult driving situations (Owsley et al., 1999; Ramulu et al., 2009; West et al., 2003).

In addition, we expected to find a two-way interaction between distraction and either age or simVI, but this was not present. In comparison, Lee et al. (2016) found that distraction had a greater effect on the hazard detection of older than younger participants in the presence of simVI. We did, however, find a weak, but significant, three-way interaction between distraction, age, and simVI. Distraction increased RTs of older participants to a slightly greater extent when driving with than without simVI whereas the opposite was the case for younger participants. This might suggest that our distraction task was not as difficult or as distracting as the task used by Lee et al. (2016) However, the lack of an age-by-distraction interaction could be explained by the fact that older participants were able to compensate for the distraction by driving more slowly during the driving simulator detection task, but they could not do so during the video-based hazard perception task in the Lee et al. (2016) study.

The effects of age, simVI and distraction on lane keeping measures

All participants drove slightly to the right of the lane center, consistent with the lane position findings of previous driving simulator studies for normally sighted participants (Bowers et al., 2010) as well as for participants with real CVL (Bronstad et al., 2016). This consistent rightward lane offset may be indicative of a strategy used by drivers to position the vehicle further away from oncoming traffic in the left lane when driving on the right side of the road. In doing so, drivers are less likely to collide with an oncoming vehicle but are also more likely to leave their lane on the right-hand side (see Figure 9).

Neither simVI nor distraction affected either average lane position or the variability of participants' lane position. However, there were age effects in that younger participants had an average lane position that was further to the right than that of older participants. These effects may be indicative of the fact that the older participants were more experienced and confident in their lane keeping. However, younger participants also had a smaller variability in their lateral lane offset (i.e., younger participants were more efficient in maintaining a steady lane heading than older subjects). The fact that simVI and distraction both affected detection measures, but not lane-keeping measures, is consistent with previous work. Brooks and colleagues (2005) demonstrated that blur up to 10 diopters negatively affected participants' abilities to recognize objects and hazards but did not influence their lane keeping in a driving simulator. Similarly, Woods and colleagues (2009) found that distraction significantly impaired participants' sign detection performance but had no effect on their lane keeping ability in a closed-road driving course.

Audiobook performance

Older participants recalled significantly fewer words on the audiobook task (both between and during pedestrian events) than younger participants. This is most likely a result of the older subjects having a more limited cognitive resource pool than younger participants (Ball & Owsley, 1991; Mathias & Lucas, 2009). For both age groups, cognitive resources are finite (Corbetta, Patel, & Shulman, 2008). Previous studies have shown that older drivers have worse multitasking abilities than younger subjects, both in the driving simulator (Ball & Rebok, 1994; Ward et al., 2018) and on the road (Adrian et al., 2011; Anstey et al., 2005; Freund et al., 2002; Stutts & Wilkins, 2003). Older participants recalled fewer words on the

audiobook task but did not have significantly fewer safe detections. These findings suggest that older participants were able to maintain satisfactory performance on the detection task by prioritizing the detection task over the audiobook task. In addition, they compensated by driving more slowly with auditory distraction. The resultant increased RTs and worse word recall rates in older participants suggest that older participants were not processing either task as well as their younger counterparts.

Interestingly, audiobook word recall rates were found to be lower when a pedestrian was on screen than when a pedestrian was not on the screen. This suggests that participants were reallocating their attention resources depending on moment-to-moment demands of the driving task. Therefore, it seems that when a pedestrian was on screen, participants allocated more attention to the driving task (i.e. by processing the pedestrian hazard and formulating an appropriate motor response) at the cost of correctly performing the audiobook task.

Limitations

When interpreting the results of the main study, some methodological limitations need to be considered. First, the average age of participants in the older group was 67 years, which is a relatively “young” older group. Declines in cognitive capacities and crash risk both increase markedly in the 70+ age group (Mizenko et al., 2015; Salthouse, 2009). Thus, the effects of simVI and distraction might have been greater if we had included more participants over 70 years of age. Furthermore, we did not quantify cognitive capacities of younger and older participants (e.g., by conducting tests of working memory (Conway et al., 2005) and cognitive capacity / load; Brünken, Seufert, & Paas, 2010). This means we could not directly test the hypothesis that the greater effects of simVI in older participants were associated with

them having a more limited cognitive resource pool, though it is well established that cognitive resources decrease with increasing age (Hahn, Wild-Wall, & Falkenstein, 2011; Hicks & Birren, 1970; Mathias & Lucas, 2009).

Second, simulating VI in people with normal vision is useful in achieving reasonably uniform levels of VA and CS reductions. However, individuals suffering from real CVL may behave differently to participants with simVI as they will have had much longer to adapt to their vision impairment. SimVI also fails to capture all aspects of real CVL. In the current study we simulated reductions in VA and CS, but did not simulate central visual field loss (scotomas) which is an important characteristic of AMD. One way by which individuals may compensate for VI, especially visual field loss, is to scan their surroundings more extensively with head and eye movements. We did not record gaze movements of the participants in this study because it was not possible to reliably track the eyes through the diffusing filters.

Third, we need to consider the limitations of the driving simulator task. We extended prior research (Lee et al., 2016; Wood, Chaparro, & Hickson, 2009) by using a driving simulator paradigm in which the pedestrians were hazards approaching on a collision course and participants had to control vehicle speed and position. However, the pedestrian figures were highly salient, participants did not have to make judgments about whether pedestrians were hazards, and pedestrians appeared more frequently than would be the case when driving on rural highways in the real world. Nevertheless, an important advantage of driving simulator studies is that participants are never at risk for real collisions, which is a major concern for on-road studies. Furthermore, frequent presentation of hazards enabled reliable measurement of RTs. In the real world, pedestrian hazards may be less frequent and

unexpected and therefore we would probably expect to find greater effects of central CVL and distraction on response times and safety.

To ensure that the pedestrians were truly on a collision course (constant bearing angle), we instructed participants to drive as close to 97 kph as possible whenever they thought it safe to do so. This likely had two consequences. Firstly, it increased the difficulty level of the drives to a certain degree and secondly, it may have reduced the amount by which participants might have otherwise compensated for either distraction or simVI by driving slowly. However, this instruction was the same for all conditions and participants were able to use the brake to reduce speed whenever they felt unsafe. The relatively straightforward detection task and driving may explain why distraction did not have greater adverse effects on participants' detection and vehicle control measures. We suggest that the harder the driving task becomes, the more effortful the allocation of cognitive resources to both tasks will become. We predict that the effect of distraction and simVI would be more pronounced during more difficult scenarios as the driving task will require more cognitive resources to complete safely.

3.5 Conclusion

In the main study we found that simVI increased response times to a much greater extent in older than younger participants, despite similar levels of VA and CS reductions. Neither older nor younger participants adapted their speed in response to simVI, resulting in unsafe detections. However, older subjects appeared to compensate for the auditory distraction by driving more slowly, possibly perceiving a greater threat to their driving safety from the auditory distraction than from the simVI.

So far in this project, all the participants had been normally-sighted and we had simulated CVL. However, simulated CVL does not capture all aspects of real CVL and people with real CVL have time to adapt to their vision loss (whereas our normally-sighted participants had only limited exposure to the simVI). Therefore, the next step in our investigation was to conduct a small, preliminary study to examine the effects of auditory distraction in participants with real CVL.

CHAPTER 4– PARTICIPANTS WITH REAL CENTRAL VISION LOSS (CVL)

4.1 Introduction

CVL can be caused by a number of ocular conditions, with the most prevalent being age-related macular degeneration (AMD; Bronstad et al., 2013). Many CVL patients, however, still have VA sufficient to obtain a restricted drivers' license in many states (Peli & Peli, 2002). Prior studies have shown that CVL can negatively affect driving, as participants with CVL tend to drive slower and have more delayed reactions to hazards than normally-sighted drivers (Bronstad et al., 2013).

As a follow up to our main study, and as a small preliminary study in preparation for a larger scale future project (which was beyond the scope of this thesis), we recruited four participants with CVL to examine the effects of auditory distraction on drivers with real CVL. We used the paradigm that we had developed in the previous two chapters. The participants completed four drives in the driving simulator, two without and two with the audiobook auditory distraction task. We expected that, similar to the main study, participants would be negatively affected by the addition of the distraction task.

4.2 Methods

Participants

Four participants were recruited from our database at the Schepens Eye Research Institute, three were males and one was a female. They were 68, 77, 57, and 21 years old. Two participants had Stargardt's disease, and two had AMD. All had prior driving experience. The average VA of the participants was 0.79 logMAR (range 0.52 – 0.98) and average CS

was 1.24 log units (range 0.88 – 1.60). Binocular scotoma size and location were not measured.

Materials

Driving simulator and pedestrian detection scenarios

The driving simulator and pedestrian event set up were the same as those used in the main study (see Chapter 3).

Auditory distraction task

The distraction task, the audiobook excerpt task, was the same as that used in the main study (see Chapter 3).

Procedure

The procedure of the study was the same as that used in main study (see Chapter 3), except that participants did not use simVI goggles because they had real CVL. Each of the participants still completed four drives, two of them included the distraction task and two did not. The order of these drives and the order that the audiobook excerpts were played in were counterbalanced.

Performance measures

The detection performance measures were the same as those used in the main study, including detection rates, reaction times (RT) and safe response rates. In addition, average vehicle speed on straight segments (as detailed for the main study) and word recall rates during the audiobook task were measured. Data are reported separately for each participant using descriptive statistics. Given the small sample size, inferential statistics were not performed.

4.3 Results

Results for the four CVL participants are presented in Figures 12 – 15. For comparison purposes, data for the normally-sighted younger and older participants from the main study have been added at the end of each of the figures. Data was for the normally-sighted participants were not divided by age group in figure 13 because age was not found to have significantly affected the rate of safe detections in participants. Data for the normally-sighted participants are for the simulated vision impairment (simVI) conditions only. As each participant with real CVL behaved slightly differently, their results are reported separately below.

Participant #1

The first participant was a 68-year-old male with Stargardt's disease who was still driving. His binocular VA was 0.78 logMAR and binocular CS was 1.24 log units. His detection rate was 96% and 100% when driving with no distraction and with distraction, respectively. With distraction, his median RT was increased by 220 ms (see Figure 12) and the rate of safe detections was 19% lower (see Figure 13). He did not reduce his speed by much (0.46 km/h) when driving with distraction (see Figure 14). We did not retain the data for this participant's performance on the audiobook task, thus we were unable to assess his word recall rate.

Participant #2

The second participant was a 77-year-old male with age-related macular degeneration who was still driving. His binocular VA was 0.52 logMAR and binocular CS was 1.60 log units. His detection rate was 100% and 96% when driving with no distraction and with distraction, respectively. With distraction, his median RT was increased by 183 ms (see Figure 12).

Interestingly, the rate of his safe detections was slightly (8%) higher when listening to the audiobook (see Figure 13). This participant drove more slowly than the other CVL participants (see Figure 14). He drove 5.90 km/h faster when driving with than without distraction (see Figure 14). When driving with distraction, his word recall rate decreased by 23% when a pedestrian was on screen (see Figure 15).

Participant #3

The third participant was a 57-year-old male with age-related macular degeneration who had stopped driving 5 years ago. His binocular VA was 0.88 logMAR and binocular CS was 0.88 log units. His detection rate was 96% and 96% when driving with no distraction and with distraction, respectively. With distraction, his average RT was increased by 67 ms (see Figure 12). Interestingly, the rate of his safe detections was 30% higher when listening to the audiobook (see Figure 13). This was most likely because he drove slower (by 6.24 km/h) when driving with distraction (see Figure 14). His word recall rate when a pedestrian was present on screen was decreased by 25% when driving with distraction (see Figure 15).

Participant #4

The fourth participant was a 21-year-old female with Stargardt's disease who had stopped driving 3 years ago. Her binocular VA was 0.98 logMAR and binocular CS was 1.24 log units. Her detection rate was 100% and 96% when driving with no distraction and with distraction, respectively. With distraction, her average RT was increased by 33 ms (see Figure 12). The rate of her safe detections was 6% lower when listening to the audiobook (see Figure 13), even though she drove slower (by 5.59 km/h) when distracted (see Figure

14). When driving with distraction, her word recall rate was decreased by 6% when a pedestrian was on screen (see Figure 15).

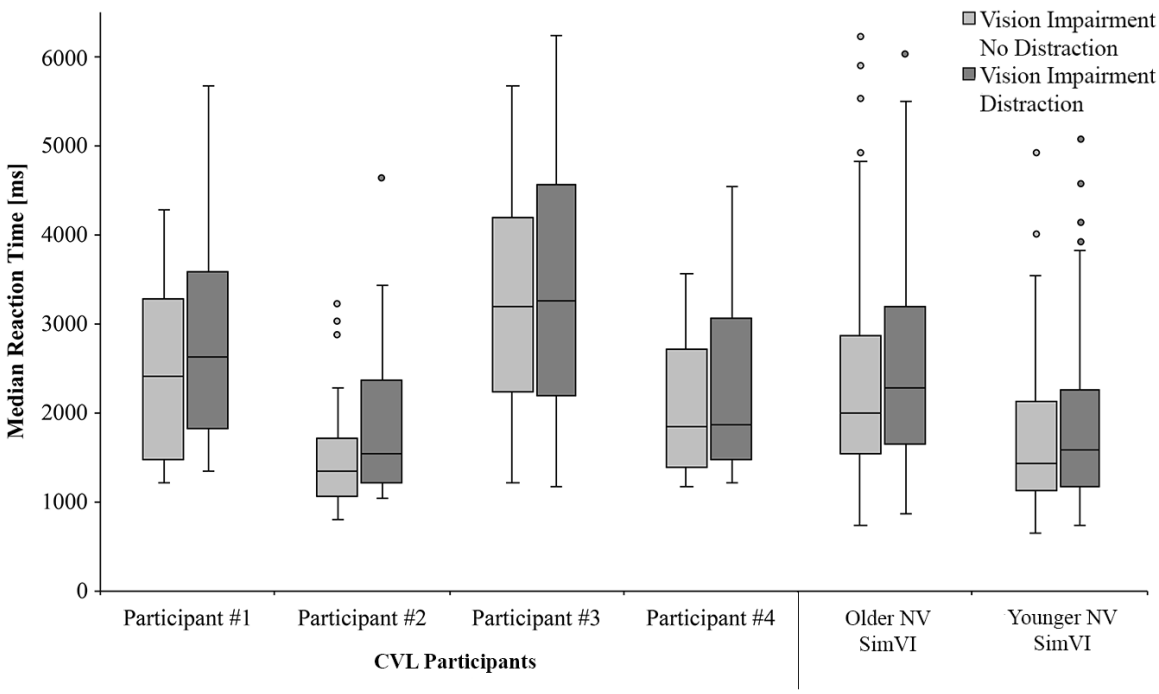


Figure 12. Median reaction times (ms) of the four CVL participants (left eight box plots) when driving without and with distraction. For comparison, data of the older and younger normal vision participants from the simVI conditions from the main study have been included (right four box plots). Thick black line represents group median; box extent represents the inter quartile range (IQR); and plot whiskers represent 1.5x IQR.

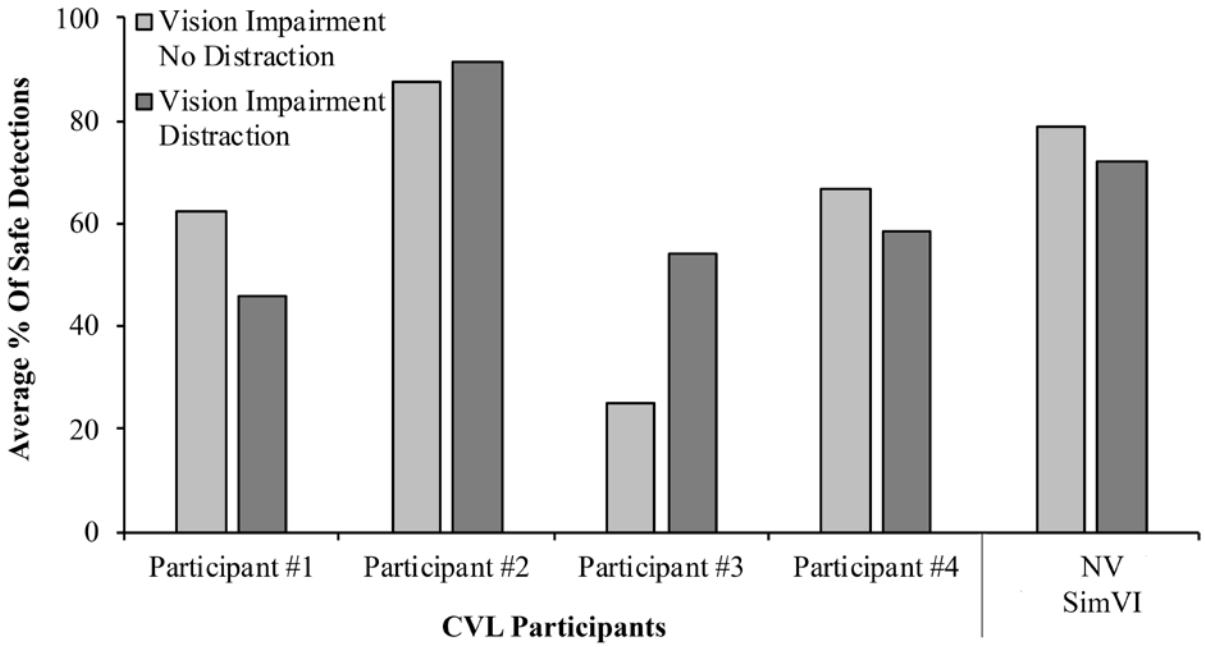


Figure 13. Average % of safe detections of the four CVL participants (left eight columns) when driving without and with distraction as well as those of normal vision participants in the simVI conditions from the main study (right two columns).

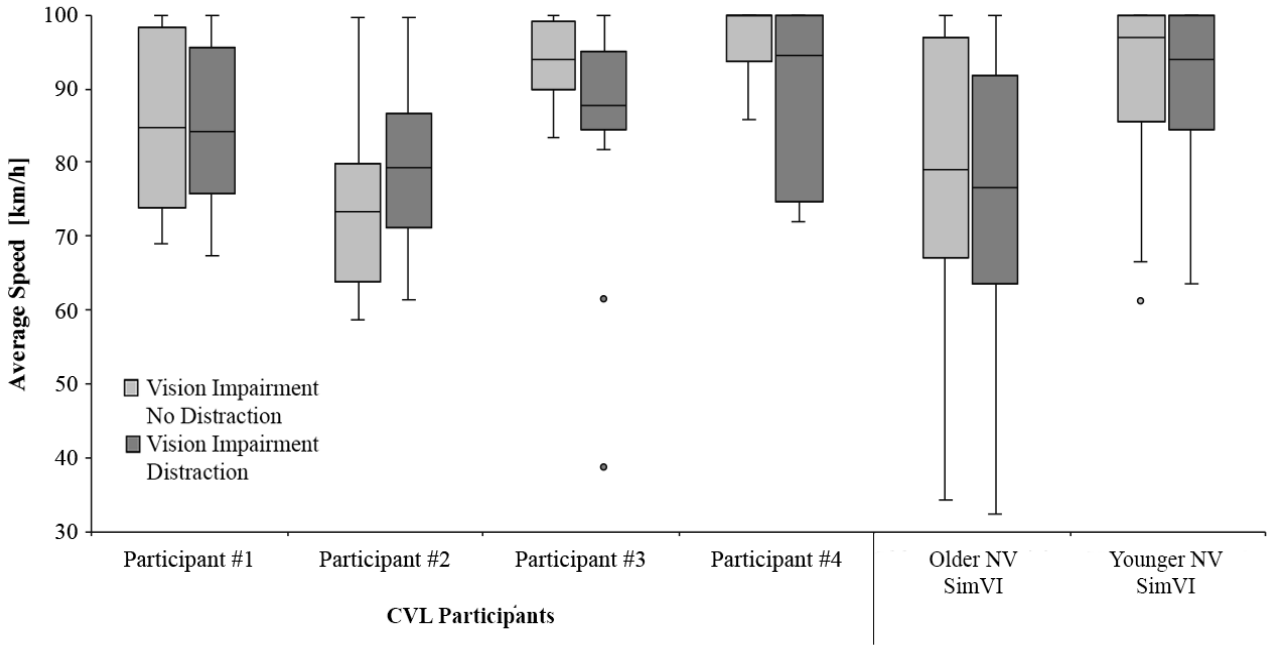


Figure 14. Boxplots for average vehicle speed of the four CVL participants (left eight boxplots) when driving without and with distraction and the older and younger normal vision participants from the simVI conditions from the main study (left four boxplots). Thick black line represents group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR. (note: the y-axis has been truncated and runs from 30-100 km/h).

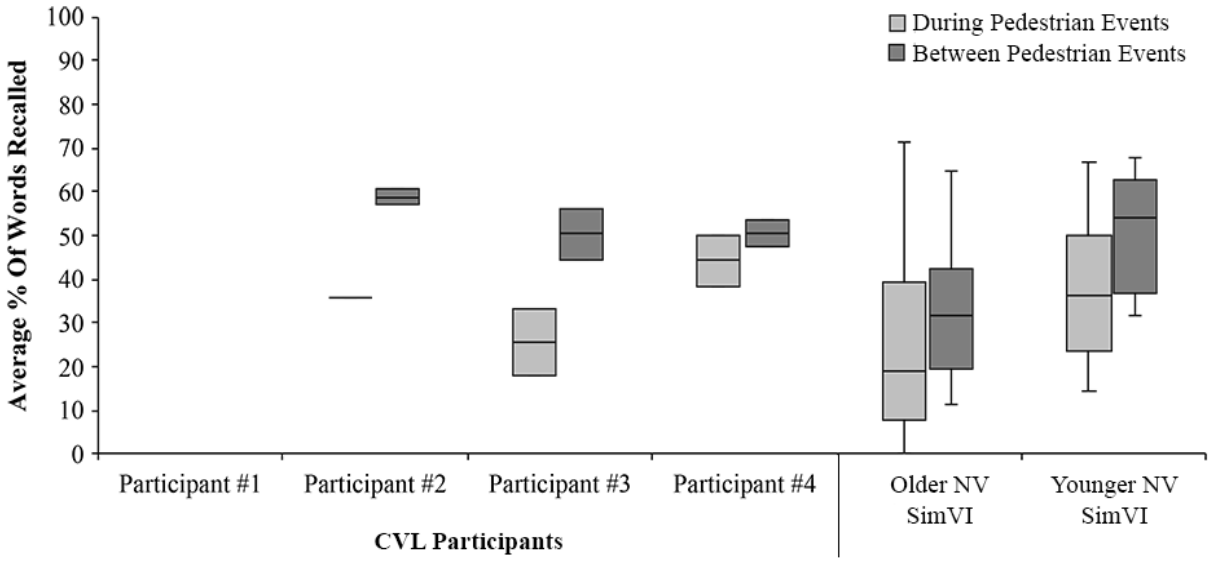


Figure 15. Boxplot of average percentage of words recalled both between pedestrian events and during pedestrian events for CVL (left six boxplots) and older and younger normal vision participants from the main study (right four boxplots). No data were obtained from participant #1. Rates were calculated by dividing the total number of words within each segment by the amount of words each participant repeated within that segment. Thick black line represents group median; box extent represents the inter quartile range (IQR); and plot whiskers represent 1.5x IQR.

4.4 Discussion

Using the same paradigm as that used in the main study of normally-sighted participants with simVI, we examined how participants with real CVL were affected by distraction. Although inferential statistics were not performed, it is worthwhile to note a few points about the results. All four CVL participants had high detection rates (> 95%) in drives both with and

without distraction. Thus, distraction did not substantially increase the rate of failed detections; the same was also true for the main study with simVI. Distraction appeared to have a small, but measurable effect, on RTs of all four participants, with increases in median RTs ranging from 33 ms to 220 ms. These increases in RTs with distraction were within the range of those found for the normally-sighted participants when driving with simVI in the main study.

The rate of safe detections varied widely across the four participants with real CVL (see Figure 13). CVL participant #2, a current driver, had the highest rates of safe detections amongst the four participants with real CVL, likely because he drove more slowly than any of the other CVL participants and also had the fastest response times. In contrast, CVL participant #3, who had stopped driving 5 years ago, had the lowest rates of safe detections amongst the participants with real CVL, likely because he had the longest response times and drove more quickly than participant #2.

Interestingly, only one CVL participant (#3) showed a noticeable decrease in median speed (8 km/h) when driving with distraction. The other 3 CVL participants drove at the same speed, or even slightly faster (participant #2) with distraction. Two of the CVL (#3 and #4) participants drove with median speeds close to those of the normally-sighted participants in the main study; the other two CVL participants drove more slowly.

Recall rates of the CVL participants in the drives with the audiobook task were within the range of the recall rates of the normally-sighted participants in the main study, both for segments when pedestrians were on the screen and segments when pedestrians were not on the screen. Thus, CVL participants appeared to perform as well as the normally-sighted

participants on the audiobook task. The recall rates of CVL participants were lower when pedestrians were on the screen, as was the case for the normally-sighted participants. This suggests that CVL participants (similar to the normally-sighted participants) were reallocating their attention resources depending on moment-to-moment demands of the driving task. When a pedestrian was on screen, they allocated more attention to the detection task at the cost of correctly performing the audiobook task.

There are many factors that could potentially affect detection and driving performance of people with CVL, including age of onset of CVL, duration of CVL, presence/absence of a central scotoma, years of driving experience before the onset of the CVL and chronological age. Given our small and heterogenous sample, we could not address any of these factors in this preliminary study.

4.5 Conclusions

In this small preliminary study, we demonstrated that participants with real CVL were able to perform both the pedestrian detection and the auditory distraction task while driving. The results suggest that auditory distraction increases RT of people with real CVL, as was found for simVI. One participant with real CVL appeared to compensate for distraction by driving more slowly, but the others did not.

Our results suggest that the methodology would be suitable for a future study with a larger sample of drivers with real CVL. However, some modifications to the methodology should be considered, including the use of scenarios where the driving task is more difficult (e.g., city scenarios with many other vehicles and pedestrians) and the hazards are more varied. Future studies of drivers with real CVL should also address the effects of distraction

on eye movements as well as detection performance and vehicle control. Prior studies of normally-sighted drivers suggest that they scan less extensively when distracted (National Safety Council, 2010; Strayer et al., 2013). In the main study with simVI we were unable to record eye movements through the simVI goggles. However, it would be important in a future study of drivers with real CVL to record eye and head movements to determine whether they scan less when distracted and whether that results in delays in making the first fixation on a hazard resulting in slower (longer) response times.

CHAPTER 5 – GENERAL CONCLUSIONS

In this thesis, we developed a paradigm for examining the effects of auditory distraction and simulated central VI (simVI) on detection of pedestrian hazards while driving in a simulator. We used a level of simVI that would qualify for restricted driving in Massachusetts and developed an auditory distraction task that was appropriate for younger and older participants and required constant engagement throughout the drive.

In the main study (Chapter 3), neither older nor younger normally-sighted participants adapted their speed in response to simVI, resulting in unsafe detections. However, older participants appeared to compensate for the auditory distraction by driving more slowly, possibly perceiving a greater threat to their driving safety from the auditory distraction than from the simulated central VI. These findings suggest that older drivers with recent onset central VI might not be aware of the extent to which the VI is affecting their responses to hazards, putting them at greater risk for at-fault collisions than drivers with long-established central VI. This interesting and unexpected finding warrants further investigation.

After completing the study with simVI, we conducted a small preliminary study of the effects of auditory distraction in four participants with real CVL using the same distraction task and driving scenarios as in the main study with simVI. Distraction increased reaction times of the participants with CVL; however, the sample size was too small for any conclusions to be drawn. The results confirmed the feasibility of implementing the methodology with participants with real CVL and provide the foundation for a future larger scale study.

In this thesis, we extended prior research by not only evaluating detection rates and

response times to hazardous events, but also evaluating the safety of responses in a paradigm where participants could modify their driving behaviors to potentially compensate for the effects of vision impairment or the effects of distraction. Findings from participants with simVI and real CVL underline the importance of using this approach which flexibly allows participants to modify their driving behaviors.

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APPENDIX I: The effects of age, distraction, and simulated central vision impairment on hazard detection in a driving simulator.

The following paper was accepted for publication in Optometry and Vision Science on December 30, 2019.

Title:

The effects of age, distraction, and simulated central vision impairment on hazard detection in a driving simulator.

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Abstract

Significance

Despite similar levels of visual acuity and contrast sensitivity reductions, simulated central vision impairment (sim VI) increased response times to a much greater extent in older than younger participants.

Purpose

Driving is crucial for maintaining independence in older age, but age-related vision impairments and in-vehicle auditory distractions may impair driving safety. We investigated the effects of age, simVI (reduced visual acuity and contrast sensitivity) and auditory distraction on detection of pedestrian hazards.

Methods

Thirty-two normally-sighted participants (16 older) completed four highway drives in a simulator and pressed the horn whenever they saw a pedestrian. Pedestrians ran toward the road on a collision course with the approaching vehicle. SimVI was achieved by attaching diffusing filters to a pair of lab goggles which reduced visual acuity to 20/80 and contrast sensitivity by 0.35 log units. For drives with distraction, subjects listened to an audiobook and repeated out loud target words.

Results

SimVI had a greater effect on reaction times (660 ms increase) than age (350 ms increase) and distraction (160 ms increase), and had a greater effect on older than younger subjects (828 ms and 492 ms increase, respectively). SimVI decreased safe response rates from 94.7% to 78.3%.

Distraction did not, however, affect safety because older subjects drove more slowly when distracted (but did not drive more slowly with simVI), suggesting that they might have perceived greater threat from the auditory distraction than the simVI.

Conclusions

Older participants drove more slowly in response to auditory distraction. However, neither older nor younger participants adapted their speed in response to simVI, resulting in unsafe detections. These results underline the importance of evaluating safety of responses to hazards as well as reaction times in a paradigm which flexibly allows participants to modify their driving behaviors.

Keywords:

Driving, Simulated driving, Simulated central vision impairment, Hazard detection, Distraction, Aging, Driving safety.

Introduction

Driving is vital in maintaining one's independence and quality of life in the United States, especially with increasing age.[1] However, older drivers are also more frequently involved in motor vehicle collisions.[2] Both age-related degradations of vision[3-5] and cognitive resources[6] may impair the ability of older drivers to respond to hazards in a timely manner, which may put them at increased risk for crashes. In addition, auditory distractions are becoming increasingly more common in today's driving environment[7] and may adversely affect hazard detection. Therefore, an important question is how impairments in vision interact with auditory distraction to affect hazard detection in both older and younger drivers.

Drivers often devote a portion of their attention resources to auditory activities such as communicating with passengers, listening to an audiobook, or interacting with in-vehicle navigation and assistance systems. Mental effort is required to engage in these activities, which decreases the amount of cognitive resources available to be devoted to the driving task which could have a negative impact on driving performance.[7] However, the nature in which vision impairment and auditory distraction interact to affect detection of hazards while driving has yet to be fully understood. Therefore, the current study is aimed at assessing the effects of age, central vision impairment and auditory distractions, and their interactions, on detection of moving pedestrian hazards.

Lee et al.[8] examined the effects of simulated reduced visual acuity, using positive sphere lenses, and auditory distraction on hazard perception performance of older and younger drivers. The auditory distraction task involved determining whether a given navigation instruction was logical or impossible to follow according to the road layout. Their results suggested that simulated

visual acuity loss and auditory distraction both led to an increase in reaction times to hazards. Older drivers were more greatly distracted and responded more slowly to hazards than younger drivers. Lee and colleagues[8] made use of a standard video-based hazard perception paradigm, which involved watching a series of video clips but did not require subjects to be actively engaged in motor coordination tasks important for driving such as steering or operating the brake and accelerator.[8]

Wood et al.[9] conducted a study that examined the effects of central vision impairment (simulated reduced visual acuity and simulated cataracts with reduced visual acuity and contrast sensitivity), age, and distraction on a closed-road driving course.[9] Distraction was created using a mental arithmetic task that was either visual or auditory (reporting the sum of two numbers that were either presented on the dashboard or were played through speakers). The authors investigated the effects of these factors on road sign recognition and hazard avoidance. A key finding was that the combined adverse effects of visual distraction and simulated cataracts were significantly greater for older than younger participants. However, the hazards along the course were large pieces of low contrast foam,[9] which were stationary, and did not pose real danger to the subjects. By comparison, in open-road driving, many hazards are moving and present real collision risks.

Therefore in the current study we used a driving simulator to provide a safe, controlled and replicable experimental environment in which to evaluate the effects of age, central vision impairment and auditory distraction on detection of moving pedestrian hazards[10, 11] in scenarios where participants were actively engaged in controlling vehicle speed and steering. One potential way to compensate for vision impairment, and/or auditory distraction would be to drive more slowly (as has been reported for drivers with real central vision impairment[12]). Thus, an important advantage of simulated driving tasks over video-based hazard perception tasks is that

subjects are able to control the speed at which they drive. If age, vision impairment, or auditory distraction increased participants' reaction times, it might be assumed that the responses would be less safe. However, if the participants also compensated by driving more slowly, a longer reaction time would not necessarily be less safe than a shorter reaction time when driving more quickly. We, therefore, measured both reaction times to the pedestrian hazards and the safety of the response (i.e., whether or not detection was made in enough time to avoid a collision given the speed and distance of the car to the pedestrian at the time of detection). As in several prior studies,[9, 13-15] we used a simulation of central vision impairment comprising reduced visual acuity and reduced contrast sensitivity. Simulated vision impairment ensures a relatively homogeneous degree of impairment, which can be difficult to achieve with a heterogeneous sample of people with real vision impairment. Auditory distraction was created by instructing subjects to listen to audiobook excerpts while driving, a task that was relevant to both younger and older drivers and required a continuous level of engagement throughout the drive.[16]

Our primary hypotheses were that age, simulated vision impairment and distraction would each adversely affect detection performance (increasing reaction times and reducing safe detections) and that the three factors would interact to further impair detection performance. Specifically, we predicted that the effects of distraction and simulated vision impairment would be greater when the two factors were combined and that both the effects of simulated vision impairment and distraction would be greater for older than younger participants. Finally, we expected that subjects might drive more slowly to compensate for the simulated vision impairment and/or auditory distraction.

METHODS

This study implemented a 2 (levels of age - younger vs. older) x 2 (levels of distraction - with vs. without distraction) x 2 (levels of simulated vision impairment - with vs. without simulated vision impairment) mixed design. The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the institutional review board (IRB) at the Schepens Eye Research Institute.

Participants

A total of 32 subjects (Table 1), 16 younger adults (range 22 - 37 years) and 16 older adults (range 60 - 82 years), were recruited from the New England College of Optometry and a database of subjects at the Schepens Eye Research Institute. Subjects were English-speaking, current drivers with at least two years of driving experience. They had no adverse ocular history of eye disease that might affect visual acuity or visual fields. All subjects were able to participate in a conversation without any hearing difficulties (without or with a hearing aid - as evaluated by the experimenter during the informed consent process). All subjects' vision exceeded the requirements for an unrestricted license in Massachusetts (visual acuity of at least 20/40 and a 120° visual field extent[17]). The level of lens opacity among older subjects, as measured in accordance with the LOCS III grading system[18] (SL990 slit lamp; SCO Ophthalmic, Scandicci, Italy), was on average trace to grade 1+ nuclear sclerotic, anterior cortical, and/or anterior subcapsular cataract. No subject had cataract grading worse than grade 2. Only one rater (the first author) graded lens opacity. Two older subjects were pseudophakes.

Driving simulator and pedestrian detection scenarios

A high-fidelity LE-1500 driving simulator (FAAC, Inc., Ann Arbor, MI) with five 42-inch liquid crystal display monitors (LG M4212C-BA, native resolution of 1366 x 768 pixels; 225° x 32° field of view) was used. The simulator included a motion-based seat, with three degrees of freedom in its movement, standard driving controls for an automatic transmission vehicle, and an interior dashboard modeled on a Ford Crown Victoria (see Figure 1). Data from the driving simulator, including the subjects' vehicle control inputs (steering, horn presses, etc.), and positional information of the vehicle and scripted entities in the world, were logged at 30Hz throughout the drive.

Scenarios and pedestrian events were created using the Scenario Toolbox (FAAC Inc., Version 3.9.4.25873) and were based on scenarios used in prior driving simulator studies of pedestrian detection by drivers with real vision impairment.[10, 11] In brief, four rural highway routes were used, each including oncoming traffic (average 16 vehicles, range 15-19) and 12 moving pedestrians (2.0 m tall, subtending 0.9° vertically when they first appeared, and dressed in a white shirt and blue jeans). The routes were along undivided highways (60 mph posted speed limit, equivalent to 97 kph) with a single lane in each direction, including long straight sections and long gentle curves without any sharp turns (lessens the likelihood of simulator sickness), no stop signs or traffic lights, and no lead cars. There were, however, speed limit signs and directional road signs. The background scenery contained grassy hills with some trees (see Figure 1) and buildings along the side of the road.

Pedestrians appeared at pseudorandom intervals every 15 to 60 seconds. They appeared from either the left (n = 6) or right side (n = 6) of the road when the car was approximately 5 seconds away (if travelling at the set speed limit of 97 kph). Pedestrians were programmed to run at a constant velocity toward the road on a trajectory perpendicular to the subject's travel lane, as if

to cross in front of the subject's vehicle. If the subject's vehicle was travelling at 97 kph, the pedestrian was on a direct collision course with the subject's vehicle (with a constant bearing angle between the vehicle and the pedestrian) and the two road users would have reached the collision point in the middle of the driving lane at the same time. If the participant drove more slowly than the speed limit, then the pedestrian would have reached the collision point before the car, but would still have appeared as a potential hazard (unless the participant drove extremely slowly). However, to avoid upset from actual collisions, the pedestrians were programmed to stop just before entering the participant's driving lane. We instructed subjects to drive as close to 97 kph (60 mph) as possible to ensure that the pedestrians were on a true collision course (a constant bearing angle) as well as to increase the difficulty of the driving task. The subject's task was to press the horn as soon as they perceived a pedestrian; they were not asked to make any judgments about the level of hazard posed by the running pedestrian.



Figure 1. LE-1500 driving simulator (FAAC, Inc., Ann Arbor, MI) used in this study. The

auditory distraction task was delivered though a pair of speakers (Amazon Basics A100 Multimedia Speakers, China) positioned to the left and right of the participant's seat (white circle). A video recorder (yellow circle – DVC, WEILIANTE Co., Ltd, China) was positioned above and behind the car seat to simultaneously record participants' repetition of target words in the auditory distraction task along with video of the central screens of the simulator (to facilitate scoring of auditory task performance for segments without and with pedestrians on the screen).

Simulated central vision impairment goggles

When visual acuity falls below the minimum requirement for an unrestricted license (e.g., 20/40 in Massachusetts), the majority of jurisdictions in the United States still permit people to drive but on a restricted license (e.g. no highway driving, or must use a bioptic telescope[19]). We selected to simulate a level of visual acuity (20/80) which would be within the range permitted for a restricted license in many states.[17]

To simulate the central vision impairment, Bangerter diffusing filters (Fresnel Prism & Lens Co., Eden Prairie, MN) were fitted to both lenses of a pair of laboratory safety goggles (Guardian Pro Over-The Glass, Safety Glasses USA Inc., Three Rivers, MI). These filters have been widely used in prior studies[14, 15, 20] to simulate central vision impairment. The filters reduced subjects' visual acuity and contrast sensitivity (Table 1) without reducing their binocular field of view. Based on a prior study,[15] we used a combination of a 0.1 opacity filter applied on the front surface and a 0.4 opacity filter on the back surface of the safety goggles' lenses. Subjects always wore the simulated vision impairment goggles (hereafter referred to as "goggles") over their habitual corrections for testing of their visual acuity and contrast sensitivity, as well as for the drives in the simulator.

Our aim was to achieve a similar amount of visual acuity reduction in the older and younger age groups. Therefore, for each of the older participants, we verified that their binocular visual acuity with the goggles was within ± 0.1 logMAR of the average binocular visual acuity of the younger participants with the goggles (Table 1 - this was possible because the data for younger participants were collected before the data for older participants). There was only one older participant whose visual acuity with the goggles was outside ± 0.1 logMAR of the average of the younger participants. For this participant a different pair of goggles was used with a 0.1 opacity filter on the front surface of the lenses only, which reduced that participant's visual acuity to 20/80.

Auditory distraction task

In selecting an auditory distraction task, we had three main criteria: the task would have face validity and be relevant to both older and younger participants; the task would be neither too easy for younger subjects nor too difficult for older subjects; and the task would be continuous throughout the drive encouraging a constant level of engagement from the participant. Mental arithmetic [9, 21] and n-back[22] tasks are commonly used as distraction tasks in driving research, but they lack relevance and face validity (i.e. they are not tasks one would normally perform when driving). On the other hand, listening to an audiobook is something that people do when driving and is relevant to drivers of all ages.

The audiobook distraction task involved listening to professional recordings of two short excerpts from the novel "Boy" by Roald Dahl during two of the four experimental drives. A third extract from "The Hitchhiker" by Roald Dahl was used during the practice drive. The reading difficulty of both audiobook excerpts were calculated using the "Flesch Reading Ease Score

(FRES)" (www.readabilityformulas.com). Both excerpts were considered fairly easy – easy to read (Excerpt 1 – 70.2 FRES – fairly easy to read; Excerpt 2 – 82.9 FRES – easy to read). Recordings were played through computer speakers (Amazon Basics A100, China; Multimedia Speakers). During the practice drives we adjusted the volume of the audiobook task for each individual so that it could easily be heard above the simulator's engine noise. Engagement in the audiobook task was ensured by requiring subjects to state out loud two predetermined target words whenever they were heard in the excerpts and by asking two comprehension questions at the end of each drive. Younger subjects answered the questions correctly 74.2% of the time, while older subjects were correct 62.1% of the time. Subjects' responses on the audiobook task were video and sound recorded using a video recorder (DVC, WEILAND Co., Ltd, China), which was positioned above and behind the car seat (see Figure 1 – yellow circle).

The time taken to complete each drive differed between subjects (depending on their driving speed). As a consequence, the total number of target words presented by the end of each drive also varied across subjects. Thus, one high frequency target word ("the") that was present throughout all three audiobook excerpts was chosen along with a one medium frequency word present throughout each excerpt ("school", "father" or "mother"). The first excerpt (for experimental drives) was 10:48 minutes long, where "the" took up 5% (97 words) of the total word count and "father" took up 1% (21 words). The second excerpt (for experimental drives) was 10:29 minutes in length, where "the" took up 5% (93 words) and "school" 0.5% (13 words) of the total word count. The third excerpt for the practice drive was 11:47 minutes in length, where "the" took up 4% (82 words) and "mother" 2% (41 words) of the total word count.

Procedure

Subjects' binocular distance visual acuity was measured with a logMAR chart (Test Chart 2000 PRO, Hertfordshire, UK) at 120 cm, which was similar to the distance between the car seat and the center monitor in the driving simulator. Subjects' binocular letter contrast sensitivity was measured with the MARS letter contrast sensitivity chart at 50 cm (The Mars Perceptrix Corporation, Chappaqua, NY). Each test was performed once without the goggles (either without or with the habitual correction, as appropriate for that viewing distance) and again with the addition of goggles (over subjects' glasses, if worn).

In the driving simulator, subjects first completed an acclimatization drive in a highway scenario, with no traffic or pedestrians, to become familiar with controlling the virtual car. A practice drive followed, which contained all the elements of the experimental drives (including pedestrian events and oncoming vehicles). Subjects began the practice drive without any distraction and without simulated vision impairment and were instructed to press the horn as soon as a pedestrian was seen. After they had driven for about two minutes, they stopped the vehicle to put on the goggles and wore them for the rest of the practice drive. After another two minutes of driving, they stopped the vehicle and were given instructions on the auditory task. Subjects practiced performing the auditory task without driving until they were sufficiently comfortable with it, after which they began driving again and completed the rest of the practice drive with the goggles and the auditory distraction task.

Once subjects were comfortable with driving while wearing the goggles and performing the auditory task, they began the experimental drives. Subjects completed a drive in each of the four conditions: 1) normal vision and no auditory distraction, 2) simulated vision impairment and no distraction, 3) normal vision and auditory distraction, and 4) simulated vision impairment and auditory distraction combined. At the end of the experimental drives with auditory distraction,

subjects answered two comprehension questions based on the excerpt to which they had listened. The order of the conditions was counterbalanced across subjects using a Latin Square Design in order to counteract any learning and adaptation effects. The order of the two audiobook excerpts was also counterbalanced across the two audiobook drives. Each drive lasted approximately 8 to 10 minutes depending on the speed at which the subject drove.

Subjects were instructed to obey all road regulations, to drive as close to 97 kph as possible while maintaining safe control of the vehicle and to press the horn as soon as they saw a pedestrian. We implemented a speed cap at 97kph so that subjects were not required to monitor their exact speed. Thus, to maintain a constant 97 kph, subjects were only required to have their foot on the gas pedal and could take their foot off the gas pedal and engage the brake as needed to slow down (e.g. when going round curves). Subjects had full control of vehicle steering. During the drives with auditory distraction, subjects were told that their performance on both the driving and the auditory task were equally important and that performance on both tasks was being scored.

Performance measures

Detection performance measures included detection rates (percent of total number of presented pedestrians that were detected), reaction times (from the time of pedestrian appearance to the horn press) and safe response rates (percent of total number of presented pedestrians for which there was a safe response). The safety of a response was calculated based on the deceleration (m/s^2) that would have been required to stop the vehicle before reaching the collision point with the pedestrian:

$$\text{Deceleration} = \frac{V_f^2 - V_h^2}{2D_h}$$

Where V_f is the final velocity that was fixed to be 0, V_h is the vehicle's velocity at the time of horn press, and D_h is the vehicle's distance to the collision point at the time of the horn-press. The collision point was the location where the front of the car would have intersected with the pedestrian, assuming that the pedestrian had continued on its trajectory. If the necessary deceleration to stop the car prior to the collision point was greater than -5 m/s^2 the detection was considered unsafe.[23] In addition, any event where there was no horn-press response (i.e., the pedestrian was not detected) was categorized as unsafe. The cut off of -5 m/s^2 was chosen because it is commonly considered to be an unsafe deceleration rate.[23] Decelerating at this rate would result in the driver either becoming a hazard to themselves (if the road conditions were wet or slippery) or to the driver in the car behind them.

Vehicle speed was computed for two pre-defined straight road segments in each drive.[24] These segments were selected to be pedestrian-free because reaching to press the horn might affect vehicle speed. As simulator data were recorded at 30 Hz, a straight segment 200 m long driven at 97 kph (26.9 m/s) would have 223 samples from which each of the measures was computed.

Performance on the audiobook task was scored from the video recordings. The number of target words correctly repeated out loud was counted for the time between pedestrian events (when no pedestrian was in the scene) and the time during pedestrian events (when the pedestrian was in the scene). In some cases, there were no target words during a pedestrian event because they were quite brief (e.g., 5 s). Therefore, the total number of words repeated across all pedestrian events was tallied for each subject for each drive and expressed as a proportion of the total

number of target words presented during pedestrian events in that drive. The proportion of words correctly repeated between pedestrian events was computed in a similar manner.

Statistical analyses

Prior to running our analyses, we excluded data where a subject had pressed the horn but it did not register due to mechanical issues. This removed a total of 12 trials, leaving a total of 1536 trials that went into our subsequent analyses.

We evaluated the effects of age (older vs. younger), distraction (with vs. without distraction), and simulated vision impairment (with vs. without goggles) on detection performance and vehicle speed. Only one older subject missed one pedestrian in the audiobook condition. Otherwise all pedestrians were detected. Therefore, detection rates for older (average: 99.8%) and younger (100%) subjects were at ceiling in all conditions and were not analyzed further. However, reaction times and safety of the detections varied sufficiently across conditions and age groups for us to conduct statistical analyses. We also evaluated subjects' audiobook task performance by comparing the effects of age and simulated vision impairment on the rate of correctly repeated words between pedestrian and during pedestrian events.

Reaction times were analyzed with Linear Mixed Models (LMMs) constructed in the R statistical programming environment. A log10 transformation was applied to normalize the raw reaction time data. We then winsorized our data by removing all outliers greater than ± three standard deviations from the mean.[25] This removed only 0.3% of the total data. All analyses were performed on the transformed data; however, results are reported in milliseconds for ease of interpretation. Binomial outcome variables (safety of responses) were analyzed by means of Generalized Linear Mixed Models (GLMMs).[26]

We assessed the overall effect of age (young or old), simulated vision impairment (with and without goggles), and distraction (with and without the audiobook task) by entering these as fixed factors in our models. In order to examine the interaction of age with both distraction and simulated vision impairment, we dummy coded simulated vision impairment (0 – without goggles; 1 – with goggles) and distraction (0 – not distracted; 1 – distracted) variables. We also constructed random effects structures for subject (to account for any variability contributed by individual differences between our subjects) and unique pedestrian events (to remove any random variability contributed by the different pedestrian events as well as to remove any variability contributed by learning / practice effects). In addition, contrast sensitivity was included as a random factor, but visual acuity was not, because prior studies found that contrast sensitivity (but not visual acuity) was a strong predictor of hazard response times,[9, 15] and baseline contrast sensitivity differed significantly between the older and younger groups (Table 1).

P-values for main effects were estimated by means of the lmerTest package.[27] Any interactions between age, distraction, and simulated vision impairment were computed by means of model comparisons. For each interaction, we compared a baseline model (with all interactions between the fixed factors removed) with the same model plus the interaction of interest by means of analyses of variance (ANOVAs). The resulting χ^2 values represented the significance of the interaction of interest.

The effects of age, simulated vision impairment and distraction on measures that were not normally distributed (vehicle speed and word recall rates in the auditory task) were analyzed by means of non-parametric tests. The effect of age group (young vs old; a binary factorial variable) was analyzed by means of an independent-samples Mann-Whitney U test. The effect of

condition (within-subjects factor with 4 levels) was analyzed by means of a Kruskal-Wallis rank sum test. The difference in audiobook recall rates between and during pedestrian events was analyzed by means of a paired-samples Wilcoxon Signed Rank Test.

Results

Sample characteristics

Sample characteristics are provided in Table 1. The baseline visual acuity (without goggles) of the older group was on average 0.04 logMAR (i.e., 2 letters) worse than that of younger subjects (Table 1). Although the difference was just statistically significant, it was not a clinically meaningful difference. Thus, the two groups were reasonably well matched in terms of baseline VA. The difference in contrast sensitivity (without goggles) between the two groups was significant and slightly greater in magnitude, being 0.1 log units worse on average in the older group (Table 1). As such, baseline contrast sensitivity was included as a covariate in analyses (see Statistical Analysis section).

Table 1. Demographics, vision measures and driving exposure for study participants

	Younger (n=16)	**Older (n=16)**	**P-value***
Demographics[#]			
Age [years]	27 (6.7)	67 (4.9)	<.001
Male [n]	7	8	1
Vision measures[#]			
Visual Acuity without goggles [logMAR]	.02 (0.05)	.06 (0.09)	.03
Visual Acuity with goggles [logMAR]	.62 (0.14)	.58 (0.14)	.73
Contrast Sensitivity without goggles [logCS]	1.78 (0.06)	1.67 (0.11)	.001
Contrast Sensitivity with goggles [logCS]	1.43 (0.08)	1.33 (0.11)	.001

Driving exposure[†]			
Number of days driven in a week	3.5 (.8 - 7)	5 (2.4 - 7)	.97
Average travel distance per week [km]	64 (28 - 209)	89 (46 - 227)	.69

*P-values are for the difference between older and younger subjects

[#] Mean (SD)

[†]Median (IQR)

Effects of simulated vision impairment on visual acuity and contrast sensitivity

The goggles reduced binocular visual acuity from about 20/20 to 20/80 in both age groups (Table 1). Visual acuity with the goggles did not differ between the older and younger subjects $F(1, 26)= .31$; $P= .58$, and the average change in visual acuity with the goggles also did not differ (older 0.52 and younger 0.60 logMAR change, $F(1,26)= 2.98$; $P= .1$). By comparison, there was a significant age group difference in contrast sensitivity with the goggles, $F(1,26)= 11.9$; $P= .002$ (Table 1). However, the average reduction in contrast sensitivity with the goggles did not differ significantly between the two age groups (older 0.35 and younger 0.35 log units change; $F(1,26)= .03$, $P= .86$).

Detection Performance Measures

Reaction Times

Age ($\beta= .19$; $SE= .049$, $t = 3.96$, $P< .001$), distraction ($\beta= -.07$; $SE= .01$, $t= -6.02$, $P< .001$), and simulated vision impairment ($\beta= -.03$; $SE= .01$, $t= -22.1$, $P< .001$) each significantly increased subjects' reaction times (Figure 2). Collapsed across distraction and simulated vision impairment conditions, average reaction times of older subjects (average: 1501 ms) were 350 ms slower than

those of younger subjects (average: 1151 ms). Collapsed across age and simulated vision impairment conditions, distraction produced a 161 ms delay in reaction times (average without distraction: 1327 ms, average with distraction: 1488 ms). Lastly, when collapsed across age and distraction conditions, simulated vision impairment produced a 660 ms delay in reaction times (average without goggles: 1327 ms, average with goggles: 1987 ms). We found a significant interaction between simulated vision impairment and age ($\chi^2(1, 9)= 8.66$; P= .003; Figure 2). This interaction came about as the cost of simulated vision impairment on older subjects reaction time was 828 ms (average without goggles: 1501 ms, average with goggles: 2329 ms), whereas the cost of simulated vision impairment on younger subjects' reaction times was only 492 ms (average without goggles: 1151 ms, average with goggles: 1643 ms). Thus, older subjects incurred a cost to reaction times with the simulated vision impairment which was 336 ms greater than for younger subjects.

Figure 2. Average reaction time for each condition plotted separately for older and younger subjects. Error bars represent the standard error of the mean.

No significant interactions were found between distraction and simulated vision impairment ($\chi^2(1, 9)= 1.77$; P= .18) or between distraction and age ($\chi^2(1, 9)= .011$; P= .92). However, we found a significant, but weak, three-way interaction between distraction, simulated vision impairment , and age ($\chi^2(4, 12)= 10.49$; P= .03). Specifically, the cost of distraction was greater for older participants with than without the simulated vision impairment (165 ms with goggles

vs. 146 ms without goggles), but the opposite was true for younger participants (125 ms with goggles vs. 177 ms without goggles). Given that the difference between without and with the simulated vision impairment was only 21 ms for older subjects and 52 ms for younger subjects, this three-way interaction has little real-world significance.

Rate of safe detections

Simulated vision impairment had a significant detrimental effect on safe detection rates (β= 1.13, SE= .12, z= 9.45, P < .0001; Figure 3). Collapsed across age and distraction conditions, simulated vision impairment reduced safe detections by 16.4% (78.3% with, 94.7% without goggles). However, distraction (β= .18, SE= .11, z= 1.60, P= .11) and age (β= -.30, SE= .250, z= -1.19, P= .23) did not cause any significant changes in the rate of safe detections. There were no significant interactions (P > 0.60).

Figure 3. Percent of safe detections for each condition split by older and younger subjects. Error bars represent the standard error of the mean.

Average speed

Older subjects drove more slowly than younger (averages 91.8 km/h and 98.6 km/h, respectively; W= 4944, P< .001; Figure 4). Collapsed across age, a Kruskal-Wallis test revealed that subjects drove more slowly when they were distracted ($\chi^2(1)= 6.5$; $P= .01$) but not when driving with simulated vision impairment ($\chi^2(1)= .19$; $P= .66$). We found that younger subjects did not adjust their speed in response to either distraction ($\chi^2(1)= 1.93$; $P= .16$) or simulated vision impairment ($\chi^2(1)= 37$; $P= .54$). In contrast to this, older subjects did drive more slowly as a response to distraction ($\chi^2(1)= 4.93$; $P= .03$) but not in response to simulated vision impairment ($\chi^2(1)= .91$; $P= .34$).

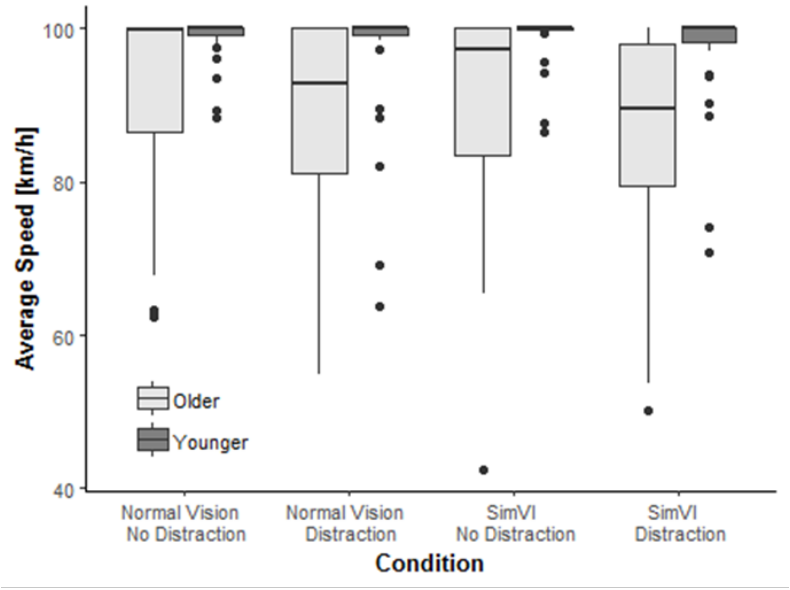


Figure 4.

Figure 4. Boxplots for vehicle speed of older and younger subjects for each condition. Thick black line represents group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR. (Note: the y-

axis has been truncated and runs from 40-100 km/h)

Word recall rates

When collapsing across age, word recall rates were significantly lower during pedestrian events (when the pedestrian was in the scene) as compared to the time between events when no pedestrian was on the screen (V= 162; P< .001; see Figure 5, left panel compared to right panel). Older subjects recalled significantly fewer words than younger subjects both during pedestrian events (24.9% vs. 38.9%; W= 221.5, P= .007; Figure 7 left) and between pedestrian events (34.7% vs. 52.9%; W= 148, P< .0001; Figure 7 right). Finally, the simulated vision impairment did not significantly alter recall rates either during (W=.69; P= .41) or between pedestrian events (W= .95; P= .33).

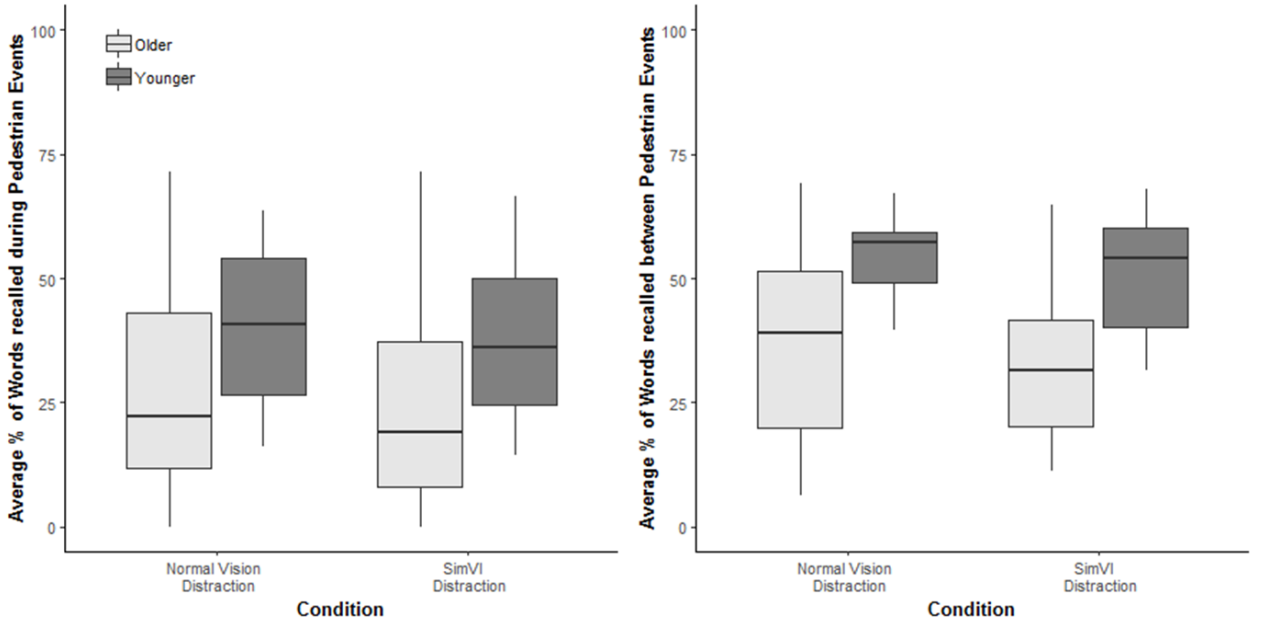


Figure 5.

Figure 5. Boxplots of average percentage of words recalled both during pedestrian events (left) and between pedestrian events (right) plotted separately for older and younger subjects. Thick black line represents group median; box extent represents the inter quartile range (IQR); and plot whiskers represent 1.5x IQR.

Discussion

Effects of age, simulated vision impairment and distraction on detection rates

The finding that neither age, nor simulated vision impairment, nor distraction affected detection rates is not surprising given that the pedestrian targets were highly salient and the detection task was relatively straightforward (press the horn when you see a pedestrian). High detection rates were also found in prior driving simulator studies for both normally sighted participants with simulated central vision impairment [28] and individuals with real vision impairment (mostly age-related macular degeneration)[10, 29] when performing a similar pedestrian detection task.

The effects of age and simulated vision impairment on reaction times and safe detection rates

In contrast to the detection rate results, age and simulated vision impairment both significantly affected reaction times. The age-related increase in reaction times was most likely a result of age-related reductions in psychomotor abilities[30, 31] (though we did not include a separate measure of psychomotor abilities). The increase in reaction times with simulated vision impairment was consistent with the effects reported in prior driving simulator studies of normally-sighted participants with similar simulations of central vision impairment[28] and individuals with real central vision impairment (compared to controls without vision impairment).[10, 29]

We found a significant interaction between age and simulated vision impairment. The increase in reaction times with simulated vision impairment was much greater for older than younger subjects even though the change in visual acuity and contrast sensitivity caused by the simulated vision impairment did not differ for the two age groups. This is an important finding because it suggests that reactions to hazards by older drivers with recent onset central vision impairment may be delayed to a much greater extent than the reactions of younger drivers with recent onset central vision impairment.

The large increase in reaction times with the simulated vision impairment resulted in a significant decrease in safe detection rates (from 95% to 78%). Interestingly, however, we found no significant effect of age on safe detection rates despite the longer reaction times in the older group. The safety calculation took account of the speed and distance of both road users at the time of the detection, so even though older subjects had significantly longer reaction times, they did not make more unsafe detections than younger subjects because they drove more slowly. However, contrary to expectations, participants did not drive more slowly with than without simulated vision impairment; the longer reaction times with the simulated vision impairment were not offset by slower vehicle speeds.

The effects of distraction on reaction times and safe detection rates

Auditory distraction had less of an effect on detection measures than either age or simulated vision impairment. Distraction increased reaction times slightly (160 ms overall) but had no significant effect on safe detection rates. Younger drivers did not drive more slowly either with simulated vision impairment or with distraction. Older drivers, however, drove more slowly when distracted but not with simulated vision impairment. These results suggest that older

drivers might have been more aware of the detrimental effects of the auditory distraction on their driving performance than the detrimental effects of the simulated vision impairment. There is, however, evidence from survey studies that older drivers do self-restrict their driving after the onset of vision impairment by avoiding difficult driving situations.[32-34]

Contrary to expectations we did not find a two-way interaction between distraction and either age or simulated vision impairment. In contrast, Lee et al,[8] found that distraction had a greater effect on hazard detection of older than younger subjects in the presence of simulated vision impairment. This might suggest that our distraction task was not as difficult or as distracting as the task used by Lee et al.[8] However, the lack of an age-by-distraction interaction could be explained by the fact that older participants were able to compensate for the distraction by driving more slowly in our driving simulator detection task, but they could not do so in the video-based hazard perception task in the Lee et al.[8] study.

The effects of age, simulated vision impairment and pedestrian hazards on audiobook performance

Older subjects recalled significantly fewer words on the audiobook task (both between and during pedestrian events) than younger subjects. This is most likely due to older subjects having a more limited cognitive resource pool than younger participants[6, 35] and attention resources being finite.[36] Indeed, older drivers have been reported to multitask less well than younger drivers in many studies, both in the driving simulator[37, 38] and on the road.[39-42] The fact that older subjects recalled fewer words on the audiobook task, yet did not have significantly fewer safe detections, suggests that they were able to maintain satisfactory performance on the detection task by prioritizing that task over the audiobook task. In addition, they compensated by

driving more slowly with auditory distraction. However, the combination of the increase in the reaction times of older subjects and their recall of fewer words than younger subjects suggests that they were not processing either task as well as their younger counterparts.

Interestingly, during drives with the audiobook task, we found that audiobook word recall rates were higher when no pedestrian was on the screen than when a pedestrian was on screen. During periods where no pedestrian was visible, subjects did not have to press the horn and were not distracted by pedestrians, allowing more attention resources to be allocated to the auditory task without compromising their detection performance. This suggests that subjects were flexibly reallocating their attention resources depending on moment-to-moment demands of the driving task. Therefore, it seems that when a pedestrian event was on screen, subjects allocated more attention to the driving task (i.e. by processing the pedestrian hazard and formulating an appropriate motor response) at the cost of correctly performing the audiobook task.

Limitations

When interpreting the results of the current study, some methodological limitations need to be considered. The average age of participants in the older group was 67 years, which is a relatively "young" older group. Declines in cognitive capacities and crash risk both increase markedly in the 70+ age group.[43, 44] Furthermore we did not quantify cognitive capacities of younger and older subjects (e.g., by conducting tests of working memory [45] and cognitive capacity / load[46]). This means we could not directly test the hypothesis that the greater effects of simulated vision impairment in the older participants were associated with them having a more limited cognitive resource pool, though it is well established that cognitive resources decrease with increasing age.[6, 47, 48]

Simulating central vision impairment in people with normal vision is useful in achieving reasonably uniform levels of visual acuity and contrast sensitivity reductions. However, individuals with real central vision impairment may behave differently to subjects with simulated vision impairment as they will have had much longer to adapt to their vision impairment. Simulated vision impairment also fails to capture all aspects of real vision impairment. For example, in the current study we simulated reductions in visual acuity and contrast sensitivity, but did not simulate central visual field loss (scotomas), which is an important characteristic of age-related macular degeneration.

We also need to consider the limitations of the driving simulator task. We extended prior research[3, 8] by using a driving simulator paradigm with moving pedestrian hazards in which participants had to control vehicle speed and position. However, the pedestrian figures were highly salient, participants did not have to make judgments about whether pedestrians were hazards, and pedestrians appeared more frequently than would be the case when driving on rural highways in the real world. Nevertheless, an important advantage of driving simulator studies is that participants are never at risk for real collisions, which is a major concern for on-road studies. Furthermore, frequent presentation of hazards enables reliable measurement of reaction times. In the real world, pedestrian hazards may be less frequent and unexpected and therefore we would probably expect to find greater effects of central vision impairment and distraction on response times and safety. Finally, our detection task required only a horn-press response. We did not measure braking, which would be a common response to a pedestrian hazard in on-road driving. However, the safety calculation did take account of the speed of the participant's vehicle at the time of the horn-press. The relatively straightforward detection task may explain why distraction did not have greater adverse effects on subjects' detection performance.

To ensure the pedestrians were truly on a collision course (constant bearing angle), we instructed subjects to drive as close to 97 kph as possible whenever they thought it safe to do so. This likely had two consequences. Firstly, it increased the difficulty level of the drives somewhat and secondly it may have reduced the amount by which participants might have otherwise compensated for either distraction or vision impairment by driving slowly. However, the instructions were the same for all conditions and participants were able to use the brake to reduce speed whenever they felt unsafe. It is also relevant to note that the sensation of speed in a driving simulator is not as strong as in a real car [49] which may have contributed to subjects not slowing down as expected when driving with simulated vision impairment.

Conclusions

Simulated central vision impairment increased response times to a much greater extent in older than younger participants, despite similar levels of visual acuity and contrast sensitivity reductions. Neither older nor younger participants adapted their speed in response to simulated vision impairment, resulting in unsafe detections. However, older subjects appeared to compensate for the auditory distraction by driving more slowly, possibly perceiving a greater threat to their driving safety from the auditory distraction than from the simulated central vision impairment. This interesting and unexpected finding warrants further investigation. Our results underline the importance of evaluating safety of responses to hazards as well as reaction times in a paradigm which flexibly allows participants to modify their driving behaviors.

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Table and Figure Legends

Table 1. Demographics, vision measures and driving exposure for study participants

Figure 1. LE-1500 driving simulator (FAAC, Inc., Ann Arbor, MI) used in this study. The auditory distraction task was delivered though a pair of speakers (Amazon Basics A100 Multimedia Speakers, China) positioned to the left and right of the participant's seat (white circle). A video recorder (yellow circle – DVC, WEILIANTE Co., Ltd, China) was positioned above and behind the car seat to simultaneously record participants' repetition of target words in the auditory distraction task along with video of the central screens of the simulator (to facilitate scoring of auditory task performance for segments without and with pedestrians on the screen).

Figure 2. Average reaction time for each condition plotted separately for older and younger subjects. Error bars represent the SEM.

Figure 3. Percent of safe detections for each condition split by older and younger subjects. Error bars represent the SEM.

Figure 4. . Boxplots for vehicle speed of older and younger subjects for each condition. Thick black line represents group median; box extent represents the inter quartile range (IQR); plot whiskers represent 1.5x IQR; and filled circles represent outliers beyond 1.5x IQR. (Note: the y-axis has been truncated and runs from 40-100 km/h)

Figure 5. Boxplots of average percentage of words recalled both during pedestrian events (left) and between pedestrian events (right) plotted separately for older and younger subjects. Thick black line represents group median; box extent represents the inter quartile range (IQR); and plot whiskers represent 1.5x IQR.