Neural Correlates of Older Driver Performance

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Neural Correlates of Older Driver Performance

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Abstract

Older drivers aged 65 and older represent the fastest-growing demographic in the United States. For older drivers, owning and driving a car often provides a sense of maintaining autonomy and independence. However, declines in visual, physical, and cognitive functions related to aging can negatively influence their driving performance. Older drivers face challenges with maneuvers required in complex traffic situations, which may lead to higher crash involvement. Challenging maneuvers include navigating intersections, making left turns against oncoming traffic, merging into traffic (gap acceptance), and making lane changes on limited-access highways.

Driving simulators have been used in several studies to assess the performance of older drivers. One common finding in these studies was that driving skills generally decline with age. These studies have also concluded that there are different levels of visual attention skill that can be recognized among older drivers using neuropsychological tests. Neuropsychological tests that assess cognitive abilities can play a key role in screening and evaluating the skills and capabilities of older drivers. Previous studies that use neuropsychological tests have found a correlation between results from tests and errors committed during driving. For example, the ability to process information, memory ability, and visuo-spatial abilities have been found to be predictors of older drivers' safe behavior. Studies have also used fMRI during simulated driving to investigate the aspects of brain activity associated with specific driving tasks (prepared actions, unprepared actions, and planning and monitoring). Even though neuropsychological tests provide valuable information concerning driving performance, there remains a gap in the research when it comes to older drivers, neuropsychological tests, and studies using fMRI.

A detailed summary of the literature review is presented in this report. In addition to the literature review, recommended experimental procedures based on previous experiences are documented. The report act as a foundation for future research that will focus on identifying/developing quick tests that can be used to screen potential dangerous drivers.

1 Introduction

Owning and driving a car often fulfills a more symbolic function for older people: maintaining autonomy and independence. Studies showed that 50% of older drivers use their own cars for daily activities such as taking care of the household and themselves. Travel studies showed that older people will continue driving and making more trips in the future [1]. Even though many older people enjoy good health, aging can influence driving-related cognitive functions and performance capacities. Older drivers reported various age-related declines, including sensory, perceptual, cognitive, physical, and general driving knowledge deficiencies. Vision deficiencies in areas such as light sensitivity, visual acuity, visual field, color vision, night vision, and spatial resolution increase with age. Perceptual abilities such as detecting and identifying objects and cognitive abilities including reactions to some driving situations decline with age. Physical deficiencies include decrease in agility and ability to do some driving maneuvers that require body movements. For instance, blind spots are affected by the decline in head and neck mobility, leading to maneuver problems. With age, the driving knowledge related to understanding basic driving practices and laws decreases. The capability of older drivers to extract and respond to information while driving may be reduced due to declines in visual and cognitive abilities. These declines may also explain their difficulty with some driving maneuvers, such as detecting and understanding traffic control devices, driving at night, and navigating routes [1] [2]. Specifically, elderly drivers have problems with complex traffic situations that may lead to higher crash involvement. These maneuvering problems include navigating intersections, making left turns against oncoming traffic, merging into traffic (gap acceptance), and making lane changes on limited-access highways [1] [2]. Furthermore, researchers have found that older male drivers are safer than older female drivers when it comes to left-turn and gap-acceptance-related crashes [1].

Generally, older drivers are aware to some extent of the declines that occur with age, mainly those related to vision, reaction time, and physical abilities. Many older drivers tend to compensate for difficulties they experience by driving at lower speeds and avoiding difficult driving conditions such as driving at night and in bad weather [3]. However, it is not easy for older drivers to decide to self-limit or even cease driving, mainly because driving is essential to maintaining a sense of mobility and independence [1].

1.1 Statement of the problem

Seniors are subject to age-related declines in sensory skills and cognitive functions that support autonomy. Deficits in these areas lead to a decline in the everyday abilities and make the elderly more prone to injuries, contributing to reductions in independence and mobility. Mobility is essential in keeping a fulfilling and independent life and maintaining social contacts. Driving is one activity that can ensure both aspects and can be affected by physical and cognitive functions. Age-related cognitive declines, vision deterioration, visual motor function problems, sensory processing problems, reduced useful field of view (UFOV), and dementia, along with reduced physical abilities affecting flexibility, agility, movement speed, and psychomotor function, all affect the ability of older drivers to collect, process, and respond to traffic information [4] [5].

Even though some older drivers apply compensatory behaviors such as day driving, avoiding bad weather conditions (mainly snow and rain), reducing driving speed, and driving with a passenger (usually a friend or a family member), the crash rate per vehicle mile traveled (VMT) for seniors aged 75 and older increases intensely. In addition to declines in physical abilities, there are also declines in attention and cognitive functions with age. This cognitive function decline affects the ability of elder drivers to process information [3].

Crash rates of older drivers based on the distance traveled are as high as those of younger drivers. Female drivers have higher rates of crash involvement than male drivers in all groups, including seniors. Older drivers were found to be involved in direct and indirect right-angle crashes along with crashes associated with turning movements [6]. Many, but not all, older drivers have deficits in their attentional skills, which is one of the primary causes of vehicle crashes among seniors. Several studies have investigated sets of probable visual/cognitive predictors of crash involvement and have confirmed that visual attention deficits are the best predictors of crash involvement in the elderly. The most highly perceptual/cognitive skill related to driving performance has been shown to be selective attention. Higher crash rates were correlated to older drivers with selective attention problems rather than those with good attention-switching ability. Other studies showed the relation between crash frequency and visual and cognitive measures. The size of the UFOV was found to be the best predictor of crashes compared to models that only assessed visual sensory function and excluded measures of information-processing skills at higher levels [4] [5].

For years, researchers have been trying to find ways to distinguish between drivers who may pose risks to their own safety – along with the safety of other road users – and drivers who do not. Studies have found that measures of visual attention and cognitive function have been effective in differentiating between these two groups. With training, visual attention skills can be enhanced, thus improving the skills that guide safe driving [4].

1.2 Objectives

This report has four key objectives:

- To summarize available information related to how older drivers' functions decay.

- To understand the state of the research regarding the use of neuropsychological tests on older drivers.
- To evaluate the feasibility of screening older drivers in an fMRI using driving simulator scenarios that can be used in a full-scale driving simulator.
- To understand what type of experiments need to be conducted to validate streamlined driving screening tools using full-scale simulation and fMRI scans conducted in a simulated driving environment.

2 Supporting Literature and Existing Practices

2.1 General Information about Older Drivers

It is well known that drivers aged 65 and older represent the fastest increasing demographic in the United States. From 1970 to 2000, the growth rate of the older population was three times greater than the total population growth [1], and it increased by more than 15% of the total population from 1993 to 2003 [7]. In 2030, it is expected that one in five U.S. residents will be aged 65 and older. The elderly population is expected to increase from 40.2 million in 2010 to 88.5 million in 2050 as the baby boomer generation gets older [8]. The number of older drivers licensed to drive has also increased with time. The U.S. driving population consisted of 8% older drivers in 1970 and 14.3% in 2000 [1]. In 2008, 32.2 million older drivers were licensed in the United States, and this number is estimated to reach more than 40 million in 2020 [9]. Older drivers are expected to triple all vehicle miles driven, from 6.7% in 1990 to an estimated 18.9% in 2030 [1]. It is expected that the fatal crash involvement of older driver will increase 155% by 2030, accounting for 54% of the total estimated fatal crashes. It is also expected by that year that older drivers involved in police-reported crashes will increase 178%. By 2030, elderly drivers are expected to account for nearly 25% of total driver fatalities, which is slightly double the current driver fatality rate [10].

Older drivers have a higher risk of being involved in crashes in which they face death or pose risks to other road users. Risk measurements based on a per-driver, per-trip, or per-mile basis play a key role in assessing the degree of risk that older drivers pose to others [11]. A study by Langford et al. [12] showed that older drivers are as safe as, or even safer, than other age groups when comparing their crash involvement per miles driven with other age groups. Langford et al. [12] also found that only older drivers with low mileage driven had elevated crash rates. Another study by Li et al. [13] concluded that the fragility of older drivers, measured as their risk of dying when involved in a crash, was the main factor leading to increased fatality rates rather than crash involvement rates.

The Traffic Safety Facts [14] shows that the involvement in crashes starts to increase at the age of 65, but that it is higher for the age group of 74 and older. The same applies for fatality rates. In 2014, the total number of people killed or injured aged 65 and above was approximately the same as those aged between 21 and 24 and less than middle-aged people, 35 to 50. That year, older drivers represented 17 percent of all vehicle occupant fatalities and 9 percent of people injured in crashes.

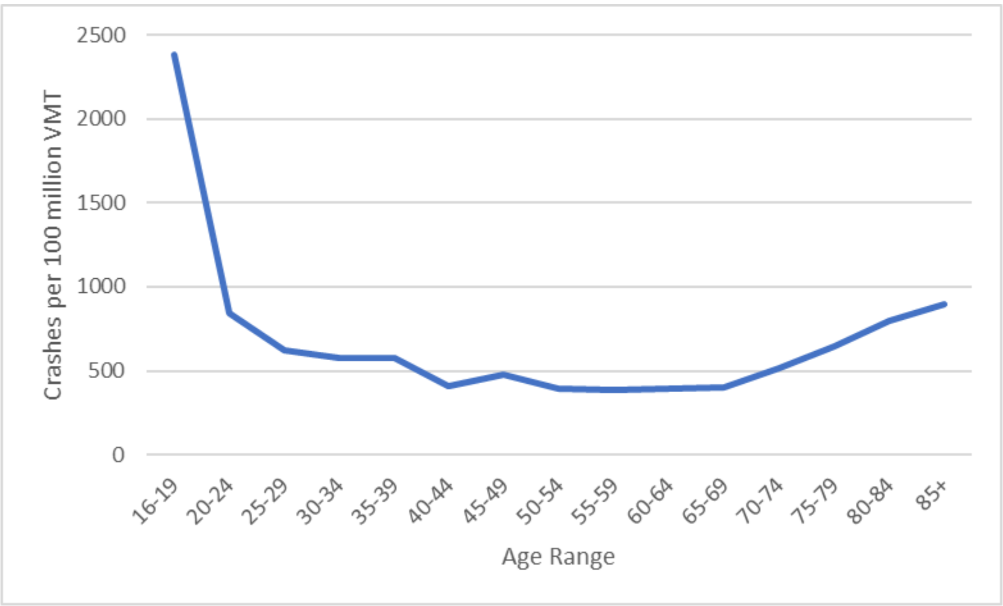

Figure 2.1 - Accident rate per VMT vs age groups [15]

The crash rate per VMT looks like a U-shaped curve for different age groups, as shown in **Error! Reference source not found.**. Young licensed drivers have a very high crash rate per VMT. This rate decreases significantly with age as a result of gaining driving experience each year. Crash rate levels off around 25 years old and remains at a steady level until the age of 65 to 70, when it starts increasing. The crash rates of seniors are equivalent to those of inexperienced young drivers. This trend was consistent in all studies, although the scale differed from one study to another, and regardless of the country under study [6] [15] [16]. It was noted that drivers aged 75 and above were at higher risk of crash involvement while driving [6].

Studies have documented a high risk of being engaged in a crash for older drivers, specifically drivers older than 75. Drivers between 75 and 79 years old are involved approximately two to three times as often as those between 65 and 69 years old. Older drivers are also three times more likely to die when involved in a crash. The increase in fatalities is mainly due to the increase of the frailty of older drivers and the decrease in their agility [6] [15]. Some studies have analyzed driver fatality rates per capita, per licensed driver, and per miles driven as a function of driver's age and sex. Drivers who are 80 years old have a 121% higher fatality rate compared to drivers that are 40 years old based on licensed drivers. Drivers aged 80 also have a 662% higher fatality rate compared to drivers aged 40 years based on miles driven. Older drivers were also found to be less responsible for the death of occupants of other vehicle compared to younger drivers [11].

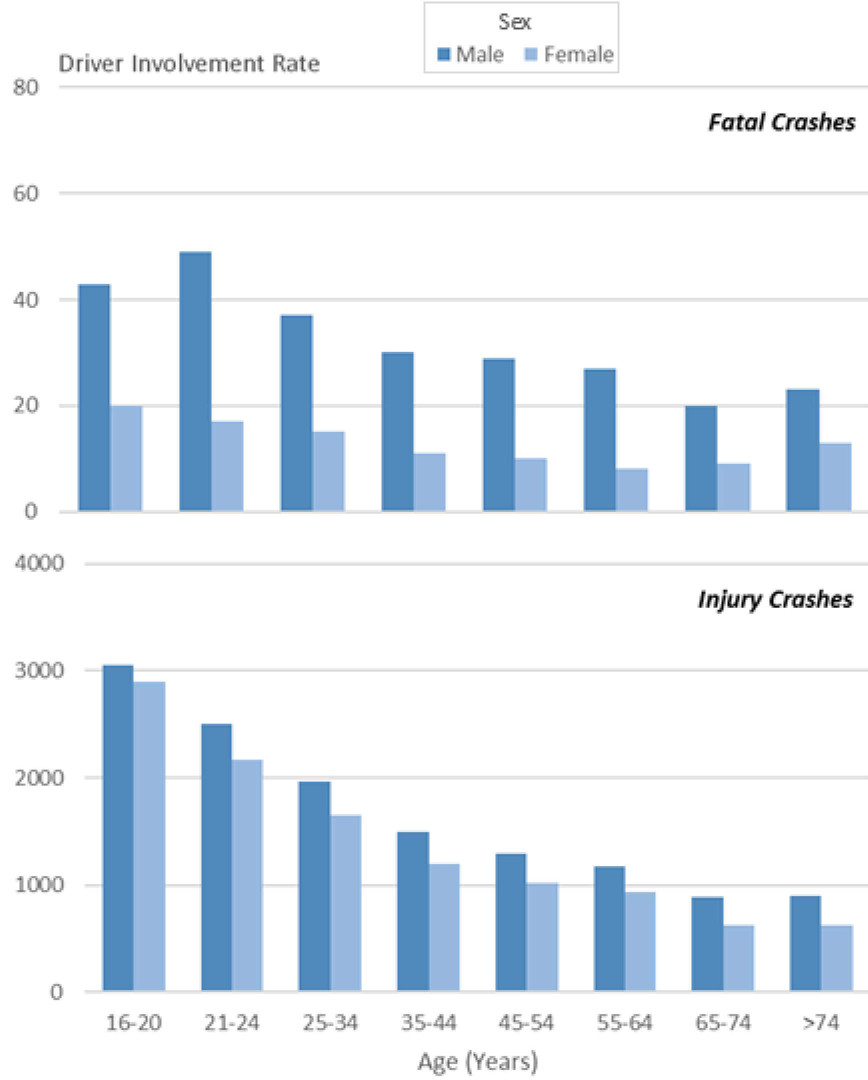

Figure 2.2 - Driver Involvement Rates per 100,000 Licensed Drivers, by Age and Sex

Figure 2.2 shows fatalities and injury crash rates based on the 2014 data from The National Highway Traffic Safety Administration [16]. Fatal and injury crash rates are higher for younger drivers than older ones. It can be seen for older drivers that men are two times as likely as women to be involved in a fatal crash. It can also be seen that older drivers are more involved in injury crashes than fatal crashes. One of the factors contributing to crash involvement is vulnerability: physical, visual, and cognitive.

Although the total number of crashes of older drivers is less than that of younger drivers, the number of crashes per VMT for older drivers is higher than drivers aged between 25 and 65 years. Crash types and the actions taken prior to a crash differ between older and younger drivers. While young drivers are involved in head-on and rear-end crashes, older drivers tend to be involved in angled crashes [6] [10] [11] [16].

Studies were conducted to evaluate the problematic maneuvers associated with crash involvement of older drivers. Crashes that occurred while turning were common among older drivers. Moreover, older drivers were 63 percent more likely to be involved in a crash while merging or changing lanes. Older drivers also had problems with gap selection. While the critical gap for other drivers at two-way stop-controlled intersections was 5.19 seconds, that of older drivers (aged 65 and above) was 7.36 seconds. The longer the critical gap, the more difficult it was for older drivers to enter a roadway at an unsignalized minor approach [1]. However, older drivers were found to be less likely to be involved in crashes related to fatigue, alcohol, weather, speeding, driving during early morning or the evening, and driving on a curved road, as well as those involving a single vehicle [17].

Although older drivers have lower crash involvement rates, they are more likely to be killed or injured if they get involved in a crash. Despite the risk, seniors still prefer driving over other modes of transportation. This is because driving represents independence, autonomy, and freedom. Driving cessation threatens older drivers' independence and represents a key change in their lives such as depending on other family members for their rides [18].

2.2 Functional Impairments

Driving safely depends on several skills, including visual, cognitive, and physical abilities [17]. With age, several physical and functional abilities decline at different rates [18]. Some of these impairments along with some medical conditions in older drivers have the potential to negatively impact driving performance and increase crash risks [19]. Studies that examined the factors associated with motor vehicle collisions among older drivers have identified the following factors: age, gender, poor eyesight, reduced speed of processing measured by the UFOV, dementia-related cognitive deficiency, declines in physical capabilities, and functional impairment. Studies have also found strong correlations between crash rates and declines in speed of processing. Likewise, increased rates of driving cessation were associated with deficits in speed of processing, reasoning, and memory [20].

Vision is the most important sense for driving, regardless of age. Around 90 percent of the information required to safely drive is associated with the capability of seeing clearly [18]. A substantial number of studies addressed the relationship between visual impairment and driving. Most of these studies examined the relationship between visual acuity (the ability to resolve details) and driving performance, visual acuity being the most common visual-screening test used in the licensing process to determine driving fitness. Combining all the work done in this area on older drivers, there is little support for a significant relationship between visual acuity and unsafe driving. Several reasons exist behind the little support of the ability of acuity tests to identify high-risk drivers. First, letter-acuity tests were designed for clinical diagnosis of eye diseases and not for the evaluation of visual performance skills in driving. Although severe visual acuity impairment affects driving performance, driving safely can be endangered by other visual impairments even in the presence of good acuity. Acuity tests cannot usually identify such impairments. Another reason for the lack of strong association between visual acuity and crash rates is that drivers with severe visual acuity impairment no longer maintain their licenses. In states where re-licensing does not require vision screening, older drivers choose to give up driving or limit their driving to low-risk situations. Hence, these drivers are no longer involved in crashes and cannot be used as participants in any study evaluating the relationship between acuity and crash involvement [19] [21].

Driving performance can also be affected by visual field impairment. Visual field, or peripheral vision, is the total area that a person can see and respond to [18]. Although not common, visual field testing is used for licensing purposes in many states. Several studies used real-world motor vehicle collisions to establish a relationship between visual field impairments and driving safely. Some studies were able to find a weak relationship while others failed to. A main difference between all these studies was the definition of the extent of visual field impairment. Several studies evaluated the relationship between visual field impairment and on-and off driving performance. These studies, conducted on closed courses or in a driving simulator, found that visual field impairment affects some driving aspects – such as the ability to identify road signs, avoid obstacles, and reaction time – but not all – such as the ability to accurately estimate speed and stopping distance. The significance of the findings of these studies to real-world driving is ambiguous because the influence of an unexpected, simulated visual field constraint is different from that of a naturally occurring constraint from eye disease, for which people might develop compensatory mechanisms over time in real life. Even though studies showed that drivers with visual field deficiencies have impaired driving performance, several researchers showed that drivers with such impairments are as likely as other normally sighted drivers to be prone to driving problems [19] [21].

Contrast sensitivity, which is the ability to differentiate between two similarly colored items [18], was examined in several studies to see if it is correlated to driving performance. Similar to visual acuity and visual field studies, the results are divergent. Contrast sensitivity impairment was significantly associated with recent crash history for older drivers with cataract. Like visual acuity, studies focused on the relationship between contrast sensitivity and driving performance rather than driving safety. Both on-road and simulator studies on drivers with Parkinson's disease and on-road research on drivers with hemianopia and quadrantanopia support the important role of contrast sensitivity in driving performance [19] [21].

Color discrimination is another vision screening test performed in both personal and commercial licensing to confirm that drivers can obey color traffic control devices and other color signals on the road, but it is not used as a measure for potential crash involvement. Studies concluded that drivers with color deficiencies have longer reaction times to traffic control devices with color signals and make more color confusions than drivers with normal color vision. However, color discrimination was found to be of less importance since critical road information can be obtained through several information sources, such as luminance, position, and pattern. Hence, no association between color vision deficiencies and vehicle crash involvement was found. In fact, vision deficit by itself does not increase crash risk; rather it may impact the driving performance of older drivers if other road cues are not available [19] [21].

Other visual impairments such as motion perception, eye movement disorder, and glare sensitivity have been raised as a potential area of consideration for driving performance. A few studies addressed the relationship between these impairments and driving performance and crash risk. However, researchers were not able to link these deficiencies to increased crash risk on the road [21].

The above-mentioned visual-sensory impairments and eye diseases alone cannot identify people at high risk of crash involvement. Visual-cognitive tasks, i.e., visual information-processing skills, are important for driving safely, especially visual attention. In 1970, studies found an association between visual attention and crash involvement. Later in 1980, the UFOV test was developed to evaluate the visual field area over which information can rapidly be extracted with no eye or head movement. This test depends on high-order processing skills, such as selective and divided attention, and rapid visual-processing speed. Studies on older drivers found that a reduction in the UFOV was related to a history of crash involvement. Another study showed that older drivers with slowed visual processing speed, particularly under divided attention conditions, were two times more likely to face a crash in the following three years [19]. This finding was independent of any visual-sensory test and was confirmed by several subsequent studies. Based on this finding, studies suggested that visual attention and visual processing speed tasks are better screening modes than visual-sensory tests in evaluating safe driving [21]. Several studies used the UFOV to examine crash susceptibility in drivers with Alzheimer's disease (AD). The findings indicated that UFOV reduction is one of the most effective predictors of crash involvement in a driving simulator, but a poor one for on-road testing. Studies also found that crash involvement and poor driving performance are related to impaired performance on other tests of higher-order visual-processing abilities. Unsafe driving was found to correlate with deficits in visual-search and -sequencing abilities, selective attention tasks, spatial memory, perception of three-dimensional structure from motion, and trails. Generally, the strength of the relationship between visual-cognitive deficits and driving performance is reliably much stronger than with visual-sensory function alone [19].

In addition to visual-processing abilities, controlling a vehicle involves several cognitive skills, such as visual attention, memory, and reasoning. The decline in short-term memory, attention, orientation, judgment and problem-solving skills, and visual-spatial skills is referred to as cognitive impairment [19]. Dementia, which results in decrease in cognitive functions, has a significant effect on safe driving behavior and is commonly found in elderly people [18]. Several studies confirmed that cognitive impairments among older drivers are a risk factor for unsafe driving. Researchers found that older drivers with cognitive impairment, regardless of the cause, are at least twice as likely to be involved in a crash. Moreover, several studies showed that poor on-road or simulated driving performance and crash involvement are related to attention problems/impairments in visual search and spatial memory [19].

Along with visual and cognitive abilities, safe driving requires the physical ability to maneuver and control a vehicle. More specifically, some of the important characteristics of physical ability for driving include strength, coordination, and range of motion (head, neck, arms, and legs), along with flexibility, balance, and gait. Little to no information exists about the relationship between physical functions and crash involvement. Studies performed in this field concluded that older drivers with physical limitations such as reduction in strength, restricted ability to turn head, and other restricted physical abilities tend to reduce or even avoid driving [19].

Studies have found that measures of visual attention and cognitive function have been effective in distinguishing between drivers who pose risks to themselves and others and those who do not. Studies also concluded that with training, visual attention skills can be enhanced, thus improving the skills that guide safe driving [4]. Cognitive training can improve the cognitive performance of older drivers. In the Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) clinical trial, cognitive training for reasoning, memory, and speed of processing was found to positively improve health-related quality of life for older drivers. In particular, training for speed of processing improved the results of the UFOV test and hence improved on-road safe driving. Training for speed of processing and reasoning resulted in reduced at-fault crashes for older drivers for a six-year period after training [20].

2.3 Driving Simulator Studies

Using on-road tests to evaluate driver performance is costly, ineffective, and stressful—especially to older drivers [22]. Rapidly developing electronic and computer technology have allowed relatively low-cost, laboratory-based driving simulators that convey the impression of driving a vehicle. They use several computer monitors to implement life-sized graphics. Over the last 45 years, studies have been conducted to evaluate the usefulness of using driving simulators as a validation tool. Many researchers concluded that driving simulators provide a safe and economical means of evaluating driver behavior that can have potentially dangerous consequences [23]. Several studies confirmed that driving simulators can detect differences between different groups of drivers: healthy drivers vs. drivers with central nervous system impairment, normally sighted vs. visually impaired drivers, young vs. old drivers, experienced vs. inexperienced drivers, and drivers with vs. without sleep deprivation. Other studies were conducted to test whether driving simulators can be used as an off-road screening tool to measure drivers' performance. These studies evaluated the relationship between simulator and on-road driving. Five of these studies showed a moderate to high correlation between simulator and on-road driving, while the other two showed low correlation. Similarly, six studies compared the results between simulator and on-road evaluations of patients with acquired brain injuries. Moderate to high correlation was found in five of these studies, and little correlation was found in one of the studies where only reaction time was used to measure simulator performance [24] [25]. Driving simulators were used extensively in several studies to assess the performance of young and middle-aged drivers. A number of studies have attempted to use driving simulators to assess older drivers [23].

In 2002, a study [23] investigated a driving simulator and identified evaluation criteria for older drivers as an off-road assessment tool for driving performance. The assessment criteria used to evaluate participants were divided into performance indicators such as speed violation and proper signaling, and operational parameters such as curvature error and lane position. The senior participants drove faster than advanced-aged participants; however, they both traveled at speeds suitable for the traffic conditions. The response to the divided attention task stimuli was reported to be poor, which is consistent with age-related declines in visual abilities. This study found that performance indicators were sensitive in distinguishing group differences in driving skills. Operational parameters, on the other hand, were not as sensitive.

Another study [22] directly compared the performance of older drivers using a driving simulator with on-road driving performance. A set of assessing criteria was used to evaluate the driving performance in the driving simulator. Some measures were directly recorded by the simulator: driving speed, use of indicator, decision and judgment, confidence at high speed, and attention tasks. Rule compliance, traffic sign compliance, road use obligation, working memory, and multi-tasking were collected by laboratory personnel. As for on-road test performance, participants were evaluated in their vehicles by a principal investigator based on a set of on-road assessment criteria. These criteria included road use obligation, traffic sign compliance, traffic light, T-junction, general driving skill, normal driving, error detection, error recovery, use of indicator, driving speed, and working memory. A high positive correlation was found between simulated driving index and road assessment index (simulated driving index explained over 2/3 of the variability of the road assessment index), validating the use of driving simulators as an off-road screening tool. Performance of older drivers was found to negatively correlate with age, which confirms that driving skills decline with age.

A quasi-experimental study [26] was performed to validate the use of driving simulators for older drivers by measuring their visual attention skill. To measure the visual attention skill, the reaction time of participants was recorded in response to a visual stimulus where the participants were expected to use the left turn indicator. Older drivers were found to perform poorly on tasks requiring visual skills, with gender having no effect.

In a retrospective study [27], the driving simulator was used to assess the relationship between simulators and crashes among older drivers. Measures related to driving performance, such as driving speed, use of indicator, lane position, and stopping distance, were collected by the simulator. Other measures related to driving behavior, including observing traffic rules, the ability to address two tasks at the same time, and rear mirror usage, were collected by a laboratory assistant. In addition to a negative correlation between driving and age, this study found that driving simulators could identify older drivers at inflated risk of motor vehicle crashes. Impairment of some cognitive skills increased the probability of a crash event. These cognitive skills related to crash occurrence include but are not limited to: working memory, judgement under time pressure, ability to make quick decisions, and confidence in driving at high speed. Of these measures, the inability to make fast decision and judgment were highly significant and influential.

Older drivers at risk of traffic violation were identified using a driving simulator in a three-year study [28]. Simulated driving tasks such as driving speed, use of indictor, visual attention tasks, and others were collected from the simulator. Other measures such as rule compliance, working memory, multi-tasking, and others were collected by lab personnel. The study found that appropriate use of indicator would decrease crash rates. The use of the indicator requires appropriate reaction and efficient motor coordination, which might decline with age, hence affecting driving skills. Working memory was found to be positively correlated with road violation.

The previous five studies used the driving simulator to assess the performance of older drivers. They found that a linear relationship exists between age and performance. It was also found that different levels of visual attention skill can be differentiated among older drivers. These studies reported that over 67% of on-road driving behavior can be explained by observations from driving simulator assessments. A summary of these five studies is presented in Table 2.1.

Table 2.1 - Summary: Driving Simulator Studies on Older Drivers

Name	Purpose	Sample	Outcome Measure	Main Findings	Recommendation
Identification of appropriate assessment criteria to measure older adults' driving performance in simulated driving. Lee, Drake and Cameron (2002) [23]	To identify assessment criteria associated with cognitive functions and to investigate the ability of driving simulator in detecting several driving levels of skill.	N = 53 aged 65-85	STISIM driving simulator - Performance indicators: total run length, speed violation, proper signaling, divided attention tasks, and off-road accident. - Operational parameters: curvature error, heading angle error, steering-wheel rate, and lane position.	Performance indicators are able to differentiate the driving skills of older drivers whereas operational indicators cannot.	There is a need to validate the driving simulator with on-road testing
Assessing the driving performance of older adult drivers: on-road versus simulated driving. Lee, Cameron and Lee (2003) [22]	To validate the driving simulator in measuring on-road driving performance of older driver	N = 129 aged 60-88 78% were male	STISIM driving simulator -Automatically recorded: driving speed, use of indicator, decision and judgement, confidence at high speed, and attention tasks -Collected by laboratory assistant: rule compliance, traffic sign compliance, road use obligation, working memory, and multi-tasking. Road test assessment -Criteria: road use obligation, traffic sign compliance, traffic light, T-junction, general driving skill, normal driving, error detection, error recovery, use of indicator, driving speed, and working memory.	Performance of older drivers is negatively associated with age as confirmed by the simulated driving index and the road assessment index. A high positive relationship exists between the driving simulator and on-road tests. This makes the driving simulator a cost-effective alternative screening tool.	Driving simulator can be used as an initial assessment tool by which further driving assessment can be used for unsafe older drivers.

Validation of a driving simulator by measuring the visual attention skill of older drivers. Lee, Lee and Cameron (2003) [26]	To validate the driving simulator as an off-road screening tool for older drivers by measuring their visual attention skill	N = 129 aged 60-89 22% were female	STISIM driving simulator -Visual attention skill: engage the turn indicator when a red triangle appears and measure the reaction time.	Visual attention skills decline with increased age. However, the effect of gender was not significant.	Use of driving simulator to assess other cognitive and perceptual functions
Using a driving simulator to identify older drivers at inflated risk of motor vehicle crashes. Lee, Lee, Lee, Cameron and Li-Tsang (2003) [27]	To develop assessment criteria to measure older drivers' performance and to identify older drivers at risk of motor-vehicle crashes.	N = 129 aged 60-88 78% were male	STISIM driving simulator -Automatically recorded: driving speed, use of indicator, decision and judgement, confidence at high speed, and attention tasks -Collected by laboratory assistant: rule compliance, traffic sign compliance, road use obligation, working memory, and multi-tasking.	The driving skills generally decline with age. The presence of impairment in cognitive skills such as working memory, ability to make rapid decisions, judgement under time pressure, and confidence in driving at high speed increases the probability of a crash.	Future studies to use driving simulator to determine their ability to predict future crash occurrences
Identifying older drivers at risk of traffic violations by using a driving simulator: A 3-year longitudinal study. Lee and Lee (2005) [28]	To identify problematic older drivers based on their 3-year driver violation point records.	N = 129 aged 60-88 22% were female	STISIM driving simulator -Automatically recorded: driving speed, use of indicator, decision and judgement, confidence at high speed, and attention tasks -Collected by laboratory assistant: rule compliance, traffic sign compliance, road use obligation, working memory, and multi-tasking. Motor vehicle crashes and traffic violation history	The driving skills generally decline with age. The use of indicator and the working memory were highly associated with higher traffic violations.	Target working memory and correct use of indicator when assessing older driver for safe driving

Driving simulators were used by occupational therapists as a safe substitute to on-road screening because of the little risk simulated crashes pose to drivers. For instance, a study used the driving simulator to improve drivers' performance skills, such as visually scanning the environment, and patterns, such as checking the right lane before merging. Other than assessing driver performance, the driving simulator was used to assess driver interaction with the environment (negotiating intersections) and in-vehicle technologies (lane-departure warning systems) [29].

2.4 Simulator Sickness

Driving a simulated vehicle can cause a physical discomfort called simulator sickness, which is caused by incompatible signals from the visual, auditory, and motion systems. In the absence of true motion, simulator sickness can affect the driver. Early signs of simulation sickness include paleness, dizziness, fatigue, headache, eyestrain, and sweating. More serious discomfort can be experienced and can include nausea, increased salivation, and vomiting [29].

Age plays a role in contributing to simulator sickness. Studies show that participants of age 70 and older experience statistically significantly more simulator sickness symptoms than those of age 50 and younger [29]. In regards to gender, some studies showed that women experience statistically significantly more simulator sickness symptoms than men, while other studies showed that gender had no effect on simulation sickness susceptibility [30]. Another study conducted on older drivers found that the degree of reported simulator sickness increases when driving in a curves environment and in an environment requiring left/right turns [31]. Researchers also found that older drivers who failed to complete the experiment and dropped out had simulation sickness. One study investigated the relationship between dropping out due to simulator sickness and driving performance while performing some cognitive tests. No association was found between dropping out due to simulator sickness and cognitive differences. Moreover, simulator sickness does not affect driver performance. Hence the driving simulator is a safe alternative screening tool to on-road testing for older drivers [32].

2.5 Neurophysiological tests

Older drivers encounter a decline in cognitive abilities, which contributes to problematic driving performance. A driver's violations and crash history can forecast future unsafe driving, and yet it is not an ideal predictor. On-road driving evaluations are considered the standard screening tool to determine old drivers' fitness to drive. However, on-road driving, which is informative yet expensive, is not representative of someone's typical driving behavior during the evaluation. Neuropsychological assessment – a performance-based method to evaluate cognitive functioning – provides a more practical approach to evaluate driving risk for older drivers [33].

One of the fundamental questions during a neuropsychological evaluation is the ability to safely drive a vehicle, especially for older drivers with both normal and impaired cognitive abilities. Studies have shown that neuropsychological tests can predict driving capacities among older adults [34]. Neuropsychological predictors are divided into several main groups, and Table 2.2 shows this classification for tests used in most studies. One of the most commonly studied testing procedures to evaluate aspects of visual attention is determining the size of the UFOV. The size of the UFOV depends on several types of visual abilities, such as spatial resolution, light sensitivity and contrast sensitivity, divided attention, selective attention, and the speed by which visual input is processed [35]. Another important test is the trail-making test, which reveals several cognitive abilities such as attention, visual search and scanning, sequencing and shifting, ability to execute and modify a plan of action, and ability to maintain two trains of thought simultaneously [36]. Digit symbol substitution is another main assessment tool that evaluates the magnitude of cognitive dysfunction and monitors changes in cognitive performance over time [37].

Table 2.2 - Classification of Neuropsychological Tests Used in Most Studies

Domain	Cognitive Ability	Cognitive Test
Attention	Selective attention	Number cancellation Shifting attention from one aspect of an image to another Dot counting test
	Divided attention	Sharing attention between images presented together Tracking task
	Visual attention	UFOV
	Range of attention	Response to parafoveal image - simple
Perceptual and visuo-spatial ability	Visuo-perceptual	Movement perception test
	Mental flexibility	Incompatibility test
	Digit matching	Figure matching
	Perceptual speed	Identifying target within image field
	Visuospatial ability	Hooper organization test AARP ‘RT’ Missing pattern Respond to simple image Paper-folding test
Speed and Reaction time	Psychomotor speed	Number tracking
	Abstract RT	Respond to square
	Meaningful RT	Respond to brake lights
	Simple RT	Computer-generated neurobehavioral evaluation system
	Complex RT	Computer-generated neurobehavioral evaluation system
	Choice RT	Respond to nature of stimulus
	Visual tracking	Tracking a laterally moving image
Memory	Delayed memory	Identifying previous figure series
	Memory	Word recall
	Digit memory	Digit matching
	Figure memory	Figure matching
	Visual memory	Wechsler memory scale
	Verbal memory	Wechsler memory scale
	Traffic sign recognition	Traffic sign recognition
Trail Making Test	Trail making	Trail A Trail B
Executive function	Executive function	Stroop Color Word Tower of London Wisconsin Card Sorting Identifying missing card from deck of 52

Even though the decline in cognitive abilities is associated with higher crash risks for older drivers, a small number of studies investigated the relationship between on-road driving and neuropsychological test performances. No association between driving and neuropsychological test performances was found, but some studies found that individual neuropsychological tests and complex keys of cognitive status are significantly correlated with driving safely [33]. Studies have shown that attention (selective attention, divided attention, visual attention, and range of attention) was associated with on-road performance and crash involvement. Specifically, a simple letter cancellation task was found to have a high correlation with crash involvement. Poor scores on the UFOV were also associated with increased crash involvement. A low to moderate relationship was found between other attention assessment tests and on-road driving. Moderate to high correlations were found between visuo-perceptual tests and driving performance. One study has shown that the movement perception test had the highest correlation with on-road driving; however, the result is not generalized due to the small sample size used in the study. As for the visuo-spatial tests, the paper-folding test, which is the most cognitively complex test of the visuo-spatial tests, revealed the highest correlation with driving performance despite the small sample size in the study. The movement-perception test, the identifying-target-within-a-field test, and other perceptual tests compromised speed processing and depended on vision. These tests are better explained by visual and speed-of-processing functions. Low correlation was found between simple reaction time and crash involvement. Moderate association was found between reaction time and on-road driving performance, with higher correlation found for complex reaction time rather than simple reaction time. Significant correlations were found between memory measures and driving performance. Higher associations were found with older drivers with dementia. Some studies found a low to moderate association between driving performance and memory. Despite the wide use of the Trail Making Test, a lack of significant relationship was found between driving performance and Trail B. Drivers with crash history performed worse than drivers with no crash history on several executive function tests. Researchers found that cognitive impairments may reduce driving performance. Drivers with crash history performed slowly on the Trail Making Tests, poorly on the Stroop Color Word Test, and worse on the Tower of London and the Wisconsin Card Sorting Test [38].

Studies also investigated the relationship between neuropsychological tests and driving simulators. One study found a correlation between several neuropsychological tests and some driving simulator performance. Lane boundary crossing in the simulator was significantly correlated with Trails A and B, memory cognitive tests (visual and logical), block design, and Digit Symbol. Brake pedal pressure was significantly correlated with Trails A and B, logical memory, and digit span tests. Speed correlated significantly with Trails A and B, logical memory, and block design tests. Eye movement measured while driving the simulator correlated with the digit span and the visual form discrimination tests [39]. Other studies showed that perceptual, visuo-spatial, and attention tests are highly associated with driving simulator performance. UFOV seems one of the best tests that associates visual attention for safe driving and driving simulators [30]. The mini-metal state examination (MMSE) was used in several studies to relate between cognitive impairment and crash risk. Studies found that MMSE related to simulator driving performance. In addition to the previously mentioned tests, complex reaction time, the Stroop Color Word Test, and clock drawings were found to predict driving problems using a driving simulator [40].

Neuropsychological tests assessing cognitive abilities play a key role in screening and evaluating older drivers for driving capability. The results of these tests have been shown to have a significant association with driving performance and errors committed during driving. Speed of processing, memory, and visuo-spatial abilities were found to be predictors of older drivers' safe behavioral driving. Most studies focused on either normal older drivers or drivers with specific diseases while evaluating cognitive, perceptual, and behavioral impairments in order to identify unsafe driving. In any case, these cognitive tests were able to provide valuable information concerning driving performance [33].

Several studies used the driving simulator along with neuropsychological tests to evaluate older drivers' performance. The studies presented in Table 2.3 focused on healthy drivers. These studies concluded that older drivers scan their environment less than younger drivers. However, active training can increase older drivers' scanning behavior. As for the studies summarized in

Table 2.4, participants were both healthy older drivers and those with cognitive impairment. These studies showed that average speed, reaction time, lane position, and headway were the simulator variables most likely to distinguish between groups of older drivers: healthy and cognitively impaired individuals.

Table 2.3 - Summary of Driving Simulator Studies using Neuropsychological Tests on Healthy Older Drivers

Name	Purpose	Sample	Outcome Measure	Statistical Test	Main Findings
Improving the road scanning behavior of older drivers through the use of situation-based learning strategies Romoser [2008] [41]	To evaluate older drivers' risk of being involved in an angled crash using a driving simulator, and to assess the use of error training with feedback as a tool to train older drivers to negotiate turns more safely	Experiment 1: 18 older drivers (age > 70) 18 younger drivers (25 < age < 55) Experiment 2: 54 older drivers (mean age = 77.54)	**Experiment 1 and 2:** Review-and-feedback of driving: - Failed to take a secondary look during a turn - Turned too slowly - Merged too close to vehicle - Failed to glance into the adjacent lane before merge - Failed to fixate on the risk in periphery - Other **Experiment 2:** - Snellen Far Visual Acuity - Snellen Near Visual Acuity - Trail Making Test A - Trail Making Test B - Rey Auditory Verbal Learning Test - Rey-Osterreith Complex Figure Test - Get Up and Go - Grooved Pegboard Test - Flexibility	Student-Newman-Keuls (SNK) analysis ANOVA Stepwise regression	**Experiment 1:** Older drivers scan their environment less than younger drivers while driving. Providing customized feedback for errors older drivers made in the simulator was effective in changing older drivers' perception of their ability, making them more willing to change driving behavior. **Experiment 2:** Capturing older drivers' errors in the simulator, providing customized feedback, and active training in the simulator increased the road-scanning behavior of older drivers in both post-training simulator and field drives. Passive classroom-style training showed no improvement.

The effect of active versus passive training strategies on improving older drivers' scanning in intersections Romoser and Fisher [2009] [42]	To determine whether older drivers looked less often for potential threats while turning than younger drivers and to compare the effectiveness of active and passive training on older drivers' performance and evaluation of their driving skills in intersections	**Experiment 1:** 18 older drivers (mean age = 77.7) 18 younger drivers (mean age = 35.0) **Experiment 2:** 54 older drivers (mean age = 77.54)	**Experiment 1 and 2:** Review-and-feedback of driving: - Failed to take a secondary look during a turn - Turned too slowly - Merged too close to vehicle - Failed to glance into the adjacent lane before merge - Failed to fixate on the risk in periphery - Other **Experiment 2:** - Snellen Far Visual Acuity - Snellen Near Visual Acuity - Trail Making Test A - Trail Making Test B - Rey Auditory Verbal Learning Test - Rey-Osterreith Complex Figure Test - Get Up and Go - Grooved Pegboard Test - Flexibility	F tests Mann-Whitney U Pearson R	**Experiment 1:** Older drivers were more likely to turn too slowly and looked less often while turning than younger drivers. **Experiment 2:** Active training is a more effective approach to for increasing older drivers' probability of looking for threats while turning. Older drivers who received passive training or no training showed no improvement.
Comparing the glance patterns of older versus younger experienced drivers: Scanning for hazards while approaching and entering the intersection Romoser et al. [2013] [43]	To analyze the differences in scanning behavior between older and experienced younger drivers in intersections.	18 older drivers (mean age = 77.7) 18 younger experienced drivers (mean age = 35.0)	Trail Making Test B Snellen eye test Flexibility test Horizontal angle of the driver's point-of-gaze	T test Bonferroni method	Older drivers have difficulties scanning intersections due to attentional deficits leading to their failure to scan hazards outside their travel path.

Table 2.4 - Summary of Driving Simulator Studies using Neuropsychological Tests on Healthy Older Drivers and Those with Cognitive Impairment

Name	Purpose	Sample	Outcome Measure	Statistical Test	Main Findings
Evaluating driving performance of outpatients with Alzheimer disease Cox et al. [1998] [44]	To determine the differences of driving performance between patients with AD and control drivers, using a driving simulator, and to determine how these differences related to mental status	29 AD patients (mean age = 72) 21 control participants (mean age = 70.1)	Background and driving-history questionnaire Mini-Mental State Examination (MMSE) Driving simulator variables: **Steering variables** - Steering wheel rotation - Number of times car travels off road - Risk midline **Braking variables** - Full stops - Missed stops - Maximum brake pressure - Bump collisions **Speed variables** - Low speed - High speed - Stop sign hesitation - Standard deviation of speed - Left turning time	T test Logistic regression	Driving simulator performance was able to distinguish AD patients from control participants and correlated with MMSE scores. Patients with AD: - were less likely to comprehend and operate the simulator cognitively, - drove off the road more often, - spent more time driving considerably slower than the posted speed limit, - spent less time driving faster than the speed limit, - applied less brake pressure in stop zones, - spent more time negotiating left turns, and - drove more poorly overall
Unsafe rear-end collision avoidance in Alzheimer's disease Uc et al. [2006] [45]	To test if older drivers with mild AD are at a higher odds of unsafe outcomes in a simulated complex driving situation that posed a hazard for a rear-end collision compared to neurologically normal drivers	61 AD patients (mean age = 73.5) 115 control participants (mean age = 69.4)	Mini-Mental State Examination (MMSE) **Cognitive tests** - Composite cognitive score (COGSTAT) - Auditory Verbal Learning Test Recall (AVLT-recall) - Benton Visual Retention Test (BVRT) - Complex Figure Test-Recall (CFT-Recall) - Judgment of Line Orientation (JLO) - Block Design (Blocks) - Complex Figure Test-Copy (CFT-Copy) - Trail-Making Test A (TMT-A) - Trail Making Test B (TMT-B) - Controlled Oral Word Association (COWA)	Wilcoxon Rank Sum test Fisher's Exact test Linear regression Logistic regression	Drivers with AD had more unsafe outcomes: a rear-end collision or a risky avoidance behavior (slowing down abruptly or prematurely, or swerving out of the traffic lane) compared to control participants. Drivers with AD had difficulty responding to driving conditions that present a risk for a rear-end collision. Unsafe outcomes were predicted by UFOV, JLO, CFT, BLOCKS, and TMT-B along with motor tests.

			Visual tests - Near visual acuity (NVA) - Far visual acuity (FVA) - Contrast sensitivity (CS) - Structure from motion (SFM) - Useful field of view (UFOV) **Motor tests** - Grooved Pegboards - Get-Up-and-Go - Functional Reach **Measures of Vehicular Control** - Steering wheel position - Accelerator and brake position - Vehicle speed - Position in lane - Longitudinal acceleration - Lateral acceleration		
Predictors of driving safety in early Alzheimer disease Dawson et al. [2009] [46]	To measure the association of cognition, visual perception, and motor function with driving safety in Alzheimer's disease (AD)	40 AD Patients (mean age = 75.1) 115 Healthy Controls (mean age = 69.4)	Mini-mental state examination (MMSE) **Cognitive tests** - Complex Figure Test-Copy (CFT-Copy) - Complex Figure Test-Recall (CFT-Recall) - Block Design (Blocks) - Benton Visual Retention Test (BVRT) - Trail Making Test A (TMT-A) - Trail Making Test B (TMT-B) - Auditory Verbal Learning Test (AVLT) - Judgment of Line Orientation (JLO) - Controlled Oral Word Association (COWA) - Composite cognitive score (COGSTAT) **Visual tests** - Contrast sensitivity (CS) - Useful field of view (UFOV) - Near visual acuity (NVA) - Far visual acuity (FVA) - Structure from motion (SFM) **Motor tests** - Get-Up-and-Go - Functional Reach - Grooved Pegboards **Driver safety errors** - Starting and pulling away from curve - Traffic signals - Stop signs	Wilcoxon rank sum test Multiple linear regression	Lane observance errors were significantly more common in the AD group. Serval individual test errors were found to be significant predictors of safety errors in subjects with AD, including the Benton Visual Retention Test, Complex Figure Test-Copy, Trail Making Subtest-A, and Functional Reach Test.

			- Other signs - Turns - Lane observance - Lane change - Overtaking - Control of speed - Backing up - Parallel parking - Head-in parking - Curves - Railroad crossing - Miscellaneous		
Effects of Alzheimer's disease and mild cognitive impairment on driving ability: a controlled clinical study by simulated driving test Frittelli et al. [2009] [47]	To assess the effects of Alzheimer's disease (AD) and mild cognitive impairment (MCI) on simulated car driving ability	20 AD Patients (mean age = 72) 20 MCI Subjects (mean age = 71.6) 19 Healthy Controls (mean age = 68.9)	STISIM Driving Simulator: - length of run - number of infractions - number of stops at traffic lights - mean time to collision - number of off-road events Simple Visual Reaction Time (S-VRT) test Mini-Mental State Examination (MMSE)	One-way analysis of variance Bonferroni post hoc test or Kruskal-Wallis test Pearson correlation coefficients	Patients with AD performed significantly worse than MCI subjects and controls on: - length of run - mean time to collision - number of off-road events MCI subjects had only a significantly shorter time to collision than healthy controls. S-VRT were significantly longer in patients with AD, compared to other groups. Unsafe driving behavior in AD patients was not predicted by MMSE scores.
Effects of mild cognitive impairment on driving performance in older drivers Kawano et al. [2012] [48]	To compare the driving performance of adults with amnestic subtype of MCI (aMCI) and of older and younger adults with normal cognition, using a driving simulator	19 younger adults with normal cognition (mean age = 39.3) 26 older adults with normal cognition (mean age 70) 12 older adults with aMCI (mean age 71.8)	Neuropsychological measures: - Digit Span Test, - Trail Making Test A (TMT-A) - Trail Making Test B (TMT-B) - Clock Drawing Test - Modified Stroop Test (mST) Driving simulator tasks: - road tracking (distance variation) - car-following (lateral position) - harsh-braking task (reaction time)	Multiple linear regression	A significant difference between older adults with aMCI and older adults with normal cognition was predicted by the car-following tasks. The difference may be associated with flexibility of visual attention and executive function. TMT - B significantly predicted the car-following performance.

Beyond summarized measures: predictability of specific measures of simulated driving by specific physical and psychological measures in older drivers van Breukelen and Wets [2012] [49]	To investigate whether age and/or functional ability predict driving performance of older drivers	47 participants (mean age = 76.21)	**Neuropsychological testing battery:** - Mini Mental State Examination (MMSE) - Montreal Cognitive Assessment (MoCA) - Digit Span Forward Test - Useful Field of View (UFOV) - Attention Network Test (ANT) - Visual acuity (Snellen chart) - Four-test balance scale - Functional reach test - Get-Up-and-Go Test - Road Sign Recognition (RSR) **Driving simulator test measures:** - Mean speed - Speed violations - Standard deviation of lateral position - Gap acceptance - Following distance - Maximum deceleration (pedestrian/sign) - Initial break point (pedestrian/sign) - Complete stop at a stop sign - Detection of road hazard - Reaction to road hazard - Collisions	Linear regression	Age is not the only predictor of driving performance. Functional age is more representative than chronological age. Neuropsychological tests are important for the prediction of driving performance; cognitive tests are better predictors than physical tests.
Does attention capacity moderate the effect of driver distraction in older drivers? Cuenen et al. [2015] [50]	To investigate whether attention capacity has a moderating effect on older drivers' driving performance during visual distraction (experiment 1) and cognitive distraction (experiment 2)	Experiment 1: 17 participants (mean age = 78.12) Experiment 2: 35 participants (mean age = 75.69)	Mini-Mental State Examination (MMSE) Useful Field of View (UFOV) **Driving measures:** - Mean driving speed - Standard deviation of lateral lane position (SDLP) - Following distance - Complete stops at stop signs - Brake initiation at pedestrian crossings - Brake initiation at stop signs - Crashes	ANCOVA ANOVA	Crash occurrence increased with visual distraction and was negatively related to attention capacity. Complete stops at stop signs decreased, initiation of braking at pedestrian crossings was later, and crash occurrence increased with cognitive distraction.

Do simulator measures improve identification of older drivers with MCI? Vardaki et al. [2015] [51]	To examine the degree to which driving simulator can predict drivers with MCI	12 MCI subjects (mean age =64.8) 12 control participants (mean age = 59.5)	**Neuropsychological Tests:** - Mini Mental State Examination (MMSE) - Immediate Recall Hopkins Total - Hopkins Delayed Recall - Letter Number Sequencing (LNS) - Judgment of Line Orientation (JLO) - Symbol Digit Modalities Test (SDMT) - Trail Making Test Part A (TMT-A) - Trail Making Test Part B (TMT-B) - Immediate Recall BVMTTotal - BVMT Delayed Recall **Simulator measures:** - Speed	Two-way mixed ANOVA Ordered multinomial logistic regression	Drivers with MCI performed significantly more poorly on a sign-recall task across varying levels of driving task demand than control group. Message recall scores, self-reported frequency of driving avoidance, and age did not predict a clinical diagnosis of MCI; only self-reported changes in global driving ability were significant in this regard.

Can driving at the simulator “diagnose” cognitive impairments? Papadimitriou et al. [2017] [52]	To test whether the driving simulator can be used as a screening tool for the presence of cognitive impairments	21 AD patients (mean age = 75) 38 MCI subjects (mean age = 70) 27 healthy controls (mean age = 65)	**Neuropsychological Tests:** - Mini Mental State Examination (MMSE) - Clock Drawing Test - Semantic and Phonemic Fluency - Symbol Digit Modalities Test - Written & Oral - Hopkins Verbal Learning Test-Revised - Trail Making Test **Driving simulator variables:** - Average speed - Speed variability - Mean Lateral position - Lateral position variability - Gearbox position - Gearbox position variability - Engine rounds per meter - Engine rounds per meter variability - Mean headway from lead vehicle - Steering angle - Steering angle variability - Number of engine stops - Number of hits of roadside bars - Number of lane departures - Number of sudden brakes - Number of speed limit violations - High engine rounds per meter - Reaction time at first unexpected event - Accident occurrence at first unexpected event	Discriminant analysis Wilks’ Lambda F-tests	The variables most likely to distinguish between healthy, MCI, and AD individuals are - average speed, - gearbox position, - mean headway, - reaction time at incident, - accident occurrence at incident, - age, and - lateral position variability. The developed functions were able to correctly classify around 60% of individuals.

2.6 Neuroimaging Studies

Neuroergonomics is a multidisciplinary approach that combines elements of neuroscience, cognitive psychology, human factors, and ergonomics and aims to study the brain structure and function. When used in driving studies, neurology, neuroscience, and cognitive psychology can be used to elucidate the mechanisms of cognitive breakdown that might be related to a specific subgroup of drivers [2]. In addition to assessing driving behavior, the driving simulator was used in a small number of functional neuroimaging studies to study brain activity stimulated during driving. From a neuroscience viewpoint, identifying and understanding such brain activity is important, but evaluating the relationship between brain regions and driving performance is a key point that might identify unsafe driving behavior [53].

The electroencephalography (EEG) was used in a few functional neuroimaging studies with the driving simulator to investigate the relationship between simulated driving behavior and the brain, and to examine cognitive processing of traffic signs. However, EEG was not well suited for evaluating brain activity due to the limited depth penetration and spatial resolution of EEG. Functional magnetic resonance imaging (fMRI), on the other hand, provides a better alternative for the understanding of the brain functions. It records noninvasive, hemodynamically spatially distributed, and temporally dynamic neural activity with high resolution [53].

A small number of fMRI studies used simple visual stimulus presentations and foot pedal or button press response recordings in order to examine visuomotor characteristics of driving performance while driving on familiar versus unfamiliar routes or while detecting an event [53] [54]. Other fMRI studies used one or several joysticks to examine the association between aspects of brain activity and simulated driving behavior, speed maintenance, and driving under distraction. These studies contributed to the overall understanding of brain activity [55] [56] [57] [58]. However, these studies lacked controlling devices found in real-world driving such as the steering wheel and foot pedals. Hence, these studies could not comprehensively associate brain activity to on-road driving [53]. Some studies involved steering wheel and foot pedals in fMRI studies under the assumption that these controlling devices provide better association to driving skills. Researchers studied the aspects of brain activity associated with driving behavior in young healthy adults, and the effect of alcohol on brain activity in simulated driving [59] [60].

All previous studies commonly showed that a network of brain regions including the parieto-occipital cortices, cerebellum, and cortical regions associated with perception and motor control are more active during driving than rest periods. The increased demands on vision, motor skills and visuomotor integration were the main reasons for activations in these regions [54] [55] [56] [57] [60]. Furthermore, activity in frontal, parietal, occipital, and thalamic regions was found to correlate with average driving speed [55] [61]. One of the studies also found that the number of crashes was negatively correlated with activity in the posterior cingulate, while another study showed that the ability to maintain a safe driving distance was negatively correlated with activity in anterior cingulate [56]. One study [58] investigated the relationship between brain activity and specific driving tasks. The driving process was divided into three events: prepared actions, unprepared actions, and planning and monitoring. The brain regions responsible for each event were identified. Prepared actions such as starting, turning, reversing, and stopping were related to a mutual network containing premotor, parietal, and cerebellar regions along with other additional brain areas. Unprepared actions such as swerving and avoiding collisions were related to the activation of lateral occipital and parietal regions, insula, as well as a more posterior region in the medial premotor cortex than prepared actions. Planning future actions and monitoring fellow road users were associated with activity in superior parietal, lateral occipital cortices, and the cerebellum. The anterior pre-SMA was also recruited during action planning. The right lateral prefrontal cortex was specifically engaged during the processing of road traffic rules. These additional activations in posterior brain regions were accredited to the increased strain that driving puts on vision and motor skills, along with visuomotor and visuospatial integration [40]. Another study investigated the effect of distraction on brain activity while driving on simulated driving performance using fMRI. Reduction in the parietal lobe was the main finding of the research which confirms the results of studies on distraction without using fMRI [62]. Another study showed that during distracted driving, brain activity shifted from the posterior, visual, and spatial areas to the prefrontal cortex [63]. A summary of the main driving functions of major brain regions is summarized in Figure 2.3 [64]:

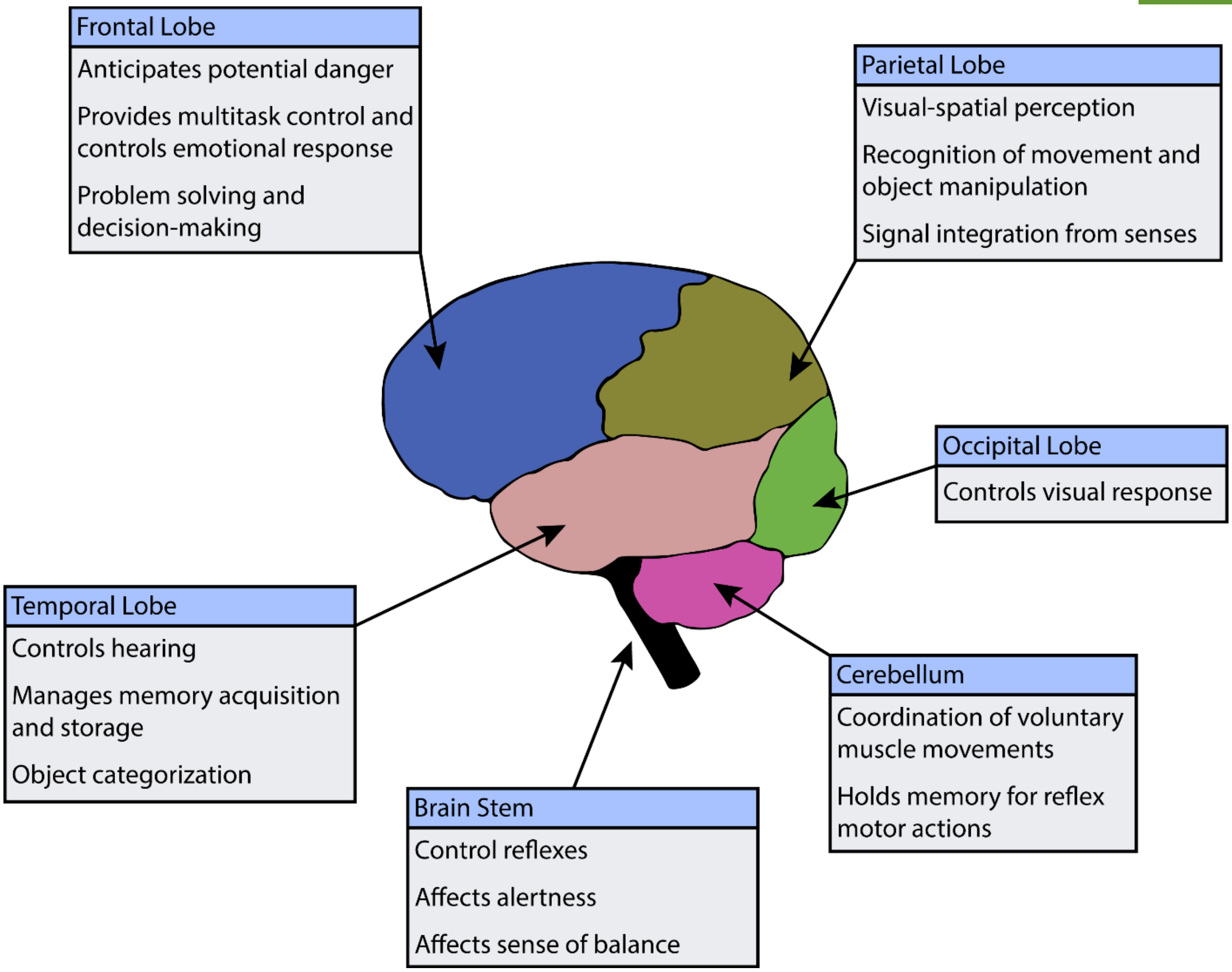

Figure 2.3: Brain regions related to driving

3 Assessment of fMRI Driving Simulation

As the literature demonstrated, the use of fMRI to understand how parts of the brain related to driving are activated is a promising area of research. As part of the project, one of the goals of the research team was to evaluate the feasibility of having a scenario that can be used both in a full-scale driving simulator and on a portable simulator that a subject inside an fMRI machine can control. A simple, streamlined scenario was created for a Realtime Technologies (RTI) simulator that can run in a full-scale simulator as well as on a desktop simulator. An fMRI-compatible steering wheel was configured to work with the desktop version of the simulator. The desktop version of the simulator was then used to understand the nature of "driving simulator" experiments inside an fMRI machine. Figure 3.1 shows a member of the research team testing the desktop simulator inside the fMRI machine.

Figure 3.1: Customized fMRI with compatible steering wheel

In the figure, the computer running the simulation is located outside the fMRI room and connected to a projector that projects the image into a screen inside the fMRI room. A mirror inside the fMRI chamber makes the simulation projected on the screen visible to the subject inside the chamber. Using the fMRI-compatible steering wheel, the subject inside the chamber can control the simulation. Significant limitations in the field of view inside the chamber exist since only part of the projection screen is visible to the subject through the mirror. From the simulation control perspective, the team found difficulties in controlling the simulation through simple movements due to the nature of the confined environment of the fMRI chamber. Due to the scenario control limitations, even simple simulator scenarios could become difficult to use inside the fMRI machine. Based on the experience during the fMRI test, the research team determined that the idea of running the same driving simulator scenario in a full-scale driving simulator and in a desktop simulator running inside an fMRI machine is not feasible. Therefore, when developing streamlined screening tests that can be used to detect potentially unsafe drivers and can be validated through a mix of full-scale driving simulator and fMRI experiments, the goal should be to identify scenarios that are similar (in terms of what the scenario is designed to measure) but that is optimized for each platform.

4 Conclusion and Future Work

This report presented a literature review that highlights previous research that studied the characteristics of older drivers. Three key areas were explored in the literature: general research on older drivers using driving simulators, research on older drivers that relied on neuropsychological tests, and research that relied on neuroimaging studies. The goal of understanding the current literature is creating a foundation that will support the development of screening tests in the future focused on identifying streamlined tests that can be administered to older drivers to detect potential driving performance issues.

One of the reasons for focusing on the driving performance of older drivers is that driving a car is often considered an important part of the culture that people are not excited to give up as they age. In the case of drivers 65 and older, driving a car provides a sense of independence and autonomy. However, with age, people experience visual, physical, and cognitive impairments that affect their driving performance. Such changes may decrease the ability of older drivers to extract and respond to information in the driving environment. Older drivers encounter difficulties with maneuvers required in complex traffic situations. Such maneuvers include navigating intersections, making left turns against oncoming traffic, merging into traffic (gap acceptance), and making lane changes on limited-access highways. Neuropsychological tests were found to correlate with on-road driving and driving simulator tests and provide valuable information concerning driving performance. In addition to visual screening, speed of processing information, visuospatial processing, and memory assessment were found to be key predictors of drivers' competence. Neuroimaging studies have also used fMRI to investigate aspects of brain activity associated with driving. All the literature points to science having the necessary tools to develop streamlined tests that can be used to screen drivers for potential safety concerns. However, these tests need to be developed and tested using technology such as driving simulation and fMRI to validate their accuracy.

In addition to the literature review, the research team also conducted tests inside an fMRI machine to assess the feasibility of conducting driving simulator studies and fMRI studies that involve driving simulation using the same scenario. Conducting tests that involve the same scenario was deemed unrealistic. Therefore, when developing and evaluating streamlined screening tests that need to be evaluated using driving simulator and fMRI studies, the researchers deemed the best approach to be the creation of driving simulator and fMRI experiments that target the evaluation of similar skills but that do not necessarily share the same scenario given the significant difference between the fields of view and capabilities of each platform. Based on findings from the literature, streamlined screening procedures developed in future research should focus on measuring variables correlated to how drivers perform in full-scale driving simulator studies and fMRI studies that employ some form of driving simulation.

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