The influence of cognitive functioning on driving behaviour in older age

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The influence of cognitive functioning on driving behaviour in older age

Abstract

Driving safety is reduced in older age, with cognitive, sensory, and physical decline considered key contributory factors to worse driving performance. Despite this, findings on the association between driving performance and cognitive tests are mixed, and little is known as to how spatial orientation performance relates to driving behaviour. Whilst clinical guidance from the DVLA recommends assessment of cognitive functioning in evaluating driving fitness, there is no uniformly recommended cognitive assessment for driving safety. This thesis therefore aims to establish the impact of cognitive changes – including spatial orientation – on driving behaviour within healthy older adults using a novel online cognitive battery.

There are four experimental chapters addressing this. Chapter 2 establishes the reliability and validity of the NeurOn battery, which validated against the MoCA, a clinical tool for evaluating cognitive impairment. Chapter 3 demonstrates that spatial orientation is a key cognitive component underpinning driving changes in ageing and is associated with driving frequency and driving difficulty – including making turns across oncoming traffic. In Chapter 4, it is shown how geographical settings, specifically living in rural or urban environments, mediates the relationship between cognitive ability and driving mobility and safety. Chapter 5 then explores how GPS technology affects driving behaviour, showing that it mitigates the impact of spatial orientation impairments to improve driving mobility.

Overall, this thesis advances the understanding in how cognitive functioning is associated with driving behaviour in ageing, and how this interacts with geographical settings and in-vehicle technology. These findings improve the understanding of how cognitive screening can be implemented in driving fitness assessments, provide insights into how cognitive impairments might exacerbate driving decline in dementia, and offer a foundation for policy recommendations to improve road safety and mobility for older drivers.

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List of Abbreviations

A	Attention
ACE-R	Addenbrooke's Cognitive Examination
AD	Alzheimer's Disease
ANCOVA	Analysis of Covarience
AO	Allocentric Orientation
CCI	Cognitive Change Index
CDR	Clinical Dementia Rating scale
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CI	Confidence Interval
CNS	Central Nervous System
DHQ	Driving Habits Questionnaire
DON	Driving, Orientating, and Navigating questionnaire
DVLA	Driver and Vehicle Licensing Agency
EF	Executive Functions
EM	Episodic Memory
EO	Egocentric Orientation
GPS	Global Positioning Systems
ICC	Intraclass Correlation Coefficients
IVT	In-Vehicle Technology
LGCM	Latent Growth Curve Modelling
LME	Linear Mixed Effects
M	Mean

MANCOVA	Multivariate Analysis of Covariance
MCI	Mild Cognitive Impairment
MMSE	Mini-Mental State Examination
MM:SS	Minutes: Seconds
MoCA	Montreal Cognitive Assessment
OR	Odds Ratio
PS	Processing Speed
RTI	Road Traffic Incident
ROCF	Rey Osterrieth Complex Figure
RMSEA	Root Mean Square Error of Approximation
SBSOD	Santa Barbara Sense of Direction
SD	Standard Deviation
SEM	Structural Equation Modelling
SES	Socioeconomic Status
SMT	Snellgrove Maze Task
SO	Spatial Orientation
SRMR	Standardised Root Mean Square Residual
TLI	Tucker-Lewis Index
TMT-A	Trail Making Test-A
TMT-B	Trail Making Test-B
UK	United Kingdom
US	United States of America
UFOV	Useful Field of View
VST	Virtual Supermarket Task

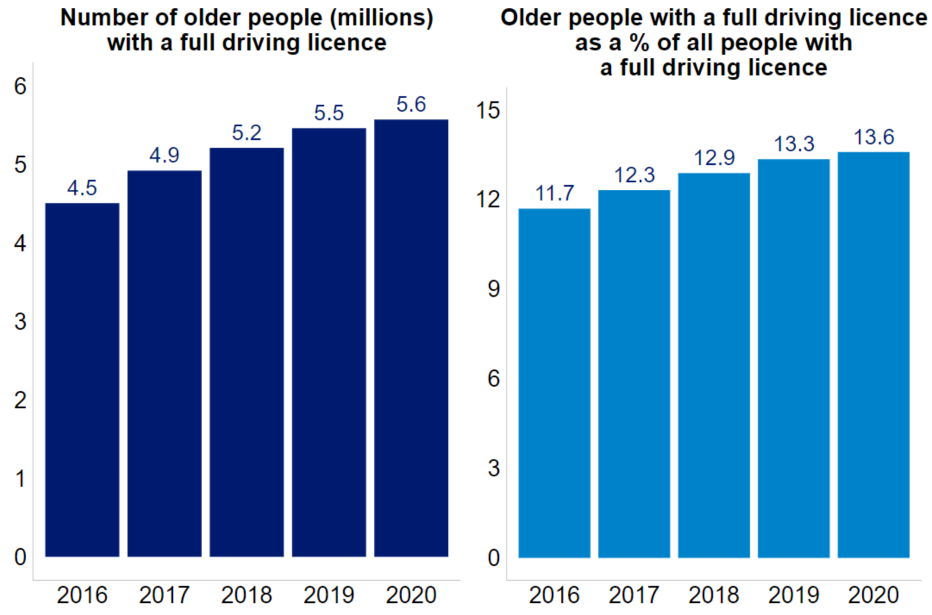
Chapter 1: General Introduction

Importance, impairment, and implications: the challenges facing driving mobility and safety in older age

1.1. Introduction

With the demographic shift of the ageing population and the increasing tendency for older adults continuing to be active drivers, the proportion of older adults maintaining a driver's license is increasing (Coughlin, 2009) (see Figure 1.1). In the UK, 73% of adults over the age of 70 hold a current driving license (UK Department for Transport, 2023), with this number expected to rise due to improved life expectancy and greater reliance on driving in older age. For older adults in particular, driving is paramount for maintaining independence and activity participation within the community. Older adults who drive with greater frequency report higher engagement in social activities and a greater overall wellbeing (Pristavec, 2018; Suntai et al., 2023). Indeed, transportation is recognised as a social determinant of health (Rachele et al., 2017), with the ability to maintain a personal vehicle in older age playing a vital role in helping older adults access resources and social support, including essential services, such as healthcare. Driving remains the preferred method of transportation in older age (Lin & Cui, 2021; Rosenbloom, 2012), and car ownership is highly correlated with independence, wellbeing, and life satisfaction among this population (Gagliardi et al., 2010).

Figure 1.1. Data from the DVLA showing the increase of older adults with a full driving license in the UK between 2016-2020 (reproduced from the UK Department for Transport, 2022).



1.1.2 Changes to driving mobility in older age

Studies assessing driving in older age generally focus on two key aspects: driving safety and driving mobility. Driving safety often encompasses aspects such as road crashes, driving violations, or changes to road performance, whereas driving mobility typically examines driving behaviours such as exposure, mileage, driving space, and engagement with specific driving situations (Edwards et al., 2017). Research investigating the driving status of older drivers demonstrate that a sizeable proportion of older adultsover the age of 80 still drive independently (Hajek & König, 2022). During the ageing process, however, decline in health and cognitive abilities often lead to reduced driving, and eventually most older adults will stop their driving entirely. Indeed, each additional year of age after 65 is associated with a 13% increase in the likelihood of driving cessation (Schouten, Blumenberg, et al., 2022). There are also gender differences in driving cessation, with older women being more likely to reduce driving in older age compared to older men. However, in recent years this effect appears to be waning amongst younger older age cohorts (Schouten, Wachs, et al., 2022).

Driving reduction in older age is a complex and gradual process, and typically begins with limiting travelling to during only daylight hours, avoiding bad weather, making only essential trips, and keeping to familiar routes that are near the home (Ang et al., 2019). It can be challenging for non-drivers to meet their mobility requirements following cessation (Han et al., 2021), and the cessation of driving in older age has been associated with a range of negative life outcomes, with reported detriments in cognitive, physical, mental, and social health (Chihuri et al., 2016). Indeed, reduced driving in older age has been associated with increased brain atrophy (Shimada et al., 2023); worse cognitive trajectories (Choi et al., 2014); increased rates of depression (Chihuri et al., 2016); and reduced quality of life (Pellichero et al., 2021). The process leading to driving cessation is often multifaceted, with health conditions such as visual impairments, neurological conditions, increased frailty, and socioeconomic difficulties being commonly cited as reasons that trigger the decision to cease driving (Edwards, Lunsman, et al., 2009; Emerson et al., 2012; Foley et al., 2000; Freeman et al., 2005; Mielenz et al., 2024; Ragland et al., 2004). It is considered that there is a bidirectional relationship between adverse health outcomes and driving cessation, as ill health is thought to trigger driving cessation, which in turn leads to further adverse health consequences. Maintaining driving mobility in older age is therefore a priority to ensure older adults can age in place with better health outcomes.

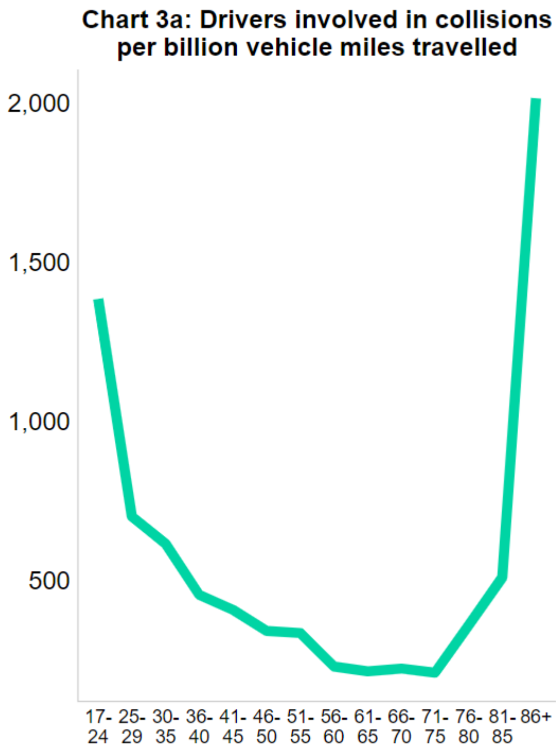
1.1.3 Changes to driving safety in older age

Despite the importance in maintaining driving mobility in older age, it is also considered that older adults have reduced road safety in comparison to the general population. Within driving research, various approaches have been used to measure driving safety in older age. Although the gold-standard approach is on-road assessments with a licensed driving evaluator, this method is often unfeasible within large samples, and on-road assessments have been criticised for low validity and reliability, limiting the ability to generalise findings across older adult populations (Selander et al., 2011). Consequently, a variety of alternative methods to measure driving safety have been used – including driving simulators, objective road traffic history statistics, self-reported driving behaviour and history, and naturalistic driving studies (Babulal et al., 2016; Dickerson et al., 2014; Karthaus & Falkenstein, 2016; Ross et al., 2012; Toups et al., 2022).

Although many older adults continue to drive safely, research indicates that they have an increased risk of road traffic incidents (RTIs) when accounting for the number of miles driven, and that these collisions are more likely to be fatal (Lombardi et al., 2017; Pitta et al., 2021; Rakotonirainy et al., 2012). Government statistics typically show that older adults are over-represented in RTIs compared to other population groups, with data typically showing a

U-shaped curve in RTI prevalence with the youngest and oldest drivers significantly more likely to be involved in road collisions per miles travelled (see Figure 1.2). The risk of RTIs in older age is heightened by the increased physical frailty amongst older adult populations, which is associated with increased injury severity due to a lower tolerance to physical trauma (Thompson et al., 2013). Reduced road safety in older age has influenced policy recommendations internationally, with various countries implementing older age licensing policies requiring older adults to self-renew their driving license at an age threshold to improve road safety (Freed et al., 2023; Shen et al., 2021; Siren & Haustein, 2015).

Figure 1.2. Data showing the U-shaped curve in the number of road collisions across age groups in England, 2020 (reproduced from Department for Transport, 2022).



It is considered that age-related decline in sensorimotor functioning and cognitive performance are the principal cause behind reduced road safety in older age (Anstey & Wood, 2011; Boot et al., 2014; Fraade-Blanar et al., 2018). It is therefore of paramount importance to improve the understanding of how cognitive decline in ageing is associated with changes toward driving behaviour.

1.2 The impact of ageing on cognitive functioning and driving behaviour

Driving a vehicle is a complex and multifaceted task that requires the fluid integration of cognitive, sensory, and physical functions (Simons-Morton & Ehsani, 2016). Throughout the ageing process, however, biological changes impact these mechanisms, affecting driving performance (Karthaus & Falkenstein, 2016). For example, sensory functions such as visual acuity, contrast sensitivity and glare sensitivity decline due to structural changes of the eye during the ageing process (Owsley & McGwin, 2010). Age-related eye diseases such as glaucoma, cataracts, and macular degeneration are common, and strict specific visual are requirements to be met before driving in the UK (Kotecha et al., 2008). Physical and motor functions such as reduced foot sensitivity and neck mobility can affect driving performance, as well as common age-related conditions such as arthritis (Marshall, 2008). These physical limitations can increase the difficulty of performing essential driving tasks, such as using pedals precisely and checking blind spots.

Cognitive abilities are typically divided into several specific cognitive domains that broadly map onto specific brain regions. During the ageing process, neurophysiological changes in brain structure – such as reduced volume and connectivity (e.g. grey matter volume and white matter tract integrity) – lead to decline in cognitive functioning by reducing the efficiency of neural connections. These changes can affect brain areas to varying extents, with the prefrontal cortex and temporal lobes showing the greatest decline in brain volume in older age (Peters, 2006; Raz et al., 2005). There is significant heterogeneity in how and when cognitive decline emerges within the ageing process, which is influenced by various genetic, lifestyle, cognitive reserve, and social engagement factors (Hayden et al., 2011; Hsu & Bai, 2022; Salthouse, 2019). Most cognitive abilities are relatively preserved until one reaches their 60s, at which point more pronounced decline begins to emerge (Rönnlund et al., 2005; Salthouse, 2009). Sufficient cognitive performance is necessary for decision-making, responding to road challenges, and performing driving manoeuvres.

Although driving in older age is a well-learned skill, with older drivers often being more experienced drivers than other population groups, deficits in these cognitive processes during ageing impair driving performance. Indeed, cognitive functioning is crucial for driving performance and is considered the most significant factor leading to reduced road safety in older age (Fraade-Blanar et al., 2018). However, despite considerable efforts and an extensive literature base, significant gaps remain in understanding how cognitive decline in ageing affects driving behaviour. This is largely due to methodological variability in the assessment of cognition and driving performance, making it difficult to determine the extent to which specific cognitive functions impact different aspects of driving performance. This is reflected within driving guidelines in the UK, as the DVLA (Driver and Vehicle Licensing Agency) legally requires that specific sensory and physical health conditions are reported and evaluated by medical professionals to maintain driving safety, but acknowledge there is a grey area for assessing fitness to drive in conditions involving cognitive impairment – such as mild cognitive impairment (MCI) and dementia (DVLA, 2024).

1.3 Which cognitive domains have been implicated in driving performance?

All cognitive domains assessed in relation to driving behaviour have been associated with driving performance to some degree, with a consistent pattern showing that better cognitive performance is associated with more skilled driving. The majority of studies have looked at global cognition in relation to driving ability (Depestele et al., 2020), and therefore it has been difficult to evaluate which domains are most significantly related to driving. Among the individual domains associated with impaired driving, executive functioning, processing speed, attention, and visuospatial skills have more consistently been related to driving performance in older age (Anstey & Wood, 2011; Bélanger et al., 2015; Clay et al., 2005; Depestele et al., 2020; Emerson et al., 2012; Hird et al., 2016; Mathias & Lucas, 2009; Stefanidis et al., 2023). Understanding how driving relates to specific cognitive functions is important in establishing preventative measures to mitigate the impact of age-related cognitive decline on driving performance.

1.3.1 Executive functioning

Executive functioning, corresponding primarily to frontal brain areas such as the prefrontal cortex, involves cognitive flexibility and the organisation of low-level cognitive processes to successfully engage in independent, purposeful behaviour (Chan et al., 2008; Lezak et al., 2012). Executive functioning is closely related to driving, as both require the integration of both lower and higher-order processes while controlling inhibitory processes, such as minimising distraction. When driving, executive functioning is important for multitasking, such as the monitoring of mirrors, changing gears, and following directions. Executive functioning tests have therefore been popularly employed as a cognitive domain with high ecological validity to driving.

A multitude of studies have been conducted using different executive functioning tests on driving performance within differing population groups – ranging from younger older adults to clinical populations (Ghawami et al., 2022). Within older adult populations, worse executive functioning performance has been found to be associated with worse performance during on-road assessments, increased risk of RTIs, observation errors, driving errors in lane position, and overall driving performance (see Adrian et al., 2019; Asimakopulos et al., 2012; Peng et al., 2022). Indeed, further support from brain imaging studies have found that event-related potentials within frontal lobe brain regions relevant for executive functioning have been associated with driving performance (Rupp et al., 2019). Other studies have reported mixed outcomings relating executive functions with driving behaviour (Aksan et al., 2015; Bennett et al., 2016), which can be attributed to methodological variability in how both executive functions and driving behaviour have been measured.

Although a variety of executive functioning tests have been used in the literature, the Trail Making Test-B (TMT-B) has been identified as a sensitive screening tool for assessing driving safety and is frequently used within clinical evaluations for identification of cognitively impaired at-risk drivers (Dobbs & Shergill, 2013; Papandonatos et al., 2015). The TMT-B task provides two measures: completion time and error rate. In driving research, completion time is more regularly used as error rate is considered to be less related to driving performance (Duncanson et al., 2018). Longer time to complete the TMT-B has been associated with worse driving performance, such as reduced ability to stay in the centre of the lane when driving (Aksan et al., 2017). Although normative data exists for the TMT-B, research studies developing optimal cutoff scores for driving performances, with recommended cutoffs ranging from 90 seconds (Hargrave et al., 2012) to 180 seconds (Betz & Fisher, 2009). Furthermore, there is limited predictive utility of cutoff scores for identifying at-risk drivers among older adults (Roy & Molnar, 2013).

1.3.2 Processing speed

Processing speed involves the ability to perform cognitive tasks quickly and efficiently – integrating the perception, interpretation, and responding to information. Although age-related changes to processing speed in ageing is considered to be resultant of neurophysiological changes to a range of neural networks, frontal and cerebellar patterns of gray and white matter atrophy have been previously related to reduced processing speed (Eckert et al., 2010). Due to the importance of processing speed in facilitating other cognitive faculties, decline in processing speed performance has been implicated as a significant hypothesis for age-related cognitive decline in ageing populations (Salthouse, 1996).

Alongside executive functions, processing speed has been postulated as one of the strongest correlates to driving skills in ageing. When driving, processing speed is important for quick interpretation of information and reacting to external stimuli, such as traffic lights, signs, vehicles, and pedestrians. During the ageing process, a natural decline in processing speed can significantly impact the ability to manage the changing demands of driving (Ross et al., 2016). This decline may result in delayed reaction time, difficulty in decision-making, and challenges in adapting changes in the environment. Slower processing speed in older age has therefore been associated with greater RTI risk in older drivers (Bélanger et al., 2015) as well as increased risk of future driving cessation (Edwards et al., 2010).

The Trail Making Test-A (TMT-A), considered to be a precise measure for visual processing speed (Vaucher et al., 2014), and has commonly been used to assess processing speed in relation to driving performance. Numerous studies have provided time cutoffs for evaluating safe and unsafe driving (Bédard et al., 2008; Duncanson et al., 2018; Papandonatos et al., 2015; Vaucher et al., 2014), although similarly to the TMT-B, these proposed cutoffs also demonstrate considerable variability (e.g. 53 seconds (Vaucher et al., 2014) - 38 seconds (Bédard et al., 2008).

1.3.3 Attention

Attention involves three main components: selective attention – the ability to selectively focus on specific stimuli whilst ignoring others; sustained attention – the ability to sustain concentration over time; and divided attention – the ability to focus on multiple stimuli simultaneously when necessary (McAvinue et al., 2012). Attention is therefore highly involved in executive functioning and strongly associated with processing speed, where age-related slowing is considered to be prominently due to declining attentional processes after 60 years of age (Godefroy et al., 2010; Harada et al., 2013). Attention has clear relevance to driving, as it is necessary for maintaining focus on the road whilst maintaining awareness of other surroundings, such as traffic signals. Issues with maintaining attention whilst driving can be caused by failure of the driver to attend to appropriate stimuli, as well as failing to ignore irrelevant stimuli (Trick et al., 2004).

Studies assessing how attention relates to driving have found that better attention performance is associated with lower RTI risk, safer driving speed and steering control, better road anticipation, and better vehicle positioning (Andrews & Westerman, 2012; Bélanger et al., 2015; Park et al., 2011; Stinchcombe et al., 2011). Moreover, as well as driving safety, recent research has shown that better attentional control is associated with greater driving mobility in older age, including more driving trips and a greater driving space (Aschenbrenner et al., 2022). At the neural level, impaired driving performance associated with worse attention in older adults has been associated with reduced activation in frontoparietal regions and connectivity in the default mode network compared to healthy younger adults (Eudave et al., 2018).

A range of cognitive tests have been used to assess different aspects of attention in how they relate to driving. As well as being utilised as a measure for processing speed and executive functioning performance, TMT-A & TMT-B have also commonly been used as a measure of selective attention and attentional set-shifting in driving research, respectively (Dawson et al., 2010; Depestele et al., 2020). Furthermore, The Useful Field of View (UFOV) task, a computer administered test measuring different components of visual attention, has been widely cited within the literature and has been consistently related to at-fault RTI involvement in retrospective and prospective crash statistics (Clay et al., 2005; Wood & Owsley, 2014). The UFOV has also shown consistent results in clinical populations, including individuals with early Alzheimer's disease (AD) (Krasniuk et al., 2023).

1.3.4 Visuospatial ability

Visuospatial ability involves the perception, processing and interpretation of visual information in an environment (Aul et al., 2023). Whilst relying on visual acuity for raw sensory data in perception, visuospatial functioning is a higher order cognitive process that involves the perception of visual information independently of visual acuity (Owsley, 2013). Within the ageing brain, visuospatial functioning is impacted by not only sensory changes to the eye that impact the quality of information provided to the brain, but also by structural changes within the brain such as reduced brain volume in frontoparietal regions (Alichniewicz et al., 2012; Hromas & Bauer, 2019). Visuospatial processing is a core cognitive function underlying the performance of other aforementioned cognitive functions mentioned above, in particularly executive functioning (Mewborn et al., 2015).

Within the context of driving, visuospatial functioning is vital for aspects such as determining lane positioning and anticipating movements from road-based stimuli. Indeed, impairments to visuospatial functioning has been found to be strongly related to worse performance in on-road assessments, greater risk of RTIs, and less safe driving performance (Dawson et al., 2010; Ledger et al., 2019; Mathias & Lucas, 2009; Michaels et al., 2017).

Visuospatial functioning tests typically require the subject to analyse a visual stimulus and act upon it, with some tests examining visuomotor processing speed (assessing how fast people can analyse and act upon information) and others requiring only accuracy with no time demands. Tests evaluating visuospatial functioning, such as the Rey Osterrieth Complex Figure Test (ROCF) (Shin et al., 2006), typically incorporate one or both of these aspects, with both aspects being associated with driving impairments in older age – inferring that both visuomotor speed and precision are important for driving performance (Dawson et al., 2010).

1.3.5 Summary

Overall, executive functioning, processing speed, attention, and visuospatial functioning are critical cognitive abilities frequently assessed in relation to driving performance (Depestele et al., 2020). These functions are closely linked to specific driving behaviours and have also been implicated in reduced driving safety in older age. The involvement of these cognitive domains within driving research is largely due to a-priori hypothesis that the theoretical basis underlying these cognitive domains will be relevant to driving performance. Other key domains relevant to ageing, such as memory, have been less implicated in relation to driving (Mathias & Lucas, 2009). Additionally, other cognitive domains highly relevant to driving performance have yet to be thoroughly explored within the literature.

1.3.6 Lost from the driving literature: where is spatial orientation?

Spatial orientation is a mental ability which enables us to transform, represent, generate and recall spatial information such as size, shape, distance, location, and direction (Linn & Petersen, 1985). From a neuroanatomical perspective, spatial orientation is guided by the usage of self-motion cues (motor, vestibular, proprioceptive) and environmental cues (landmarks, environmental boundaries) to determine one's orientation within the surrounding environment. These cues provide the foundations of two distinct yet complementary spatial orientation strategies: allocentric and egocentric orientation. Allocentric orientation, primarily processed within the medial temporal lobe, involves the processing of object-to-object representations in space. Egocentric orientation, primarily processed within the parietal cortex and subcortical regions, involves the representation of objects relative to one's own position (Burgess, 2008; Coughlan et al., 2018).

Spatial orientation has clear relevance to driving, as one must first plan a route to a location – involving the knowledge of spatial locations in relation to one another. Secondly, when orienting a vehicle, the driver must be aware of their positioning in relation to the surrounding road environment, which requires dynamic updating as the vehicle moves. Allocentric and egocentric perspectives are fundamental in contributing to the successful performance of these tasks. However, since research has not yet been conducted on how these spatial representations are utilised in driving behaviour, how they are implicated within driving behaviour remains to be theoretical. When considering how these processes may be implicated in driving, egocentric orientation may be employed when drivers focus on their own position relative to other objects in the immediate environment, such as other vehicles and lane markings. This orientation perspective enables drivers to make judgements during manoeuvres, such as merging lanes or parking, by continuously updating their perception of the distance and direction of other road stimuli relative to their own position. Allocentric orientation, in contrast, may involve a more global perspective, enabling the driver to conceptualise their broader environment – such as the spatial road layout and the spatial relationships between road objects. This may help drivers to anticipate upcoming turns, plan routes in the event of detours (such as during road closures), and navigate complex routes by mentally mapping their position within the greater environment.

Worse spatial orientation ability can potentially impact a multitude of road situations, such as judging the distance of the vehicle from other road objects, anticipating turns, and maintaining correct lane positioning. It is therefore surprising that very little research to date has examined the role of spatial orientation in relation to driving behaviour in older age, particularly when considering that self-reported navigation difficulties are the most commonly identified obstacle for older drivers (Vrkljan & Polgar, 2007).

This oversight is particularly notable when considering the role of spatial orientation performance as a key indicator for cognitive trajectories in older life. Throughout the ageing process, shrinkage within the medial temporal lobe and reduced hippocampal integrity corresponds with both self-reported and observed deterioration in spatial orientation performance amongst older adults (Burns, 1999; Moffat, 2009). Additionally, spatial orientation is an early cognitive marker for the trajectory toward neurodegenerative disease, as impaired spatial orientation performance is present within preclinical dementia and is exacerbated along the spectrum of cognitive impairment between mild cognitive impairment (MCI) and AD (Allison et al., 2016; Coughlan et al., 2018). Concurrently, higher CNS amyloid levels, an indicator of AD pathology prior to clinical diagnosis, have been associated with worse road test performances across both objective and self-reported measures (see Bayat & Roe, 2022). Amongst MCI and AD populations, a systematic review found that driving ability in these populations is related to the degree of cognitive impairment (Hird et al., 2016). Additionally, longitudinal studies within AD have shown that driving safety reduces corresponding to advancing disease stages, where greater cognitive impairments are present (Duchek et al., 2003; Eby & Molnar, 2012; Ott et al., 2008).

Given the associative triangular relationship between spatial orientation performance, neurodegenerative disease, and reduced driving safety, investigating how spatial orientation relates with driving behaviour in healthy ageing may provide a vital understanding into reduced road safety in both healthy older adults and cognitively impaired populations.

1.3.7 Cognitive screening assessments for driving fitness

With cognitive changes being associated with reduced driving safety in older age, screening for at-risk drivers is of key importance for individuals, families, medical professionals, policymakers, and wider society. Consequently, there is increasing emphasis on establishing sensitive cognitive screening tests for healthcare and driving assessment professionals to carry out in establishing at-risk drivers. By quick examination of cognitive components that are associated with driving specific skills, screening assessments can potentially identify for which individuals may require further driving evaluations compared to those who are likely safe drivers (Korner-Bitensky et al., 2005). Indeed, clinicians often administer cognitive screening tests to assess whether an individual is cognitively fit to drive, with the majority of cognitive tests involving the tools for evaluating general cognitive status, typically used for diagnostic purposes of MCI or dementia. The Clinical Dementia Rating scale (CDR), Mini-Mental State Examination (MMSE), Montreal Cognitive Assessment (MoCA), & Addenbrooke's Cognitive Examination (ACE) have all been assessed in relation to impaired driving performance in older age and cognitive impairment (Bennett et al., 2016; Ferreira et al., 2012; Kokkinakis et al., 2021; Mathias & Lucas, 2009; Pauldurai & Gudlavalleti, 2023; Reger et al., 2004; Wagner et al., 2011). However, the use of global cognitive evaluation tools are limited, as these tests are designed to diagnose cognitive impairments and are not tailored for specific cognitive abilities relating to driving performance. The association between global cognitive test battery performance and driving outcomes is weak (Karthaus & Falkenstein, 2016; Kwok et al., 2015; Molnar et al., 2006), with reduced sensitivity for identifying driving errors within healthy populations.

As previously discussed, individual neuropsychological tests have also been used to establish how individual cognitive domains are related to driving behaviour. However, studies establishing how neuropsychological tests relate to driving performance are limited by referral bias, small sample sizes, and the need for replication at other sites (Carr et al., 2019).

Given the wide range of cognitive functions implicated in successful driving, it is considered that grouping neuropsychological relevant to driving into a composite battery provides the most valid approach to determine driving safety (Bennett et al., 2016). A screening battery has yet to be developed to sensitively assess at-risk driving in older age (Bédard et al., 2008; Castellucci et al., 2020; Dickerson & Bédard, 2014), with validation in larger sample sizes and other clinical settings required to assess the generalisability of results (Carr et al., 2019).

Additionally, the majority of research assessing cognitive impairments in relation to driving performance have assessed cognitively normal adults in comparison to clinical groups, such as MCI and dementia populations (Apolinario et al., 2009; Hird et al., 2016; Ott et al., 2008; Uc et al., 2017). Whilst these studies are valuable in establishing how driving safety differs across varying level of cognitive impairment, these studies may not enable for identifying subtle cognitive changes that take place in typical ageing that can help establish the 'warning signs' for at-risk driving within cognitive impairment. As previously discussed, cognitive functioning in older age is heterogeneous, and therefore research is necessary within this population group to establish cognitive domains that reliably correlate with driving behaviour. Focusing on cognitively healthy populations may allow for earlier detection of at-risk driving prior to cognitive impairment, providing the opportunity for intervention that can improve driving safety within older adult populations.

It is also important to monitor how longitudinal changes in cognition relate to driving behaviour, as this can reveal valuable insights encompassing individual and group variability into cognitive trajectories and their impact on driving performance over time. These studies can inform whether driving-related cognitive abilities should be regularly assessed, as well as the appropriate timing for follow-up evaluations. Longitudinal studies involving healthy older adults are limited. These studies suggest that changes in driving safety over time are generally small in this population, with driving-related cognitive decline emerging more gradually than in clinical populations (Aksan et al., 2012; Balzarotti et al., 2022). Furthermore, it has not yet been made clear how intrinsic (person-centred) differences in ageing are influenced by extrinsic (environment-centred) differences.

1.4 The influence of geographical setting on driving behaviour and safety

The region in which people live has a significant impact on the importance of driving to help meet their mobility needs and continue activities within their community. In recent years, there has been increasing focus on the consequences of urban-rural migration of older adults in the UK, with the most recent annual report from the Chief Medical Officer highlighting that these demographic shifts pose unique challenges for transportation and mobility within rural and coastal areas that require urgent understanding to ensure older adult needs are met (Whitty, 2023).

As mentioned earlier in this chapter, maintaining driving mobility in older age is vital for one's independence and engagement with their local community. This is pronounced for individuals living in rural settings, where reduced public transportation access and greater distances to amenities leads to greater dependence on personal vehicles for completing daily activities and social engagements (Arcury et al., 2005; Hamano et al., 2016). Within the UK, the majority of older adults live in rural areas (Office for National Statistics, 2024). In rural areas, public transportation has been found to be largely unavailable, unreliable, or deficient (Jo et al., 2021), and consequently individuals living in rural areas depend substantially more on personal vehicle transportation as their only method of transportation compared to those who live in cities or small towns (Ritter et al., 2002). It is therefore of little surprise that driving is considered more important to individuals living within rural areas (Strogatz et al., 2020), who typically report travelling further distances than urban residents (Payyanadan et al., 2018; Pucher & Renne, 2005).

Additionally, features of the urban road environment may contribute to reduced driving in urban areas. Older adults experience increased anxiety within congested areas and speeding traffic (Hakamies-Blomqvist & Wahlström, 1998), and a positive relationship has been established between reduced driving mobility in areas of increased roadway density and congestion (Vivoda et al., 2017). It is possible that within urban areas that the increased reduction in driving is also in part influenced by the increase in alternative transportation options, as urban areas have a greater prevalence of public transportation options and have more capable infrastructure for pedestrian mobility with typically shorter distances to amenities.

Rural and urban settings do not only impact driving mobility but also present unique risks for driving safety, particularly for older adults. Despite the greater reliance of driving in rural areas, studies show that there is a greater risk of fatalities on rural roads. US-based studies have shown that older adults are over two-times more likely to have fatal road traffic incidents on rural roads than urban roads (Zwerling et al., 2005). Similarly, UK government statistics show that although urban roads amount in a greater likelihood of RTIs, largely because of a more dynamic road traffic environment, rural roads are a greater risk for fatal RTIs (Department for Transport, 2023). This is due to less safe aspects of the road environment in rural areas, including narrow roads and higher road speed limits (Payyanadan et al., 2018; Thompson et al., 2013), which elevate the potential severity of RTIs.

The increased risk of fatal RTIs within rural areas may also be influenced by how the heightened dependency on personal driving affects individuals with cognitive impairments. In rural settings, drivers with cognitive impairment may struggle more with effectively self-regulating their driving compared to urban residents due to this increased dependency, leading to a potentially higher risk of fatal RTIs (Byles & Gallienne, 2012; Hanson & Hildebrand, 2011).

Whilst existing research has explored how physical impairments impact driving mobility across rural and urban environments, showing that measures of physical functioning were more predictive of driving behaviour in larger urban cities (Anstey et al., 2005; O'Connor et al., 2012), there remains a significant research gap regarding cognitive functioning. To date, there has been limited investigation into how cognitive impairments influence driving mobility and safety across rural and urban settings. Research addressing this gap could provide important insights into whether targeted interventions may be required to mitigate the driving safety and mobility challenges within rural and urban settings.

1.5 Can technology improve mobility and safety amongst older drivers?

So far, this chapter has explored how cognitive impairments in older age are associated with reduced driving mobility and road safety risks. It is therefore of great interest to establish approaches that can address age-related cognitive changes and mitigate decline in driving performance to improve comfortability and driving performance of older adults. Recent advances in the development of in-vehicle technology systems (IVT) offer promising solutions to enhance driving mobility and comfort for older adults. IVT, such as blind spot and lane departure warnings, parking sensors, and automatic emergency braking, may offer potential solutions to specific challenges older drivers may face on the road, improving driving safety (Eby et al., 2016).

In addressing previously discussed physical limitations, blind spot cameras may be useful for older adults with reduced neck mobility, while automatic braking systems may assist population groups who have reduced foot sensitivity. In addressing cognitive impairments, IVT can reduce the cognitive workload involved in driving by making it easier to perform driving behaviours (Classen et al., 2019). One example is in the use of global positioning system (GPS) technologies to assist in wayfinding. Wayfinding during driving utilises significant cognitive resources, which can divert resources from the primary task of maintaining safe driving performance. As discussed earlier in this chapter, spatial orientation is typically impaired during ageing, which may significantly increase the resources required to navigate successfully. GPS technologies may mitigate age-related impairments in spatial orientation to assist in maintaining driving mobility. Previous studies have shown that older adults with worse cognitive performance have greater difficulty wayfinding on unfamiliar routes (Bryden et al., 2013), and a subjective poor sense of direction has been associated with constricted driving space among older drivers (Turano et al., 2009). Older drivers with worse subjective spatial abilities may therefore limit their driving to familiar and less complex routes, reducing their overall mobility and independence. GPS technologies may therefore be beneficial to these populations by providing a navigational aid that can help older adults navigate both familiar and unfamiliar routes with greater confidence.

Compared to other population groups, older adults typically have low technology adoption rates (Coughlin, 2009). This trend is influenced by cohort effects, whereby oldest generations are less likely to use technological driving advancements that are more commonly adopted by younger cohorts (Chiu et al., 2016). However, the majority of older adults over the age of 65 own a smartphone and use the internet, and new populations of older adults will be increasingly familiar with technology usage (Hunsaker & Hargittai, 2018). Consequently, increasingly familiarity with technology may potentially lead to greater adoption of in-vehicle assistive technologies. Indeed, a systematic review on the use and benefits of in-vehicular technologies amongst older drivers demonstrated that older adults commonly employ IVT and perceive them to be assistive to their driving performance (Eby et al., 2016).

Despite the potential benefits, little is known regarding how IVT can mitigate age-related impairments to improve driving performance in older age. A scoping review on advanced technologies and road safety find that many studies do not specify the demographics of the drivers being tested (see Furlan et al., 2020). Furthermore, scoping and systematic reviews have shown that literature assessing the impacts of IVT on driving in older age has focused upon improvements upon driving safety (see (Classen et al., 2019; Eby et al., 2016; Furlan et al., 2020)), with little understanding on driving mobility. In understanding how IVT can be used to mitigate age-related changes driving performance in older drivers, it is crucial to improve the understanding in how IVT use relates to cognitive functioning in older age.

1.6 Conclusion

With the demographic shift of the ageing population, many developed countries will see a significant shift in the increased proportion of drivers of the age of 65 on the road in future years. Policymakers will therefore face a challenging predicament on the balance between maintaining driving mobility in older adults while ensuring road safety for older individuals as well as wider society. Consequently, it is becoming increasingly urgent to establish how cognitive changes in ageing relate to driving performance to establish sensitive fitness to drive evaluations.

To date, literature assessing the association between cognitive performance and driving behaviour has been limited by use of small sample sizes, referral bias, variable methodology in cognitive tests and driving measures, alongside little validation in the usage of cognitive batteries. Additionally, the majority of research conducted thus far has been cross-sectional in nature, capturing only a single timepoint of cognition in relation to driving behaviour. While these studies have value in furthering the understanding in how population level characteristics are associated with driving behaviour, cognitive performance and driving behaviour are variable across the population and are influenced by a myriad of social, medical, and environmental factors. Longitudinal approaches in large samples are necessary to establish trajectories in cognitive functioning and driving performance, improving the limited understanding in how cognitive faculties relate to driving performance over time in ageing, and enabling the identification of critical periods for intervention.

As discussed throughout the chapter, it is unclear how environmental settings and IVT influence the interaction between cognitive performance on driving behaviour. There is also a gap in the literature in establishing how spatial orientation performance, which is significantly relevant to both age-related cognitive decline and driving abilities, is associated with driving behaviour in older age. Addressing these limitations will significantly advance the understanding of how cognitive functioning in older age relates to driving behaviour, advancing the potential for the development of interventions and support programs to improve both mobility for older adults and road safety for the general population.

1.7 Thesis Aims and Objectives

The principal aim of this thesis is to investigate how cognitive functioning impacts driving behaviour amongst healthy older adults. Specifically, the aims of the project are to:

- Establish the validity and reliability of NeurOn, a novel cognitive battery for driving assessments (Chapter 2)
- Understand how cognitive functioning, and in particular spatial orientation, impacts driving frequency, space, and difficulty in healthy older adults (Chapter 3)
- Examine how environmental settings interact with age-related cognitive changes to impact driving behaviour and road safety over time (Chapter 4)
- Investigate how older adults use GPS technology and whether its usage is associated with cognitive functioning and driving mobility (Chapter 5)

A consolidation of the thesis and the discussion of the experimental chapters will be presented in the closing chapter – the general discussion (Chapter 6). Each experimental chapter will include a set of specific hypotheses. The overarching hypotheses of this research thesis are:

- NeurOn, the novel online cognitive battery, will demonstrate reliability and validity with gold-standard, traditional cognitive tests.
- Spatial orientation will be a sensitive cognitive marker for driving behaviour in ageing.
- The relationship between cognitive performance and driving behaviour will vary across rural and urban environments. Cognitive impairments may have a lesser influence on driving mobility in rural areas compared to urban areas, as limited transportation alternatives in rural areas increases the dependency on driving.
- Older drivers with worse cognitive functioning who use GPS technology will show better driving mobility than those who do not use IVT.

1.8 Summary of statistical methods

In addressing the above aims and objectives within this thesis, a variety of analytical approaches will be employed. Below, I will briefly address the key analytical approaches for answering the key research aims of this thesis.

In Chapter 2, establishing the validity and reliability of the novel NeurOn battery utilised throughout this thesis, correlation analysis will assess the construct validity in how individual cognitive test performance within the NeurOn battery relates to performance in traditional pencil and paper based cognitive tests measuring the same constructs. Two-way mixed effects intraclass correlation coefficients (ICCs) and paired sample t-tests will examine the test-retest reliability of cognitive tasks within the NeurOn battery.

In Chapter 3, structural equation modelling (SEM) will be employed to derive the relationship between specific driving behaviours with different cognitive domains, including spatial orientation. SEM has been commonly utilised within neuroscience and driving behaviour separately – with previous studies employing SEM to investigate how driving characteristics, alcohol usage, and disease severity influence driving behaviour (Zhao et al., 2019; Kumar Yadav & Velaga, 2019; Dong, Xie, & Yang, 2022). However, to current knowledge, research studies have not yet utilised SEM in establishing how driving behaviour relates to cognitive functioning.

SEM involves two main components: a measurement model and structural model. The measurement model consists of a confirmatory factor analysis (CFA) assessing how well observed variables constitute conceptually derived latent variables. This measurement model is particularly advantageous when assessing driving behaviour, as latent variables can be developed through grouping observed variables that measure a similar domain (i.e. driving space can consist of the distance one traverses during their trips, as well as the crossing of geographical boundaries, such as different regions, when driving). The second part of SEM – the structural model – assesses the relationship between the model variables, consisting of latent, observed, independent and dependent variables. Path diagrams can then be utilised to demonstrate the causal direct and indirect effects between variables.

Utilising this approach, SEM can consider complex relationships between multiple dependent and independent variables. It is also advantageous to use SEM when considering the relationship between driving and cognition, as this enables for comparison in the strength of the relationship between different cognitive domains and latent driving variables. When considering the mixed findings in the relationship between driving behaviour and cognitive functioning, as well as the limited understanding as to how spatial orientation compares with other cognitive functioning in impacting driving behaviour, SEM is a valuable tool to address these research gaps.

In Chapter 4, linear mixed effect modelling (LME) will be employed to assess whether living in rural or urban environments influences driving mobility over time. Within the driving literature, LME has previously been utilised for establishing how driving performance changes within specific environments using repeated measures (El Mendelek et al., 2023), longitudinal changes in driving mobility across race and ethnicity (Babulal et al., 2019) and assessing how driving performance changes within preclinical AD (Roe et al., 2019). LME is advantageous as it enables the measurement of repeated measures over time as it can capture both between-group variability and within-group variability while controlling for fixed-effect factors. A random intercept term to capture within-group variability is particularly valuable in driving research, as individuals within specific populations (e.g. rural or urban locations) will have variation in their level of driving mobility due to individual differences and other factors. Furthermore, by including age as a covariate within the model, this enables for the measurement in how rural and urban locations influence driving mobility over time while reducing the influence of a known impact on driving mobility, which may conflate results and muddy interpretation.

Within Chapter 5, multiple linear regression modelling will be used to establish the relationship between GPS usage frequency with demographic factors and cognitive performance. Analysis of Covariances (ANCOVA) analyses will be utilised to establish how GPS situational context usage is associated with cognitive functioning, as well as how cognitive differences affect driving mobility across GPS usage groups.

Chapter 2: Feasibility and reliability of online vs in-person cognitive testing in healthy older people

Published paper

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2.1 Introduction

As discussed in Chapter 1, neurophysiological changes within the brain during the ageing process typically result in a decline in cognitive functioning (Boyle et al., 2021; Salthouse, 2009). Neuropsychological testing is therefore required to measure changes in cognitive functioning (Ashford et al., 2022; Gates & Kochan, 2015). Nonetheless, routine cognitive assessments in healthy ageing are rarely conducted and rely upon quick to administer paper-based tests (Alzheimer's Association, 2019). The current gold-standard tests for assessing cognitive impairment, such as the MMSE, were developed to screen for dementia, but are less sensitive in identifying milder cognitive impairment (Rentz et al., 2013; Scott & Mayo, 2018). Furthermore, clinic assessments involving paper-based tests are limited as they are prone to practice effects (Goldberg et al., 2015) and cognitive changes may be masked by fluctuations in cognitive performance or differences in cognitive reserve (Soldan et al., 2018).

In recent years, significant developments in online cognitive testing have increased its usage in both research and clinical environments (Bauer et al., 2012). Notably, online assessments can be performed remotely to improve accessibility and frequency of online cognitive testing, enabling the identification of more subtle changes in cognitive decline (Öhman et al., 2021; Sliwinski et al., 2018). Digital assessments also provide enhanced precision in data measurement, standardised presentation, pseudorandomisation to reduce practice effects, and greater cost-efficiency (Bauer et al., 2012; Miller & Barr, 2017). Most computerised testing to date has focussed upon processing speed and attention tasks, with many demonstrating promising results (Domen et al., 2019; Feenstra et al., 2016, 2017). A recent systematic review found early evidence suggesting that computerised cognitive testing shows potential clinical utility in diagnosing neurocognitive disorders, but there has been limited validation work in cognitive batteries to date (Tsoy et al., 2021).

Validation of cognitive batteries is necessary to establish whether they are feasible for clinical applications, such as conducting screening assessments for at-risk driving. Studies assessing the relationship between digitalised and traditional paper-based neuropsychological tests have yielded mixed results, with some studies show considerable agreement (Parsey & Schmitter-Edgecombe, 2013; Williams & McCord, 2006) while others show little agreement (Carpenter & Alloway, 2018; Feenstra et al., 2016). Additionally, the test-retest reliability of performance on these digital tests is not yet well-established.

NeurOn, a recently developed novel cognitive battery (https://neuropsychology.online/), can assess cognitive performance remotely as the cognitive tasks are hosted online. NeurOn is a comprehensive cognitive battery testing a variety of cognitive domains and critically also assesses spatial orientation ability, which as discussed in Chapter 1, has been virtually unexplored in relation to driving performance and is also a key cognitive marker for preclinical dementia (Coughlan et al., 2018).

The currently study evaluates the psychometric properties of the NeurOn battery by measuring the reliability and validity in both supervised in-person and unsupervised online settings against established traditional neuropsychological assessments. It is hypothesised that online cognitive tasks will demonstrate test-retest reliability over a one-week period; online/remote cognitive tasks will demonstrate concurrent validity with in-person/traditional cognitive task equivalents; and cognitive performance in the neuropsychological battery will validate against established clinical tests in measuring cognitive performance.

2.2 Methods

2.21 Participants

Thirty-three older adults (65+) were recruited from the community via online and offline advertisements to take part in the study. All participants were pre-screened to assess whether they were cognitively and physically healthy; had any history of psychiatric or neurological disease; history of substance abuse disorder; drive once per week or more; and whether they had previously taken part in a study using the online cognitive platform. Recruitment and testing of participants took place between 1st October 2022 and 30th March 2023. Written informed consent was obtained from each participant and data was attributed anonymously. Ethical approval for the study was provided by the Faculty of Medicine and Health Sciences Research Ethics Committee at the University of East Anglia (FMH2019/20-134).

To ensure adequate statistical power, a power analysis was conducted for evaluating the test-retest reliability and concurrent validity of the cognitive testing battery. A total sample size of 32 (degrees of freedom = 31) was determined for the test-retest reliability analysis, using a matched paired t-test, with a power of 0.95 and a critical t score of 1.70. The analysis was powered at a 0.95 alpha error probability, assuming a moderate effect size of 0.6.

This sample size was deemed sufficient for also powering the analysis of concurrent validity, assuming a large effect size of 0.50, an alpha error of 0.05, a power of 0.94, and a critical t score of 1.70.

2.22 Procedure

Screening was carried out via online video call (32) and telephone (1) by the study team prior to baseline cognitive assessment. One participant was excluded from the study as they only completed one testing session due to illness, and therefore 32 participants were retained for analysis (mean age: 70.19). Participants were randomised in the order in which they completed testing sessions. Prior to the baseline appointment, participants were asked with which device they would most comfortably complete the remote assessment appointment (desktop, laptop, tablet) and the device was matched for the in-person testing appointment. Both testing sessions started with completion of questionnaires pertaining to demographics, subjective cognition, and driving history. Each participant completed the follow-up testing session one week from the baseline testing session at the same time as their previous session.

2.23 Development of the online cognitive testing platform

Questionnaires and cognitive tasks were hosted on NeurOn – an online platform. The novel cognitive battery was developed by a professional programmer alongside the project team. Online neuropsychological tests were based on a combination of established, traditional neuropsychological tests and innovative tasks (Virtual Supermarket Task) and were developed for unsupervised assessment. Tests were designed to be completed in unmonitored conditions. Tasks were accompanied with written instructions and video tutorials with a voice-over (except for the Go-No/Go test) prior to test completion to promote multimodal learning. After receiving instructions, practice sessions for each task followed to ensure participants were prepared for the actual test. Participants were encouraged to complete the main test battery in one session without breaks but were advised to take a break prior to the VST due it having a significantly longer duration and greater task difficulty. If the cognitive test battery was interrupted (i.e. by participants taking a break/ internet disconnection), participants resumed the task from their current progress upon logging back in. All tasks were pseudorandomised to enable for repeated testing. All participant input was saved on a protected server throughout each test element.

Online cognitive tasks

The NeurOn battery consisted of a variety of digitalised tasks that measure cognition across a variety of domains that are sensitive to age-related cognitive impairment. A Reaction Time task, whereby participants responded as quickly as possible to a repeating on-screen stimulus, measured visuomotor speed (milliseconds). Trail-Making Test-A, involving the connecting of 25 numerically arranged points in ascending order as quickly as possible, measured processing speed (seconds). Trail-Making Test-B, involving the connecting of 25 points of alternating numbers and letters in ascending order as quickly as possible, measured executive functioning (seconds). Episodic memory involved a stimulus encoding phase of everyday objects appearing consecutively in varying screen locations, followed by a delayed testing phase where participants decided whether a stimulus was shown previously (measuring recognition memory - % correct), and, if so, its screen position (measuring source memory - % correct). A Spatial Span – Backwards task measured spatial working memory (maximum number correctly recalled), whereby participants recall and reverse an array of lit-up boxes ranging from 2-9 sequences. The Go/No-Go task measured attentional control (number of errors) by asking participants to respond to a specific stimulus (Go) and inhibit responses to other stimuli (No-go). The Fragmented Letters task assessed visuospatial functioning (% correct) by asking participants to identify a singular letter from the alphabet which is fragmented through a visual mask. Finally, the Virtual Supermarket Task, previously described in detail (Tu et al., 2015), measured allocentric and egocentric orientation (both deviation error from correct location) by asking participants to orient a trolley in a virtual supermarket according to a previously presented video clip. Detailed task descriptions are available in Appendices: Supplementary Information Table 2.1.

Remote cognitive testing

Participants completed the remote cognitive testing session from their own home. Initially, participants completed demographics and novel subjective cognition questionnaires (Spatial Memory & Driving, Orienteering, and Navigation). Participants then completed the online cognitive test battery, consisting of the Reaction Time task, Trail Making Test-A, Trail

Making Test-B, Picture Recognition, Spatial Span Backwards, Go/No-Go test, Fragmented Letters, and Virtual Supermarket Test.

In-person cognitive testing

The in-person cognitive testing session took place in a quiet testing facility and involved a combination of traditional neuropsychological tests, requiring face-to-face assessment, with our novel online tasks. Participants initially completed established questionnaires measuring subjective cognition (Cognitive Change Index (CCI) (Rattanabannakit et al., 2016) and Santa Barbara Sense of Direction (SBSOD) (Hegarty et al., 2002). Participants then completed the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005), Reaction Time task (Online), paper versions of the Trail-Making Test A & B (Reitan, 1958), Rey Osterrieth Complex Figure Test (ROCF) – delayed recall (Shin et al., 2006), Corsi Block Tapping Test (Corsi, 1972), Go-No/Go (Online), a paper version of the Fragmented Letters test (Warrington et al., 1991), and finally the Virtual Supermarket Task (Online).

2.4 Statistical analyses

Neuropsychological test measures

To create an episodic memory measure for the online cognitive battery, an average score was found between recognition and source memory percentages for each participant. Outliers were identified using boxplot analysis, and participants were excluded from a test if their average values deviated more than 3 standard deviations from the mean. For the remote session, outliers were removed for Reaction Time (1), and TMT-A (1). For the in-person testing session, outliers were removed for the CCI (1), Reaction Time (1), TMT-A (1), TMT-B (1), ROCF recall (1), and Go-No/Go (1). Two participants did not complete the Virtual Supermarket Task in either test session due to either a technical error or finding the task too difficult, and therefore were removed from analysis. One participant did not complete the Picture Recognition task due to a technical error. A Bonferroni adjusted significance level of 0.00625 (0.05/8) was used to assess statistical significance in correlations between the CCI and online cognitive assessments. Raw cognitive test scores were standardised for regression analysis, except for episodic memory which was converted into a proportion as this score measured for accuracy in percentage. Appropriate diagnostic tests and visual inspections were carried out to assess regression assumptions, including linearity and homoscedasticity, normality of residuals, independence of residuals, and multicollinearity. All analysis was carried out in R (version 4.4.0).

Concurrent validity (remote vs in-person testing)

Concurrent validity was measured by Spearman or Pearson correlations (depending on variable distribution) to assess the consistency between remote/online and in-person/traditional neuropsychological tests. A correlation threshold of ≥0.40 was used to establish acceptable concurrent validity (Trustram Eve & De Jager, 2014). The online Trail Making Tests were compared to the paper Trail-Making Tests; the Spatial Span-Backwards task was compared with the Corsi Block Tapping test; the Picture Recognition task was compared with the ROCF-delayed recall task; Fragmented Letters was compared with the paper Fragmented Letters task; and Global Cognition was compared with MoCA score.

Test-retest reliability

To examine test-retest reliability of the repeated online cognitive tasks from baseline to retest sessions, two complimentary approaches were conducted:

1. Two-way mixed effects intraclass correlation coefficients (ICCs) with measures of absolute agreement (95% CI) according to McGraw & Wong (McGraw & Wong, 1996).
2. Paired samples *t* tests assessed performance differences. A significant (p <.05) improvement over time was used as a threshold to indicate practice effects.

Global cognition

To establish a global cognition score for each testing session, Z-scores for each neuropsychological measure within each testing session were averaged to create a composite score. Z-scores were reversed to ensure consistent directionality within each task.

2.3 Results

2.31 Demographics and cognitive battery characteristics

To complete the NeurOn cognitive battery, 41% of participants used desktops, 41% used laptops, and 18% used tablet devices to complete the study. On average, the online testing session took 58 minutes and 50 seconds whilst the in-person testing session took 66 minutes and 50 seconds. No significant differences were found between age, education, MoCA score, CCI score, or time taken to complete online and in-person testing batteries between males and females (see Table 2.1).

Table 2.1. Validation study participant demographic characteristics

Variable	Gender				
	Male	**Female**	**Overall:**	***p*-value**	**Effect size**
Participants	17	15	32		
Age (years)	70.71 (5.84)	69.60 (3.50)	70.19 (4.84)	0.52	0.23
Education (years)	16.47 (4.47)	15.32 (3.30)	15.93 (3.94)	0.41	0.29
Device used (Desktop, Laptop, Tablet)	9, 7, 1	4, 6, 5	13, 13, 6	0.22	0.21
Online testing session (MM:SS)	61:19 (14:34)	56:01 (06:50)	58:50 (11:44)	0.21	0.46
In-Person testing session (MM:SS)	66:31 (12:43)	67:14 (15:34)	66:50 (13:49)	0.89	-0.05
MoCA score	27.00 (2.03)	27.27 (2.09)	27.13 (2.03)	0.72	0.13
CCI score	27.47 (6.03)	27.33 (5.45)	27.41 (5.67)	0.95	0.02

[a] Welch two samples T-tests were conducted for group differences.

[b] Chi-squared test was used to assess overall group differences in devices used.

[c] Abbrev: MoCA = Montreal Cognitive Assessment, CCI = Cognitive Change Index

[d] Cramér's V was used for effect size of devices used. Cohen’s *d* was used for effect sizes for other variables.

[e] MM:SS = Minutes: Seconds

2.32 Concurrent validity (remote vs. in-person testing)

To determine how online cognitive tests validated against traditional cognitive tests, concurrent validity was measured for online tasks with traditional cognitive test equivalents. Only TMT-B met the acceptable correlation threshold value to demonstrate acceptable concurrent validity between tasks, $r(28) = 0.615$, $p < .001$. Low correlations were established for TMT-A ($r(29) = 0.255$, $p = 0.17$), Spatial Working Memory ($r(30) = 0.268$, $p = 0.14$), and Episodic Memory ($\rho = 0.269$, $p = 0.16$, $N = 29$). A ceiling effect was observed for the Fragmented Letters task in both paper and online versions across both testing sessions (see Table 2.2).

Table 2.2 Concurrent validity between online tasks and traditional neuropsychological tests.

Test	**Online**		**Traditional**		**Spearman's ρ (S)/ Pearson's r**
	M (SD))	**Range**	**(M(SD))**	**Range**	
Trail-Making Test -A	32.13 (77.87)	18.46 - 54.77	35.67 (12.67)	16.82 - 69.58	0.25
Trail-Making Test -B	50.28 (19.16)	27.90 - 99.14	69.19 (19.47)	35.00 - 104.29	0.61***
Spatial Working Memory	5.44 (0.98)	3 - 7	5.56 (1.24)	3 - 7	0.27
Episodic Memory	90.75 (8.19)	74.10 - 100	20.24 (5.51)	1.00 - 28.50	0.27 (S)
Fragmented Letters	100 (0)	100 - 100	100 (0)	100 - 100	-
Global cognition	0.13 (0.43)	-0.64 - 0.92	0.00 (1.00)	-2.03 - 1.42	0.60**

[a] $*p < .05$, $**p < .01$, $***p < .001$

[b] Traditional tests of online tasks: Trail Making Tests: Trail Making Tests (paper versions), Spatial-Working Memory: Corsi Block Tapping Test; Episodic Memory: ROCF-delayed recall; Fragmented Letters: Fragmented Letters (paper); Global cognition: MoCA score.

[c] Global cognition was calculated by averaging reversed Z scores for main neuropsychological tasks in online and in-person test settings.

[d] Spearman's ρ was used for Episodic Memory correlation as the online episodic memory score showed a non-normal distribution.

2.33 Test-retest reliability and practice effects

Across all four repeated tasks, intraclass correlation coefficients demonstrated moderate test-retest reliability (0.50-0.80). Correlation coefficients ranged from 0.51 (Go/No-Go) to 0.75 (Egocentric Orientation). No practice effects were found for Reaction Time (online: M = 344.62 ± 69.02; in-person: M = 359.64 ± 95.18; $t(29) = -0.503$, $p = 0.619$, $d = 0.18$); Go/No-Go (online: M = 1.22 ± 1.64, in-person: M = 1.42 ± 1.36; $t(30) = -0.596$, $p = 0.556$, $d = 0.13$); Allocentric Orientation (online: M = 3.11 ± 1.57, in-person: M = 3.11 ± 1.62; $t(26) = 0.107$, $p = 0.915$, $d = 0.01$); or Egocentric Orientation (online: M = 51.31 ± 34.16, in-person: M = 56.52 ± 36.37; $t(28) = -0.684$, $p = 0.500$, $d = 0.15$), as all *t* test values were insignificant ($p > .05$) (see Table 2.3).

Table 2.3. Test-retest reliability of cognitive tasks between online and in-person testing sessions.

Test	**Online**		**In-Person**		**Practice effects (*t* (df))**	**ICC**	**Spearman's ρ (S)/ Pearson's r**
	(M (SD))	**Range**	**(M (SD))**	**Range**			
Reaction time	344.62 (69.02)	228.76 - 507.07	359.64 (95.18)	239.00 - 697.08	-0.50 (29)	0.55***	0.54**
Go/No-go	1.22 (1.64)	0 - 6	1.42 (1.36)	0 - 5	-0.60 (30)	0.51**	0.50** (S)
Allocentric orientation	3.11 (1.57)	0.85 - 7.21	3.11 (1.62)	0.87 - 6.51	0.11 (26)	0.64***	0.63***
Egocentric orientation	51.31 (34.16)	11.33 - 132.34	56.52 (36.37)	13.38 - 133.07	-0.68 (28)	0.75***	0.74***

[a] $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

[b] Spearman's ρ was used for Go/No-go correlation as the online test score showed a non-normal distribution.

2.34 Association with established cognitive assessments

To determine how the online cognitive testing battery is associated with established cognitive assessments, correlation analysis was carried out between individual cognitive tests and total CCI score. Spearman rank correlation analysis found that higher CCI score was positively associated with worse egocentric orientation performance, $r(27) = -.453$, $p = .014$, however this was not statistically significant after Bonferroni correction. No other cognitive assessments were found to correlate with the CCI (see Table 2.4).

Table 2.4. Correlation analysis between online cognitive testing and CCI score.

Test	Spearman's ρ
Reaction Time	-0.004
Trail Making Test -A	0.021
Trail Making Test -B	-0.137
Spatial Working Memory	-0.084
Episodic Memory	-0.211
Go/No-go	-0.005
Allocentric Orientation	-0.258
Egocentric Orientation	*-0.453**

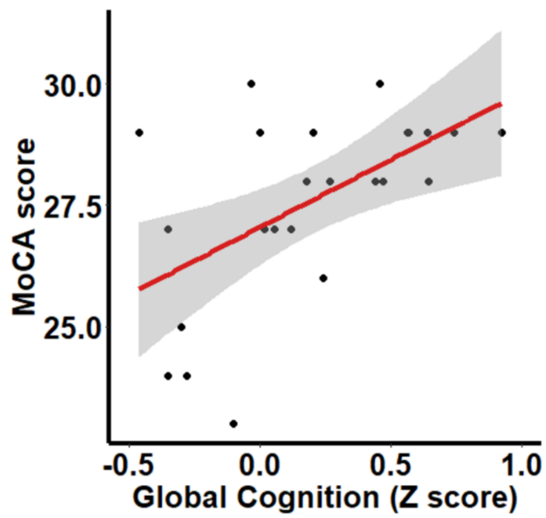
[a] $*p < .05$, $**p < .01$, $***p < .001$

[b] Italics indicate significance following Spearman's correlation, bold italics indicates significance following Spearman's rank and Bonferroni correction.

[c] Bonferroni corrected alpha value = 0.00625

Correlation analysis was then conducted to establish whether global cognitive performance from the online cognitive battery validated against the MoCA. A Pearson's correlation found that global cognition performance showed a moderate negative correlation with MoCA performance, r(24) = .598, p = .001 (Figure 2.1).

Figure 2.1. Regression plot showing the relationship between MoCA score and global cognitive performance in the NeurOn battery.



2.35 Influence of factors on neuropsychological testing

To explore how demographic factors influenced performance in the online cognitive battery, a multiple linear regression analysis was conducted using the variables of traditional test scores, age, gender, and education. Traditional test scores significantly predicted performance in TMT-B performance ($\beta = 0.49$, $p = 0.002$, CI[0.20, 0.78]) and Global Cognition ($\beta = 0.09$, $p = 0.003$, CI[0.04, 0.15]). Older age was associated with worse performance in TMT-A ($\beta = -0.12$, $p = 0.030$, CI[-0.23, -0.01]), allocentric orientation ($\beta = -0.10$, $p = .007$, CI[-0.16, -0.03]), and global cognition ($\beta = -0.05$, $p = .007$, CI[-0.08, -0.01]). Gender was positively associated with episodic memory, with being female predicting better episodic memory performance ($\beta = 0.07$, $p = .03$, CI[0.01, 0.13]). More years in education was associated only with allocentric orientation ($\beta = 0.09$, $p < .05.$, CI[0.00, 0.17]).

2.4 Discussion

With the demographic shift towards an ageing population, there is an urgent need to establish screening tools for early identification of cognitive decline during ageing. In this chapter, the aims were to investigate the feasibility, reliability, and validity of a novel online cognitive testing battery in an older adult population to establish its applicability in acquiring cognitive performance data in a healthy older adult population within unsupervised, remote settings.

Importantly, it is demonstrated that global performance in the NeurOn cognitive battery validates against the MoCA, one of the most popular tests for screening for MCI. To date, very few studies have validated online cognitive assessments in older adults (De Roeck et al., 2019), and fewer still have shown that online cognitive assessments provide comparable diagnostic accuracy to the MoCA (Paterson et al., 2022). The results in this study indicate that the NeurOn battery provides a promising instrument for measuring cognitive performance remotely at a similar accuracy with clinical testing appointments.

Many traditional cognitive assessments used within driving evaluations, such as the MoCA and MMSE, are limited by practice effects which may compromise the ability to interpret whether cognitive change is due to task experience rather than true cognitive changes (Cooley et al., 2015; Galasko et al., 1993). Practice effects are more likely to occur within shorter testing intervals and are prominent across one week re-testing intervals (Calamia et al., 2012; Duff, 2014). In the present study, despite a short retesting period of one week, no statistically significant improvement was found across any of the repeated tasks. This lack of improvement may be due to the pseudorandomisation of task material within the NeurOn battery, which prevents participants from learning task specific content. Although a one-week retesting period is not typically used for clinical relevance for neuropsychological testing (Duff, 2014), it can be valuable for assessing cognitive changes after short-term intervention studies (Bell et al., 2018). Reduced practice effects also enable for identification of subtle changes in cognitive trajectories longitudinally, which are rarely conducted in routine clinical appointments due to being resource intensive. This has potential benefits for cognitive screening assessments for driving in older age.

As discussed in Chapter 1, a limitation in the current body of literature assessing cognitive performance in older drivers is that most studies assess the relationship between driving and cognition using cross-sectional methodologies, which does not account for heterogeneity within the population or whether individuals are exhibiting cognitive decline. In the implementation of cognitive screening assessments for identifying at-risk drivers, adequate test-retest reliability and minimal practice effects are vital for ensuring that longitudinal cognitive screening can sensitively identify changes to key cognitive processes associated with reduced driving safety that can flag for further driving evaluations.

Contrary to the hypotheses, only the TMT-B and global cognitive measures demonstrated concurrent validity to traditional paper-based tasks, respectively. Previous research shows that concurrent validity of online cognitive testing is typically low (median 0.49) (Feenstra et al., 2016), and therefore correspondence between online cognitive tests and paper-based tasks is typically moderate at best. It is possible that digitalising some traditional paper-based tasks influences test performance, and therefore comparing online cognitive test performance to non-computerised normative data may be less valid in assessing cognitive impairment.

Nevertheless, due to the enhanced precision, standardisation, and objectivity in data measurement offered by online cognitive testing, computerised cognitive tasks can be used to develop new normative data thresholds that can assess more sensitively for cognitive changes. Furthermore, online testing opens the possibility of testing a significantly larger and more diverse population demographic who may not have access to clinical assessments. By establishing extensive normative datasets, it is possible to establish how cognitive changes over time differ across specific subpopulations, which enable for more accurate diagnostic markers (Coughlan et al., 2019). Given that age-related variability in cognitive performance increases rapidly after age 60 (Laplume et al., 2022), it is essential to account for sociodemographic factors that may influence interpretation of cognitive trajectories.

As outlined in Chapter 1, driving requires a range of cognitive functions, with processing speed, attention, executive functioning and visuospatial functioning most prominently implicated in older age driving performance (Matthias et al., 2009; Anstey et al., 2005; Depestele et al., 2020). The NeurOn battery utilises a wide range of cognitive functions, including those most prominently indicated in driving performance, and further provides the potential to explore for the first time the extent to which spatial orientation processes impact driving behaviour in older age.

In conclusion, the NeurOn cognitive assessment battery demonstrates a promising instrument for assessing cognitive performance within healthy older adult populations. The battery demonstrated adequate usability and feasibility in measuring cognitive performance remotely, as all participants were able to complete the assessment remotely and unsupervised using a variety of devices (see Appendices: Supplementary information Table 2.4 to see cognitive task performance across devices). Importantly, the composite battery validated against MoCA performance; showed negligible practice effects; and demonstrated moderate test-retest reliability. Within the next chapter, the NeurOn battery will be used to assess how cognitive functions relate with driving behaviour within healthy older adults.

Chapter 3: The Impact of Spatial Orientation Changes on Driving Behaviour in Healthy Ageing

Published Paper

Morrissey, S., Jeffs, S., Gillings, R., Khondoker, M., Patel, M., Fisher-Morris, M., Manley, E., & Hornberger, M. (2024). The Impact of Spatial Orientation Changes on Driving Behavior in Healthy Aging. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *79*(3). https://doi.org/10.1093/GERONB/GBAD188

3.1 Introduction

As discussed in Chapter 1, the majority of large-scale cognitive driving studies have only employed screening tests for cognitive impairment (Depestele et al., 2020; Mathias & Lucas, 2009), which, despite their sensitivity to detect cognitive changes, do not allow for the identification of which specific cognitive aspects impact driving behaviour.

In-depth cognitive batteries driving performance have been limited to relatively small sample sizes (Roy & Molnar, 2013), and have not taken into account how spatial orientation/navigation, a critical process for everyday mobility, impacts driving performance in ageing. Therefore, there is currently little understanding as to how both egocentric and allocentric spatial orientation behaviours interact with driving safety. This is surprising given that safe driving requires understanding how one's vehicle is positioned in relation to the surrounding environment. There is therefore an urgent need to understand how spatial orientation/navigation changes, which are well-established in ageing (Lester et al., 2017), impact driving performance.

Within many developed countries, including the UK, there is a pre-70/ post-70 age screening policy for mandatory renewal of driving licenses (Siren & Haustein, 2015). The implementation of age-based driver screening has been controversial due to both limited symmetry with chronological age-based crash risk (Langford et al., 2006) as well as increasing driving cessation rates amongst safe drivers which can lead to negative health consequences. Furthermore, research on age-based differences in driving has largely categorised populations as older and younger drivers, which does not account for changes that take place along the older age continuum (Svetina, 2016).

The current study addresses these shortcomings by i) determining which specific cognitive factors are related to driving behaviour in a large cohort of healthy older adults; ii) exploring the role of spatial orientation on driving behaviour; and iii) establishing a large normative dataset for in-depth cognitive phenotyping of driving behaviour in older adults. It is hypothesised that worse performance in executive functioning and processing speed will be associated with reduced driving frequency, replicating previous findings; worse attention, processing speed and executive functioning will be associated with increased driving difficulty, as these domains have been most frequently identified within the literature; and reduced driving space will be associated with worse spatial orientation performance. Given the vital role for spatial orientation in vehicle manoeuvring and its previously reported issues amongst older adults, it is further hypothesised that spatial orientation deficits will be associated with increased driving behaviour difficulty.

3.2 Methods

3.21 Participants

804 older adults were recruited between February 2021 and August 2021 to complete the study. The inclusion criteria for the study were as follows: being age 65 or older, having a current driving license, being a regular driver (driving at least once per week). The exclusion criteria for the study were as follows: not driving regularly, having a medical condition that contraindicates driving, having an untreated significant visual or physical impairment, having a diagnosis of mild cognitive impairment or dementia, taking medications for dementia, and high alcohol consumption (> 45 units per week). Participants were recruited via online and media advertisement, such as through dementia research databases (Join Dementia Research (https://www.joindementiaresearch.nihr.ac.uk/) and online driving forums (https://olderdriversforum.com/decision-study/). Signed informed consent was obtained from each participant prior to conducting the experimental protocol and data was attributed anonymously. Ethical approval for the study was provided by the Faculty of Medicine and Health Sciences Research Ethics Committee at the University of East Anglia (FMH2019/20-134).

3.22 Procedure

Participants completed online questionnaires related to their demographic information, health status, driving history, driving habits, road traffic incident history, spatial memory, and navigation ability. Following this, participants completed a set of neuropsychological testing battery that assessed for cognitive performance across a variety of domains. Questionnaires were carried out using an online server whilst neuropsychological tasks were hosted on NeurOn.

Cognitive battery

The cognitive battery consisted of a variety of tests tapping into domains previously associated with both driving behaviour and cognitive impairment. These include reaction time; processing speed (TMT-A); executive functioning (TMT-B); spatial working memory (Spatial Span Backwards); episodic memory (Recognition and Source Memory); and spatial orientation (allocentric & egocentric) (Virtual Supermarket Task). Fragmented Letters task performance was assessed only to identify sensory impairments amongst participants and was not included within the analysis. Task descriptions for each cognitive test are outlined in Table 3.1.

Table 3.1. Cognitive battery tasks

Task:	**Domain:**	**Description:**
Reaction time	Reaction time	Participants respond (via keyboard, touchscreen) as quickly as possible after perceiving a repeating stimulus appearing on the screen. Reaction time is measured by capturing the average duration of participant responses to the repeating stimulus.
Trail-Making Test -A	Processing speed	Participants connect a set of 25 numerically arranged points in ascending order as quickly as possible. Processing speed is measured by task completion time in connecting each point in the correct order.
Trail-Making Test -B	Executive functioning	Participants connects a set of 25 points that are arranged alphabetically and numerically in ascending order alternating between numbers and letters. Executive functioning is measured by the time it takes to complete the task in connecting each point in the correct order.
Picture Recognition	Recognition memory & Source memory	Participants initially view a set of pictures of everyday objects that appear consecutively at the top, bottom, left, and right of the screen in a learning phase. After a break, participants are tested on whether they correctly recognise pictures they previously learned in the learning phase, forming a recognition memory test, and are then asked to locate the position they appeared on the screen in a source memory test. Both recognition and source memory measures are established by dividing the number of correct responses by the number of trials to develop an accuracy percentage measure.
Spatial Span – Backwards	Spatial working memory	Based on the Corsi block test, participants are presented with an array of geometric shapes that light up in a different sequential order per trial. After each trial, the participant must relay the previous sequence in reverse order. The difficulty increases systematically from

		two box to nine box sequences. The task aborts if participants relay two wrong sequences in the same trial sequence length. Spatial working memory is measured by the maximum sequence capacity correctly recalled.
Fragmented Letters	Visuospatial impairment	Participants identify a singular letter from the alphabet that is fragmented through a visual mask. Participants must then choose the shown letter out of multiple choices. There are 10 trials in total. The visuospatial impairment measure is calculated by the number of correct responses divided by the total number of trials.
Virtual Supermarket Task	Allocentric & Egocentric orientation	Participants view 14 randomly ordered 20-40 second clips of a trolley moving through a virtual supermarket. Each video is presented in first-person perspective and contain optic flow cues via the changing scenery as the shopping trolley moves throughout the supermarket. Following the video clip, participants are asked to indicate a direction to the starting point of the video - assessing egocentric orientation - and then are asked to draw the path presented in the video from a birds-eye view of the supermarket – assessing allocentric orientation. This task has been described in detail by Tu et al. (2015). Both allocentric and egocentric orientation measures involved an average error measurement. For allocentric orientation, this was the average distance between the final location of their drawn path from the final location of the path drawn by participants across all allocentric orientation trials. For egocentric orientation, this was the average angular error – constituting the difference between the exact starting location to participants estimated starting direction across all egocentric orientation trials.

Driving behaviour measures:

To assess how cognition relates to driving behaviour, seven measures for driving behaviour were selected from the Driving Habits Questionnaire (Owsley et al., 1999) and a custom driving history questionnaire. These measures were filtered into 3 main factors: frequency, space, and difficulty (O'Connor et al., 2012) (see Appendices: Supplementary Table 3.1. for detailed summary). Driving frequency consisted of three measures: average annual mileage, average number of days driven per week (ranging from 0 to 7), and weekly average number of trips. For weekly average number of trips, participants provided how often drive for different purposes (i.e., shopping, work, appointments) in a typical week and this was totalled to create an overall measure.

Driving space also consisted of two variables. One was developed from a driving space measure assessing how often participants drove within their immediate neighbourhood (lowest), to outside their region (highest). For each question, scores were rated from one (a few times in the year) to four (every day). Scores were totalled across all six items, with a higher score indicating a greater driving space. The second driving space measure consisted of maximum weekly trip distance, which was ascertained by the highest number of miles participants would typically drive for a trip.

Within the Driving Habits Questionnaire, participants were asked whether they completed a particular challenging driving situation within the past three months (i.e., driving in the rain; driving alone; making turns across oncoming traffic). The number of situations avoided per participant was totalled to create a situation avoidance measure, ranging from nought to eight. If participants had driven in a particular situation, they were asked to rate how difficult they found each situation on a Likert scale (one = extremely difficult, five = not at all difficult). Participants reporting that they avoided the situation due to finding it too difficult were coded as having extreme difficulty (O'Connor et al., 2012). An average driving difficulty measure was calculated across all driving situations.

Older age and driving behaviour:

As there is currently a limited understanding in how driving behaviour differs across the pre/post age 70 cut-off period that is commonly employed in driver licensing policies (Siren & Haustein, 2015), a post-hoc analysis was conducted to investigate how cognitive changes within the older age spectrum before and after the age 70 mandatory cut-off related to driving behaviour. Individuals were categorised into below and above age 70 groups, which had 370 and 430 participants respectively.

3.23 Statistical Analysis

Raw cognitive test scores were standardised for analysis, except for recognition memory and source memory which were transformed into proportions as these scores represent inaccuracy percentage. Q-Q plots and histograms were carried out to assess the distribution both cognitive and driving variables. To account for potential measurement error of online cognitive testing (i.e. distraction, technical faults), extreme outliers were removed above and below the 99^{th} percentile for Reaction Time (18), Trail-Making Test-A (16), Trail-Making Test-B (16), Spatial Working Memory (5), Recognition Memory (3) and Source Memory (8). For Egocentric and Allocentric orientation, trials with Z-Scores outside of 3 SD were removed for each participant. Extreme outliers were also removed for Annual Mileage (18), Weekly Trips (8), and Weekly trip distance (11). For the structural equation modelling (SEM), modelling followed a two-stage approach. Firstly, a confirmatory factor analysis (CFA) measurement model was carried out to assess whether our driving variables could be appropriately categorised into Frequency, Space, and Difficulty factors. Weekly trips and Weekly trip distance were removed from CFA and SEM analysis as their inclusion resulted in a poorly fitting model, possibly due to significantly reduced observations (448 compared to 784). The CFA model showed acceptable goodness-of-fit ($\chi 2$ (3, N = 784) = 11.321, $p<0.05$; CFI = 0.989; TLI = 0.962; RMSEA = 0.058; SRMR = 0.021), and therefore was extended to a SEM to establish how each cognitive domain related to Frequency, Space, and Difficulty individually. The final sample size for SEM analysis was 387. Hierarchical regressions were then conducted to establish how each cognitive domain related to each driving characteristic individually to account for varying sample sizes across cognitive tests. As regressions assessing age and gender revealed a significant effect on cognitive functioning, both variables were included as covariates. Driving characteristic data with non-normal distributions (Weekly trips, Weekly trip distance) underwent logarithmic transformations for analysis. An alpha threshold of 0.05 was used to assess statistical significance. Post-hoc analysis was then carried out to establish how cognitive domains predicting driving difficulty were associated with specific driving situation difficulty. For post-hoc analysis of driving situations and cognitive functioning, a Bonferroni adjusted significance level of 0.00625 (0.05/8) was used to assess statistical significance. Secondary post-hoc analysis of how cognitive functioning impacts driving behaviour within both under age 70 and over age 70 groups were carried out only in variables that demonstrated a significant relationship within the main analysis controlling for effect of gender. Analysis was conducted in R using lavaan, olsrr, and psych packages.

3.3 Results

3.31 Demographics

Within our cohort, on average males drove with greater frequency (p <0.001; p <.01; p<.01); had a larger driving space (p <0.001); and reported significantly less driving difficulty than females (p <.0001; p <0.001) (see Table 3.2).

Table 3.2. Participant demographic and driving characteristics

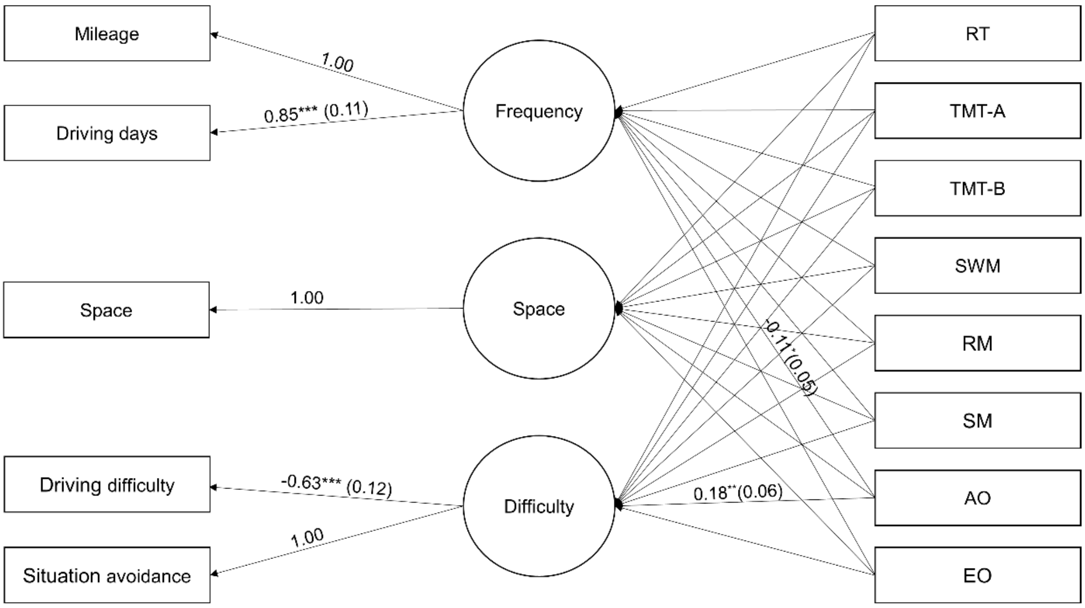
Variable	**Gender**			
	Male	**Female**	**Overall:**	***p*-value**
Age (years)	71.87 (5.38)	70.38 (4.39)	71.05 (4.91)	<.0001
Education (years)	14.92 (2.64)	14.85 (2.61)	14.88 (2.62)	0.70
Driving experience (years)	51.72 (6.62)	47.55 (7.13)	49.42 (7.21)	< .0001
Subjective driving ability	3.81 (0.63)	3.77 (0.64)	3.78 (0.64)	0.38
Frequency				
Mileage (annual)	7,558.73 (3,240.45)	6,070.373 (3,286.33)	6,736.92 (3,346.76)	<.0001
Weekly driving (days)	4.38 (1.60)	4.02 (1.60)	4.18 (1.61)	<.01
Weekly trips	2.21 (1.98)	1.71 (1.58)	1.92 (1.77)	<.01
Space				
Driving space	10.33 (2.80)	9.25 (2.96)	9.74 (2.94)	<.0001
Maximum weekly trip distance (miles)	10.42 (12.84)	8.54 (10.29)	9.28 (11.39)	0.10
Difficulty				
Driving difficulty	4.78 (0.27)	4.59 (0.45)	4.68 (0.39)	<.0001
Situational avoidance	0.79 (0.97)	1.37 (1.48)	1.11 (1.31)	<.0001

Note. Independent samples T-test conducted for group differences. Welch's t test used for situational avoidance.

3.32 Cognitive facilities relating to driving behaviour

A confirmatory factor analysis (CFA) measurement model demonstrated appropriate goodness-of-fit in assessing whether driving variables could be appropriately categorised into Frequency, Space, and Difficulty factors ($\chi 2$ (3), N = 784) = 11.321, $p = 0.01$; CFI = 0.989; TLI = 0.962; RMSEA = 0.059; SRMR = 0.021). SEM was carried out to establish whether cognitive variables were associated with driving Frequency, Space, and Difficulty. The final model showed a good fit to the data, ($\chi2$ (19, N = 385) = 26.300, p = 0.12; CFI = 0.976; TLI = 0.937; RMSEA = 0.032; SRMR = 0.024). The examined variables accounted for 7% of variance for frequency, 3% of space, and 16% of difficulty. The only cognitive factor significantly related to driving behaviour functions was allocentric orientation; which predicted driving frequency (β = -0.11, p<0.05, CI[-0.21, -0.01]) and driving difficulty (β =0.18, p<0.01, CI [0.07, 0.29]) (see Figure 3.1).

Figure 3.1. Conceptual path analysis of structural equation modelling model with standardised coefficients and standard errors.
Note: Only significant relationships are presented between cognitive variables and latent variables.



A hierarchical regression design was then employed to assess how objective cognitive performance across each domain related to each individual driving behaviour after controlling for age and gender effects. Better TMT-A (β = -394.52, p <0.01, CI[-640.90, -148.13]), TMT-B (β = -276.81, p <0.05, CI[-525.03, -28.60]), and Source Memory performance (β = -2406.22, p <0.01, CI[-4156.44, -656.00]) predicted increased mileage. Worse recognition memory performance predicted more weekly trips (β = 0.87, p <0.05, CI[0.08, 1.65]) and a greater weekly trip maximum distance (β = 1.84, p <0.01, CI[0.70, 2.98). Better reaction time (β = -0.03, p <0.05, CI[-0.06, -0.00]), TMT-A completion time (β = -0.03, p <0.05, CI[-0.06, -0.00]), Source Memory (β = -0.21, p <0.05. CI[-0.42, -0.00]) and Allocentric Orientation (β = -0.07, p <0.001, CI[-0.10, -0.03]) performance predicted reduced driving difficulty (see Figure 3.2). Worse recognition memory (β = 1.43, p <0.05, CI[0.23, 2.63]), Allocentric Orientation (β = 0.13, p <0.05, CI[0.07, 0.33]), and Egocentric Orientation (β = 0.14, p <0.05, CI[0.01, 0.26]) performance predicted more avoidance of challenging driving situations (see Table 3.3).

Figure 3.2. Regression plots for significant relationships between driving behaviour and cognitive performance.

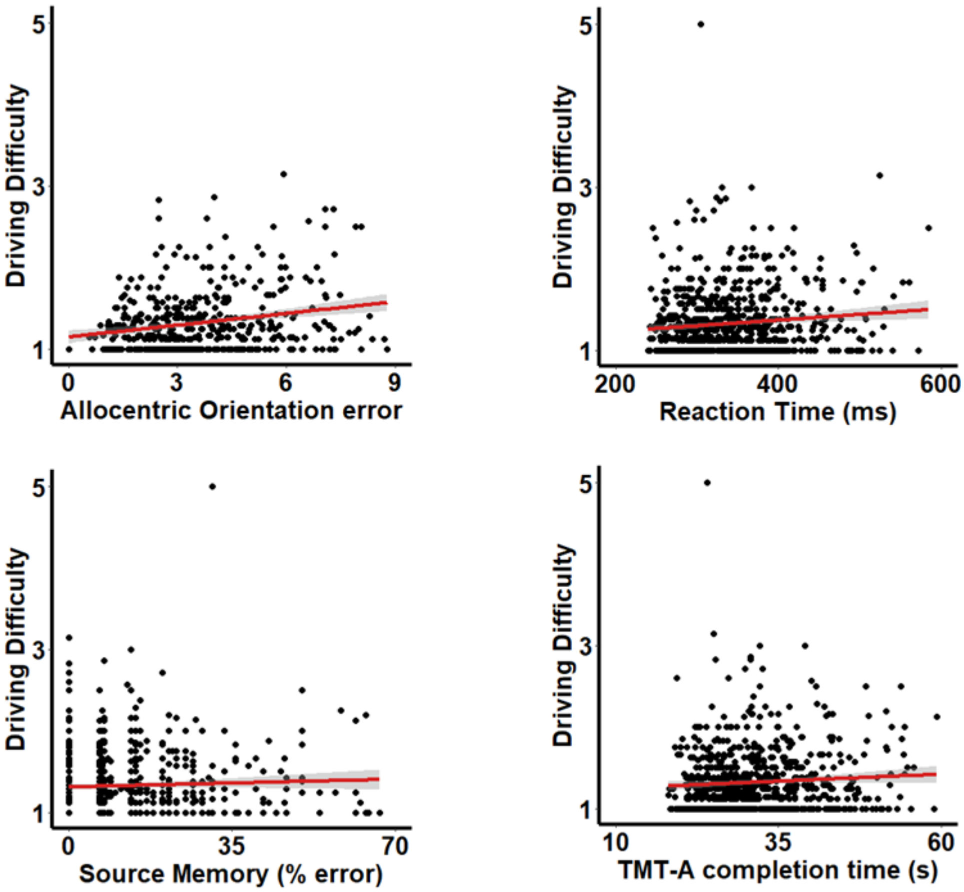


Table 3.3. Cognitive functioning and driving behaviour.

Driving Characteristic	**Allocentric Orientation**	**Egocentric Orientation**	**Reaction Time**	**Spatial Working Memory**	**Recognition Memory**	**Source Memory**	**Trail Making Test -A**	**Trail Making Test -B**
Frequency								
Mileage (annual)	-286.21	-210.78	-176.38	39.46	-2,738.51	**-2,406.22****	**-394.52****	**-276.81***
Weekly driving (days)	-0.02	-0.09	-0.02	0.06	-0.31	-0.47	-0.09	0.05
Weekly trips	0.03	0.06	-0.02	0.02	**0.87***	0.22	0.03	0.02
Space								
Driving space	-0.15	-0.19	-0.12	0.04	-1.61	-0.50	0.01	0.01
Weekly trip distance	0.09	0.10	-0.02	-0.04	**1.84****	0.49	0.07	0.03
Difficulty								
Driving difficulty	**-0.07*****	-0.01	**-0.03***	0.00	-0.30	**-0.21***	**-0.03***	-0.02
Situations avoided	**0.13***	**0.14***	0.07	-0.03	**1.43***	0.49	-0.04	0.04

Note. Hierarchical regressions assessing how individual cognitive facilities explain driving behaviour measures after controlling for age and gender. Values represent standardised beta coefficients. Bold values represent significant relationships. Cognitive data was standardised for analysis (Recognition Memory and Source Memory were converted to proportions). Logarithmic data transformations were performed on Weekly trips and Weekly trip distance.

*$p < .05$, **$p < .01$, ***$p < .001$

3.33 Driving situations and cognitive performance

Post-hoc Spearman correlations were performed to establish how cognitive domains associated with driving difficulty related to challenging driving situations individually. Following Bonferroni corrections for multiple comparisons, worse allocentric orientation performance predicted greater difficulty in performing turns across oncoming traffic *(p* <0.001) and parallel parking (*p* <0.001). Worse reaction time was also associated with greater difficulty performing turns across oncoming traffic (*p* < 0.001) (see Table 3.4).

Table 3.4. Difficulty during driving situations and cognitive performance

Driving situation	**Allocentric orientation**	**Reaction Time**	**Source Memory**	**Trail-Making Test -A**
Turns across oncoming traffic	***-0.160****	***-0.181****	-0.055	-0.066
Motorways	*-0.136**	0.003	-0.027	-0.050
Driving in the rain	*-0.106**	-0.047	0.004	-0.019
High traffic	*-0.114**	-0.057	-0.044	-0.053
Driving alone	-0.045	-0.054	-0.031	-0.029
Rush hour	-0.035	-0.048	-0.040	-0.061
Parallel parking	***-0.182****	*-0.121***	-0.015	*-0.088**
Driving in the night	*-0.127**	-0.050	-0.041	0.000

Note: Spearman's correlations showing association between difficulty experienced during driving situations and cognitive performance. Values represent Rs values of correlations. Italics indicate significance following Spearman's correlation, bold italics indicates significance following Spearman's rank and Bonferroni correction. Bonferroni-corrected alpha value = 0.00625.

*p < .05. **p < .01. ***p < .001

3.34 Older age and driving behaviour

T-tests were used to assess group differences between under and over 70 age groups in driving behaviour. Analyses found that individuals under the age of 70 had a higher typical annual mileage (*p* <0.05) and higher maximum weekly trip distance than individuals over 70 (*p* <0.01) (see Appendices: Supplementary Table 3.2). Hierarchical regressions were conducted to establish whether age differences across the older age spectrum influences the relationship between cognitive functioning and driving characteristics.

For the under 70 group, worse TMT-A (β = -505.65, *p* <0.05, CI[-890.38, -120.92]) and Source Memory (β = -3802.05, *p* <0.01, CI[-6396.99, -1207.10]) was predictive of mileage. Further, avoiding driving situations was associated with cognitive functioning, with worse Recognition Memory (β = 3.25, *p* <0.001, CI[1.46, 5.03]), Allocentric Orientation (β = 0.22, *p* <0.05, CI[0.04, 0.42]), and Egocentric Orientation performance (β = 0.30, *p* <0.001, CI[0.14, 0.47]) predicting greater avoidance of challenging driving situations.

For the over 70 group, worse TMT-B performance predicted mileage (β = -392.26, *p* <0.05, CI[-702.12, -82.41]) and worse Recognition Memory predicted weekly trips and maximum trip distance (β = 2.39, *p* <0.01, CI[0.92, 3.86]).

Both under 70 (β = -0.07, *p* <0.05, CI[-0.12, 0.01]) and over 70 (β = -0.07, *p* <0.01, CI[-0.11, -0.02]) groups demonstrated that worse allocentric orientation was associated with increased driving difficulty (see Appendices: Supplementary Table 3.3). Performance of key cognitive domains across under 70 and over 70 age groups are presented in Appendices: Supplementary Figure 3.1.

3.35 Reliability of online cognitive testing

Internal consistency of the online cognitive battery was assessed by performing Cronbach alpha assessments on reaction time test data. Reaction time data consisted of unaggregated participant level reaction time data for one testing session per participant. Internal consistency of reaction time data was very high, with a Cronbach alpha at 0.98, indicating that the online cognitive testing was highly reliable across participants and age groups (see Appendices: Supplementary Table 3.4).

3.4 Discussion

The results show that driving behaviour difficulty and avoiding difficult situations is associated with worse spatial orientation ability within healthy ageing. This study also replicates previous findings that processing speed is a key cognitive domain affecting driving behaviour in ageing.

As discussed in Chapter 1, studies assessing the relationship between impaired cognitive functioning with driving have found associations with visual attention, processing speed, and executive functioning (Anstey et al., 2005; Emerson et al., 2012). Specifically, processing speed has been associated with increased driving impairment in older adults (Papandonatos et al., 2015; Svetina, 2016). The present study replicates previous findings by reporting that reduced processing speed was related to self-reported driving difficulty. Older adults in the present study also displayed reduced mileage and trip distances, consistent with previous research indicating decreased driving frequency with age.

More notably, the present study demonstrates that spatial orientation is related to self-reported driving difficulty within healthy older adults. Spatial orientation has clear relevance to driving behaviour, as deficits will lead to increased difficulty in judging the position of the vehicle in relation to the surrounding environment. Furthermore, spatial orientation was the only cognitive domain demonstrating a significant effect on driving behaviour across the older age spectrum. This aligns with previous research in smaller cohorts showing that worse spatial navigation ability was associated with reduced lane changing smoothness across both younger and older adults (Kunishige et al., 2020). Similarly, greater use of an allocentric survey spatial strategy has been associated with reduced driving errors in a sample of younger adults (Nori et al., 2020). Taking the results of this study into account with the aforementioned lifespan effects, spatial orientation may provide a robust cognitive indicator for impaired driving throughout the lifespan.

To the best of current knowledge, this study also reports for the first time that allocentric orientation performance predicts driving frequency. This may be influenced by the relationship between allocentric orientation and driving difficulty, as individuals who find driving to be less difficult may drive more frequently. However, allocentric orientation was not associated with increased driving space; of which it would be predicted that a greater driving space would require a more extensive cognitive map and therefore better allocentric orientation performance. Contrary to our hypothesis, driving space was not related to cognitive deficits, and instead worse episodic memory performance was associated with increased weekly trips and maximum weekly trip distance. This is surprising, as greater driving space has previously been associated with better cognitive function (Aschenbrenner et al., 2022; Phillips et al., 2016). Within the post-hoc analysis, only individuals over age 70 demonstrated a significant relationship between worse episodic memory and trip frequency and distance. This clearly needs to be further investigated in the future.

Reduced levels of driving frequency and space within the over 70 age group may be influenced by current driving license screening policy, as age-based screening policies have been found to increase rates of driving cessation (Kulikov, 2011). The findings indicate that individuals over age 70 may be restricting their driving despite not reporting changes to driving difficulty, which supports research indicating that age-based screening policies do not provide safety benefits (Siren & Haustein, 2015). However, avoidance of challenging driving situations was only related to better cognitive performance within the under 70 age group, and therefore it is possible that individuals over the age of 70 were self-regulating their driving less effectively. Future research integrating objective driving measures with qualitative assessments regarding driving cessation causes are required to sufficiently untangle the relationship between self-regulation, driving ability, and the impact of age-based screening policies.

In conclusion, the present study provides large-scale normative data of cognitive functioning within healthy older adults using online cognitive assessments; offers a hypothesis as to investigating why older adults may be at greater risk of motor vehicle collisions; and paves the way for investigation into the relationship with driving performance and spatial orientation in both healthy ageing and neurodegenerative disease. Within the next chapter, it will be established how longitudinal cognitive changes are associated with driving mobility and safety within rural and urban environments.

Chapter 4: The impact of urban vs rural environments on driving in ageing

Under review

4.1 Introduction

As discussed in Chapter 1, rural and urban settings present unique challenges in maintaining driving mobility and safety in older age. In rural areas, driving is paramount for maintaining mobility and engagement within the community and is regarded as more important among rural older drivers than their urban counterparts (Strogatz et al., 2020). This is reflected in driving mobility findings, as rural residents typically report travelling further distances than urban residents (Payyanadan et al., 2018; Pucher & Renne, 2005).

When considering driving safety, findings also demonstrate a divergence between rural and urban environments, as data shows there is a greater risk of driving collisions taking place in urban settings, but a greater risk of fatal collisions in rural settings (Department for Transport, 2023; Zwerling et al., 2005). It is considered that the increased road congestion in urban areas is the primary factor behind increased road collisions, whereas road features such as higher speed limits and unmarked roads increase the risk of road traffic collisions being fatal in rural areas (Payyanadan et al., 2018; Thompson et al., 2013).

In Chapter 3, it was found that worse cognitive performance was associated with both reduced driving frequency and increased driving difficulty, with spatial orientation being the key cognitive marker indicating for changes in driving performance in older age. While worse cognitive performance has previously been implicated with reduced mobility and increased risk of RTIs in older age, how this interacts with rural and urban settings remains unclear.

With the demographic shift of the ageing population and the increased urban-rural migration of older adults within the UK (Whitty, 2023), it is crucial to understand how environmental differences interact with cognitive performance in older age, as this will inform for whether different interventions and/or support systems are required to improve driving mobility and safety across rural and urban areas. Additionally, given the heterogenous relationship between cognitive functioning and driving behaviour in older age, it is important to establish longitudinally how driving behaviour interacts with environmental settings over time. This approach will provide insights into how cognitive decline and environmental factors interact in influencing driving behaviour and safety in older adults over time.

The current study addresses these gaps in knowledge by establishing how driving mobility changes across rural and urban settings over a one-year period within a large sample of community-dwelling older adult drivers. This study will further establish how road safety differs across rural and urban environments. Finally, it will be explored how cognitive changes over one-year are associated with changes in driving mobility and driving safety across geographical settings. Specifically, this study will i) compare driving characteristics and mobility across geographical settings; ii) assess how road traffic incident frequency interacts with cognitive functioning across geographical settings; iii) examine how driving mobility changes over time across geographical settings; and iv) identify whether global cognitive changes are associated with changes to driving mobility within rural and urban areas separately. It is hypothesised that i) drivers within rural areas will rely more upon driving their personal vehicles than community transportation or public transport; ii) drivers in rural areas will demonstrate greater driving frequency and space than individuals in urban areas, as they will be more dependent on driving to meet their mobility needs; iii) drivers in urban environments will experience more road traffic incidents due to driving more frequently in more dynamic, high-traffic environments; iv) urban older drivers will show a reduced driving mobility over time, whereas this is maintained in rural older drivers; and v) older drivers with global cognitive changes living in urban areas will show greater reduction in their driving mobility compared to those living in rural areas.

4.2 Methods

4.21 Participants

969 older adults (mean age: 71.01, 540 female, rural: 296) were recruited between February 2021 and August 2021 to complete the study. The inclusion criteria for the study were being age 65 or older, holding a valid driving license, and being a regular driver (driving at least once per week). The exclusion criteria for the study were not driving regularly, having a medical condition that contraindicates driving, having an untreated significant visual or physical impairment, having a diagnosis of mild cognitive impairment or dementia, taking medications for dementia, and high alcohol consumption (> 45 units per week). Participants were recruited via online and media advertisement, such as through dementia research databases (Join Dementia Research (https://www.joindementiaresearch.nihr.ac.uk/) and

online driving forums (https://olderdriversforum.com/decision-study/). Signed informed consent was obtained from each participant prior to conducting the experimental protocol and data was attributed anonymously. Ethical approval for the study was provided by the Faculty of Medicine and Health Sciences Research Ethics Committee at the University of East Anglia (FMH2019/20-134).

4.22 Procedure

Participants initially completed online questionnaires related to their demographic information, driving habits, health status, driving history, driving habits, and a custom driving-based navigation questionnaire. Following this, participants completed a neuropsychological testing battery assessing cognitive performance across a variety of domains, including reaction speed, processing speed, executive functioning, spatial working memory, episodic memory, visuospatial functioning, and spatial orientation (see Table 3.1 for task descriptions). Participants were then invited to complete a follow-up testing phase one year after baseline data collection, undergoing the same procedure. 574 participants took part in the follow-up testing phase (mean age: 71.95, 314 female, 174 rural).

4.23 Driving mobility and safety measures

Driving mobility and safety measures were derived from the DHQ, as well as novel Driving History and RTI questionnaires. Driving mobility measures included annual mileage, weekly driving days, driving space (the geographical area in which people drive), weekly trips, maximum weekly trip distance, situation avoidance, driving speed (relative to the general flow of traffic), and transport preference (Drive yourself, Driven by someone else, Public transport). Driving safety was measured by whether someone was in a recent RTI (within the past 3 years). We also collected the number of in-vehicle technologies used (parking assistance, cruise control, lane control, sat-nav, and Bluetooth) (see Appendices: Supplementary Table 4.1 for detailed information on mobility and safety measures).

4.24 Statistical Analysis

Participants were divided into rural or urban groups depending on the outward code (the first part) of their postcode location based on the 2011 Rural-Urban classification data (Department for Environment, Food & Rural Affairs, 2021). Differences in driving characteristics between people living in rural and urban areas were established using two sample t-tests and chi-squared tests for continuous and categorical variables respectively.

Analyses of Covariances (ANCOVAs) were conducted to assess whether driving mobility differed across environmental locations after controlling for age as a covariate. In assessing how avoidance of driving situations differed across environmental locations, weekly driving days was added to the model as a covariate. A Pearson's chi-square test was conducted to establish whether there were differences in transport preferences (Drive yourself, Someone else drives, or Public transport/ Taxi) across environmental locations. A binary logistic regression was used to assess whether environmental location predicted whether individuals were more likely to have a recent road traffic incident after accounting for age and annual mileage as covariates as they have previously been associated with increased road traffic incident risk. Post-hoc logistic regression analyses were then conducted to assess whether global cognitive functioning was associated with recent RTIs between rural and urban environments separately after controlling for age and mileage. Individual spatial orientation tests were not assessed with recent RTIs due to few rural residents with a recent RTI completing spatial orientation tests. A post-hoc independent samples t-test analysis was then conducted to assess whether the annual mileage for individuals who had experienced a recent RTI differed across rural and urban residents. It was then assessed whether driving mobility changes over a one-year period were associated with environmental location using linear mixed effect (LME) modelling. For LME analysis, difference in driving mobility was calculated by subtracting the baseline score from the follow-up score. Age was included as a covariate and a random intercept term was added to the model to account for individual variability. The relationship between global cognitive performance and driving mobility variables was assessed using linear regression models across geographical settings, separately. Cognitive functioning across both geographical settings was comparable as a Mann-Whitney U test revealed that there was no significant difference in global cognitive performance between rural and urban areas ($W = 39425$, $p = 0.14$). Following this, it was assessed whether cognitive change over time is associated with change in driving mobility within environmental locations separately. To develop a global cognitive change score, cognitive data (reaction time, processing speed, executive functioning, spatial working memory, episodic memory) was standardised within each cognitive measure using the grand mean from both timepoints, and average performance across all tasks was derived across baseline and follow-up test phases. Cognitive change was established by subtracting follow-up global cognition from baseline global cognition. Spatial orientation tests (allocentric & egocentric orientation) were omitted for global cognitive change measurement as fewer participants completed these tests across both testing phases and therefore there would have been a substantive reduction in global cognitive change data (172 compared to 311 participants). Post-hoc analysis was therefore conducted to establish whether spatial orientation performance change over time was associated with driving mobility changes across environmental locations separately.

To account for potential measurement error of online testing, outliers were assessed for baseline and follow-up data using boxplots, Q-Q plots, and histograms. For online cognitive data, extreme outliers outside of 3 SD were removed for reaction time (baseline: 8, follow-up: 6), TMT-A(10, 6), TMT-B (16, 8), spatial working memory (5, 0), allocentric orientation (2, 0), egocentric orientation (2, 0), and subjective sense of direction (5, 3). Extreme values above and below the 99th percentile were removed for recognition memory (8, 5) and source memory (8, 5). For self-reported driving data, extreme outliers were also removed for typical annual mileage (18), driving space (1, 0), weekly trips (13, 2), and weekly trip distance (11, 12), number of passengers (7), years spent with current car (8), and cars regularly driven (8). Weekly trips and maximum weekly trip distance variables were given a logarithmic transformation for analysis due to high positive skewness. For ANCOVA and LME analysis, checking normality of outcome variables was conducted using visual inspection of histograms and normality of residuals was conducted by Q-Q plots. Linearity assumptions and multicollinearity were checked for regression analyses. A significance threshold of 0.05 was used to assess statistical significance. All analysis was carried out in R (version 4.3.1) using car, lme4, and nlme packages.

4.3 Results

4.31 Driving characteristics of older rural and urban residents in the UK

Within the present cohort, individuals living in rural environments had more years of driving experience ($p<.05$), and less use of in-vehicle technology than urban drivers ($p<.05$) (see Table 4.1). 125 participants self-reported recent RTIs (95 living in urban locations).

Table 4.1. Participant demographic and driving characteristics

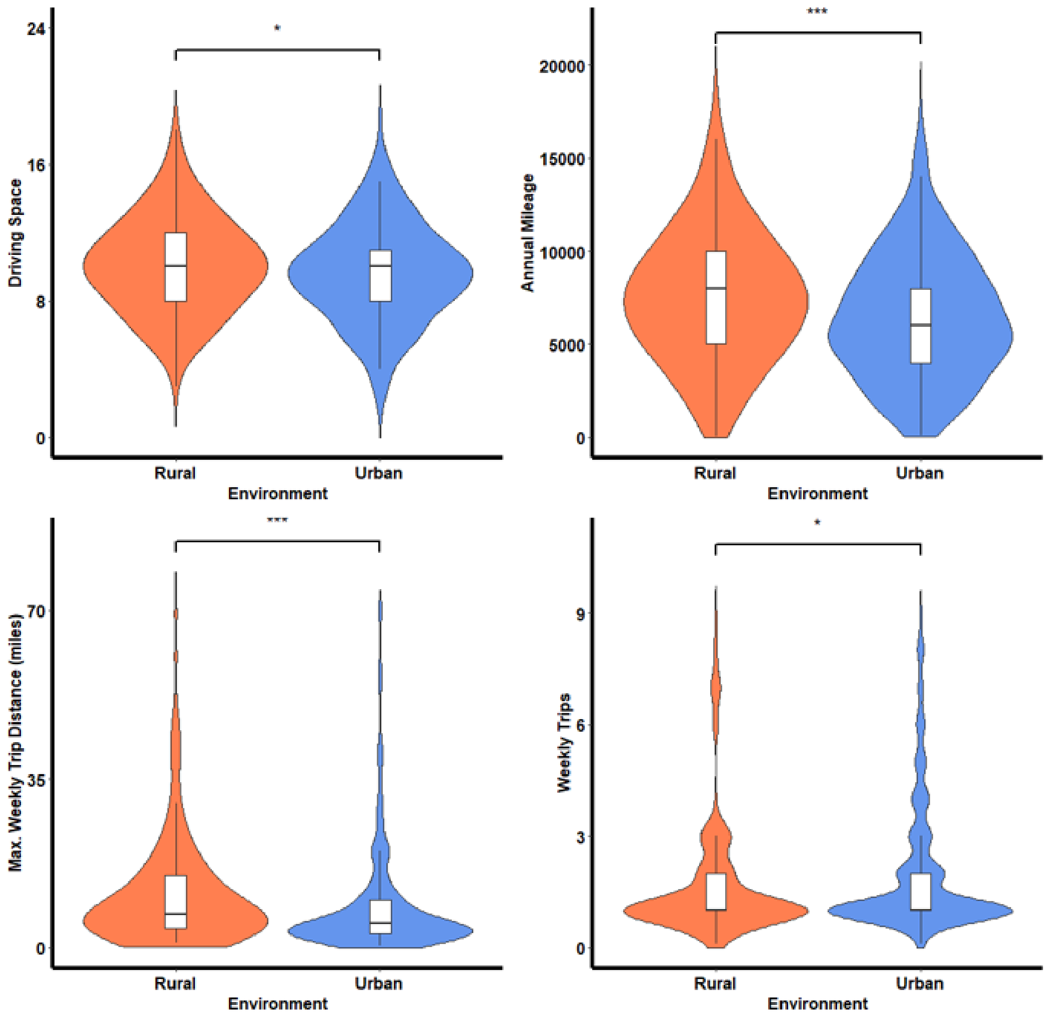
Variable	Environment			
	Rural	**Urban**	***p*-value**	**Effect size *(d)***
Participants	296	673		
Age (years)	71.38 (5.30)	70.85 (4.78)	0.14	0.11
Gender (% female)	52.36	57.21	0.18	0.94
Education (years)	14.78 (2.85)	14.90 (2.71)	0.54	0.04
Driving experience (years)	50.27 (7.13)	48.96 (7.52)	0.01	0.18
Subjective driving ability	3.79 (0.62)	3.79 (0.65)	0.99	0.00
Cars regularly driven	1.34 (0.57)	1.31 (0.51)	0.45	0.06
Time with current vehicle (years)	2.82 (3.45)	3.23 (3.80)	0.11	0.11
N. of regular passengers	1.07 (1.11)	1.18 (1.19)	0.20	0.09
Use of in-vehicle technology	0.91 (0.69)	1.03 (0.81)	0.02	0.16
GPS use	1.01 (1.02)	1.18 (1.04)	0.14	0.16
Driving speed	3.03 (0.49)	2.99 (0.43)	0.18	0.10

Note.
[a] Welch's two sample t test conducted for group differences. Chi squared test of independence used for Gender analysis.
[b] Cramér's V effect size used for Gender analysis. Cohen's D effect sizes calculated for other variables.

4.32 Impact of urban vs rural environment on driving mobility

Rural residents showed a significantly greater driving space ($F(1, 939) = 6.164$, $p<.05$, η_p^2 (partial eta squared) = 0.01); typical annual mileage, ($F(1, 924) = 23.684$, $p < .001$, $\eta_p^2 = 0.02$); higher maximum weekly trip distance ($F(1, 554) = 17.960$, $p<.001$, $\eta_p^2 = 0.03$), but made less weekly driving trips than urban residents ($F(1, 588) = 5.886$, $p <.05$, $\eta_p^2 = 0.01$) (see Figure 4.1). Urban residents avoided more driving situations than rural residents ($F(1, 943) = 9.701$, $p<.01$, $\eta_p^2 = 0.01$. There were no significant differences in driving days or relative driving speed between groups.

Figure 4.1. Driving mobility differences across rural and urban settings.



Significant differences in transport preferences were found between rural and urban residents, ($\chi2 = 7.27$, df = 2, $p < .05$), with rural residents less likely to use public transport or rely upon a friend to drive them than people living in urban areas.

4.33 Impact of urban vs rural environment on driving safety

Urban residents were more likely to have been in a recent road traffic incident than rural residents (OR = 1.57, $p<.05$, CI[1.02, 2.48]) (see Figure 4.2). Worse global cognitive functioning was predictive of a greater incidence of RTIs within urban residents (OR = 1.98, $p<.05$, CI[1.00, 3.88]), but not rural residents (see Table 4.2). Among individuals involved in a recent RTI, there was no significant difference in typical annual mileage between rural and urban residents.

Table 4.2. Multiple logistic regression analysis comparing recent road traffic incident (RTI) occurrence across rural and urban environments.

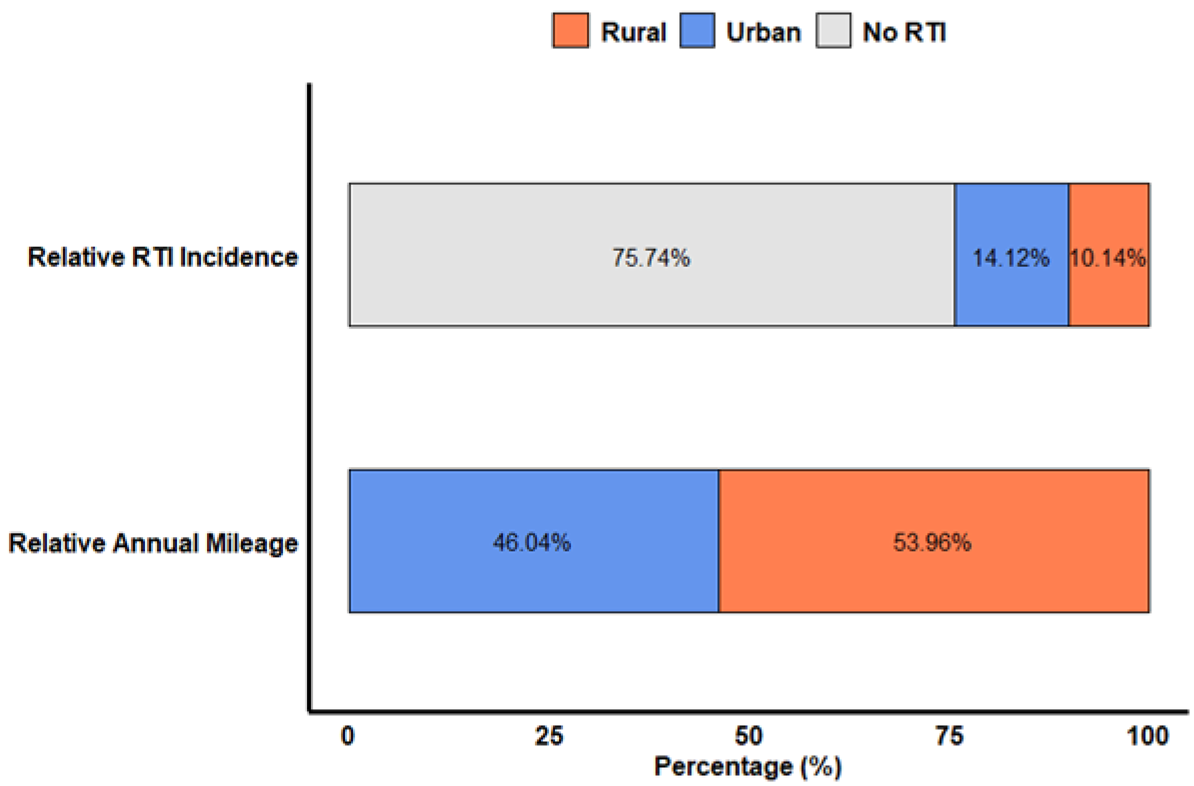
Variable	Global Cognition	Age	Mileage
Rural – Recent RTI	0.96 (0.29 - 2.98)	1.05 (0.94 - 1.67)	1.00 (1.00 - 1.00)
Urban – Recent RTI	**1.98* (1.00 - 3.88)**	1.02 (0.96 - 1.08)	1.00 (1.00 - 1.00)

Note.

*p < .05, **p < .01, ***p < .001

[a] Displaying Odds Ratios and 95% Confidence Intervals.

Figure 4.2. Relative RTI incidence and relative annual mileage across rural and urban areas.



4.34 Impact of cognitive performance across urban vs. rural environments.

Worse global cognitive functioning was associated with a smaller driving space ($\beta = -1.12$, $p<.05$, CI[-2.04, -0.20]) and slower driving speed ($\beta = -0.22$, $p<.05$, CI[-0.39, -0.05]) among rural residents, and less annual mileage amongst urban residents ($\beta = -803.09$, $p<.05$, CI[-1581.20, -24.98]). Post-hoc spatial orientation tests revealed that worse allocentric orientation was associated with less annual mileage ($\beta = -596.41$, $p<.001$, CI[-943.17, -249.66]) and smaller driving space ($\beta = -0.361$, $p<.01$, CI[-0.62, -0.10]) within rural areas, and greater avoidance of driving situations ($\beta = 0.115$, $p<.01$, CI[0.03, 0.20]) within urban residents. Worse egocentric orientation performance was associated with reduced driving space ($\beta = -0.01$, $p<.05$, CI[-0.02, -0.00]) and greater avoidance of driving situations ($\beta = 0.006$, $p<.01$, CI[0.00, 0.01]) in urban residents (see Table 4.3).

Table 4.3. Multiple linear regression analysis establishing how cognitive performance interacts with driving mobility across rural and urban environments.

Variable	**Driving days**	**Driving space**	**Annual mileage**	**Weekly trips**	**Max. trip distance**	**Situational avoidance**	**Driving speed**
Rural							
Global cognition	-0.46	**-1.12***	-900.02	0.12	-0.21	0.19	**-0.22***
Allocentric orientation	-0.10	**-0.36****	**-596.41*****	-0.03	0.00	0.09	-0.01
Egocentric orientation	0.00	0.01	-7.85	0.00	0.00	0.00	0.00
Urban							
Global cognition	-0.15	-0.00	**-803.09***	-0.12	0.22	0.12	-0.04
Allocentric orientation	-0.01	-0.11	-169.73	0.02	0.00	**0.11****	-0.01
Egocentric orientation	-0.00	**-0.01***	-7.61	0.00	0.00	**0.01****	0.00
Note. *p < .05, **p < .01, ***p < .001 [a] Displaying unstandardised beta coefficients							

4.35 Longitudinal driving changes across urban vs rural environments.

Urban residents exhibited a greater decline in their driving space over time ($\beta = -0.652$, $p<.01$, CI[-1.10, -0.21]), and were more likely to avoid more driving behaviours over time than rural residents ($\beta = 0.334$, $p<.001$, CI[0.138, 0.530]). No significant differences were found in driving days, weekly trips, maximum weekly trip distance, or driving speed (see Appendices: Supplementary Table 4.2).

No significant associations were found between global cognitive changes and driving mobility over time across environmental location. Post-hoc analysis of the association between spatial orientation performance and driving mobility across rural and urban locations showed that in urban residents the decline in allocentric orientation performance predicted reduced driving space over time ($\beta = 0.338$, $p<.05$, CI[0.02, 0.65]).

4.4 Discussion

Within a large sample of healthy older adults, the present study examined how driving mobility and safety differs across rural and urban environments over a one-year period and establishes how this relates to cognitive functioning. Overall, it was found that rural residents show a greater driving mobility than urban residents and were less likely to decrease their driving mobility over time. This study also builds upon the findings in Chapter 3 by demonstrating that worse cognitive performance is associated with lower driving mobility in both rural and urban areas, but only urban residents with decline in spatial orientation ability reduced their driving space over time. Importantly, the results corroborate previous findings showing that urban residents were more likely to be in a recent collision than rural residents and build upon previous findings to show that people with worse global cognition are more likely to be in RTIs within urban areas.

Within the present sample, approximately 14% of urban residents and 10% of rural residents self-reported a recent RTI, supporting previous evidence that RTIs are more common in urban environments (Merlin et al., 2020). Worse cognitive functioning has previously been associated with an increased presence of RTIs within older age (Ball et al., 2006; Emerson et al., 2012; Fraade-Blanar et al., 2018; Kosuge et al., 2017), however this study is the first in current knowledge to show that worse cognitive functioning is associated with increased RTI risk amongst urban but not rural residents. Urban road environments present greater hazards due to a more dynamic road environment, and cognitive deficits in healthy ageing have previously been associated with experiencing challenges for road features common in urban road environments, such as intersections and higher traffic volume (Son et al., 2011; Swain et al., 2021). The heightened risk of RTIs among urban residents may therefore be attributed in part to the interaction between cognitive decline in ageing individuals and the complexities in navigating urban road environments. One potential explanation for the lack of a concurrent effect in rural drivers could be attributed to our observation that rural drivers with worse cognition were more likely to reduce their speed relative to other drivers on the road, but not urban drivers. This differential response may be linked to the perception that altering speed limits poses a greater risk on urban roads compared to rural ones (Cox et al., 2017), possibly due to greater environmental complexity on urban roads requiring more attentional resources. The higher speed limit and less congested nature of rural roads may enable cognitively impaired rural drivers to compensate by reducing their travel speed, mitigating the risk of RTI involvement. Rural drivers with cognitive impairments who do not reduce their relative speed may therefore be at a greater risk of RTIs, which at higher road speeds are more likely to be fatal. Future work looking more granularly at real-world driving behaviour, such as via sharp decelerating/braking events, may be able to more accurately unravel the relationship between cognitive impairment and driving safety in rural areas.

Aligning with the study hypotheses, rural residents demonstrated a greater driving mobility than urban residents: driving at a greater annual mileage, covering greater driving space, and having a higher distance in weekly trips. In reverse, urban residents reported a greater number of weekly trips. The greater reliance on driving in rural areas is consistent with previous findings in the US and Australia showing that older rural drivers have greater driving mobility than urban drivers (Pucher & Renne, 2005; Payyanandan et al., 2018; Byles & Galliene, 2012). Differences found in weekly trip frequency across geographical settings may be related to accessibility of amenities and local services, as urban households living closer to intended destinations would be more likely to take shorter, more frequent trips than more isolated rural residents, who may be less inclined to be on the road again after travelling further distances to reach their destination and may conduct multiple stops in one trip.

This study also establishes that urban residents are more likely to avoid challenging situations than rural residents, corroborating previous focus-group findings where older urban drivers reported greater difficulties in driving through heavy traffic, and preferred using interstate highways as they reduced challenging driving situations (Payyanandan et al., 2018). Driving in urban areas may therefore provide greater possibilities for compensating by avoiding difficult situations, which may not be possible in rural areas where there are fewer route alternatives due to less street network intersections. This is supported by the longitudinal findings in this study, showing that urban residents were more likely to decrease their number of challenging driving situations faced and their driving space after a one-year period compared to rural residents.

Lastly, this study employed LME modelling to establish how driving mobility was impacted over time across rural and urban areas. As discussed within Chapter One, LME has been utilised within multiple aspects of driving research and is a well-established approach for modelling relationships in longitudinal data. One alternative approach for analysing factors associated with driving mobility and safety over time is latent growth curve modelling (LGCM). LGCM has previously been used to assess the relationship of cognitive and belief factors over time with driving safety and mobility (Ball, Ross, Roth & Edwards, 2014; Walshe et al., 2019; Endriulaitienė et al., 2020). LGCM is a type of SEM modelling, whereby latent intercepts and linear slope factors can be used to account for individual variability, similarly to random slopes in LME analysis. In Chapter 3, SEM was employed to establish latent driving factors of frequency, space, and difficulty from observed variables. LGCM can therefore be used in future research to establish linear or curvilinear trajectories of these linear factors over time. Modelling non-linear trajectories of driving mobility is particularly important in older age populations, as specific contextual factors such as cognitive, sensory, or physical decline may lead to accelerated decline in driving mobility at different timepoints.

In conclusion, the present study establishes the differential impact of age-related cognitive changes on driving mobility and safety within rural and urban areas over time, emphasising the importance of considering the interaction between cognitive functioning with regional setting in managing changes to driving safety and mobility in older age. The present study builds upon study findings in Chapter 3, showing that there are differences in how cognitive functioning interacts with driving mobility across rural and urban environments over time and that spatial orientation performance is sensitive to changes in driving behaviour in older age. Within the next chapter, it is investigated whether GPS technology can potentially ameliorate age-related cognitive decline to improve driving mobility in older age.

Chapter 5: GPS navigation assistance improves driving mobility in older drivers

Published Paper

Morrissey, S., Jeffs, S., Gillings, R., Khondoker, M., Varshney, A., Fisher-Morris, M., Manley, E., & Hornberger, M. (2025). GPS navigation assistance is associated with driving mobility in older drivers. *PLOS Digital Health*, *4*(4), e0000768. https://doi.org/10.1371/JOURNAL.PDIG.0000768

5.1 Introduction

Electronic navigation assistance systems, such as satellite navigation, integrate GPS vehicle location information with digital maps to provide drivers with a sequence of steps to enable the driver to navigate an optimal route to their chosen destination. GPS use is rising within older age drivers in alignment with the increased prevalence of smartphones amongst older adult populations (Sixsmith et al., 2022). Operating a vehicle requires the intricate coordination of cognitive and physical abilities, and GPS can alleviate the cognitive demands of navigation, thereby enhancing driving performance (Cochran & Dickerson, 2019). This has led to the proposal for optimising in-vehicular technologies (IVT), such as GPS, to potentially offset age-related impairments in older adults to improve their driving safety and enable for greater mobility (Band & Perel, 2007; Eby et al., 2016; D. Marshall et al., 2014).

Research on GPS use in older adult populations has to date focussed upon attitudes and safety concerns, with GPS usage generally being positively associated with high usability and improved safety (Classen et al., 2019; Eby et al., 2016; Emmerson et al., 2013; Stinchcombe et al., 2017). However, it currently remains unclear how prevalent GPS use is amongst older adult population groups, which driving contexts are associated with GPS usage, and whether GPS usage influences driving mobility. Additionally, it is also not yet understood how GPS usage in older drivers is related to cognitive performance. This is of particular interest when considering that spatial orientation detriments reduce driving mobility, as found in Chapters 3 and 4, as GPS use may potentially ameliorate these impairments as a navigation aid.

The current study addresses these research shortcomings by establishing the driving mobility patterns of GPS usage in a large sample of community-dwelling older adult drivers, and how this relates to their cognitive changes. Finally, it will be explored whether GPS allows to ameliorate cognitive changes in driving mobility of older drivers. Specifically, i) the prevalence and demographic profiles of older drivers who use GPS across different driving situations and how this relates to other in-vehicle technologies; ii) whether GPS usage is associated with changes to driving frequency and space; iii) how GPS usage is related to objective and subjective cognitive measures of spatial navigation and episodic memory, and iv) whether GPS usage enables individuals with worse wayfinding ability to have a greater driving mobility. It is hypothesised that i) drivers further along the older age spectrum will be most likely to use GPS and other in-vehicle technologies more frequently; ii) older drivers who use GPS will drive more frequently and at a greater driving space; iii) older drivers with worse spatial navigation and memory performance will use GPS more frequently and in more familiar environments; and iv) individuals with worse wayfinding performance who use GPS will have greater driving mobility than those who do not use GPS.

5.2 Methods

5.21 Participants

895 older adults (mean age: 71.04, 514 female) were recruited between February 2021 and August 2021 to complete the study. The inclusion criteria for the study were being age 65 or older, having a current driving license, and being a regular driver (driving once per week minimum). The exclusion criteria for the study were not driving regularly, having a medical condition that contraindicates driving, having an untreated significant visual or physical impairment, having a diagnosis of mild cognitive impairment or dementia, taking medications for dementia, and high alcohol consumption (> 45 units per week). Participants were recruited via online and media advertisement, such as through dementia research databases (Join Dementia Research (https://www.joindementiaresearch.nihr.ac.uk/) and online driving forums (https://olderdriversforum.com/decision-study/). Signed informed consent was obtained from each participant prior to conducting the experimental protocol and data was attributed anonymously. Ethical approval for the study was provided by the Faculty of Medicine and Health Sciences Research Ethics Committee at the University of East Anglia (FMH2019/20-134).

5.22 Procedure

Participants initially completed questionnaires online related to their demographic information, driving habits, health, driving history, driving habits, and a custom questionnaire on navigation ability. Following this, participants completed a neuropsychological testing battery assessing cognitive performance across a variety of domains (see Table 3.1) (only allocentric orientation, egocentric orientation, recognition memory, and source memory were used for this analysis).

5.23 GPS frequency, situational use, and wider technology usage

Within the driving history questionnaire, participants were asked "Which of the following in-car technology do you use?" If participants selected Sat-Nav (dedicated device) or Sat-Nav (app on mobile phone), they were asked "How often do you use (in-car technology)?" (No use – Rarely – Some Journeys – Most Journeys – Every time I drive). This comprised the GPS frequency measure. The number of non-navigation assistance technological items participants used (i.e., Bluetooth audio device, Cruise control, Lane control, Parking assistance, or Other) were totalled for the wider IVT usage measure. Participants were also asked, "In which of the following situations do you use Sat-Nav?" (I do not use Sat Nav – If I get lost on a new route – As a backup in case I forget a planned route – When following a new route to a familiar destination – The entire journey, when driving to a new destination – The entire journey, when driving along a familiar route. The most GPS dependent situation was coded for each participant ("I do not use Sat Nav" = least dependent, "The entire journey, when driving along a familiar route" = most dependent). This comprised the GPS situational usage measure.

5.24 Driving, Orientating, and Navigating questionnaire (DON)

We developed a custom driving-based navigation questionnaire, the Driving, Orientating, and Navigation questionnaire (DON) (see Supplementary Information S5.1), which assesses for subjective sense of direction and spatial strategy when driving and navigating. Supplementary analysis within Chapter 2 demonstrated that the DON validates against the Santa Barbara Sense of Direction of Scale (SBSOD) (Appendices: Supplementary Table S2.5). The DON comprised of five questions related to landmark-based navigation strategies, seven questions related to allocentric navigation strategies, and four questions related to egocentric navigation strategies. These questions were totalled for each category. The total DON score comprised a sense of direction score.

5.25 Driving behaviour measures

As part of the DHQ, participants were asked "What is your annual mileage in a typical year?". This comprised a driving frequency measure. Participants were also asked how often they drive within 6 geographical divisions, from within their immediate neighbourhood (lowest), to outside their region (highest). For each question, scores were rated from one (a few times in the year) to four (every day). Scores were totalled across all six items, and this measure comprised driving space.

5.26 Statistical analysis

Firstly, the prevalence of GPS usage was estimated across the sample, and binary GPS use status (use/no use) was associated with demographic and driving variables using t-tests and chi-squared tests. It was then assessed how frequency and contextual usage of GPS related to demographic differences using linear regression (frequency) and multinomial logistic regression (situational usage). A post-hoc analysis was then conducted to assess how non-GPS in-vehicle technology usage related to demographic variables to enable comparisons with GPS usage. ANCOVA was used to assess how situational usage of GPS related with cognitive functioning, and hierarchical regressions were conducted to assess the relationship between GPS frequency and cognitive functioning. MANCOVA was used to assess how contextual usage affected driving mobility (driving frequency and space). In assessing the relationship between GPS use and cognitive variables, age and gender (0 = male, 1 = female) were used as covariates for analysis due to their previously established effects on spatial orientation and episodic memory. Age was also used as a covariate for analysis between GPS frequency use and driving behaviour as older age is associated with a reduced driving frequency and space. To establish whether GPS use can offset wayfinding impairments to improve driving mobility, a median split was conducted on the allocentric orientation measure to define good and poor navigators, and it was compared among worse spatial navigators whether there are differences in driving frequency and driving space between GPS status use groups (use/no use). ANCOVAs were used to assess how driving mobility differed between both groups.

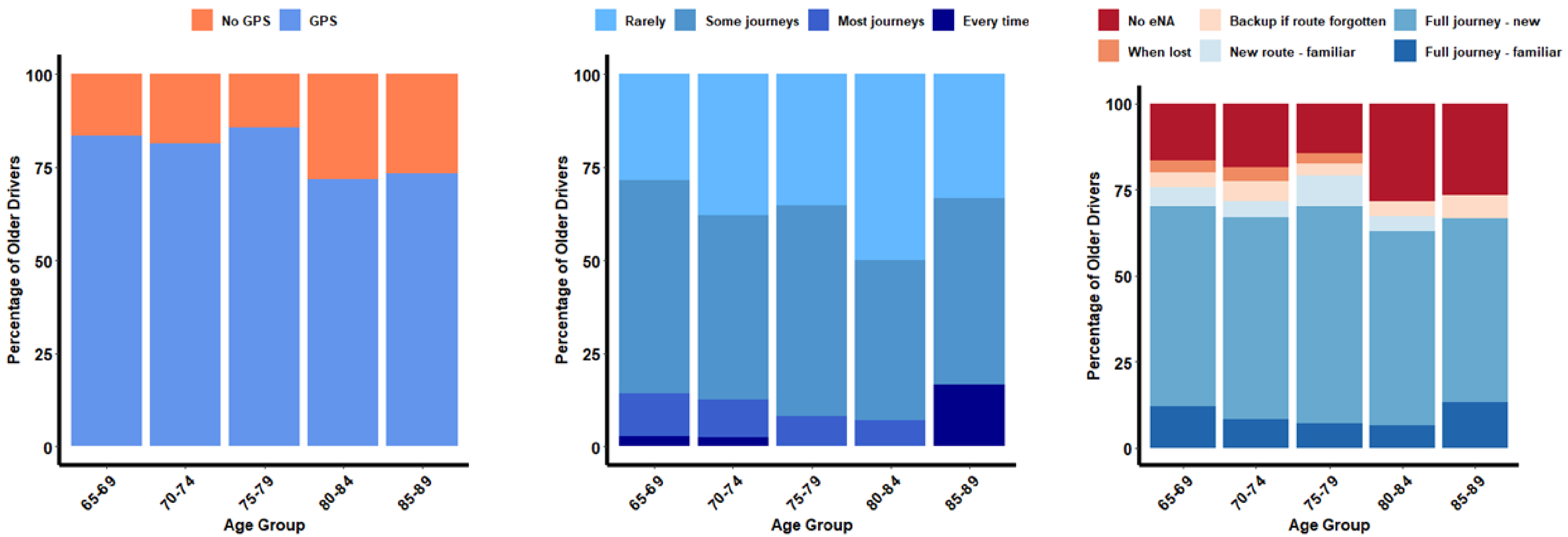
Outliers were assessed using boxplots, Q-Q plots, and histograms. Extreme outliers were removed using for recognition memory (16), source memory (17), typical annual mileage (17), weekly trips (14), and weekly trip distance (11). A significance threshold of 0.05 was used to assess statistical significance. Tukey’s post-hoc comparisons were carried out to establish group differences in driving mobility and cognitive performance across GPS situational usage groups. Multinomial logistic regressions were used to assess how both demographic and cognitive variables predicted GPS behaviour. The reference group selected for each regression was individuals who do not use GPS, as this provided the greatest theoretical contrast to GPS usage situations. For MANCOVA analysis, checking normality of outcome variables was conducted using visual inspection of histograms and normality of residuals was conducted by Q-Q plots. For regression analysis, appropriate diagnostic tests and visual inspections were conducted to assess linearity and homoscedasticity, normality of residuals, independence of residuals, and multicollinearity. All analysis was carried out in R (version 4.3.1) using multcomp, nnet, olsrr, car, stats, and psych packages.

5.3 Results

5.31 The demographic patterns of GPS usage amongst older adult drivers

Within the present cohort, 82.35% of older drivers reported using GPS. Of the individuals who use Sat Nav, 53.63% reported using GPS on some journeys, 33.87% reported rarely using GPS, 10.08% reported using GPS on most journeys, and 2.42% reported using GPS every time they drive. The majority of drivers used GPS for the entire journey to a new destination (71.64%); followed by the entire journey along a familiar route (11.94%); on new routes to familiar destinations (6.65%); for backup in case of forgetting a route (5.70%); and then when lost on a new route (4.07%) (see Figure 5.1).

Figure 5.1. Prevalence of GPS usage across older driver age groups.



Individuals who use GPS reported a higher number of driving days per week (*M* = 4.27, SD = 1.59) compared to those who do not use GPS (*M* = 3.91, SD = 1.70), *p* = .02, *d* = 0.22 (small effect); as well as a greater number of trips per week (*M* = 2.01, SD = 1.86 compared to *M* = 1.61, SD = 1.22), *p* = .008, *d* = 0.23 (small effect); a higher typical annual mileage (*M* = 6923.47, SD = 3491.63 compared to *M* = 5475.45, SD = 3843.82), *p* <.001, *d* = 0.41 (medium effect); and had a greater driving space (*M* = 9.85, SD = 2.79 compared to *M* = 9.06, SD = 3.31), *p* = .006, *d* = 0.27 (small effect) than individuals who do not use GPS. Furthermore, individuals who use GPS used more other in-vehicle technologies (*M* = 0.74, SD = 0.68) than individuals who do not use GPS (*M* = 0.24, SD = 0.43), *p* <. 001, *d* = 0.77 (strong effect) (see Table 5.1).

Table 5.1. Participant demographics and driving characteristics

Variable	**GPS usage**			
	No GPS	**GPS**	***p*-value**	**Effect size *(d)***
Participants	158	737		
Age (years)	71.51 (5.25)	70.94 (4.90)	0.21	0.11
Education (years)	14.91 (2.63)	14.80 (2.77)	0.64	0.04
Driving experience (years)	48.62 (7.85)	49.35 (7.34)	0.29	0.10
Subjective driving ability	3.72 (0.66)	3.79 (0.64)	0.17	0.12
Weekly driving (days)	3.91 (1.70)	4.27 (1.59)	0.02	0.22
Typical mileage	5475.45 (3843.82)	6923.47 (3491.63))	<.001	0.41
Weekly trips	1.61 (1.22)	2.01 (1.86)	<.01	0.23
Driving space	9.06 (3.31)	9.85 (2.79)	<.01	0.27
Maximum weekly trip distance (miles)	9.22 (10.22)	9.59 (12.08)	0.77	0.03
Other in-vehicle technology	0.24 (0.43)	0.74 (0.68)	<.001	0.77
Note. Welch’s two sample t test conducted for group differences. Cohen’s D was used to assess effect sizes.				

A multiple regression was conducted to assess how age, gender, and education were associated with GPS frequency. Only being male gender was associated with increased GPS frequency (β = -0.24, p =.03, CI[-0.45, -0.02]) (see Table 5.2).

A multinomial logistic regression was conducted to assess how age, gender, and education predicted GPS situational usage. Being of early old age (expβ = 0.93, p <.01, CI[-0.13, -0.02]) and being of male gender (expβ = 0.25, p <.001, CI[-1.93, -0.81]) was associated with increased usage of GPS for the entire journey when driving to a familiar environment.

5.32 The demographic patterns of wider IVT usage amongst older drivers

A linear regression was then conducted to assess how non-GPS IVT usage is associated with age, gender, and education. Being of early old age (β = -0.01, p = 0.001, CI[-0.02, -0.01]) and being of male gender (β = -0.29, p < .001, CI[-0.38, -0.20]) was associated with greater usage of other IVT (see Table 5.2).

Table 5.2. Multiple linear regression analysis comparison between frequency of GPS usage and other IVT usage

Variable	Age	Gender	Education	Model R^2
GPS frequency	-0.01	**-0.24***	0.02	0.02
Other IVT usage	**-0.01****	**-0.29*****	-0.01	0.04

Note.
*p < .05, **p < .01, ***p < .001
† IVT = In-vehicle technology
†† Displaying unstandardised beta coefficients.

5.33 How is GPS situational usage associated with driving mobility?

A MANCOVA design was employed to assess how GPS situational usage influences driving frequency and driving space after controlling for age. There was a statistically significant difference between GPS situational usage groups on driving space and driving frequency combined, $F(5, 874) = 4.786$, $p < 0.001$, η_p^2 (partial eta squared) = .05. Tukey's post-hoc pairwise comparisons revealed that individuals who do not use GPS have a lower annual typical mileage (M = 5475.45, SD = 3843.82) than those who use their GPS when travelling new routes to a familiar destination (M = 7275.51, SD = 3830.55); for the entire journey to a new destination (M = 6685.28, SD = 3418.51), and for the entire journey to familiar destinations (M = 8521.60, SD = 3613.28). Individuals who used GPS for the entire journey to familiar destinations also had a higher typical mileage than those who used GPS for the entire journey when driving to new destinations and those who use their GPS when they are lost (M = 5933.33, SD = 3400.64). Tukey's post-hoc comparisons also revealed that individuals who use GPS for the entire journey to familiar destinations also had a greater overall driving space (M = 10.63, SD = 2.47) than those who do not use GPS (M = 9.06, SD = 3.31) and those who use GPS only when lost (M = 8.90, SD = 2.81).

5.34 How is GPS frequency associated with driving mobility?

A hierarchical regression design was then employed to establish whether GPS frequency is associated with driving mobility after controlling for age effects. More frequent GPS usage was associated with a greater typical annual mileage ($\beta = 555.40$, $p = 0.001$, CI [221.43, 889.32]) and greater driving space ($\beta = 0.38$, $p = 0.008$, CI [0.10, 0.66]).

5.35 How is GPS frequency associated with cognitive performance?

A hierarchical regression design was employed to establish whether GPS frequency is associated with objective cognitive performance after controlling for age and gender effects. No objective cognitive functions were associated with increased GPS frequency.

A hierarchical regression model was employed to establish whether GPS frequency is associated with subjective navigation ability after controlling for age and gender effects. A worse subjective sense of direction was associated with greater GPS frequency when driving ($\beta = -1.62$, $p = 0.003$, CI [-2.70, -0.55]) (see Table 5.3).

5.36 Is GPS situational usage associated with cognitive performance?

An ANCOVA design with age and gender as covariates was carried out to establish how GPS situational usage is associated with objective cognitive performance (see Table 5.3). The only cognitive function with significant associations with GPS situational usage was source memory ($F(5, 645) = 2.327$, p = 0.04, $\eta_p^2 = 0.018$). Post hoc comparisons with a Tukey correction revealed significantly worse source memory performance in individuals who use GPS as backup in case they forget a route (M = 83.67, SD = 14.91) compared to individuals who do not use GPS (M = 91.39, SD = 9.94) and those who use GPS for everyday journeys to familiar destinations (M = 90.29, SD = 12.15) (see Figure 5.2).

An ANCOVA design with age and gender as covariates also revealed that subjective sense of direction is associated with GPS situational usage ($F(5, 818) = 6.792$, p < 0.001, $\eta_p^2 = 0.04$).

Post hoc comparisons with a Tukey correction revealed that individuals who use GPS for the entire journey to new destinations have a subjectively worse sense of direction (*M* = 89.89, SD = 11.69) than individuals who use GPS when following a new route to a typical destination (*M* = 95.45, SD = 11.28), those who use GPS as a backup in case they forget a planned route (*M* = 95.24, SD = 11.43), and those who do not use GPS (*M* = 94.40, SD = 10.19) (see Figure 5.2).

Table 5.3. The association between cognitive ability and GPS contextual usage

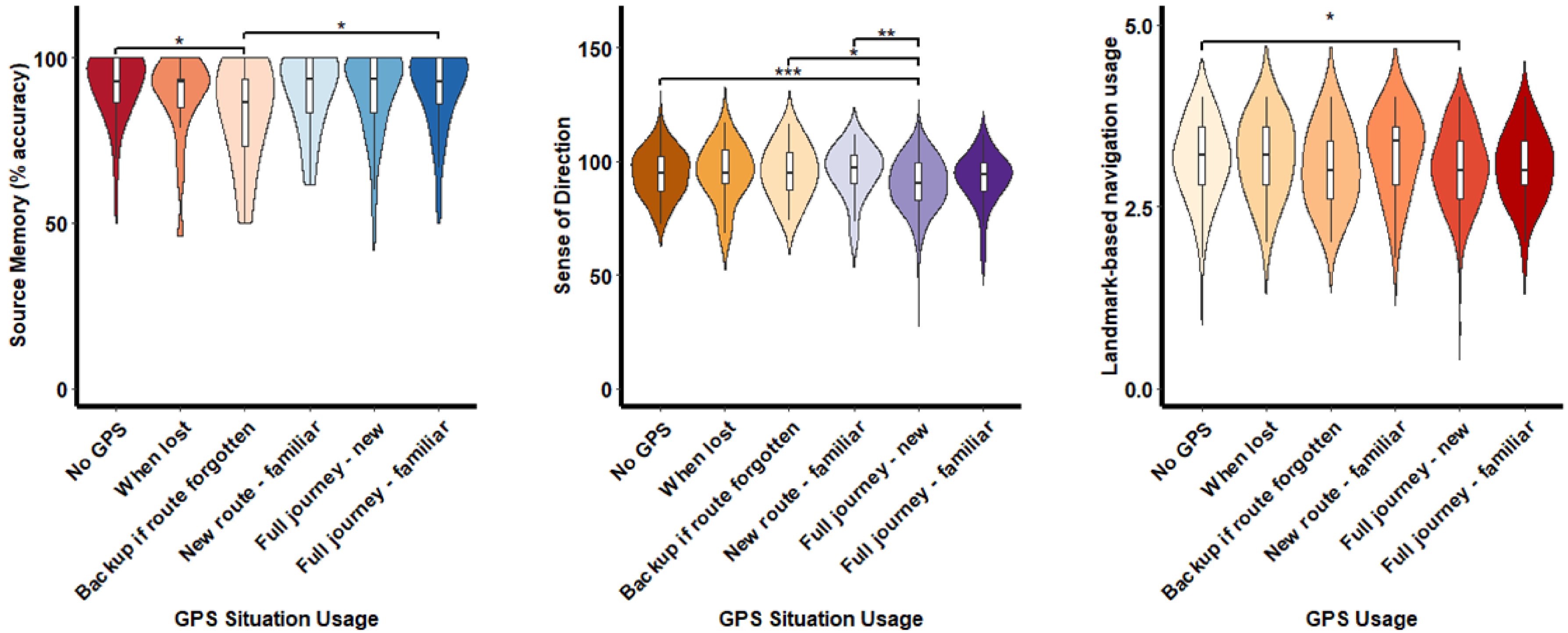
	GPS situational usage categories						
Cognitive variable:	**No GPS (1)**	**When lost (2)**	**Backup if route forgotten (3)**	**New route – familiar (4)**	**Full journey – new (5)**	**Full journey – familiar (6)**	**Sig. group differences**
Allocentric orientation	4.09 (1.87)	3.56 (1.43)	3.72 (1.51)	4.15 (1.87)	3.64 (1.84)	3.25 (1.47)	-
Egocentric orientation	64.64 (34.40)	55.96 (35.48)	60.43 (29.57)	55.50 (26.56)	59.06 (35.26)	42.06 (28.28)	-
Recognition Memory	94.91 (6.13)	92.88 (8.18)	95.87 (4.11)	96.88 (3.51)	95.17 (5.62)	95.22 (5.80)	-
Source Memory	91.39 (9.94)	88.01 (13.23)	83.68 (14.91)	90.04 (11.71)	89.09 (12.38)	90.29 (12.15)	$^{£, \$}$
Sense of Direction	94.40 (10.19)	94.72 (12.00)	95.24 (11.43)	95.45 (11.28)	89.89 (11.69)	91.88 (11.38)	$^{\%, ?, €}$
Landmark-based navigation usage	3.14 (0.54)	3.19 (0.52)	3.05 (0.54)	3.24 (0.54)	3.04 (0.53)	3.05 (0.49)	$^{!}$

Note.

For Landmark-based navigation usage, all groups using GPS (2-6) were compared with the reference group of no GPS (1).

$^{£}$ = (1) vs (3), *p* = 0.01; $^{\$}$= (6) vs (3), *p* = 0.05; $^{\%}$ = (4) vs (5), *p* < 0.01; $^{?}$ = (1) vs (5), *p* < .001; $^{€}$ = (3) vs (5), *p* < .05; $^{!}$ = (1) vs (5), *p* <.05.

Figure 5.2. The association between GPS situational usage and cognitive variables.



5.37 Is GPS usage associated with subjective spatial strategy?

A linear regression was conducted to establish whether GPS situational usage is associated with increased landmark-based navigation strategies. Only individuals who use GPS for everyday journeys to new destinations had a significant association with reduced landmark-based navigation strategies compared to individuals who do not use GPS ($\beta = -0.10$, $p < .05$, CI[-0.20, -0.00]) (see Figure 5.2).

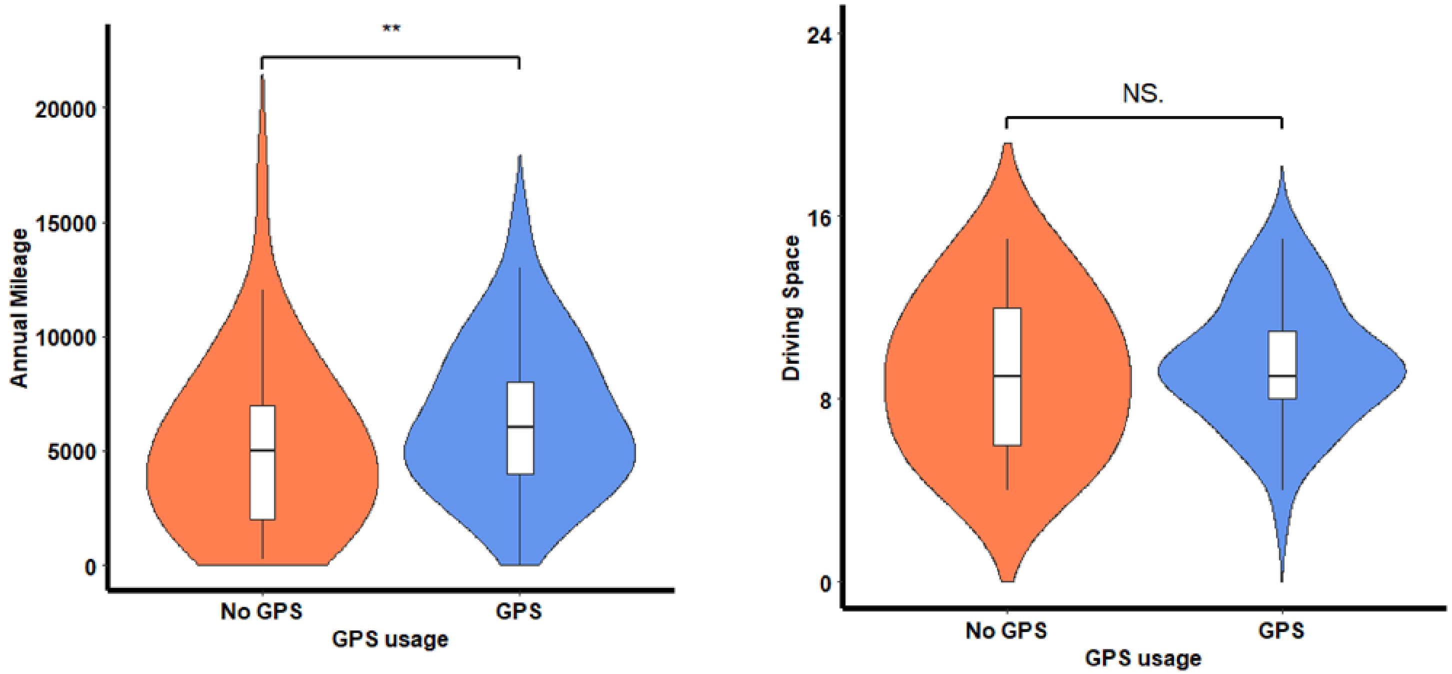
A linear regression revealed that there was no association between GPS frequency and landmark-based navigation strategies.

5.38 Can GPS usage ameliorate cognitive changes to improve driving mobility?

After defining good and poor navigators, it was found that within the poor wayfinding group, 161 older drivers used GPS compared to 44 who did not. An ANCOVA design revealed that individuals with wayfinding impairments who use GPS have greater driving frequency than individuals who do not use GPS, F(1, 200198) = 5.5626.434, p = 0.021, ηp2 = .03. Tukey's post-hoc tests revealed that individuals who use GPS have a greater typical mileage (M = 6387.51468.29, SD = 3264.9804.76) than individuals who do not use GPS (M = 4994.36, SD = 3510.35).

ANCOVA revealed no significant differences between the same groups for driving space (see Figure 5.3).

Figure 5.3. Driving mobility of older drivers with poor wayfinding ability split between GPS usage.



5.4 Discussion

Overall, this study shows that a very high percentage (> 80%) of older people use GPS in car driving, and that drivers who use GPS more frequently have greater driving mobility, in particular driving greater distances and having a greater overall driving space even when reporting a reduced subjective sense of direction. Importantly, it is demonstrated that GPS use facilitates driving mobility in individuals who show reduced wayfinding ability. This study also expands on previous findings showing that the contextual situations in which drivers rely on GPS are indicative of both subjective and objective cognitive differences.

In more detail, within a large community-dwelling sample of older drivers, the majority of older adults reported using GPS technology when driving (82.49%). These patterns complement previous findings within other older adult populations, where it has been found that GPS technology is commonly adopted amongst older drivers and have high acceptability rates (Eby et al., 2018). Most older drivers reported using GPS for some driving journeys, with the least using it every time they drive. GPS was most commonly used for the entire journey to a new destination, which mirrors findings in a smaller sample of younger adults, where GPS was predominantly used for long and unique trips, and for approximately a quarter of overall trips (Knapper et al., 2015).

Interestingly, a large US-based study (Eby et al., 2018) found that most older drivers used GPS always when driving, which may indicate there may be cultural differences influencing when older adults use GPS. One potential reason for this discrepancy may be driving distance, as within the US older drivers may be more likely to travel longer distances to reach their destination than in the UK, and therefore be more likely to use GPS for longer trips. Such potential country/culture specific differences need to be further explored in the future.

The findings in this study also contrast previous findings that older drivers are more likely to use GPS than younger drivers (Kostyniuk et al., 1997). However, in the aforementioned study, older drivers were compared with younger driver populations and therefore variances across the older age spectrum were not tested for specifically. Furthermore, GPS use has since become considerably more pervasive and is commonly pre-installed in modern vehicles, increasing access to this technology across age groups. One potential reason why GPS use is less prominent amongst older individuals on the older age spectrum may be due to difficulty in using the devices, as older populations may find difficulties in setting up and using GPS devices (Bryden et al., 2013). Early old age males were more likely to show greater dependence on the devices during driving, as they were significantly more likely to use them when navigating during the whole journey to familiar destinations. This relationship may be influenced by the propensity to use in-vehicle technology in general, as it was found that the same demographic of early old age males were also more likely to use other IVT, replicating previous survey findings (Eby et al., 2018). Having a greater technological literacy may therefore increase the ease of use for adopting GPS technologies.

Importantly, this study establishes for the first time that GPS technologies can mitigate age-related cognitive changes to facilitate greater driving mobility, as older adults with poor navigation performance who use GPS reported a greater annual mileage than those who do not use GPS. This supports the proposal that in-vehicular technologies can potentially compensate for age-related cognitive impairments in enabling driving mobility and independence in older drivers (Band & Perel, 2007; Eby et al., 2016; Gish et al., 2017). As worse wayfinding performance is associated with reductions in driving mobility, as found in Chapters 3 and 4, GPS technologies can potentially aid in route guidance and reduce the cognitive load during navigation.

When assessing the relationship between GPS usage and cognition, it was found that increased GPS frequency and situational usage indicating greater dependency on GPS (i.e. using GPS for the entire journey to new destinations) was associated with a reduced self-reported sense of direction within healthy older adults, but not objective spatial navigation impairments. These results indicate that usage of GPS when driving may be determined by confidence in wayfinding successfully, as opposed to wayfinding ability. As GPS technology became more common in the 2000s (Hurst & Clough, 2013), it is possible that older adults may have established their spatial cognitive abilities prior to the emergence of regular GPS usage, and therefore current measures of spatial orientation performance may be representative of lifetime navigation skill, determined less by current GPS reliance. Previous experimental studies, conducted amongst younger populations, have found that driving whilst using GPS is associated with impairments to route learning (Brishtel et al., 2021; Burnett & Lee, 2005). Therefore, whilst greater GPS usage may not impair objective cognitive facets overall, they may impair learning of spatial environments to which they are applied.

In conclusion, this study provides valuable insights into understanding how the older adult population uses GPS technology, shows how contextual use of GPS can indicate for subjective and objective cognitive differences, and demonstrates that drivers with poorer wayfinding abilities can effectively use GPS technology to improve their driving mobility.

Chapter 6: General Discussion

6.1 Summary of main findings

The principal aim of this thesis is to improve the understanding of how cognitive functioning impacts driving behaviour in healthy older age. With the increased urgency to develop a cognitive screening tool to evaluate driving performance in older age, this thesis aimed to examine how a novel online cognitive test battery could be used to assess driving behaviours over time within a large sample of older adults. As spatial orientation abilities are critical to cognitive changes in both healthy ageing and neurodegenerative disease yet have not been explored in relation to driving behaviour, a main objective of this thesis was to examine how spatial orientation performance relates to driving behaviour and to establish the strength of this relationship in comparison to other cognitive tests. Against the backdrop of evidence showing demographic shifts in increasing urban-rural migration of older adults within the UK, a secondary aim of this thesis was then to explore how the relationship between cognitive functioning and driving behaviour relates to environmental differences. Finally, we move beyond the investigation of neurocognitive profiling for driving behaviours, aiming to understand how the use of IVT can be used to offset the impact of impaired cognition to improve driving conditions for older adults.

Chapter 1 discusses how mixed evidence and approaches taken in understanding cognitive functioning in relation to driving behaviour in older age has posed challenges in developing practical cognitive screening tools for driving performance; synthesised the pre-existing evidence on how executive functioning, processing speed, attention, and visuospatial skills are more consistently implicated within the literature as cognitive domains that most sensitively relate to driving behaviour; and spotlights how – despite strong theoretical alignment to driving performance – spatial orientation performance has been virtually unexplored in relation to driving behaviour. Chapter 2 introduced the novel cognitive battery, NeurOn, which underpins the cognitive investigations throughout this thesis. We demonstrate moderate test-retest reliability of the novel cognitive battery and moderate validity to gold-standard cognitive assessment tools, discussing the implications in translating traditionally implemented paper-based in-clinic cognitive tests to digital, online cognitive assessments conducted in a remote environment. Chapter 3 establishes spatial orientation performance as a critical cognitive component for driving frequency and difficulty in older age, as it was the only cognitive component within the novel cognitive battery demonstrating robust associations across the older age spectrum, and hypothesises how spatial orientation impairments may contribute towards the increased risk of road intersection-based RTIs amongst older populations. Chapter 4 demonstrates how the interaction between cognitive functioning on driving behaviour is modulated by environmental context, as rural and urban settings pose unique challenges in maintaining driving mobility and safety. The final experimental component, Chapter 5, establishes the relationship between GPS navigation usage and increased driving mobility in older populations, with individuals with impaired navigation performance showing increased driving frequency when using GPS navigation devices compared to those who do not use GPS navigation when driving.

6.2 Revisiting the A-Z: cognitive mapping of driving behaviour

The overarching goal of this thesis is to improve the understanding in how cognitive functioning impacts driving behaviour within a healthy older adult population, and to develop the neurocognitive profiling in how driving behaviour changes during older age. In Chapter 1, it was discussed that the literature on cognitive phenotyping of driving behaviour has been limited by methodological limitations such as small sample sizes, a sporadic selection of cognitive tests, and limited research in some cognitive domains relevant to driving behaviour. These limitations have impeded the ability to make robust conclusions on the relationship between cognitive functioning and driving in older age, as well as the development of reliable assessments that can accurately predict driving performance in older adults. This thesis, and Chapter 3 in particular, addresses these gaps by leveraging a large sample size of cognitive data (>800 participants) related to driving behaviour. The larger sample provides not only benefits in increasing the statistical power of the findings, enabling for more reliable and generalisable conclusions, but also provides a nuanced understanding of how the variability of age-related cognitive changes impact driving behaviour. Furthermore, the wide range of cognitive domains assessed within this thesis enable for a comprehensive understanding into developing a neurocognitive profile of driving behaviours in older age. By integrating less explored domains, such as spatial orientation, alongside domains with which significant research has been undertaken, this enables for a comparative understanding into which cognitive domains have the strongest relationship with different driving behaviours.

The findings from Chapter 3 align with well-established findings that executive functioning, attention, and processing speed are significantly related to driving behaviour in older age. Worse cognitive performance across these domains consistently related to reduced driving mobility, corroborating previous literature showing that reduced worse cognitive functioning is associated with increased driving impairments and reduced driving exposure in older age (Anstey et al., 2005; Rapoport et al., 2013). As discussed in Chapter 1, these cognitive domains demonstrate considerable overlap, with subcomponents in each of these domains being involved in the performance across all domains during cognitive assessments. There is also dovetailing in neural architecture, with these domains relying heavily on frontal brain areas, which are particularly susceptible to age-related cognitive decline (Zanto & Gazzaley, 2019). This interconnectedness suggests that age-related neurophysiological changes to frontal brain regions significantly impact these cognitive components underpinning driving performance. As outlined in Chapter 1, successful driving performance is predicated on the performance of the aforementioned cognitive functions to be performing sufficiently. It is therefore of little surprise that worse cognitive performance in these domains is associated with increased driving challenges. In explaining as to why cognitive impairments are associated with reduced driving exposure, it is considered that experiencing cognitive problems is associated with increased driving-related discomfort, which when recognised amongst older adults, leads to modifying driving behaviours such as undertaking changing trip frequencies (Meng et al., 2013).

6.21 The role of spatial orientation and driving performance in older age

A key objective of this thesis has been to develop an understanding of how spatial orientation relates to driving behaviour in older age. Across Chapters 3 and 4, spatial orientation changes were established as a key cognitive marker associated with both driving mobility and safety in older age. Within Chapter 3, SEM analysis found that spatial orientation was the only cognitive domain associated with driving frequency and difficulty and was also the only cognitive marker demonstrating robust effects across the older age spectrum. This was supported within Chapter 4, where global cognitive changes over were not associated with changes to driving mobility but decline in allocentric spatial orientation functioning was indicative of reduced driving space among urban residents over a one-year period. Taken together, one of the major findings of this thesis is the pronounced role of spatial orientation as an indicator for driving performance.

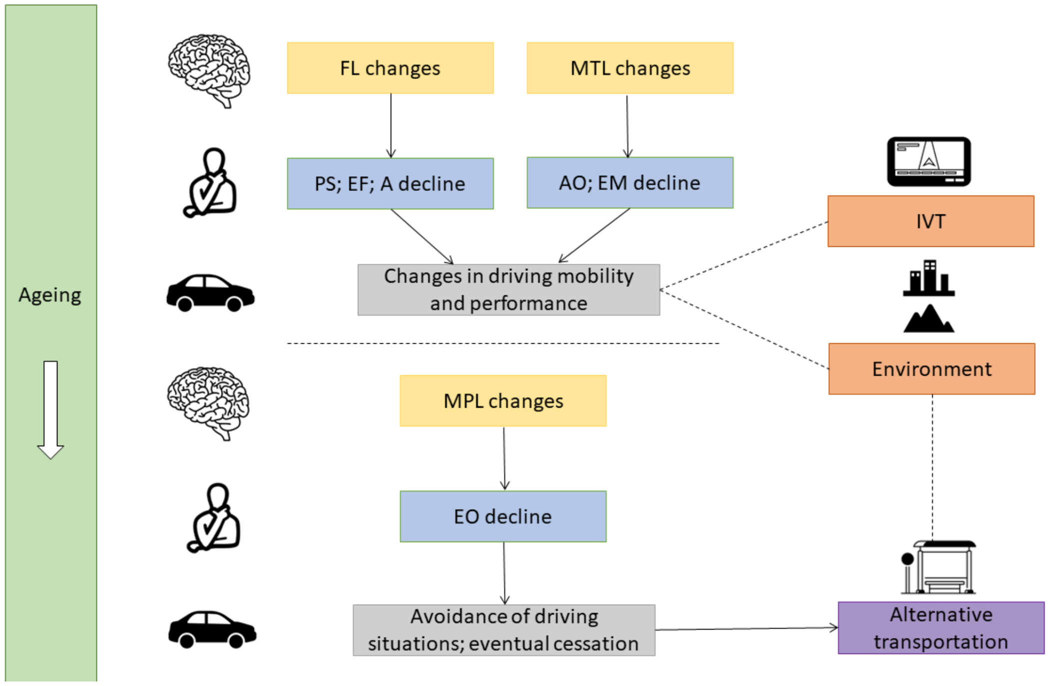
The findings in Chapter 3 show that worse spatial orientation performance is associated with impaired driving and reduced driving frequency in older age. Specifically, allocentric orientation ability was related to increased driving difficulty, and individuals with allocentric orientation impairments experienced significantly more difficulty in driving situations such as turning across oncoming traffic and parallel parking. In both of these situations, the individual must understand where the positioning of their vehicle is in relation to other road vehicles as well as the spatial road layout, utilising allocentric orientation abilities. This is supported by findings assessing the smoothness of lane changing in relation to spatial navigation abilities, where both older and younger adults demonstrated an effect of reduced spatial navigation performance and reduced lane smoothness – with this effect being exacerbated in older adults (Kunishige et al., 2020). Furthermore, Nori et al., (2020) demonstrated that greater usage of survey spatial strategies, utilising an allocentric perspective, predicted fewer driving violations and errors than route and landmark strategy users. Taken together, the findings demonstrate that allocentric orientation is a key cognitive function associated with driving behaviour in older age.

Furthermore, spatial orientation deficits may exacerbate driving deficits related to executive functioning, processing speed, and attention, as these impairments increase the cognitive load required to perform driving tasks. For example, if a driver is struggling to accurately judge the distance between their car and other vehicles, the additional resources involved to this processing may detract from their ability to task switch effectively or maintain attention on the road, impairing overall driving performance. These effects are potentially bidirectional in nature, as processing speed and executive functioning are involved in the planning of complex route planning scenarios and reference frame switching between egocentric and allocentric orientation (Colombo et al., 2017; Li & King, 2019). However, this remains to be speculative, as there is contrasting evidence on the effect of cognitive load on lane keeping performance. There is a divergence of views on whether increased cognitive load impairs lane keeping performance (Mehler et al., 2009; Reimer, 2009), or improves lane keeping through increasing the awareness of maintaining focus (Engström et al., 2005; He et al., 2014). Alongside providing further clarity into the effects of cognitive load on maintaining adequate road positioning, future research should focus on establishing the role of spatial orientation impairments on cognitive load when driving.

Whilst allocentric orientation was significantly related to driving difficulty, egocentric orientation deficits showed greater predictivity in avoiding challenging driving situations. This may exemplify how reduced performance in medial-temporal lobe based spatial strategies are often compensated by increased medial-parietal based egocentric strategy usage in older age (Burgess, 2008). When no longer able to rely on the compensatory mechanism for orienting their environment, individuals with egocentric deficits may then cease high-difficulty situations to reduce their driving risk. Egocentric orientation deficits may therefore be a key signature for restricting driving behaviours, and eventually driving cessation.

A theoretical model outlining how spatial orientation and wider cognitive changes processes impact driving behaviour in ageing is outlined below in Figure 6.1. An explanation of the figure is as follows: during the ageing process, brain changes that take place within the frontal lobe and medial-temporal lobe result in decline in cognitive functions such as spatial orientation (in particularly allocentric orientation), episodic memory, processing speed, executive functioning, and attention (Harada et al., 2013; Salthouse, 2009). As found within Chapters 3 and 4 within this thesis, these cognitive functions lead to reduced driving mobility and an increase in driving difficulty. The interaction between cognitive decline and driving behaviour is mediated by environmental settings and the use of IVT, as established in Chapters 4 and 5, respectively. As the neurophysiological impacts of ageing progresses, changes in the brain emerge within the medial-parietal lobe, leading to impairments toward egocentric orientation performance (Burgess, 2008; Colombo et al., 2017). As found in Chapter 3, egocentric impairments showed the strongest relationship with the avoidance of challenging situations in older age, and therefore it may be these cognitive changes that lead to reduction in driving and eventual driving cessation. At this stage, the individual is then dependent on alternative methods to maintain mobility – which is influenced by their environmental setting and proximity to transport alternatives (Mielenz et al., 2024; Strogatz et al., 2020).

Figure 6.1. A theoretical model outlining how cognitive changes in ageing affects driving behaviour.



Abbreviations: FL = Frontal Lobe; MTL = Medial-Temporal Lobe; PS = Processing speed; EF = Executive functions; A = Attention; AO = Allocentric orientation; EM = Episodic memory; MPL = Medial-Parietal Lobe; EO = Egocentric orientation[1].

The role of spatial orientation in predicting driving difficulty also provides a potential explanation as to why road safety is reduced in Mild Cognitive Impairment (MCI) and Alzheimer's disease, where medial temporal and medial parietal lobe atrophy increases respectively. Whilst individuals with dementia are often able to drive in the early stages of the disease, accident risks are between two and five times higher than healthy older adults (Marshall, 2008). Similarly, within MCI, recognised as the transitional stage between healthy aging, individuals are significantly more likely to fail on-road assessments and make errors during simulated driving (Hird et al., 2017). Within the present cohort, which did not include individuals with MCI or dementia, allocentric orientation deficits were associated with increased difficulty in turning across oncoming traffic and parallel parking. Likewise, it has been previously found that individuals living with dementia, who typically report greater allocentric orientation deficits, are more likely to avoid making turns across oncoming traffic

[1] Icons used in Figure 6.1: "Brain" by Giorgi; "Thinking" by Takao Umehara; "Car" by Langtik; "sat nav" by Lee Hills; "Urban Rural" by OCHA Visual"; "bust stop" by intan sari".

(O'Connor et al., 2013). Older adults are overrepresented particularly in intersection crashes that involve multiple vehicles (Lombardi et al., 2017), and therefore orientation deficits are a key individual risk factor for road collisions involving turns across oncoming traffic.

6.22 Mixed results: Cognitive domain, or test selection?

The findings in Chapter 3 showing that episodic memory performance significantly relates to driving behaviour, and in particularly increased driving difficulty, are intriguing as there is mixed evidence on the association between episodic memory on driving performance in healthy ageing populations (Mathias & Lucas, 2009). One potential reason for this discrepancy is in differences used within the methodology to measure memory. As a cognitive domain, memory is one of the most complex and multifaceted, with a variety of cognitive tests used to measure different subcomponents of memory (Harvey, 2019). This is reflected within the driving literature, as tests representing memory are diverse and range from word-based and verbal memory tests (e.g. Immediate & delayed word recognition, Rey Auditory Verbal Learning Test) to visual memory tests (e.g. RCFT – immediate recall, Wechler Memory Scale) (Depestele et al., 2020). These different tests tap into distinct neural processes and memory systems, which may vary in their relevance to driving tasks.

The picture recognition task used within the present study utilises only visual memory, which has previously been found to be associated with driving behaviour (Ledger et al., 2019; Reger et al., 2004; Richardson & Marottoli, 2003). The spatial component in the picture recognition task, utilised in assessing for source memory, may more sensitively be related to driving behaviour in ageing due to its activation of the spatiotemporal network involved in episodic memory, which similarly to the spatial orientation network, relies heavily on medial temporal lobe structures including the hippocampus (Ekstrom & Hill, 2023). This is supported by the findings in Chapter 3, which show that source memory is related to driving difficulty in older age, but not recognition memory. Given the close relationship between spatial orientation and driving behaviour, the overlap in neural architecture between spatial orientation and episodic memory mechanisms suggests that tasks engaging spatial memory may more sensitively be associated with driving than other memory tasks. Whilst more research needs to be conducted to assess how different aspects of memory are associated with driving behaviour, this methodological variability underscores the importance of carefully selecting measures that align with the specific cognitive demands of driving when investigating the association between cognition and driving.

This issue may also be present for visuospatial skills within this thesis, as although the driving-cognition literature consistently cites visuospatial skills as a key contributory domain to driving behaviour (Sommer et al., 2008), the findings in this thesis demonstrated a ceiling effect when measuring visuospatial ability, limiting the ability to assess visuospatial performance variability with driving behaviour. A variety of measures have previously been incorporated within neuropsychological evaluations (Wolfe & Lehockey, 2016), with the block design, motor-free visual perceptual test, and clock drawing tests showing predictive utility for driving capacity among older adults (Mathias & Lucas, 2009; Oswanski et al., 2007; Schultheis & Fleksher, 2009). The fragmented letters task, a component of the visual object and spatial perception (VOSP) visuospatial perception battery, utilised within this thesis, has previously been associated with worse driving performance in dementia (Lincoln et al., 2006; Yamin et al., 2016). In the context of healthy ageing, however, the observed ceiling effect suggests that this measure may not have been sensitive enough to detect subtle variations in visuospatial skills among participants, therefore resulting in an undetectable relationship with driving behaviour.

One example of a test that may more sensitively identify road safety risk among healthy controls, as well as in neurodegenerative disease, is the Snellgrove Maze Task (SMT). The SMT was specifically designed to examine for aberrant driving performance and correlates with test performance assessing for visuospatial skills, executive functioning, and attention (Snellgrove, 2005). The SMT has also shown strong predictive utility in predicting the outcomes of on-road test assessments across cognitive impairment (Zhang et al., 2024; Staplin et al., 2013; Carr et al., 2011). As the test encompasses spatial problem-solving during movement through the maze, it is also ecological to spatial problem-solving during driving – such as distance estimation to boundaries and route planning. Usage of the SMT or other maze tests, as measured by time completion, may therefore provide more sensitive measures for evaluating the relationship between visuospatial construction and driving behaviour. An additional benefit of the SMT and other maze tasks is that they are not language based and are not strongly confounded by educational attainment or country of birth (Carr et al., 2011), which is advantageous for developing cognitive test evaluations for driving that can be employed universally.

Other visuospatial tests previously involved to assess its relationship to driving in older age have typically involved paper-based tasks, such as the Clock Drawing Test, Rey Osterrieth Complex Figure - Copy, and the Paper Folding Task (Andrews & Westerman, 2012; Anstey et al., 2005; Depestele et al., 2020; Ledger et al., 2019). Recent research has also examined an online digitalised version of the clock drawing task, which has been associated with driving errors in older adults (Yamauchi et al., 2024). However, Tinella et al. (2020) suggest that visuospatial tasks involving a spatial rotation component – such as the Paper Folding Task – may be particularly relevant to driving in older age. Future work should therefore look to assess how different digitalised versions of visuospatial tests more sensitive in healthy ageing relate to driving behaviour to determine which are most sensitive.

6.23 Possibilities afforded by digitalised cognitive testing

The advance of online cognitive assessments for monitoring cognitive trajectories in relation to driving opens up opportunities for developing new, digitalised cognitive tasks that are reliable and sensitive to both cognitive changes in ageing as well as driving performance. Within the SEM analysis in Chapter 3, only allocentric orientation was significantly associated with driving frequency and difficulty. The pronounced associations between driving behaviour and spatial orientation measures relative to other cognitive functions may be due to higher ecological validity between the Virtual Supermarket Task (VST) and real-world driving. During the VST, individuals must form a mental map of the environment, translating between first and third-person spatial representations to orient themselves in a virtual environment, akin to how one orientates themselves whilst driving on both a micro (lane positioning) to macro (location on a given route) scale. Future cognitive tasks assessing driving-related domains may therefore prioritise ecological components in their design to more effectively capture the impact of age-related cognitive changes on driving. Research on the Hazard Perception Test supports this approach, as Malone & Brünken (2016) found that greater ecological validity enables better differentiation in driving experience. Whilst traditional cognitive tasks typically take a reductionist approach – isolating domains at an individual level – future assessments may incorporate multidimensional, dynamic elements that combine multiple cognitive domains whilst enabling measurement of individual domains within the task, more closely mirroring the ecological validity of the complexity of driving. Nonetheless, task difficulty and length should be considered when developing new cognitive tasks sensitive to driving behaviour, as within this thesis, spatial orientation, as measured by the Virtual Supermarket Task, saw higher participant drop-out rates in Chapter 4 compared to other cognitive tests due to its increased difficulty and duration compared to other cognitive tests. This increased burden for participants was witnessed first-hand during in-person data collection of the VST within Chapter 2.

One potential approach to reduce the attrition rate over longitudinal cognitive change studies due to task difficulty, afforded by the digitalisation of cognitive testing, is to use adaptive study designs. Adaptive digitalised cognitive testing utilises selection algorithms to tailor task difficulty to the participant's performance, enabling participants with varying cognitive abilities to complete the same cognitive task at suitable difficulty levels. This reduces ceiling and floor effects of cognitive test performance, improving test sensitivity. A further advantage of adaptive cognitive tests is that they can potentially compensate for learning effects in longitudinal testing by adjusting for participant performance over time. Adaptive designs have been piloted in assessing global cognitive performance, performing with similar accuracy to traditional in-person cognitive assessments (Gibbons et al., 2024; Wouters et al., 2009). Furthermore, adaptive designs have also previously utilised driving tasks, whereby executive functioning and attention have been measured via a gamified cognitive driving task which continuously alters its game dynamics to ensure task difficulty maintains at 80% relatively for all participants (Hsu et al., 2021). Such approaches may therefore be considered in the future for developing new cognitive tasks for driving safety evaluations.

While age-related cognitive changes over time are robust, subtle changes taking place in prodromal dementia over a one-year period are more difficult to establish (Baker et al., 2016). Another potential benefit of remote, digitalised cognitive testing is that it enables for measurement burst design methodologies (Sliwinski, 2008). Measurement burst designs are particularly advantageous in assessing for subtle changes in prodromal dementia as they involve an intensive longitudinal design of multiple measurements of cognitive performance in a 'burst' approach, typically involving many tests over a few days, constituting as a single testing session. These can account for potential retest effects found in typical longitudinal cognitive measurements, such as variability in task performance or learning effects, to enable for more accurate assessment of long-term changes in cognitive performance (Oravecz et al., 2022). Examples of such approaches have found that, in testing with multiple short testing sessions each day over 7 days (maximum of 28 tests per session), remote burst testing designs are reliable, show sensitivity to AD biomarkers, and have greater statistical power than typical cognitive assessments (Hassenstab et al., 2020; Wang et al., 2024). While it has been established that additional assessments beyond one per day are not required to boost statistical power (Wang et al., 2024), future burst design measurement assessments will need to establish in cognitively impaired populations how testing can be adapted to reduce participant burden and drop-out rates for longitudinal assessments.

When considering the assessment of cognitively impaired populations, such as for people living with dementia or other neurodegenerative diseases, remote cognitive assessments have received positive user experience feedback and feasibility in individuals with AD and MCI (Howell et al., 2022). Within the NeurOn battery, online instruction videos were provided to demonstrate how to complete each cognitive task. In adapting cognitive tasks to be feasible for cognitively impaired populations, patient and public involvement can also be incorporated in developing task instructions guided by individuals with lived experience to improve comprehension, such as delivering audiovisual information at a reasonable pace. Adaptive designs can also be utilised to ensure the task is at an appropriate difficulty level for participants to complete without distress. Furthermore, testing sessions can be carried out in supervision of a healthcare professional to assist the individual in carrying out tasks, as assessments involving supervised videoconferencing approaches have demonstrated concurrent validity with in-person assessments (Belleville, LaPlume, & Purkart, 2023).

6.3 There's a time and place: the interaction between longitudinal cognition and environmental settings

Chapter 4 within this thesis presents, to the best of current knowledge, the first study to explore how intrinsic cognitive factors interact with extrinsic environmental settings over time to influence driving behaviour. The findings show that older adults living in urban areas are significantly more likely to be involved in recent RTIs than those living in rural areas after controlling for confounding variables previously implicated in RTI risk – driving mileage and age. The analysis further revealed that worse global cognitive functioning is also linked to an increased risk of RTIs in urban areas. This finding aligns with research primarily conducted in cognitively impaired populations, demonstrating that greater levels of cognitive impairment in neurodegenerative disease is associated with increased rates of RTIs. The findings in this chapter therefore support emerging evidence that in non-clinical populations, cognitive decline is associated with increased risk of RTIs (Ball et al., 2023; Fraade-Blanar et al., 2018; Park et al., 2011).

In context of the previous discussion on how cognitive impairments can increase cognitive load, one potential factor for the interaction between cognitive functioning and RTIs in urban but not rural environments may be due to difficulties in processing the increased environmental complexity in urban areas. The increased road activity within urban environments, coupled with more traffic signposting and more frequent decision-making due to a dense road network layout, has previously been found to increase attentional and cognitive load compared to natural scenery (Grassini et al., 2019). During increased cognitive load, it is established that reaction time to repeated stimuli increase and processing of visual information decreases (Engström et al., 2010; Salvucci & Beltowska, 2008), which theoretically increases road safety risks, as previously discussed. Despite this, findings have shown that increased cognitive load does not lead to slower response times in critical lead-vehicle braking scenarios within middle-aged adults (Nilsson et al., 2018). Crucially, however, to the best of current knowledge this research has not yet been conducted within ageing populations, who are more likely to experience exacerbated effects of increased cognitive load due to age-related cognitive impairments. Future research should establish how cognitive load across rural and urban environments influences the driving behaviour and safety risks of older adults specifically, considering the differential influence of these settings found within Chapter 4.

Alternatively, it is possible that the discordance in findings between rural and urban areas may be impacted by the lower numbers of RTIs in rural areas within the study sample (30 compared to 95 in urban areas) which could have affected the ability to detect similar patterns across environmental settings. Notably, the low incidence of RTIs in rural areas limited the ability to compare the interaction found in global cognitive functioning and environmental setting on RTI risk with post-hoc spatial orientation tests. This limitation is unfortunate, given the established importance of spatial orientation in driving performance among older adults throughout this thesis.

Within both rural and urban areas, it was observed that worse global cognitive functioning was associated with reduced driving mobility. Longitudinally, however, only urban residents with declining allocentric spatial orientation ability reduced their driving mobility, showing a significant reduction in driving space over time. Rural residents with cognitive impairments may therefore be less inclined to reduce their driving than urban residents, possibly due to fewer transportation alternatives to meet their mobility needs. There is a potential bidirectional component to the relationship between allocentric orientation decline and reduced driving space, as it is unclear whether individuals may show reduced driving space because of cognitive decline, or whether individuals are experiencing cognitive decline due to reduced hippocampal activation involved in allocentric spatial processing. As discussed within Chapter 1, successful allocentric spatial orientation is highly dependent on cognitive mapping within the medial temporal lobe, which is one of the earliest brain areas to undergo neurophysiological changes in advanced normative ageing (Raz et al., 2004). It is possible that due to being more closely located to amenities and services, older urban residents travel less frequently to distant locations over time and engage less with hippocampal-based cognitive mapping processes, leading to worsening allocentric spatial orientation ability. Maintaining driving in older age and living in more spatially complex environments has previously been associated with reductions in hippocampal brain atrophy in older age (Shimada et al., 2023; Shin et al., 2024). Reducing one's driving space, and keeping to familiar routes, may therefore result in declining allocentric spatial orientation performance over time due to hippocampal atrophy. Furthermore, as allocentric spatial orientation was the only cognitive modality associated with reductions in driving mobility longitudinally, this is supportive of findings in Chapter 3, demonstrating that allocentric orientation is a key cognitive marker toward driving changes in healthy ageing.

Interestingly, the finding that allocentric orientation decline is associated with reduced driving space in rural areas, while egocentric orientation decline is associated with urban areas, may reflect differences in the road structure across these environments. Research suggests that more organic environments foster richer spatial mapping processes (Coutrot et al., 2022), and therefore places greater emphasis on allocentric orientation. Rural areas, with their less uniform and more organic layouts, may require more complex allocentric processing in regular navigation. Conversely, urban areas tend to feature more grid-like road networks, with more frequent navigational decision points, encouraging the more frequent employment of turn-based egocentric strategies. Future research should investigate, in greater detail, how environmental settings and route familiarity in driving are associated with egocentric and allocentric orientation.

6.4 Turning a corner: improving driving mobility and safety for older adults

Given that the importance of maintaining driving mobility for health and wellbeing in older age, as outlined in Chapter 1, it is vital to establish approaches that support both driving safety driving mobility. Within Chapter 5, it is shown that the use of GPS devices is associated with improved driving mobility in older adults with spatial orientation impairments, as individuals who reported using GPS drove at a greater mileage than individuals who do not use GPS. Additionally, individuals who reported having a worse sense of direction were also more likely to use GPS more frequently when driving, supporting the proposal that IVT can improve comfortability for driving in older age.

In considering why GPS technology may be associated with driving mobility in older age, the finding that frequency of GPS use was positively associated with self-reported sense of direction in older age indicates that the technology alleviates navigational concerns, which has previously been associated with reduced driving space (Turano et al., 2009). Notably, whilst greater driving space was associated with GPS usage, there was no significant difference in the driving space of individuals with spatial orientation impairments regardless of their GPS use status. Driving space was also not associated with spatial orientation when looking at which cognitive factors are associated with driving behaviours in Chapter 3, which challenges the theoretical understanding that travelling greater distances would require greater spatial processing network processing. However, given that driving space was associated with spatial orientation differences when filtering between rural versus urban environments in Chapter 4, it is possible that the measure for driving space – taking into account how often one drives across different regions – may be sensitive to the geographical setting in which individuals are based.

As well as demonstrating improvements in driving mobility, GPS technology may reduce the cognitive load of recollecting and planning complex routes when driving, which as discussed earlier, may be a key factor in why spatial orientation impairments lead to road traffic collisions, Indeed, recent findings show that GPS devices can improve driving performance by reducing errors that may be caused by wayfinding burden within older adults (Dennis Thomas et al., 2020; Lee & Cheng, 2008; Stinchcombe et al., 2017). The implementation of GPS technology may therefore also improve road safety by reducing cognitive load when driving, allowing the driver to attenuate more to their immediate road environment.

In Chapter 1, it was theoretically outlined how spatial orientation processes are implicated in driving at both local (road positioning) and more global (route planning) levels. Whilst GPS technology may reduce the cognitive load of remembering routes at a global route planning level, it does not necessarily address spatial orientation impairments at a local level, in how one perceives and orients their immediate road environment. Alongside GPS technology, it would be therefore valuable to assess how other IVT such as lane control systems – which uses sensors to detect the vehicle's position in the lane and provides a warning if drifting outside of the lane (Eby et al., 2016) – interacts with spatial orientation changes to improve driving performance in older age. This could be particularly relevant considering the finding that lane changing smoothness was associated with spatial navigation impairments (Kunishige et al., 2020). For lane control technology, it may not be that this technology assists driving mobility by reducing the cognitive load when driving – as the driver must still allocate the same resources in maintaining careful positioning in the road – but instead may improve the perceived comfortability of driving, which may increase driving mobility by reducing concerns about driving safety. However, it is important to consider that IVT may not be universally beneficial to all older drivers, as it is a secondary task that may increase cognitive load for drivers who are less comfortable in using the technology. It should therefore be considered that usage should be tailored on an individual basis (Classen et al., 2019).

As other cognitive domains, such as speed of processing and attention, were also found to be associated with reduced driving mobility in older age, research should investigate how other IVT may potentially mitigate cognitive decline in those areas. For example, forward collision warnings can provide a warning when one is about to collide with an object and potentially provide a brake so that there is no collision (Eby et al., 2018), which may potentially offset impairments to processing speed where one's reaction speed may be too slow to apply the brakes in an emergency. Additionally, the potential impact of semi or fully automated vehicles should be considered. These vehicles are expected to allow older adults to live more active and healthy lifestyles by reducing the role of the individual and offsetting age-related impairments to driving behaviour (Duarte & Ratti, 2018). Nevertheless, significant obstacles remain in the widespread implementation of automated vehicles in the near future (Tengilimoglu et al., 2023). It is also important to consider that IVT and automation are often in modern, more expensive vehicles and therefore may be less accessible to older adults of a lower socioeconomic status – a factor which is also associated with accelerated ageing and reduced mobility (Hodgkin, 2011).

It is therefore important to consider alternate approaches to improving driving mobility in older adults. In recent years, a wide variety of older driver interventions have been examined in the literature to counter age-related decline (see Castellucci et al., 2020; Fausto et al., 2021; Ishii et al., 2023). Indeed, cognitive training has been implemented to improve performance of cognitive functions and transferring these benefits toward driving mobility (Ball et al., 2010; Casutt et al., 2014; Cuenen et al., 2016; Edwards, Delahunt, et al., 2009; Ross et al., 2017; Teasdale et al., 2016). The majority of studies utilising cognitive training have focussed on attention and speed of processing training, which have demonstrated associations with improved driving mobility over extended periods (Edwards, Delahunt, et al., 2009; Ross et al., 2017). Given that a main finding in this thesis is the importance of spatial orientation performance to driving in older age, establishing how training in this domain relates to driving performance is warranted in future research. Although previous studies have demonstrated post-training improvements in spatial orientation performance, the transfer effects to real-world behaviours – such as driving, have yet to be established (Fricke et al., 2022).

6.5 Policy implications

The findings in this thesis inform the potential shaping of future evaluations in driving fitness in older age, as well as initiatives to improve driving safety and mobility for older adults. Most notably, the comprehensive mapping of specific cognitive functions in how they relate to driving behaviours, along with the validation of a novel cognitive test battery utilising domains relevant to driving behaviour, can advance evidence-based driving evaluations. These evaluations can potentially be used to identify markers for at-risk driving performance more sensitively than age-based licensing policies in the future.

The results in this thesis provide an understanding as to how the effect of cognitive changes on driving behaviours compare between pre/post mandatory license-renewal age groups of before and after age 70. With the improved development of cognitive screening assessments, a prudent next step is in establishing whether these assessments can more accurately identify at-risk drivers than current age-based licensing policies. More sensitive, standardised, and evidence-based screening for at-risk drivers is advocated for at an international scale (Siren & Meng, 2012; Toups et al., 2022). This progress is vital in maintaining road safety for older drivers and other road users in lieu of the increasing proportion of older drivers on the road.

In translating the cognitive battery from a theoretical understanding to how driving is impacted by cognitive changes towards practical screening tools for identifying at-risk drivers, there are several steps to overcome: 1) Establishing the most sensitive cognitive test(s) across each cognitive domain most relevant to driving with large and diverse samples; 2) Establishing cognitive test performance thresholds associated with at-risk driving performance, enabling differentiation between safe and at-risk drivers; 3) Establishing the feasibility in administering the online cognitive screening battery within driving assessment centres; 4) Assessing the sensitivity of online cognitive battery against real-world driving evaluations, which may require an iterative process in adapting tasks to ensure it high sensitivity and specificity in identifying at-risk drivers; and 5) Determining appropriate follow-up intervals for monitoring cognitive testing to flag for drivers in need of further driving evaluations.

This thesis also provides valuable insights into the interaction between cognition and environment on driving mobility and safety that have several important implications for policymakers and future investigation. Environmentally tailored interventions may be needed to address the specific challenges faced by older drivers in urban and rural settings. As the findings of this thesis show there is a greater risk of road traffic incidents associated with cognitive impairments in urban areas, urban focused interventions should emphasise cognitive screening for older drivers and integrate education campaigns on navigating complex urban traffic patterns. Future design of urban areas should focus on understanding how cities can support older adults ageing in place and undertake more local activities, as urban residents are more likely to reduce their driving space over time (Vivoda et al., 2017; Wang et al., 2021). In rural areas, as rural drivers rely more upon driving to meet their transportation needs, cessation has the potential to be deeply impactful for their community participation and mobility (Mielenz et al., 2024; Strogatz et al., 2020). Rural communities may therefore benefit from increased support and resources for older adults who face challenges in accessing transportation alternatives. Potential initiatives may include volunteer driver programs and/or expanded access to public transportation services to reduce the impact of driving cessation in older age.

6.6 Methodological considerations and future research directions

6.61 Limitations of self-report data in driving, cognition and health research

Whilst limitations for this thesis have been addressed throughout previous chapters, there are overarching limitations which warrant discussion. A significant limitation of this thesis lies in the use of self-reported data to measure driving history and mobility in healthy older adults. Although self-report data is beneficial for generating larger samples of data and being convenient for participants, it may compromise accuracy, as discrepancies have previously been reported between self-report and objective report self-report data in driving mobility and RTI involvement (Kaye et al., 2018; McGwin et al., 1998). To mitigate bias, participants were given assurance that their data will be handled with confidentiality and anonymity, and information provided would not impact their driving insurance or license. This assurance reduced bias by encouraging participants to provide true self-report data without fear of repercussions to their driving status. Additionally, the usage of well validated self-report driving measures, such as the Driving Habits Questionnaire (Owsley, 1999), also increases reliability. However, self-report driving data is still at risk of inaccuracy due to human error and recall bias.

Similarly, the use of self-reported data in measuring GPS behaviour in relation to driving may also lead to inconsistencies, as individuals may show individual differences in how they interpret the type of routes in which they use GPS (e.g., there may be discrepancies as to how individuals perceive a familiar destination). Moreover, in using postcode data to infer urban/rural status, this involves between-subject comparisons, similar to many driving-environment studies (Dunsire & Baldwin, 1999; Payyanadan et al., 2018; Pucher & Renne, 2005), and does not account for the extent to which individuals drive within rural or urban environments, or the rurality/urbanicity of these environments. Future research could benefit from naturalistic driving studies that use in-car sensors (Babulal et al., 2019; Davis et al., 2020), complemented by driving diaries and in-vehicle cameras. These techniques can provide more granular, objective data on driving mobility, technology usage, and road safety – as well as enabling geospatial analyses on driving differences within rural and urban environments, establishing how driving mobility changes across the rural-urban scale. Naturalistic driving data also provides an objective measure for how often individuals navigate specific routes, which will provide useful context in identifying how driving behaviour interacts with route familiarity. A strength in this thesis lies in its exploration into understanding how extrinsic influences on driving behaviour interacts with intrinsic cognitive changes, which has been underexplored to date in driving research. By combining self-report measures with more objective, detailed data, this will enable for a greater understanding of how cognitive changes in ageing relate to driving behaviour in the real world.

Self-reporting health status also poses potential limitations across this thesis, as it is conceivable that self-reporting of health conditions may not capture the range or level of severity of health conditions that may interact with driving behaviour. It is possible that participants may have health conditions that were medically undiagnosed at the time of participation, or were forgotten or unreported within our health questionnaire, leading to potential unaccounted for effects. For example, while significant or untreated visual impairments were exclusionary criteria items within the present thesis, reduced visual acuity resultant of age-related sensory changes were not accounted for. Reduced visual acuity may lead to increased difficulty and/or avoidance of specific driving situations (Owsley & McGwin, 2010), such as driving in the rain or night driving. Future research should therefore consider incorporating objective health assessments, including medication reviews and visual screening, to establish a more comprehensive understanding in how these factors impact driving behaviour to ensure these factors are comprehensively accounted in analysis. When assessing individuals with cognitive impairments, involvement of a carer may also be helpful in verifying self-report data such as driving habits and health status, as well as reducing participant burden.

6.62 Generalisability to the general population

A secondary overarching limitation of this thesis is in the representativeness of the research sample relative to the general population. As the aims of this thesis were to establish how cognitive performance influences driving behaviour, participants who self-reported health conditions that contraindicate driving performance were excluded to reduce potential confounding effects in interpreting the results. However, given the prevalence of morbidity and comorbidity among older adult populations (nearly 75% of older adults over the age of 65 live with a long-term health condition in the UK (Age UK, 2024)), it is paramount for driving research to establish how age-related health conditions interact with cognitive performance in affecting driving performance and mobility.

Additionally, individuals who self-reported use of medications for treatment of cognitive impairment were also excluded from analysis. However, research shows that within healthy, community-dwelling older adults, use of wider medications – such as antidepressants, serotonin and norepinephrine reuptake inhibitors, sedatives or hypnotics, or nonsteroidal anti-inflammatory drugs – are associated with increased chance of failing a road test (Carr et al., 2023). Notably, the use of polypharmacy among older populations in the UK has increased considerably in recent years, as 49% of individuals over the age of 65 take five or more medications (Gao et al., 2018). It is therefore paramount to establish the relationship between comorbidity/multimorbidity, medication usage, and the impact on driving. Better understanding the mechanisms in how comorbidity and medication usage interact with cognitive, sensory, and physical factors will not only assist in ensuring findings are representative of the general population but will also help establish approaches to mitigate potential negative impacts such as reduced road safety and mobility.

An additional limitation in the generalisability of the findings in this thesis is in the lack of data on ethnicity and socioeconomic status (SES). Without these measures, it is difficult to establish how representative the sample is of the broader UK population, as it is not known whether specific interactions between driving and cognition may differ among specific subgroups. For example, higher SES has previously been found to be associated with driving in older age populations than lower SES status (Mohaqeqi Kamal et al., 2022; Anstey et al., 2017). Regarding race and ethnicity, while this has been understudied in the driving literature with most studies only measuring this as a covariate in analysis, a systematic review found that older drivers from racial and ethnic minority groups were more likely to show reduced driving (Babulal et al., 2018). Such sociodemographic factors should be included in future research on driving behaviour in older age, with a concerted effort in recruiting diverse populations to enable to improve the understanding in how these factors interact with driving behaviour and cognitive performance in older age.

6.63 The brain-level understanding of driving behaviour

A third overarching limitation in this thesis is that the proposed theoretical model on how cognitive changes in ageing impact driving behaviour (Figure 6.1) has components which remain partly theoretical, as the results do not measure for brain level changes and how these relate to ageing and cognitive performance over time. Future research should therefore look to assess the neural correlates of how brain changes relate to cognitive changes that impact driving behaviour in ageing. This will also assist in untangling the complex cause-and-effect relationship between driving cessation and neurophysiological changes, including the extent to which driving cessation causes or is caused by these brain changes, and the role driving plays in maintaining brain function (Choi et al., 2014; Shimada et al., 2023). Further research at the neural level will further elucidate how increased activation of brain networks when performing tasks in older age relates to the increased attentional demands in managing the cognitive load while driving (Depestele et al., 2020). Understanding these brain changes will provide a prudent next step in identifying how driving behaviour is impacted within the spectrum of neurodegenerative disease, with increasing evidence showing that presence of dementia-related biomarkers is associated with worse driving performance even during preclinical stages of the disease (Bayat & Roe, 2022; Doherty et al., 2023; Roe et al., 2019). An intriguing future direction is the potential of driving to serve as a novel neurobehavioural marker for preclinical dementia diagnosis, whereby not only do cognitive assessments prompt for driving evaluations, but driving performance itself prompts cognitive evaluations, enabling early diagnosis and better outcomes in neurodegenerative disease.

6.64 The road ahead: insights gained from longitudinal research

The present thesis employs a combination of cross-sectional and longitudinal study designs to investigate how cognitive functioning impacts driving behaviour amongst healthy older adults. Extending this research using longitudinal designs would provide valuable insights beyond this thesis.

In Chapter 2, a one-week longitudinal randomised crossover study design informed the reliability and validity of the NeurOn battery. Extending follow-up measurements of participant performance in remote settings over longer time periods would enable for more comprehensive measurement of the reliability and validity of the NeurOn. Furthermore, by varying the follow-up duration for retesting among different participant groups could help inform feasible approaches for follow-up testing in long-term cognitive monitoring.

In Chapter 3, which provides a cross-sectional overview of the relationship between cognitive functions and driving behaviour, incorporating a longitudinal component would enable for an understanding into whether this relationship changes over time. For example, a longitudinal study design would enable an investigation into the theoretical outline in Figure 6.1, proposing that allocentric orientation changes precede egocentric orientation changes leading toward reduced driving and eventual driving cessation. A longitudinal approach would enable for investigating within-individuals whether allocentric orientation decline increases driving difficulty linearly before egocentric orientation changes result in avoidance of specific driving behaviours before eventual cessation.

In Chapter 4, which uses a one-year longitudinal follow-up design, extending the duration of testing would enable for examining trend linearity in driving mobility over time within rural and urban regions. For example, it would be insightful to understand whether the findings that individuals living in urban areas demonstrated a significant reduction in driving space over a one-year period are maintained longitudinally, or whether rural residents show a non-linear decline with steeper reductions in driving mobility in older age.

Finally, in Chapter 5, which uses a cross-sectional approach to establish the triangular association between GPS usage, driving mobility, and cognition, a longitudinal extension would enable the examination in whether GPS usage contributes to sustained driving mobility over time and whether there is any relationship between its usage and driving cessation in older age.

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Appendices

Supplementary Information: Chapter 2

S2.1 Appendix:

S2.1. Table outlining cognitive battery tasks

Task:	Domain:	Description:
Reaction time	Visuomotor speed	Participants respond (via keyboard, touchscreen) as quickly as possible to a repeating stimulus that appears on the screen.
Trail-Making Test -A	Processing speed	Participants connect a set of 25 numerically arranged points in ascending order as quickly as possible.
Trail-Making Test -B	Executive functioning	Participants connect a set of 25 points in ascending order alternating between numbers and letters.
Spatial Span – Backwards	Spatial working memory	Based on the Corsi block test, participants are presented with an array of geometric shapes that light up in a different sequential order per trial. After each trial, the participant relays the previous sequence in reverse order. The difficulty increases systematically from two box to nine box sequences. The task aborts if participants incorrectly relay two sequences in the same trial sequence length.
Recognition & Source Memory	Episodic Memory	Participants initially view a set of everyday objects that appear consecutively at in different places (top, bottom, left, right) of the screen in a learning phase. After a break, participants are tested on whether they correctly recognise pictures they previously learnt in a recognition memory test and are then asked to locate the position they appeared on the screen in a source memory test. 30 pictures are presented in the test session.
Go/No-Go	Attentional control	Participants are asked to press a key when a circle displays (Go stimuli) and to inhibit responses when a triangle is displayed (No-go stimuli). The task consists of 150 stimuli presentations.

Fragmented Letters	Visuospatial impairment	Participants identify a single letter from the alphabet that is fragmented through a visual mask. Participants must then select the presented letter out of multiple choices. There are 10 trials in total.
Virtual Supermarket Task	Allocentric & Egocentric orientation	Participants view 14 randomly ordered 20-40 second clips of a trolley moving through a virtual supermarket. Each video is presented in first-person perspective and contain optic flow cues via the changing scenery as the shopping trolley moves throughout the supermarket. Following the video clip, participants are asked to indicate a direction to the starting point of the video - assessing egocentric orientation - and then are asked to draw the path presented in the video from a birds-eye view of the supermarket – assessing allocentric orientation. This task has been previously described in detail (Tu et al., 2015).

S2.2 Appendix: Regression models between cognitive tests and demographic characteristics

S2.2A: Full model of MRA between Reaction Time and demographic characteristics

Effect	***B***	***SE***	**95% CI**		***p***
			LL	**UL**	
(Intercept)	0.93	2.72	-104.26	665.27	0.74
Age	-0.01	0.04	-0.09	0.06	0.76
Gender	-0.65	0.36	-1.40	0.09	0.08
Education	0.01	0.04	-0.08	0.11	0.79

[a]Standardised beta coefficients displayed.

S2.2B: Full model of MRA between TMT-A performance and demographic characteristics

Effect	***B***	***SE***	**95% CI**		***p***
			LL	**UL**	
(Intercept)	8.05	3.89	0.06	16.04	0.049
Traditional test score	0.20	0.17	-0.16	0.55	0.27
Age	-0.12	0.05	-0.23	-0.01	0.03
Gender	0.19	0.34	-0.50	0.88	0.58
Education	0.02	0.04	-0.07	0.11	0.60

[a]Standardised beta coefficients displayed.

[b] Traditional test score = Paper-based TMT-A

S2.2C Table: Full model of MRA between TMT-B performance and demographic characteristics

Effect	*B*	*SE*	95% CI		*p*
			LL	UL	
(Intercept)	1.87	3.25	-4.81	8.56	0.57
Traditional test score	0.49	0.14	0.20	0.78	0.002
Age	-0.04	0.04	-0.13	0.05	0.35
Gender	-0.11	0.26	-0.65	0.42	0.67
Education	0.07	0.04	-0.00	0.15	0.06

[a]Standardised beta coefficients displayed.
[b] Traditional test score = Paper-based TMT-B

S2.2D Table: Full model of MRA between Spatial Working Memory performance and demographic characteristics

Effect	*B*	*SE*	95% CI		*p*
			LL	UL	
(Intercept)	5.31	2.66	-0.15	10.77	0.06
Traditional test score	0.23	0.18	-0.15	0.61	0.22
Age	-0.07	0.04	-0.15	0.01	0.07
Gender	-0.25	0.35	-0.98	0.47	0.48
Education	-0.02	0.05	-0.11	0.08	0.70

[a]Standardised beta coefficients displayed.
[b] Traditional test score = Corsi block tapping test.

S2.2E Table: Full model of MRA between Episodic Memory performance and demographic characteristics

Effect	*B*	*SE*	95% CI		*p*
			LL	UL	
(Intercept)	0.71	0.23	0.25	1.18	0.004
Traditional test score	0.02	0.02	-0.01	0.05	0.19
Age	0.00	0.00	-0.00	0.01	0.58
Gender	0.07	0.03	0.01	0.13	0.03
Education	0.00	0.00	-0.01	0.01	0.64

[a]Standardised beta coefficients displayed.
[b] Traditional test score = ROCF-delayed recall test.

S2.2F Table: Full model of MRA between Go/No-Go performance and demographic characteristics

Effect	*B*	*SE*	95% CI		*p*
			LL	UL	
(Intercept)	-3.14	2.70	-8.67	2.38	0.25
Age	0.03	0.04	-0.05	0.10	0.45
Gender	0.58	0.35	-0.15	1.30	0.12
Education	0.06	0.05	-0.04	0.15	0.23

[a]Standardised beta coefficients displayed.

S2.2G Table: Full model of MRA between Allocentric Orientation performance and demographic characteristics

Effect	***B***	***SE***	**95% CI**		***p***
			LL	**UL**	
(Intercept)	5.44	2.38	0.55	10.33	0.03
Age	-0.10	0.03	-0.16	-0.03	0.007
Gender	-0.26	0.32	-0.92	0.41	0.44
Education	0.09	0.04	0.00	0.17	0.045

[a]Standardised beta coefficients displayed.

S2.2H Table: Full model of MRA between Egocentric Orientation and demographic characteristics

Effect	***B***	***SE***	**95% CI**		***p***
			LL	**UL**	
(Intercept)	-0.30	2.76	-5.97	5.38	0.91
Age	-0.01	0.03	-0.09	0.07	0.74
Gender	0.38	0.37	-0.39	1.15	0.32
Education	0.06	0.05	-0.04	0.16	0.20

[a]Standardised beta coefficients displayed.

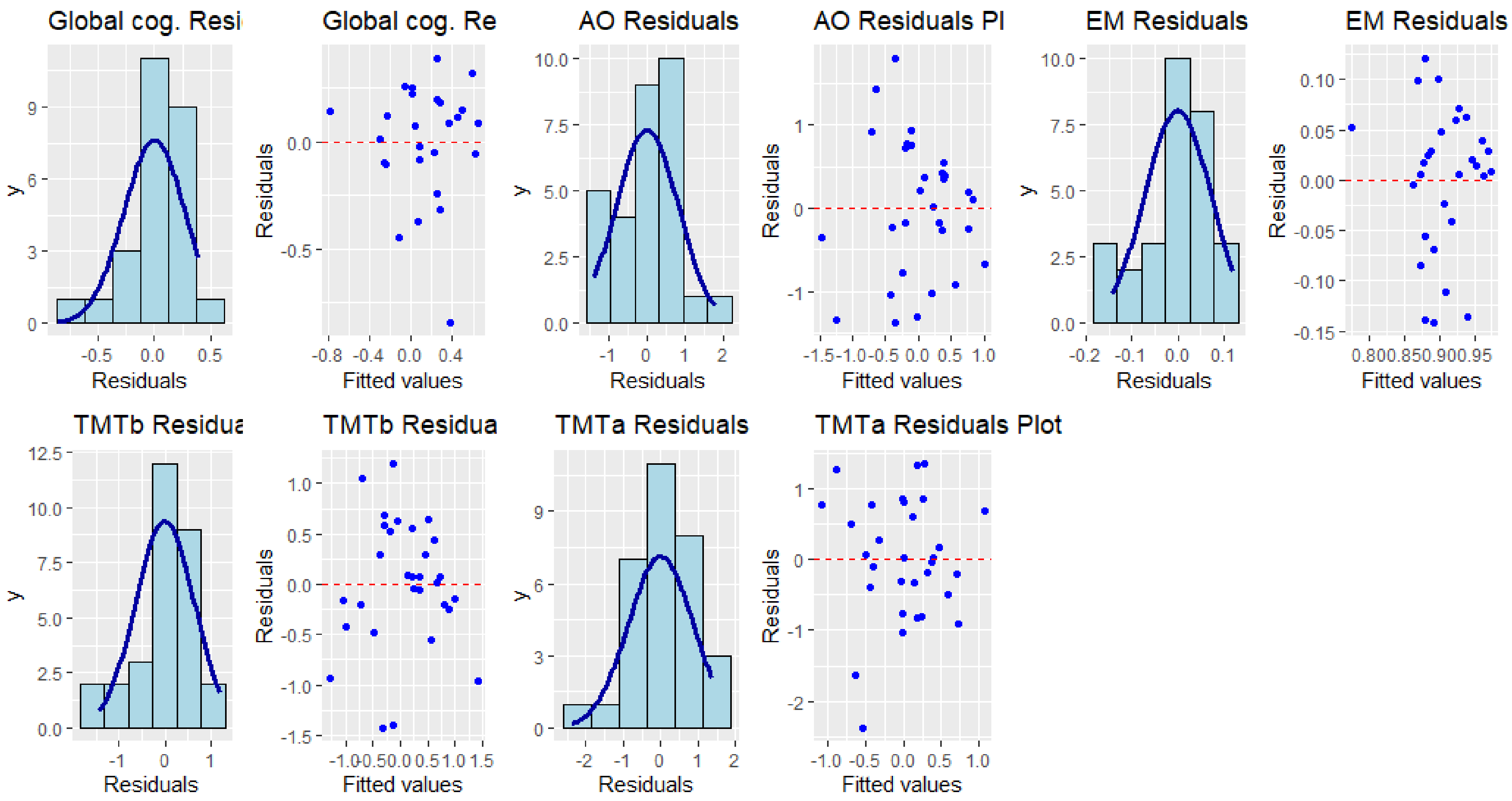
S2.2I Table: Full model of MRA between global cognitive performance and demographic characteristics

Effect	*B*	*SE*	95% CI		*p*
			LL	UL	
(Intercept)	0.40	1.56	-2.84	3.63	0.81
Traditional test score	0.11	0.03	0.04	0.17	0.003
Age	-0.05	0.02	-0.09	-0.02	0.007
Gender	-0.05	0.12	-0.30	0.19	0.66
Education	0.03	0.02	-0.00	0.06	0.09

[a]Standardised beta coefficients displayed.
[b] Traditional test score = MoCA

S2.3 Appendix:

S2.3 Figures: Residuals distribution for significant multiple regression results



S2.4 Appendix:

S2.4 Table: Cognitive task performance compared across devices used for testing

Variable	PC	Laptop	Tablet	*F*
Reaction Time (ms)	316.37 (34.57)	345.79 (80.33)	415.03 (63.13)	*4.410**
Trail-Making Test A (s)	31.28 (9.52)	34.88 (13.63)	35.54 (8.70)	1.013
Trail-Making Test B (s)	50.27 (19.88)	48.77 (20.82)	53.59 (16.38)	0.184
Spatial Working Memory	5.31 (0.85)	5.38 (1.04)	5.83 (1.17)	0.691
Episodic Memory	89.38 (10.00)	90.17 (6.21)	94.66 (7.78)	0.919
Go/No-Go	1.46 (1.76)	1.54 (1.71)	0.00 (0.00)	2.203
Allocentric Orientation	2.77 (1.70)	3.04 (1.29)	4.47 (1.64)	2.277
Egocentric Orientation	60.12 (34.50)	45.67 (33.11)	40.97 (6.38)	0.737
Global cognition	0.12 (0.45)	0.16 (0.45)	0.08 (0.37)	0.051

[a] Covariates for ANCOVAs: RT (Age), TMT-A (Age), TMT-B (Age), SWM (Age), EM (Age + Gender), GNG, AO (Age + Gender), EO (Age + Gender), Global cognition (Age).

There was a statistically significant difference with Reaction Time across devices used, $F(2, 27) = 4.410$, $p = 0.02$, $\eta_p^2 = .25$. Tukey's post-hoc pairwise comparisons revealed that individuals using PCs ($M = 316.37$, SD = 34.57) demonstrated a faster reaction time individuals using tablets ($M = 415.03$, SD = 63.13).

S2.5 Appendix:

S2.5 Table: Navigation variables correlation with the Driving, Orientation, and Navigation score

Variable	Pearson's r
Santa Barbara Sense of Direction	**0.67*** **
Allocentric Navigation	-0.24
Egocentric Navigation	0.01

[a]*p < .05, **p < .01, ***p < .001

Pearson's correlations were conducted to establish the association between subjective navigation performance using the novel Driving, Orientation, and Navigation (DON) questionnaire with the established Santa Barbara Sense of Direction Scale (SBSOD) and objective spatial orientation measures – allocentric and egocentric orientation. There was a significant positive association between DON and SBSOD ratings to a moderate to strong correlation, r(30) = 0.67, *p* < .001.

S2.6 Appendix: Participant level raw scores of cognitive test performance for remote and in-person testing sessions

Table S2.61: Remote testing session performance

ID	Age	Gender	Education	RT	TMT-A	TMT-B	SWM	EM	GnG	FL	AO	EO
1	72	0	13.00	699.92	49.92	35.20	5	100.00	0	100	5.83	47.62
2	69	0	18.00	380.08	33.61	45.88	4	82.50	4	100	1.68	13.93
3	66	0	8.00	381.16	38.14	43.97	6	82.78	2	100	3.73	132.34
4	71	0	11.00	274.60	32.54	83.49	6	78.89	5	100	5.41	94.59
5	65	0	13.00	320.96	27.08	42.86	5	96.67	2	100	2.88	99.96
6	70	1	16.50	333.79	40.30	49.94	7	98.33	0	100	2.10	32.35
7	71	0	20.00	322.74	26.43	34.18	6	*NA*	1	100	2.97	54.78
8	67	1	19.00	304.43	20.41	27.90	6	100.00	0	100	1.88	93.32
9	70	1	14.50	418.17	25.66	77.49	6	96.67	0	100	*NA*	*NA*
10	69	1	14.50	443.78	29.53	30.34	5	87.62	2	100	2.19	35.22
11	67	0	23.00	245.72	31.17	41.99	5	*NA*	0	100	2.58	95.87
12	77	1	11.00	356.92	29.26	92.95	5	93.33	0	100	7.21	110.69
13	69	1	12.00	342.98	36.49	44.37	4	100.00	1	100	4.11	19.52
14	69	1	13.75	427.58	36.05	51.59	4	100.00	0	100	4.74	41.08
15	69	1	17.00	239.99	23.49	29.98	5	80.48	6	100	2.74	32.71
16	73	0	14.00	292.95	35.46	43.35	5	100.00	3	100	0.86	105.55
17	74	0	11.00	329.72	33.72	73.57	6	75.00	1	100	2.79	11.66
18	65	1	21.00	303.92	18.46	41.38	5	98.33	0	100	1.62	21.07
19	68	0	19.00	418.89	37.24	79.46	6	90.83	1	100	3.68	65.61
20	90	0	20.00	314.25	77.43	99.14	4	91.67	0	100	5.98	56.40
21	66	1	16.00	369.25	28.30	38.65	7	96.67	1	100	2.71	21.89
22	73	0	22.50	302.25	38.63	46.15	6	82.38	3	100	1.95	38.52
23	65	1	11.00	228.76	33.59	44.48	6	88.33	1	100	1.81	19.36
24	76	1	17.00	356.46	54.77	43.92	3	100.00	1	100	1.87	34.81
25	67	0	21.00	279.53	28.87	37.05	7	95.00	0	100	1.65	13.89
26	70	1	17.50	507.07	31.92	39.23	7	93.33	0	100	5.19	42.84

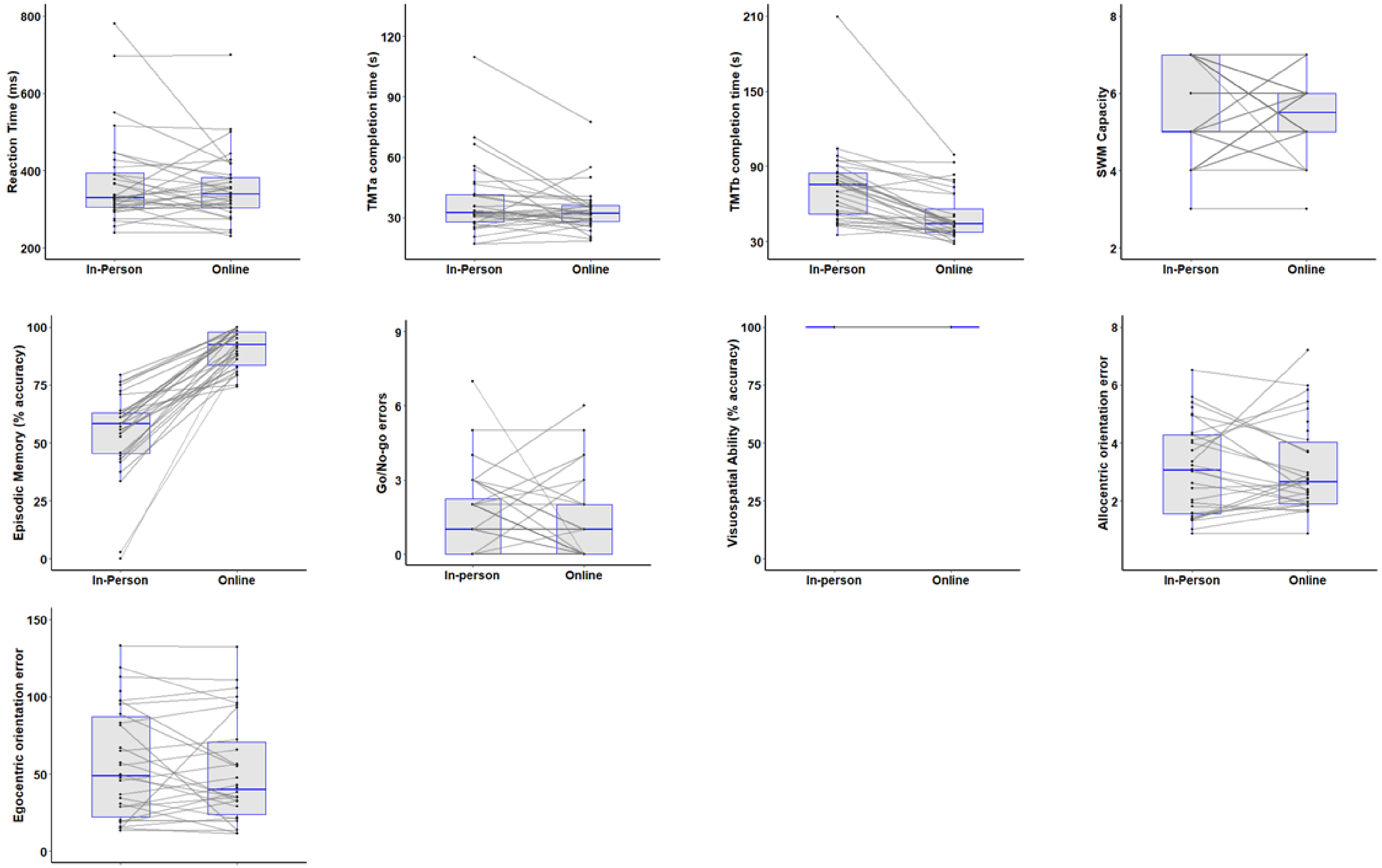
27	69	1	19.00	499.43	34.74	68.54	5	96.67	0	100	4.41	72.23
28	65	0	18.00	354.00	31.33	34.92	6	74.10	0	100	2.32	11.33
29	70	0	19.00	274.40	25.56	37.97	5	89.52	1	100	1.87	55.89
30	67	0	12.50	313.53	19.38	36.11	6	87.86	4	100	2.39	34.97
31	73	1	10.00	388.54	29.36	68.05	6	79.62	0	100	*NA*	*NA*
32	74	0	17.00	357.41	34.48	44.89	5	85.95	0	100	2.29	29.27

Table S2.62: In-person participant testing performance

ID	Age	Gender	Education	RT	TMT-A	TMT-B	SWM	EM	GnG	FL	AO	EO	MoCA
1	72	0	13.00	697.08	47.57	52.89	5	27.0	0	100	3.75	36.72	28
2	69	0	18.00	444.72	27.84	75.52	7	21.0	1	100	1.82	81.59	23
3	66	0	8.00	324.05	46.68	*NA*	5	1.0	4	100	5.39	133.07	24
4	71	0	11.00	366.34	32.00	70.00	4	22.0	5	100	4.34	82.97	27
5	65	0	13.00	376.95	30.57	85.02	4	22.5	2	100	1.37	95.23	27
6	70	1	16.50	320.62	41.00	48.00	7	15.5	3	100	1.46	66.89	30
7	71	0	20.00	255.67	17.00	44.00	6	19.0	3	100	4.00	88.59	27
8	67	1	19.00	364.27	55.42	61.93	7	27.5	0	100	1.57	15.11	29
9	70	1	14.50	780.87	35.81	104.29	7	22.5	0	100	*NA*	*NA*	25
10	69	1	14.50	310.17	20.40	42.46	7	15.5	3	100	3.01	47.57	27
11	67	0	23.00	269.55	40.72	84.19	7	20.5	1	100	2.43	119.07	23
12	77	1	11.00	389.45	33.45	94.86	5	0.0	0	100	3.36	112.88	24
13	69	1	12.00	447.68	25.28	45.18	5	19.5	1	100	4.95	20.45	30
14	69	1	13.75	409.04	69.58	78.92	4	21.0	0	100	*NA*	*NA*	24
15	69	1	17.00	239.00	31.41	79.21	5	20.0	3	100	2.02	18.56	26
16	73	0	14.00	388.54	31.80	90.54	4	21.0	0	100	0.87	97.41	29
17	74	0	11.00	291.98	32.27	94.48	4	25.5	0	100	4.27	30.64	29
18	65	1	21.00	322.18	16.82	35.00	5	28.5	0	100	1.94	34.44	29
19	68	0	19.00	550.32	35.52	90.25	6	22.0	1	100	5.58	55.75	25
20	90	0	20.00	296.09	109.58	209.57	5	12.0	7	100	6.51	45.44	27
21	66	1	16.00	327.41	25.24	43.51	7	27.5	1	100	1.33	15.91	29
22	73	0	22.50	303.41	41.57	77.00	4	20.0	2	100	2.61	19.28	28
23	65	1	11.00	316.90	24.42	54.22	6	16.5	1	100	*NA*	19.56	28
24	76	1	17.00	330.44	27.00	70.00	3	22.0	3	100	3.08	57.15	27
25	67	0	21.00	336.64	32.53	65.86	5	26.0	1	100	1.03	13.38	29
26	70	1	17.50	516.36	41.10	75.47	5	16.0	0	100	4.09	28.56	27
27	69	1	19.00	334.97	53.53	98.27	7	22.0	2	100	*NA*	65.05	29

28	65	0	18.00	305.94	30.76	58.82	5	23.0	2	100	4.99	14.87	29
29	70	0	19.00	274.64	32.02	46.95	7	19.5	1	100	1.32	97.30	28
30	67	0	12.50	312.34	26.74	50.76	6	23.0	2	100	3.22	28.54	28
31	73	1	10.00	427.60	33.32	76.16	7	13.5	0	100	5.23	103.70	25
32	4	0	17.00	298.56	66.26	81.81	7	15.0	2	100	1.41	49.75	28

S2.63 Paired data boxplots showing participant online and in-person cognitive test performance



Supplementary Information: Chapter 3

S3.1 Appendix: Table outlining driving behaviour measures

Driving Behaviour measures			
Domain	Variable	Questionnaire	Description
Frequency	Annual mileage	Driving History	Participants are asked, "What is your annual mileage in a typical year?"
	Weekly driving	Driving Habits Questionnaire	Participants are asked, "In an average week, how many days per week do you normally drive?"
	Weekly trips	Driving Habits Questionnaire	Participants are asked, "Which of the following locations do you drive to in a typical week?" (Shops; Place of worship; Work; Relative's house; Friend's house; Out to eat; Appointments, e.g. doctor, hair; Other (please specify). After selecting each relevant item, participants are asked "How many trips per week?" The number of trips across each location are totalled to create an overall weekly trips measure.
Space	Driving space	Driving Habits Questionnaire	Participants are asked, "During the past year, how often have you driven in your immediate neighbourhood?/to places beyond your neighbourhood?/ to neighbouring towns?/ to more distant towns?/ to places outside your county?/ to places outside your region?" Participants answer on a Likert scale (Not at all (0), A few times in the year (1), A few times per month (2), A few times per week (3), Every day (4)). The

			answers are totalled across each item to comprise the driving space measure.
	Weekly trip distance	Driving Habits Questionnaire	Participants were asked, “Which of the following locations do you drive to in a typical week?” (Shops; Place of worship; Work; Relative’s house; Friend’s house; Out to eat; Appointments, e.g. doctor, hair; Other (please specify). After selecting each relevant item, participants are asked, “Estimated miles from home (single trip, one-way)”. The greatest overall trip distance for each participant was selected as the maximum weekly trip distance.
Difficulty	Driving difficulty	Driving Habits Questionnaire	Participants are asked whether they performed the following driving behaviours in the last 3 months: driving in the rain; driving alone; parallel parked; completed right-turns across oncoming traffic; motorway driving; driven on high-traffic roads; driven in rush-hour traffic; night driving. If participants did perform a driving behaviour, they were asked how difficult they found each behaviour and answered on a Likert scale (Not at all difficult – 1, A little difficult – 2, Moderately difficult – 3, Extremely difficult – 4). Individuals who did not partake in a driving behaviour were asked to list the reason why (I did not have the opportunity/ I would have found it too difficult). Individuals who did not partake in a particular driving behaviour because it was too difficult were re-coded to having extreme difficulty for that item, whereas individuals

			who didn't partake in an activity because they didn't have the opportunity were excluded for that item. An average driving difficulty measure was comprised by averaging the difficulty scores across all driving behaviours.
	Situations avoided	Driving Habits Questionnaire	Participants are asked whether they performed the following driving behaviours in the last 3 months: driving in the rain; driving alone; parallel parked; completed right-turns across oncoming traffic; motorway driving; driven on high-traffic roads; driven in rush-hour traffic; night driving. If participants did not partake in a driving behaviour it was categorised as an avoided driving situation.

S3.2 Appendix: Table showing age group differences in driving behaviour

S3.2 Age group differences in driving behaviour			
Driving characteristic	**Group average:**		***p* value**
	Under 70	**Over 70**	
Frequency			
Mileage (annual)	7054.91 (3305.81)	6461.22 (3361.48)	< 0.05
Weekly driving (days)	4.19 (1.62)	4.18 (1.60)	0.884
Weekly trips	1.95 (1.79)	1.89 (1.76)	0.735
Space			
Driving space	9.92 (2.92)	9.58 (2.95)	0.097
Weekly trip distance	11.04 (13.67)	7.77 (8.74)	<0.01
Difficulty			
Driving difficulty	4.70 (0.39)	4.66 (0.39)	0.140
Situations avoided	1.04 (1.29)	1.18 (1.32)	0.141

Note.

Welch two sample t-tests were conducted

N) under 70 = 373, N) over 70 = 430

S3.3 Appendix: Table showing age group differences in cognitive functioning and driving performance

S3.3 Age group differences in cognitive functioning and driving performance Post-hoc hierarchical regressions showing association between cognition functioning and driving characteristics grouped by age														
	AO		**EO**		**RT**		**RM**		**SM**		**TMT- A**		**TMT- B**	
Driving characteristic	**Under 70**	**Over 70**	**Under 70**	**Over 70**	**Under 70**	**Over 70**	**Under 70**	**Over 70**	**Under 70**	**Over 70**	**Under 70**	**Over 70**	**Under 70**	**Over 70**
Frequency														
Mileage (annual)	-	-	-	-	-	-	-	-	**-3802.05****	-1113.50	**-505.65***	-317.27	-43.26	**-392.26****
Trips (weekly)	-	-	-	-	-	-	-0.07	**1.67****	-	-	-	-	-	-
Space														
Weekly trip distance	-	-	-	-	-	-	1.38	**2.39****	-	-	-	-	-	-
Difficulty														
Driving difficulty	**-0.07***	**-0.07****	-	-	-0.02	-0.04	-	-	-0.31	-0.12	-0.02	-0.04	-0.03	-0.02

Situations avoided	**0.23***	0.06	**0.30*****	-0.03	-	-	**3.25*****	-0.02	-	-	-	-	-	-

Note.

*$p < .05$, **$p < .01$, ***$p < .001$

Values represent standardised beta coefficients

AO = Allocentric Orientation; EO = Egocentric Orientation; RT = Reaction Time; SWM = Spatial Working Memory; SM = Source Memory; TMT -A = Trail Making Test -A; TMT -B = Trail Making Test -B

N) under 70 = 373, N) over 70 = 430

Cognitive data is standardised (except for Recognition Memory and Source Memory, which are proportions).

Appendix S3.4: Table showing the reliability of cognitive testing

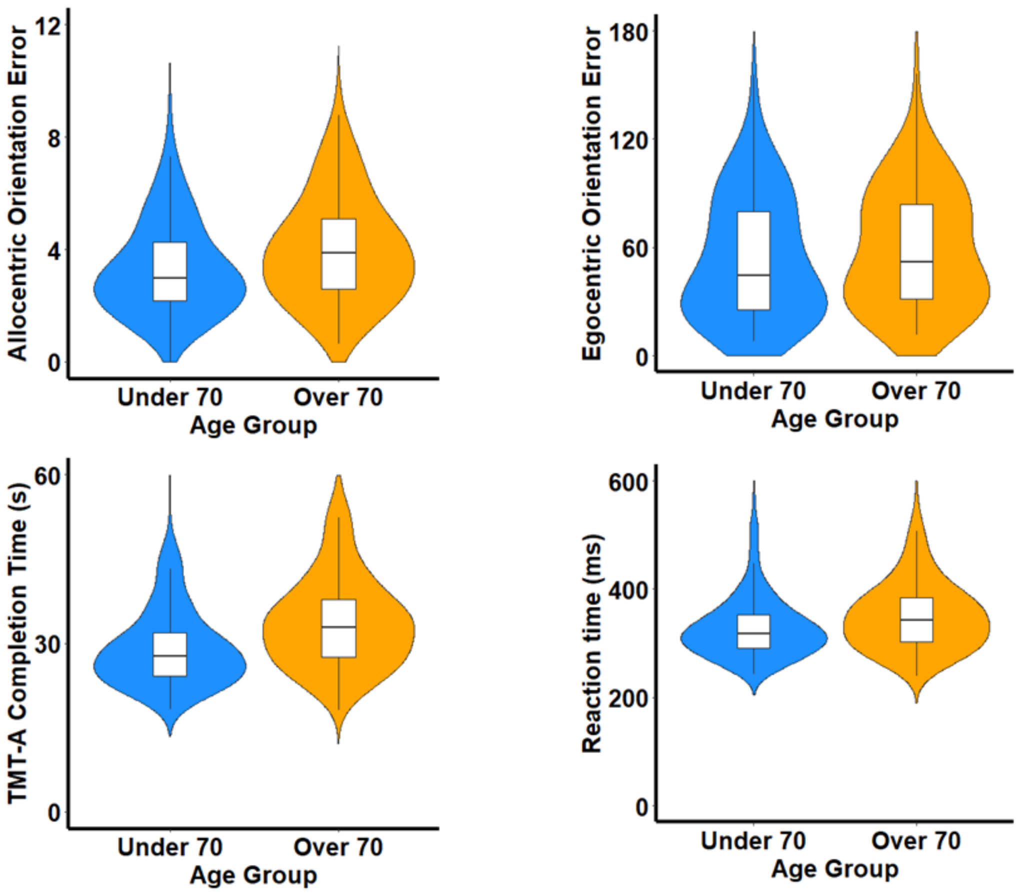
S3.4 Reliability of cognitive testing

Cronbach alpha internal consistency ratings across age groups for reaction time

Age	Reaction time
65-69	0.99
70-74	0.99
75-79	0.97
80-84	0.98
85-89	0.91

Appendix 3.5

Supplementary Figure 3.5. Violin plots of critical cognitive domains across driving screening cut-off ages



Supplementary Information: Chapter 4

Appendix 4.1

Supplementary Table 4.1. Driving mobility and safety measure descriptions		
Measure:	Questionnaire:	Description:
Annual mileage	Driving History	Participants were asked “What is your annual mileage in a typical year?”
Driving days	DHQ	Participants were asked the average number of days driven per week (ranging from 0 to 7).
Driving space	DHQ	Participants were asked how often they drive within 6 geographical areas, from within their immediate neighbourhood (lowest), to outside their region (highest). For each question, scores were rated from one (a few times in the year) to four (every day). Totalled scores across all six items comprised driving space.
Weekly trips	DHQ	Participants were asked “How many trips per week?” for each location they typically drive to. Totalled scores comprised weekly trips.
Maximum weekly trip distance	DHQ	Participants were asked to provide the “Estimated

		miles from home (single trip, one-way)" for each location they typically visit per week. The maximum single-trip distance comprised maximum weekly trip distance.
Situational avoidance	DHQ	Participants were asked whether they completed a particular challenging driving situation within the past 3 months (i.e., driving in the rain). The totalled number of situations avoided per participant comprised a situational avoidance measure, ranging from nought to eight.
Relative driving speed	DHQ	Participants were asked "How fast do you usually drive compared to the general flow of traffic?" and rated their answer on a five-point Likert scale (Much slower – Much faster).
Transport preference	DHQ	Participants were asked "which way do you prefer to get around?" and selected one of "Drive yourself/ Have someone drive you/ Use public transportation or a taxi".

Recent road incidents	RTI	Participants were asked how many RTIs they experienced in their driving history, and when their most recent RTI was. A recent RTI was classed as an RTI taking place within 3 years of data collection (since 2018).

Appendix 4.2

Supplementary Table 4.2. Linear mixed effect model analysis showing how rural and urban environments influence driving mobility over time

Variable	***B***	**t-value**	***p***
Driving space	-0.65	-2.88	<.01
Driving days	-0.11	-1.06	ns.
Max. trip distance	-2.04	-1.13	ns.
Weekly trips	-0.49	-1.56	ns.
Situational avoidance	0.33	3.34	<.001
Driving speed	0.03	0.68	ns.

Note.

[a] Displaying unstandardised beta coefficients

Supplementary Information: Chapter 5

S5.1 Appendix

The Driving, Orientating, and Navigation questionnaire (DON)

Note. When scoring the DON, Q4; Q7; Q8, Q10; Q15; Q18; Q19; Q20; Q21; Q23; Q24; Q28 are reverse scored before totalling.

Q11; Q20; Q21; Q26; Q30 were used to comprise the landmark spatial strategy usage measure.

Driving, Orientating, and Navigating questionnaire

		Never	Rarely	Sometimes	Often	Always
1	Whilst on a familiar route, I know the general direction of my destination	☐	☐	☐	☐	☐
2	If my regular route were blocked, e.g. because of road works, I could easily find an alternative route	☐	☐	☐	☐	☐
3	Once I have learned a route, I don't need to know exactly where I am, as long as I can reach my destination	☐	☐	☐	☐	☐
4	When driving along a route I know well, I have made a wrong turn because I mistook my location	☐	☐	☐	☐	☐
5	Even if I were unsure of my precise location on a new route, I would still know the general direction of my destination	☐	☐	☐	☐	☐
6	When learning a new route, I orient myself according to street layouts	☐	☐	☐	☐	☐
7	When driving to a new destination, I have found myself in the wrong place because I missed a turn	☐	☐	☐	☐	☐
8	If I were to break down on a new route, I would be unsure whether I was closer to home, or closer to my destination	☐	☐	☐	☐	☐
9	When imagining a familiar route, I think in terms of compass directions (N, S, E, W)	☐	☐	☐	☐	☐
10	I have got lost on an unfamiliar route, and have required assistance to reach my destination	☐	☐	☐	☐	☐
11	Along unfamiliar routes, I pay attention to my surroundings, e.g. buildings, shops, trees	☐	☐	☐	☐	☐
12	When learning a new route, I try to keep track of my current location throughout the journey	☐	☐	☐	☐	☐

		Never	Rarely	Sometimes	Often	Always
13	I navigate new routes in terms of compass directions (N, S, E, W)	☐	☐	☐	☐	☐
14	I give detailed instructions when people ask me for directions	☐	☐	☐	☐	☐
15	I have got lost on a familiar route, and have required assistance to reach my destination	☐	☐	☐	☐	☐
16	Even if I were unsure of my precise location on a new route, I would still know the general direction of my starting point	☐	☐	☐	☐	☐
17	On familiar routes, I get my bearings from street layouts, e.g. corners, signs, junctions	☐	☐	☐	☐	☐
18	When driving along a route I know well, I have missed a turn because my mind was elsewhere	☐	☐	☐	☐	☐
19	If I were to breakdown on a familiar route, I would have difficulty providing directions to the recovery vehicle to get me home	☐	☐	☐	☐	☐
20	Along familiar routes, I am unaware of changes in my surroundings, e.g. new buildings, autumn leaves	☐	☐	☐	☐	☐
21	When driving along a regular route, well-known landmarks have felt unfamiliar	☐	☐	☐	☐	☐
22	If I needed to stop somewhere along a new route, e.g. to check my location, I could find my current location on a map	☐	☐	☐	☐	☐
23	If someone asks me for directions, I point them the right way, but cannot give precise details	☐	☐	☐	☐	☐
24	When driving along a regular route, street layouts have felt different, even though I know they haven’t changed	☐	☐	☐	☐	☐
25	At any given point along a familiar route, I know roughly how far I am away from my starting point	☐	☐	☐	☐	☐

		Never	Rarely	Sometimes	Often	Always
26	On familiar routes, I get my bearings from distinct landmarks (e.g. churches, pubs, shops)	☐	☐	☐	☐	☐
27	If I were to stop somewhere along a familiar route, I could locate myself on a map	☐	☐	☐	☐	☐
28	When driving to a new destination, I have found myself in the wrong place because I turned off too soon	☐	☐	☐	☐	☐
29	Whilst on a familiar route, I know the general direction of my starting point	☐	☐	☐	☐	☐
30	When learning a new route, I orient myself according to distinct landmarks	☐	☐	☐	☐	☐
31	I can remember a new route after I have travelled it only once	☐	☐	☐	☐	☐