Department of Spatial Sciences

Mobility and Aging: Older Drivers' Visual Searching, Lane Keeping and Coordination

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number: # HR68_2014.

Signature: ....

Date: 08/12/2016

ABSTRACT

Motivated by the global trend of population aging and the ever-increasing complexity of traffic on our roads, this thesis adopts an interdisciplinary approach to investigate the driving behaviour and mobility of older adults. Although statistics indicate that this age group has a high involvement in car crashes, the older drivers' cohort is very heterogeneous and age itself does not necessarily translate into unsafe behaviour and crashes. Rather, it is known that several cognitive declines, in particular, visual-spatial perception and cognition, motor skills and executive function, can potentially affect older drivers' mobility and safety. It is crucial but challenging to assess the driving behaviour of older adults and identify indicators of risky behaviour. This PhD research develops new methods to measure and analyse older drivers' visual searching, lane keeping and coordination, through quantitative examinations of driver-vehicle-environment interactions, and investigates the associations between driving behaviour and cognitive conditions.

The experimental design, data collection, and data analysis were guided by a psycho-geoinformatics research framework that, defined the critical cognitive components and behaviour variables of driving. An assessment protocol was established to collect information on cognitive characteristics and driving behaviours for fifty older adults. A battery of neuropsychological tests was used to evaluate the cognitive functions of participants, while the on-road driving behaviour and visual search patterns were recorded and analysed using Global Navigation Satellite System (GNSS) tracking, eye tracking, and Geographic Information System (GIS) technologies.

The data processing involved three key techniques: 1) computing precise vehicle movement trajectories using multi-GNSS RTK (Real-time Kinematic), which formed the foundation of the project database; 2) extracting eye fixations and creating a visual-motor coordination data model to link the eye tracking and vehicle tracking data. Each eye fixation of individual drivers was geocoded to a vehicle position; 3) integrating older drivers' visual search attributes, cognitive conditions, and traffic environment into a gaze-based integrated driving assessment database.

The data analysis also consisted of a three-stage investigation for older drivers' lane keeping, visual searching and coordination. First, lane maintenance performance of older drivers and associations with their cognitive functioning were presented. Mean Lane Position (MLP) and Standard Deviation of Lane Position (SDLP) representing the lane displacement of vehicle, and manoeuvre time were used as lane maintenance parameters. Results showed that older drivers with lower visual attention performed higher MLP and SDLP; their spatial ability, processing speed, motor speed and executive function also affect the MLP in lane maintenance. Selective attention could be used as an independent predictor for lane maintenance performance in older drivers. The study also proved that the combination of cognitive variables with visual attention, spatial abilities and executive function, is capable to distinguish good and poor lane maintenance performance.

Second, older drivers' eye movement in various driving manoeuvres and the associations with their visual capacity were investigated. Results indicated that older drivers performed more frequent eye fixations when manoeuvreing through roundabouts, whereas longer eye fixations were noted when driving along straight roads. The correlation results showed that processing speed and divided attention in older drivers were associated with their eye fixations at the complex right-turns; drivers with lower selective attention capacity performed less frequent eye fixations at certain roundabout manoeuvres.

The third stage of this research moved on to investigate older drivers' visual-motor coordination. Multiple parameters of visual search and lane keeping of participants were aggregated and benchmarked using a mathematical modelling of Data Envelopment Analysis (DEA). The model calculated the relative performance of visual-motor coordination in participants so that the risky drivers, problematic behaviours and problematic road sections can be identified. Insufficient gaze behaviour was identified as the problematic visual search behaviour that resulted in poor lane maintenance performance. Results

showed that entering into roundabouts with a sharp angle can cause poor coordination in older drivers. At intersections, the most challenging driving sections for older drivers, the combination of cognitive tests explained a significant amount of the variance in visual-motor coordination performance. Selective attention, spatial abilities and executive function were among the best predictors for visual-motor coordination in older drivers.

In summary, this thesis provides a more detailed image of older drivers than many other studies. Particularly the measurement of visual-motor coordination is new in driving safety research. The impact of specific cognitive abilities on driving behaviour shows that effects are most noticeable in visual-spatial abilities and executive function condition in this group of older drivers. Driving scenarios or tasks have a significant influence on older drivers' visual patterns, lane keeping and coordination performance. Poorer visual-spatial and visual-motor abilities appear to be particularly associated with low-performing driving behaviours. It is strongly recommended that visual-motor coordination is a sensitive and effective measure for driving assessment in the older population. Future work will need to examine and model older drivers' visual-motor coordination in the face of hazardous driving situations. Further educational and training programs based on the findings of this study could be developed to enhance older drivers' behaviour behind the wheel.

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LIST OF PAPERS ARISING FROM THE PHD RESEARCH

Papers were included in the thesis

1. Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Framework for investigating older adults' driving behaviours and the underlying cognitive mechanisms. Presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. The paper was awarded as best type B and invited by *European Transport Research Review (ETRR)* for a special issue.
2. Sun, Q., Odolinski, R., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2017). Validating the efficacy of GPS tracking vehicle movement for driving behaviour assessment. *Travel Behaviour and Society, 6*, 32-43. doi:http://dx.doi.org/10.1016/j.tbs.2016.05.001
3. Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Pursuing Precise Vehicle Movement Trajectory in Urban Residential Area Using Multi-GNSS RTK Tracking. *Transportation Research Procedia.* Elsevier. Paper was presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. In press.
4. Sun, Q., Xia, J. C., Nadarajah, N., Falkmer, T., Foster, J., & Lee, H. (2016). Assessing drivers' visual-motor coordination using eye tracking, GNSS and GIS: a spatial turn in driving psychology. *Journal of Spatial Science*, 61(2), 299-316. doi:10.1080/14498596.2016.1149116
5. Sun, Q., Xia, J. C., Falkmer, T., & Lee, H. (2016). Investigating the Spatial Pattern of Older Drivers' Eye Fixation Behaviour and Associations with Their Visual Capacity. *Journal of Eye Movement Research, 9*(6). doi:10.16910/jemr.9.6.2

Paper was not included in the thesis

6. Sun, Q., Xia, J., Nadarajah, N., Falkmer, T., Foster, J., & Lee, H. (2015). *Positioning eye fixation and vehicle movement: Visual-motor coordination assessment in naturalistic driving*. Paper presented at the Research@Locate, the Academic Research Stream at Locate, R@Loc 2015 - In Conjunction with the Annual Conference on Spatial Information in Australia and New Zealand, Locate 2015, Brisbane; Australia.

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Introduction

CHAPTER 1 INTRODUCTION

1. Research Motivation

People are living longer and continuing to drive to a greater age. Age-related functional changes and the increasing complexity of traffic are putting this group at an increased risk of unsafe driving and crashes (Baldock & McLean, 2005; Dellinger, Langlois, & Li, 2002; Eberhard, 2000). Statistics have shown rising vehicle crash rates beginning at around age 65 (H. C. Lee, 2003; Li, Braver, & Chen, 2003; Rakotonirainy, Steinhardt, Delhomme, Darvell, & Schramm, 2012). The older driver cohort has the second highest fatality rates from vehicle crashes after teenage drivers (Sherrilene Classen et al., 2007). In fact, due to their frailty and fragility, this group has the highest risk of injury among all the adult driver groups (Oxley, Langford, & Charlton, 2010).

Not all older drivers are unsafe and statistics of crash reports do not reflect individual driving ability. Recent research into older drivers has moved the focus from "why do older drivers have a higher crash risk" to "which older drivers could have a higher crash risk" (Hakamies Blomqvist, 1998). Whereas there is a strong emphasis worldwide for older adults to maintain their mobility for as long as possible, the challenge is to develop appropriate evaluation methods to better interpret the characteristics of older drivers and investigate the key factors of risky driving behaviours, and to identify those older adults at higher risk of road crashes, possible training program can be made to retain their driving ability and confidence.

Older people are likely to experience a relative decline in various brain functions. Some of these functions, such as visuospatial perception, psychomotor skill and executive function, are important to the safe driving. A number of studies have reported that age-related declines in these cognitive abilities contribute to the increased vehicle crashes in older drivers (Clarke, Ward, Bartle, & Truman, 2010; S. Classen et al., 2007; Daigneault, Joly, & Frigon, 2002; Dawson, Uc, Anderson, Johnson, & Rizzo, 2010; Horswill, Anstey, Hatherly, & Wood, 2010). Knowledge of the cognitive characteristics associated with driving behaviour in older people would provide important information for improving safety and mobility in this age group. To date, various efforts from multiple disciplines have been made to obtain understandings of driving behaviour in the older population, by clinical neuropsychological tests, self-report or evaluations, on-road driving observations, computer simulations, etc., with new methodologies constantly emerging to identify and understand the mechanisms involved in the reduction of driving competency in older adults. Research findings in safety studies have also underscored the urgent need to study older drivers' mobility and behaviour through more focused public health and technological research (Owsley, 2002).

Driving mobility is a fundamental activity of daily life for older adults, directly linked to their health status and quality of life. A more nuanced image of the older population in the safety context is needed for the transport policy and planning to create a sustainable mobility in the future that meets older drivers' needs and conditions (Berg, Levin, Abramsson, & Hagberg, 2014). Despite intensive research on older drivers, a complete understanding of the aging impact on their driving behaviour is still a long way off. By taking an interdisciplinary approach and adopting a range of new technologies: such as GNSS tracking, eye tracking, and GIS, this PhD thesis proposes new methods to measure and analyse older drivers' behaviour through quantitative examinations of driver-vehicle-environment interactions. In particular, this study would offer new insights into the visual-motor coordination of older drivers. A greater understanding of the mechanisms that underpin the deterioration in visual searching, lane keeping and visual-motor coordination of older drivers will lead to a better targeted regulation in older drivers while maintaining, as much as possible, their mobility and safety.

2. Research Gaps and Rationales

Road safety studies traditionally use source data from crash reports, which are limited in the depth and quality of "real-world" information about individual drivers' behaviour and performance. The drivers' behaviour has become one of the main objectives of safety research, with attention given to the perception and cognition of the drivers. On-road driving assessment can provide the opportunity to study what drivers do and how they handle a broad range of elements in real traffic: the cars, the road infrastructure and road regulations. These assessments can shed light on how drivers interact with their vehicles and the environment, how they gain information to avoid hazards and how they adapt their visual resources to analyse increases in traffic demand (Williamson et al., 2015). Collecting on-road driving data also represents a significant evolution in driving research, because the gaze and motor characteristics observed under laboratory conditions by driving simulation may not provide an accurate reflection of a participant's natural behaviour, and investigations conducted in a real setting may reveal important mechanisms involved in their behaviours.

Previously, many on-road driving assessments had only a pass or fail outcome based on driving evaluators' clinical reasoning but not on a quantifiable scoring (Shechtman, Awadzi, Classen, Lanford, & Joo, 2010). However, many older drivers are very experienced in driving and hardly make obvious errors within the assessment period. Rather, they may demonstrate subtle changes in specific measures of driving behaviour, such as lane deviation and insufficient eye gazing, which are difficult to observe. A standardised on-road driving assessment with a quantifiable score would allow for greater objectivity in detecting risky behaviours and better evaluate the level of driving performance (Porter & Whitton, 2002). So far, few studies have been able to scrutinize detailed individual driving behaviour due to the lack of reliable data and available technologies. Despite an increasing amount of research on older drivers' safety and mobility, little quantitative evaluation has been done to investigate their visual searching, lane keeping and coordination of actions based on detailed on-road driving data.

Vehicle driving in real traffic can be considered as a dynamic human-machine-environment system involving not only the attributes of the vehicle movement, but also the human visual perception, cognition and motion of the driver. Hence, the study of driving behaviour should integrate information related to driver psychology, vehicle dynamics and road information to tackle research questions concerning driving safety. The information that a driver uses is predominantly visual (Sivak, 1996). When and where drivers look is of vital importance to the driver safety (J. D. Lee, 2008; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). A considerable amount of research focused on the drivers' gaze control during the performance, yet discussions on a driver's visual search were often separated from those on how a driver steers. Vision is usually regarded as somewhat independent behaviour (Goodale, 1998), whereas in fact when driving, eye movement and control over steering are closely linked (Chattington, Wilson, Ashford, & Marple-Horvat, 2007). Vision-motor interaction in driving plays a critical role in shaping a driver's visual pattern and driving performance. Since vision and motor actions are co-existed in space and time, the interaction or coordination between them affects the motion stability and spatial-temporal attributes of the driver's locomotion (Goodale, 1998). Therefore, robust research into vision control should be closely integrated with the study of motor action (Goodale, 1998, 2011). Several attempts have been made to detect risky drivers by coupling gaze behaviour and vehicle operating behaviour (Itkonen, Pekkanen, & Lappi, 2015; Mori, Miyajima, Hirayama, Kitaoka, & Takeda, 2013; Ramon et al., 2008; Yekhshatyan & Lee, 2013), mostly the data collected and aggregated at the section-scale level. Recent studies have rarely integrated visual and motor behaviour into a meaningful data model that allows a dynamic representation and analysis of visual-motor coordination in driving. Consequently, the nature and underlying mechanisms of the older drivers' behaviour behind the wheel have not been fully defined in publications to date (Park & Son, 2010; Qian Sun, Jianhong (Cecilia) Xia, Nandakumaran Nadarajah, et al., 2016).

The older driver group is known for its self-regulation and ability to adapt and cope with the changes affecting their driving mobility (Baldock, Mathias, McLean, & Berndt, 2006). According to Michon (1985), there are three levels of hierarchical decisions which shape driving behaviours: strategic-level decisions such as route selections; tactical-level moment-to-moment decisions such as speed choice and lane changing; and operational-level second-to-second behaviour such as braking or steering. Older drivers are more able to perform their strategic and tactical decisions than the last one. The operational-level decisions involve vehicle handling or executive actions which implement the manoeuvres decided at the tactical-level. It is performed almost without conscious thoughts (Glaser, Rakotonirainy, Gruyer, & Nouveliere, 2007), which requires effective executive functioning and coordination between actions. In general, visual-motor coordination can be construed as the extent to which visual perception and fine motor skills are well coordinated (Beery, 2004). Older drivers have exhibited difficulty in adjusting their operational-level behaviours, thus would have shown problems in the visual-motor coordination (Hong, Kurihara, & Iwasaki, 2008). The visual-motor coordination can be a sensitive but reliable measurement for the prediction of driving ability among older adults. On the other hand, older drivers must be aware of their abilities and limitations in visual-motor coordination so that they can compensate by employing defensive visual search and lane keeping behaviours to enhance their driving competencies.

3. Aims, Objectives and Expected Outcomes

This thesis adopts an interdisciplinary approach to studying mobility and driving behaviour in older adults, so that the existing body of research (older drivers' cognitive abilities, driver-vehicle-environment interactions and driving behaviour assessment, etc.) can be incorporated into a comprehensive framework and models to evaluate and ultimately improve individual older drivers' behaviour and performance. The overall aim is to understand the impact of the age-related cognitive decline in older drivers' driving behaviour and performance via measurements of their visual search pattern, lane keeping, and visual-motor coordination. A further aim is to identify those at-risk older drivers and indicators of risky driving behaviour. To achieve the aims, key objectives defined in this study are to:

1). Develop quantitative measurements for human mobility analysis in the context of driving safety, with respect to older drivers' lane keeping, visual search and visual-motor coordination;

2). Investigate relationships between older drivers' lane keeping performance and their cognitive conditions based on neuropsychological tests;

3). Assess older drivers' visual search patterns and investigate relationships between eye movement and their visual capacity;
4). Investigate relationships between older drivers' visual-motor coordination and cognitive functions;
5). Identify indicators of risky driving behaviour, and problematic road sections in older drivers' performance of visual-motor coordination.

Based on the objectives, this thesis will build a new profile of older adults' driving mobility and behaviour. The expected research outcomes are: a better defined characteristics of older drivers' visual pattern, lane maintenance and visual-motor coordination; new knowledge on the impact of age-related cognitive decline on older drivers' driving behaviors; new insights into the regulation of older drivers and specific recommendations to promote driving mobility and safety for drivers in general, and for the older population in particular.

4. Fundamental Techniques Toward Fulfilling the Objectives

A set of tools and techniques are applied in this study to resolve research problems and bridge the interdisciplinary boundaries between human mobility, traffic psychology and Geoscience, etc., and eventually to meet the research aims and objectives.

4.1. Psycho-geoinformatics framework

The idea of psycho-geoinformatics in this research was evolved from the interdisciplinary approach of psychoinformatics, which is an emerging discipline that uses tools from the information sciences to improve the acquisition, organization, and synthesis of psychological data. Yarkoni (2012) and Markowetz et al. (2014) have presented pioneer studies in this new discipline. They stated that adapting tools and techniques from computer and information sciences can help improve the measurement and modelling of psychological processes in a broad range of ways. No matter how data are collected, they must ultimately be synthesized into a meaningful form, such as by time or location, so that researchers can get a better sense of what the data are about and what can be manipulated. Psychoinformatics may achieve this goal using data from numerous sources, including mobile devices and sensors, which can be stored in a central database and implemented in an analytical platform (Markowetz et al., 2014; Yarkoni, 2012). Human movement data, collected with "wearable" equipment and analysed in a geoinformatics platform, would offer significant potential benefit for many disciplines, since both psycho and physical parameters are obtained together.

A psycho-geoinformatics approach, with more spatial functions, collects fine-level individual behavioural data and uses tools from GISciences to comprehensively investigate driver behaviour in space and over time. Microscopic scales of spatial-temporal context can reveal subtle changes in actions which suit driving behaviour tracking since both visual search and lane keeping actions update second-by-second at the micro-scale level, for example, a driver's eye fixation duration can be as short as 0.1 seconds.

Furthermore, the psycho-geoinformatics approach sets up a scalable multidimensional data infrastructure that can offer more definitive information related to the driver's visual search strategies and motor actions. The high-resolution driving events exhibit spatial distribution and temporal change in vision and motor behaviour of the driver, thereby build detailed models of the cognitive processes of individual drivers and their interactions with the traffic. From there, the driving competencies can be accurately evaluated in the system and potentially the system can provide effective feedback to the drivers to review suspicious behaviours.

Using geoinformatics tools in driving behaviour assessments would open a new era of mobility research with many possible analytical options that do not have to rely on human observations. Instead, it can receive clear indicators of the individual drivers' interaction with the vehicle and the traffic environment. The geoinformatics-based framework integrates a set of standard spatial tools and techniques and, thus, the derived products are in a standard GIS (Geographic Information Systems) format, leading to interoperable solutions that can be used as an input for any GIS based applications.

4.2. Multi-GNSS RTK tracking precise vehicle movement trajectory

In order to quantitatively study human mobility and behaviour through driver-vehicle-environment interactions, spatial and temporal attributes are required for behavioural datasets. A detailed signature of a driver's mobility in the environment is essential to establish a psycho-geoinformatics central database.

In this study, the high performance of multi-GNSS (multiple Global Navigation Satellite Systems) with Real-time Kinematic (RTK) solution is used to track precise vehicle movement trajectories. Multi-GNSS approach outperforms conventional GPS (Global Positioning Systems) positioning in terms of the satellite availability and positioning accuracy, which are essential for recording vehicle movement in an urban area when the precise vehicle positioning and continuous trajectories are required (Kubo, Hou, & Suzuki, 2014; Noomwongs, Thitipatanapong, Chatranuwathana, & Klongnaivai, 2014; Qian Sun, Xia, Foster, Falkmer, & Lee, 2016). Multi-GNSS RTK provides a relative positioning accuracy at the centimetre-level, allowing vehicle speed and lane position data to be generated from the trajectory positions for driving behaviour assessment. Also importantly, multi-GNSS RTK records high-resolution vehicle trajectories that can establish a backbone of the psycho-geoinformatics database and enable spatial and temporal analysis of driving behaviour in a GIS platform.

4.3. Context and location-aware mobile eye tracking

Eye tracking is used to record the eye movement of participants and their interactions with vehicle and environment. The fundamental data processing in this study is to extract eye fixations and fixation durations, which exhibit drivers' attention and reaction to external stimuli from the environment (Falkmer, Dahlman, Dukic, Bjällmark, & Larsson, 2008). To further analyse the data and capture the contextual information as much as possible, eye tracking video footage of on-road driving will be divided frame by frame. Each fixation is manually labelled, based on a pre-defined analysis matrix, with a series of codes indicating the characteristics of the fixated object, such as the object that was fixated; the background of the object that was fixated, and the distance of the object from the driver. The start time of each fixation can also be captured. The start time will be linked to the vehicle position recorded by the GNSS receivers and, by doing so, the resulting database accommodates the exact vehicle location when an eye fixation happened, allowing the locations of the driver's gaze origin in geospatial coordinates to be obtained. Therefore, location-aware enabled eye tracking can be also achieved along with the context awareness capability.

4.4. A visual-motor coordination data model

Gaze pattern is a crucial component of executing skilled actions and this is particularly true when controlling human locomotion (Land & Lee, 1994; Wilkie, Wann, & Allison, 2008). Driving, as described by Gibson and Crooks (1938), is a locomotion through a terrain by means of a vehicle to reach a destination. The basic activity is to achieve a path (a vehicle trajectory determined by its speed and direction), so as to follow the spatial constraints on the road and avoid collisions with obstacles. Driving is guided mainly by vision, which enables the driver to acquire environmental information from a distance in order to anticipate the future situation and to take control actions in time (Cavallo & Cohen, 2001).

The experimental design in this study employs a vision-in-action paradigm in an attempt to integrate visual-perception with motor action. Such a paradigm recognises many factors in the constraints-directed model: the driver, the task, the environment and perception-action coupling within driving visual-motor workspaces (Vickers, 2007). The participant's on-road driving behaviour can be simultaneously recorded using eye movement tracking and GNSS vehicle movement tracking. The eye tracker records eye fixations and duration on video images to analyse the visual pattern of the driver. The eye fixation data are geocoded and synchronised with the vehicle movement trajectory in order to investigate the vision-motor coordination of the driver. The geocoding and synchronising will be undertaken in a GIS environment. The (x, y) coordinates of the vision-motor behaviour data can be overlaid with other environment and transport information in GIS, by analysing spatial-temporal patterns of the synchronised eye fixation and vehicle movement data. The characteristics of the driver's vision and motor behaviour can be investigated in depth.

4.5. A gaze-based integrated driving assessment database

A gaze-based integrated driving assessment database is further developed based on the visual-motor coordination data model. It integrates driver's visual patterns, vehicle movement and the traffic environment in GIS, which enables more comprehensive examinations of driver-vehicle-environment interactions. The database is individual driver centered and the analysis and assessment based on a scalable multi-dimensional data infrastructure that is more representative of the real specific driving situations.

Eye gaze patterns are the fundamental parameters of the driving assessment database. They are guided by the interplay of top-down and bottom-up factors affecting eye movement through driving. The top-down strategies are developed through driving experience and can inhibit and influence the bottom-up visual attention (Crundall, 2005). The type of objects and the frequency and duration of eye fixations on the objects recorded by eye trackers are important metrics for understanding visual search strategies. In addition, the timing of eye fixation and the distance between fixation and road markers can affect steering performance, those elements are also included. The integrated database exhibits multi-sensory information acquired from the vehicle, driver and environment. The raw data can be analysed, linked and segmented with spatial, temporal and categorical attributes, enabling analysis of a driver's visual and motor behaviour and coordination performance at both the individual and group levels in a variety of driving sections and scenarios.

4.6. Standard neuropsychological tests

Cognition is a significant predictor of the difficulties older adults may face in their basic and instrumental activities of daily living (Burdick et al., 2005). Laboratory-based measures of cognitive abilities can reliably predict functional competence among older adults. So far a variety of cognitive abilities that decline with increasing age have been well-researched, including visual perception and attention, processing speed and executive function. These findings provide important insights into further investigation of the links between basic cognitive abilities and everyday functional abilities (Ball, Edwards, & Ross, 2007).

There are five sets of neuropsychological tests used to evaluate the relationships between cognitive functioning and new measures of driving behaviours: Useful Field of View (UFOV), Benton Judgement of Line Orientation (BJLO), Block Design (BD), Delis-Kaplan Executive Function System Trail Making tests (D-KEFS TMT) and Balloon Analogue Risk Task (BART). These tools are standardised tests that have been widely used internationally and have been evaluated to be ecologically valid to measure visual and cognitive capacities that are likely to impact upon daily functioning, including driving (Barrash et al., 2010; Hoggarth, Innes, Dalrymple-Alford, & Jones, 2013).

4.7. Spatial, statistical and mathematical analysis

The data analysis in this study engages techniques from statistics, spatial analysis and visualisation, and mathematical programming to examine drivers' driver-vehicle-environment interactions. A Data Envelopment Analysis (DEA) model (Chen, 2004; Cooper, Seiford, & Zhu, 2004; Zbranek, 2016) is used to calculate the visual-motor coordination performance of participants. DEA is a linear programming technique capable for evaluating the relative performance of decision-making units, here the older drivers, in which multiple inputs and outputs are involved. In this study, visual search parameters are considered as the inputs and vehicle control parameters as the outputs. Typical DEA inputs can be the representation of sources used and outputs reflect the level of products. However, these features may not actually represent inputs and outputs at all (Seiford & Zhu, 2002), the model still calculates the relative performance. The model can identify the optimal ways of performance rather than the averages (S. Babaee et al., 2014; Babaee, Shen, Hermans, Wets, & Brijs, 2014; Cherchye et al., 2006). A visual-motor coordination composite indicator for individual drivers will be developed, using a DEA combined with GIS that identifies low-performing driver behaviours.

5. Thesis Structure

5.1. Thesis design and linkage between chapters

This thesis combines the traditional thesis format with a "paper-based" model (Fig.1). The overall workflow is shown via the links between chapters dealing with three main research topics after the research framework in Chapter 1, whereas individual empirical chapters contain their own structure and workflow. Each main chapter acts a sub-study, but also plays an important part in the development of the entire thesis. Individual chapters contain one or more papers and a range of issues are addressed in the total of nine papers.

Fig. 1. Layout of thesis structure and the linkage between papers
(Excluding Chapter 1: Introduction and Chapter 6: General Discussion and Conclusions)

Apart from the introduction chapter (Chpater 1), and the discussion and conclusions chapter (Chapter 6), Chapter 2 provides a research framework underpinning the whole thesis. Chapter 3 describes the precise vehicle movement tracking approach, which is critical to the entire process. Chapter 3 also justifies the validity of the battery of neuropsychological tests chosen in this study. Chapter 4 describes the integration of eye movement and vehicle movement trajectory and investigates older drivers' visual search patterns in relation to their visual capacity. Chapter 5 takes one-step further to intertwine visual, motor behaviour and the environment to investigate visual-motor coordination in the driving behaviour of older adults. The structure of the thesis reveals an evolving process in thesis design: vehicle tracking - linking eye tracking with vehicle tracking - a gaze-based integrated database for the visual-motor coordination assessment.

Table 1. Contributions of individual papers towards the research objectives

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
Paper 1	Δ	Δ	Δ	Δ	Δ
Paper 2	Δ				
Paper 3	Δ				
Paper 4	✓	✓			
Paper 5	Δ		Δ	Δ	
Paper 6	✓		✓		
Paper 7	Δ			Δ	Δ
Paper 8	✓				✓
Paper 9				✓	✓

Note: "✓" : serves as the main contributing paper; "Δ": as the co-contributing paper.

Table 1 lists the contributions of individual papers towards the sub-objectives of this study. Paper 1, the thesis framework, serves as a co-contributing paper for all the five objectives. Paper 2 and 3 develop the precise vehicle movement tracking mothods and the data, as the backbone of the research database, support the measurement of lane keeping, the visual search using geocoded eye fixations and the visual-motor coordination. Paper 4 serves as the main contributing paper for lane keeping measurement and the investigation in Objective 1 and Objective 2. Paper 5 integrating eye movement and vehicle movement trajectories, contributes to the visual search investigation in Objective 1 and Objective 3, and the measurement of visual-motor coordination performance in Objective 4. Paper 6 is the main contributing paper for both the visual search measurement in Objective 1 and Objective 3. In paper 7, the gaze-based integrated driving assessment system supports the measurement of visual-motor coordination and investigation in Objective 1, Objective 4 and Objective 5. Paper 8 is the main contributing paper for the measurement of visual-motor coordination in Objective 1 and Objective 5. Paper 9 supports investigations of visual-motor coordination at intersections in Objective 4 and 5.

5.2. Contents of chapters

Chapter 2: Literature Review and Framework. This chapter contains the following paper (paper 1 of the thesis):

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Framework for investigating older adults' driving behaviours and the underlying cognitive mechanisms. The paper was presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. The paper was awarded for the best type B and invited by *European Transport Research Review (ETRR)* for a special issue. **(Paper 1)**

This paper serves as an overall guidance for the design and implementation of the thesis, which is closely related to the literature of the older drivers' issue. A framework with the psycho-geoinformatics approach for investigating older adults' driving behaviours and the underlying cognitive mechanisms is presented. This is accompanied by a substantial review on the characteristics of older drivers' driving behaviour and the age-related cognitive abilities affecting their driving behaviour. This paper also establishes the overall approach for the study. The conceptual unit of the framework introduces and describes the theory that explains why the research problem under study exists and defines the critical cognitive components and behaviour variables in driving mobility. The experimental unit of the framework presents the protocol of experiments and methods of data collections. The analysis and assessment unit of the framework summarizes the key methods used in the analysis, the process of the analysis and the outcomes of the study.

This chapter will define the critical cognitive components and behaviour variables in the driving mobility study with respect to visual searching, lane keeping and coordination between actions. An assessment protocol to collect information on neuropsychological characteristics and driving behaviour for fifty older drivers will be briefly described. In an essence, this chapter connects the current research to existing knowledge and studies.

Chapter 3: Vehicle Movement Tracking and Driving Behaviour Assessment. This chapter is covered by paper 2, 3 and 4 of the thesis:

Sun, Q., Odolinski, R., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2017). Validating the efficacy of GPS tracking vehicle movement for driving behaviour assessment. *Travel Behaviour and Society, 6*, 32-43. doi:http://dx.doi.org/10.1016/j.tbs.2016.05.001. **(Paper 2)**

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Pursuing Precise Vehicle Movement Trajectory in Urban Residential Area Using Multi-GNSS RTK Tracking. *Transportation Research Procedia.* Elsevier. Paper presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. **(Paper 3)**

Sun, Q., Xia, J. C., Falkmer, T., Foster, J., & Lee, H. (2016). Driving Manoeuvres during Lane Maintenance in Older Adults: Associations with Neuropsychological Scores. The manuscript was originally peer-reviewed and accepted by WCTRS (14th World Conference on Transport Research). [Revised and submitted to *Transportation Research Part F: Traffic Psychology and Behaviour*]. **(Paper 4)**

This chapter elaborates the collection and measurement of precise, high-resolution vehicle movement trajectory data that are then used as a locational reference to geo-code the eye fixations and construct the visual-motor coordination path and episodes in the later chapters. Through paper 2 to paper 3, various GPS/GNSS devices and positioning techniques are tested. The chapter presents the evidence that the advanced surveying technology, namely multi-GNSS with RTK (Real-Time Kinematic), can record precise accurate vehicle trajectories capable for detecting driving behaviour, e.g., calculation of lane deviations.

Based on the vehicle movement data, paper 4 investigates the lane maintenance performance in older drivers and the associations with their cognitive functioning. Mean Lane Position (MLP), Standard Deviation of Lane Position (SDLP) and manoeuvre time calculated from precise vehicle movement trajectories are used as the lane maintenance parameters. A discriminant analysis also investigates the validity of the combined cognitive variables from neuropsychological tests in determining lane maintenance performance in older drivers.

Chapter 4: Integrating Vehicle Trajectory and Eye Movement Analysis. This chapter consists of paper 5 and 6 of the thesis:

Sun, Q., Xia, J. C., Nadarajah, N., Falkmer, T., Foster, J., & Lee, H. (2016). Assessing drivers' visual-motor coordination using eye tracking, GNSS and GIS: a spatial turn in driving psychology. *Journal of Spatial Science*, 61(2), 299-316. doi:10.1080/14498596.2016.1149116. **(Paper 5)**

Sun, Q., Xia, J. C., Falkmer, T., & Lee, H. (2016). Investigating the Spatial Pattern of Older Drivers' Eye Fixation Behaviour and Associations with Their Visual Capacity. *Journal of Eye Movement Research, 9*(6). doi:10.16910/jemr.9.6.2. **(Paper 6)**

This chapter integrates visual patterns with lane keeping data. The eye fixations of eye movement are geocoded and linked to the vehicle movement trajectory to represent the visual-motor coordination of drivers in a GIS platform. The techniques are described in paper 5, where a spatial-temporal data model of visual-motor coordination is constructed. The integration extends the dimensions of eye movement tracking by adding the location of where each gaze originated and visualising the pattern of their oculomotor behaviour. Paper 6 investigates the associations between older drivers' visual capacity (processing speed, divided and selective attention) and their eye fixations in various driving manoeuvres. The influence of different driving sections on the associations between older drivers' eye movement and visual ability are explored via both spatial and statistical analysis.

Chapter 5: Assessing Older Drivers' Visual-Motor Coordination. This chapter is covered by paper 7, 8 and 9 of the thesis:

Sun, Q., Xia, J. C., He, J., Foster, J., Falkmer, T., & Lee, H. (2016). Towards Unpacking Older Drivers' Visual-motor Coordination: A Gaze-based Integrated Assessment System. Manuscript. [Submitted to *Accident Analysis & Prevention*]. **(Paper 7)**

Sun, Q., Xia, J. C., Falkmer, T., Foster, J., & Lee, H. (2016). Unpacking Older Drivers' Mobility at Roundabouts: Their Visual-motor Coordination through Driver-vehicle-environment Interactions. Manuscript. [Submitted to *International Journal of Sustainable Transportation*]. **(Paper 8)**

Sun, Q., Xia, J. C., Falkmer, T., Foster, J., & Lee, H. (2016). Unpacking Older Drivers' Manoeuvre at Intersections: Their Visual-motor Coordination and Underlying Neuropsychological Mechanisms. Manuscript. [Submitted to *Journal of Gerontology: Medical Sciences*]. **(Paper 9)**

This chapter introduces the concept of the visual-motor coordination path and episodes in driving mobility and comprehensively examines the visual-motor coordination of older drivers. Paper 7 integrates more visual search attributes and proposes a gaze-based integrated driving assessment database in order to undertake an assessment of older drivers' visual-motor coordination through driver-vehicle-environment interactions.

Paper 8 and 9 focus on assessing older drivers' visual-motor coordination and identifying indicators of risky behaviours in low-performing older drivers. Paper 8 measures older drivers' visual-motor coordination at a series of roundabouts. Their visual scanning pattern and lane keeping are aggregated and benchmarked. A Data Envelopment Analysis (DEA) model combined with GIS analysis is used to develop a visual-motor coordination composite indicator

(VMCCI) for individual drivers. Low-performing drivers, their risky driving behaviours and problematic road sections are identified through the DEA modelling. The impact of the roundabout geometrics on older drivers' visual-motor coordination is also investigated.

Further investigation looks at older drivers' visual-motor coordination performance at intersections, which is the most challenging sections for older drivers. The associations of visual-motor coordination in older drivers with their cognitive functions will be interrogated aiming to evaluate neuropsychological mechanisms underlying visual-motor coordination.

Chapter 6: General discussion and conclusions, as the final chapter, summarises the results obtained from the main sub-studies, followed by a review of the thesis objectives and evaluation of the methods and outcomes. The practical and theoretical implications, and the main contributions to the research field are reviewed and the limitations of this research are discussed, with recommendations for future research.

6. Summary of the Chapter

This chapter highlighted the issue of older drivers' behaviours and the need to promote their driving mobility and safety. It has been argued that an important step in addressing this issue is the development of better assessment methods to measure older drivers' visual searching, lane keeping and visual-motor coordination, and their associations with cognitive abilities. These can be then utilised to proactively identify risky drivers and risky behaviours. This chapter has introduced the overall techniques developed and used to fulfill the study objectives and achieve the desired outcomes. The thesis structure and contents were outlined and explained. In summary, this study attempt to investigate older adults' driving behaviours and related cognitive abilities through bridging the traditional gaps between driving psychology, traffic safety and Geosciences.

2

Literature Review and Research Framework

CHAPTER 2 LITERATURE REVIEW AND RESEARCH FRAMEWORK

This chapter is covered by the following paper (paper 1 of the thesis):

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Framework for investigating older adults' driving behaviours and the underlying cognitive mechanisms. Paper was presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. The paper was awarded for a best type B and invited by *European Transport Research Review* (ETRR) for a special issue. **(Paper 1)**

Following the research aims and objectives derived from the background in the thesis introduction, this chapter reviews the older drivers' profile and the age-related cognitive abilities affecting their driving behaviours. A framework with an interdisciplinary approach is presented for investigating older adults' driving behaviours and the underlying cognitive mechanisms. This chapter connects the current research to the existing knowledge, and establishes the overall approach of the thesis, namely the psycho-geoinformatics framework.

Three units of psycho-geoinformatics framework are developed. First, the conceptual unit introduces and describes the concepts that explain why the research problem under study exists, and defines the critical cognitive components and driving behaviour variables in driving assessment. The experimental unit presents the protocol of experiments and methods of data collections. Thirdly, the analysis and assessment unit summarizes the key means that will be used in the analysis, the process and the outcome of the analysis.

This chapter defines the three key sub-studies imbedded in current research on older drivers' driving mobility and behaviours with respect to visual searching, lane keeping and visual-motor coordination. The three sub-studies are logically connected under the psycho-geoinformatics framework.

Finally, the implementation of the framework and practical considerations are presented. An assessment protocol and a battery of psychometrics tests will be briefly described about data collections on neuropsychological characteristics and driving behaviour in 50 older adults. In order to demonstrate the feasibility and effectiveness of the proposed framework, a preliminary analysis from the authors' published work (Sun et al., 2016) will be included in this chapter.

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Framework for Investigating Older Adults' Driving Behaviours and the Cognitive Mechanisms: A Psycho-Geoinformatics Approach

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Abstract

Safe driving constantly challenges the driver's ability to response to the dynamic traffic scene under space and time constraints. It is of particular importance for older drivers to perform sufficient visual and motor actions with effective coordination between the actions. Few studies have been able to integrate drivers' visual and vehicle control data with environmental information to assess driving behaviours in a spatial-temporal context. A framework has been developed in a psycho-geoinformatics approach, for investigating older adults' driving behaviors and the underlying cognitive mechanisms. This was achieved by taking advantage of high frequency tracking of eye movement and vehicle kinematic, and spatial-temporal analysis from GISciences, and also the standard neuropsychological tests related to driving abilities. Recordings of the drivers and their interactions with the vehicle and environment at a microscopic scale give a closer assessment of the drivers' behaviours, the evolution across space and time and thus a better understanding of driver's cognitive processes. This paper aims to present the framework for the basic concepts, design and implementation of this study, as well as the practical considerations.

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Keywords: Older Drivers, Cognitive Abilities, Eye tracking, Vehicle Movement Tracking, Visual-motor Coordination, Psycho-Geoinformatics

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1. Introduction

Epidemiological studies have projected a large increase in the percentage of drivers aged 60 and older, a cohort at risk of road crashes (Aksan et al., 2012; Evans, 2000; Lyman, Ferguson, Braver, & Williams, 2002). Older drivers have one of the highest vehicle crash rates in comparison with other population groups, largely due to the functional effects of the accumulation, and progression of age-related declines in visual, cognitive and motor conditions that impact on fitness to drive (Molnar et al., 2007). A number of studies have identified that the increased crash risk for older drivers stems from above declines (Clarke, Ward, Bartle, & Truman, 2010; Classen et al., 2007; Daigneault, Joly, & Frigon, 2002; Dawson, Uc, Anderson, Johnson, & Rizzo, 2010; Horswill, Anstey, Hatherly, & Wood, 2010). Knowledge of the cognitive characteristics associated with driving behaviour of older people, has important implications for the improvement of safety on our roadways and the mobility of older adults. Various efforts have been attempted to attain a better understanding of driving behaviour, by laboratory-based neuropsychological tests, on-road driving observations, computer simulations, etc., and new methods are constantly emerging.

Currently, the commonly acknowledged “gold standard” for driving assessment is the on-road driving evaluation offering a pass or fail outcome, which is similar to the “road test” that most individuals undergo to receive their driver’s license. Although on-road driving assessment presents a naturalistic test setting, Schultheis and Manning (2011) addressed that it lacks sensitivity to detect subtle changes in driving performance when considering its utility as an outcome measure. Moreover, vehicle driving in real traffic is a complex interactive system involving human visual perception, cognition, and locomotion of the driver, vehicle movement and the environment. Driving makes demands on multiple cognitive processes for the drivers, it is challenging to generalise findings and predict safety outcomes from a single sensory tracking or isolated assessment (Lees, Cosman, Lee, Fricke, & Rizzo, 2010). Thus studying driver behaviour should consider engaging contextual driving information, drivers’ actions and thinking in an integrated format under natural conditions. For example, a platform developed by Ramon, Clarion et al. (2008) provided a reliable data acquisition and processing solution to obtain vehicle information, video and contextual data from field tests. The driver’s behaviour was assessed through various indicators, which brought abundant information to improve the validity and reliability of the assessments. Although recordings across time gave a better understanding of drivers’ behaviour (Ramon et al., 2008), one limitation is that Ramon’s system didn’t collect certain useful data to detect driver states, such as visual attention measures and advanced driving variables including lane position, Park and Son (2010) pointed out that the nature and underlying mechanisms of the monitored behaviour hadn’t been well defined in the project.

Linking the drivers’ visual actions and steering performance in the analysis can be found in several studies (Cloete & Wallis, 2011; Michael F. Land, 2006; M. F. Land & Lee, 1994). For example, Land and Lee (1994) made a simultaneous recording of steering-wheel angle and drivers’ gaze direction during a series of driving along a tortuous road, they found that the drivers relied primarily on the gaze of the tangent point on the inside of each curve of route sections. The study obtained valuable information about how humans think and act in relation to the vehicle control and environment.

Safe driving constantly requires the driver’s ability to respond to the dynamic traffic scene under space and time constraints, the ability to perform sufficient visual and motor actions with effective coordination between the actions. This is of particular importance for older drivers who are more likely experiencing cognitive declines. Integrating older drivers’ visual and vehicle control data with environmental information in a spatial-temporal context would give more valuable and closer assessment of driver behaviours. The evolution of the spatial-temporal patterns of the visual-motor coordination would, therefore, provide a better understanding of the cognitive mechanisms underlying driving behaviours (Q. Sun et al., 2015).

The current manuscript describes a research protocol, which measures mobility in older adults’ driving behaviours and related cognitive states in an innovative way, by taking advantage of high-frequency tracking of eye movement and vehicle kinematic, and spatial-temporal analysis from

GISciences, and also the standard psychometrics tests related to driving abilities. The goal is to discover links between driver's visual and motor behaviour and importantly the cognitive process from visual search to vehicle control. Such measurement cannot be obtained without geoinformatics tracking and analysis tools, which would synthesize multi-sensory data into a more dynamic and quantitative format and create a context-aware investigation platform. This study thus employs a psycho-geoinformatics approach to collect fine individual behaviour data and use tools from GISciences, incorporating statistical methods to comprehensively investigate the drivers' behaviours. Microscopic scales of spatial-temporal context can reveal subtle changes of actions in driving behaviour tracking, since both visual search and vehicle control actions update from moment to moment at the micro-scale level, for example, the driver's eye fixation duration can be as short as 0.1 seconds.

The idea of psycho-geoinformatics in this study was simply evolved from the interdisciplinary approach of psychoinformatics, which is an emerging discipline that uses tools from information sciences to improve the acquisition, organization, and synthesis of psychological data. Yarkoni (2012) and Markowetz, Błaszkiewicz and their colleagues (Markowetz, Błaszkiewicz, Montag, Switala, & Schlaepfer, 2014) are the pioneers of this new discipline. They stated that some of the applications of technology are possible to engage new types of data that don't have conventional analogues in psychology, for instance, the GPS location data. Adapting tools and techniques from computer and information sciences can improve the measurement and modelling of psychological processes in a broad range of ways. In addition, no matter how data are obtained, they must ultimately be synthesized into a meaningful form, by time or location, so we can get more sense about what the data are telling us. Psychoinformatics may achieve such a goal since it contains: 1), numerous data sources from mobile devices and sensors; 2), a central data store; and 3), an analytical platform for the project (Markowetz et al., 2014; Yarkoni, 2012). Dörrzapf, Zeile et al. (2015) further explicated that with the availability of numerable human movement data, the constantly growing movement of users with "wearable" equipment would offer a great potential for many disciplines as psycho and physical parameters can be collected on the go.

We intend to believe that in driving behaviour studies, the psycho-geoinformatics approach would set-up a scalable multidimensional data infrastructure which can offer significantly more definitive information related to the driver's visual search strategies and motor actions. The high-resolution driving events exhibit spatial distribution and temporal changes of the driver's vision and motor behaviour, thus it would help build a detailed model of the cognitive processes for individual drivers and their interactions with the traffic. From there, the driving behaviour and performance can be accurately evaluated in the system.

This paper aims to present the framework of the basic concepts, design and implementation as well as the practical considerations of the psycho-geoinformatics approach for older drivers' behaviour study. The framework is outlined in terms of its key components and process. Three sub-units were developed. Firstly, a conceptual unit defines the key factors and variables, assumptions and theories of driving behaviour assessment, and the presumed relationships between the variables involved. Secondly, an experiment unit sets out a protocol to explore a variety of older driver attributes in a single investigation. Lastly, a data analysis and assessment unit outlines the methods of data processing and integration, and spatial statistical approaches for assessments, and expected outcomes. The process adopted would allow for comprehensive data collection and analysis with minimal disruption to participants.

The ultimate goal of the entire study is to explore the relationship between neuropsychological characteristics and the driving behaviours in older adults. The following sub-objectives will be fulfilled through the guidance of the current framework: assessing the cognitive abilities of older drivers and their on-road driving behaviours; investigating the relationship between the cognitive abilities of older drivers and their driving behaviours, and identifying the predictable variables for unsafe driving behaviours in older adults in order to promote safe driving.

2. Literature Review

2.1. Driving in older adults and the crash site profile

Driving is an important activity that underpins the personal mobility and autonomy in our society. As an activity, driving involves neuropsychological capacities that are mediated by multiple areas of the brain, including visual, attentional, perceptual, cognitive and psychomotor abilities (K. J. Anstey, Wood, Lord, & Walker, 2005). Aging complies with functional and structural cerebral changes leading to cognitive decline. This decline includes a variety of cognitive sub-functions, some of the functions are closely related to driving skills. Resultantly, driving skills become impaired with advancing age. As evidenced by a study on healthy older adults, cognitive abilities necessary for safe driving can be disrupted even in older adults without dementia (Schultheis & Manning, 2011). For instance, older adults are slower at processing information, especially in a complex decision, tend to have slower motor responses and lack coordination in a range of motion (Gentzlera & Smither, 2012).

A number of studies have investigated the car crash epidemiology of older drivers and compared crashes rates across age groups. These studies have identified that older drivers have a higher crash involvement than younger drivers on a per distance driven basis, and experience a higher fatality rate than their younger counterparts (Andry Rakotonirainy, Steinhardt, Delhomme, Darvell, & Schramm, 2012; Romoser, Fisher, Mourant, Wachtel, & Sizov, 2005). The statistics of crashes also show an accelerated rise of car crash risk beginning around aged 65 years (H. C. Lee, 2003; Andry Rakotonirainy et al., 2012). In a police-reported crash database held in Western Australia, the number of older drivers above aged 70 hospitalized or killed as the resulting road crashes were more than twice as high as drivers aged 30-59 years (Meuleners, Harding, Lee, & Legge, 2006). Nevertheless, many of these people still drive. To protect these drivers and the driving public, it is very important to identify at-risk drivers and to inform them about possible interventions. The assessment of older drivers' behaviours has been an area of high priority related to the increasing older population.

Some other studies have summarised the characteristics of car crashes in older adults. Older drivers are less likely to be involved in crashes caused by fatigue, high speed, weather condition or alcohol, but are more likely to be involved in crashes involving: manoeuvres through intersections; failure to yield the right of way; failure to identify hazards or to heed stop signs/traffic signals; and problems involved in turning and changing lanes (Clarke et al., 2010; Marmeleira, Ferreira, Melo, & Godinho, 2012; McGwin & Brown, 1999). Charlton et al. (2006) surveyed the self-regulatory driving practices of 656 older drivers and found that older drivers tend to avoid driving in busy traffic or at night, and especially at nights in wet conditions. Older drivers are also more likely to be involved in angled impact crashes, as Romoser et al. (2005) postulated that it is more difficult for older drivers to gather and process information about the environment due to the gradual deterioration of sensory and cognitive processing capabilities.

Age-related physiological impairments; together with reductions in cognitive and visual motor functioning lead to unsafe driving practices in older adults (Maltz & Shinar, 1999; Sivak, 1996; Sivak, Olson, & Pastalan, 1981; Warabi, Noda, & Kato, 1986; Welford, 1968). A primary concern in older drivers is the decline in executive function, which includes higher order operations that help us organize information and regulate our behaviour, such as prioritizing, planning and following rules (T. A. Salthouse, 2004; T. A. Salthouse, Atkinson, & Berish, 2003). Also of concern is the decline in speed of processing as one age (T. A. Salthouse, 1996). For example, older adults have been shown to take twice as long as younger adults for elementary information processing operations (involving perceptual, cognitive and motor processing components) (Jastrzembski & Charness, 2007). Younger drivers have been shown to outperform older drivers in series of neuropsychological tests (involving cognitive processing speed, psychomotor functioning, visuospatial performance and executive functioning, except sustained attention) associated with driving performance (Andrews & Westerman, 2012; Cynthia. Owsley, Ball, & McGwin, 1998; Shanmugaratnam, Kass, & Arruda, 2010). In addition, sensorimotor and cognitive abilities associated with increased visual field dependence in old age can be degraded too (Rachael D Seidler & Stelmach, 1995), such as spatial orientation and sensorimotor control (Agathos et al., 2015), both are the critical factors underpinning high-level driving competence.

Age is considered to be a poor indicator of driving competence due to individual differences in functional ability, driving experience, and self-regulatory practices (Cynthia. Owsley & Ball, 1993; Smither et al., 2004; Waller, 1991). As Anstey and Wood (2005) have noted, not all older drivers are unsafe. Research into older drivers' behaviours has changed in focus from "why do older drivers have a higher accident risk?" to "which older drivers have higher accident risk?" (Hakamies Blomqvist, 1998). An age-based criterion is not sufficient for identifying risky older drivers. Rather, age-related changes in cognitive functions, including changes in information processing speed, attention, can provide better predictions for low-performing driving (Colsher & Wallace, 1993; Mathias & Lucas, 2009; Mouloua et al., 2004).

2.2. Key age-associated cognitive abilities relevant to driving in the spatial-temporal context

Across a number of studies, the most researched cognitive predictors for driving performance include visual processing speed and attention, motion perception, contrast sensitivity, visuospatial abilities, motor speed, and executive function (Schultheis & Manning, 2011). The control of movement is a complex interaction between cognitive and sensorimotor systems. In this section, we document the major changes in cognition that occur in the control and coordination of movement with respect to aging. We are particularly interested in the predictors that affect older drivers' ability to perform sufficient visual, motor actions and effect coordination between the actions.

- *Visual processing speed and attention*

Even in normal aging there is a decline in visual attention including selective attention and divided attention. Driving requires the visual ability to attend to relevant traffic information and to ignore irrelevant information in often complex visual scenes, which with present potential hazards can occur in any part of the view (Lees et al., 2010). Therefore, the speed at which visual information is processed is critical for negotiating challenging traffic situations (K. J. Anstey et al., 2005; Ball, 2003; Cynthia Owsley, 2013; Richardson & Marottoli, 2003). Several changes occur in the human eye with age making the visual system operate less efficiently, and it has been recognised that older adults are slower than younger adults in of processing speed, and such slowing of cognitive processes may have destructive effects on more complex tasks (Glisky, 2007). Older adults showed a significantly decreased ability in divide attention compared with other group of adults (Ponds, Brouwer, & Van Wolffelaar, 1988). Smither, Mouloua et al. (2004) stressed that it would take an older driver 1.5 to 1.7 times longer on average than a younger driver to scan for information. Apparently, for older drivers, visual attention is an important variable directly associated with accident risk (Cynthia. Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Richardson & Marottoli, 2003). A strong argument was made by a psychologist and researcher that the study of sensory and motor systems should not be separated (Goodale, 1998, 2011). For older drivers, sensory function should not be considered in isolation, other contributing factors such as cognitive ability, and other health-related and motor problems must also be considered (Ball, 2003).

- *Spatial cognitive abilities*

Spatial abilities involve the generation and processing of visual-spatial information (Colom, Contreras, Botella, & Santacreu, 2002). General spatial abilities reach the peak during our 20s to 30s, then decline steadily in later life (T. Salthouse, 1982). Smither, Mouloua et al. (2004) stressed that deficits in these abilities cannot be attributed to the general slowing down of processing that accompanies aging, as they are apparent even when spatial ability tests are not time limited. As a result, older adults experience difficulty with spatial relations and with mental rotation tasks, for example, localizing objects in a 3D space and interpreting information displayed in the rear view and side mirrors of a car. Older adults are also likely to have more difficulties in route finding and learning when information displayed in a schematic as opposed to verbal form (Smither et al., 2004).

Studies have linked spatial cognition to older persons' driving behaviours (Kaarin J. Anstey, Horswill, Wood, & Hatherly, 2012; Colom et al., 2002; Eby, Trombley, Molnar, & Shope, 2004). Since spatial cognition is frequently utilised in driving and related to the safe and efficient operation of a vehicle (Eby et al., 2004), the decline of spatial ability in older drivers can adversely affect their driving behaviour and performance.

- *Psychomotor skill and motor speed*

Motor skills in driving, such as pedal control and steel wheel control are psychomotor skills that developed as a result of constant practice, so individuals need little thought to perform them but require input from both the physical and the mental attributes, and coordinate and balance in order to achieve a certain goal (Stelmach & Nahom, 1992). Age-related motor skill declines can be seen as balance and coordination deficits, and slow movement (Rachael D. Seidler et al., 2010), also as alterations in cognitive-motor processes (Rachael D. Seidler et al., 2010; M. W. Smith, Sharit, & Czaja, 1999). In addition, the motor executions by the older adults would require more psychomotor ability and dependent on cognitive control (Claudia Voelcker-Rehage, 2008).

Poorer movement skill in older adults results in reduced speed and accuracy (Raw, Kountouriotis, Mon-Williams, & Wilkie, 2012). Smither, Mouloua et al. (2004) summarized the motor related changes affecting driving as follows: older drivers' slower response for situation weakens the ability to react quickly to imminent danger; their reduced control ability impacts safe driving in a timely fashion, such as taking longer to initiate movement and carry through; and older drivers' slower to accomplish eye movements to fixate on objects moving around in the environment. As also identified by Anstey and Wood et al. (2005), older adults adopt a different movement strategy when facing a motor task requiring steadily movement under spatial-temporal constraints. Raw, Kountouriotis et al. (2012) stated that older adults are aware of their level of motor skill and intend to adjust their movement strategy to meet task demands.

- *Executive function and visual-motor coordination*

Another critical cognitive function related to driving is the executive function, and the decline in normal aging has been supported by neuroimaging studies showing age-related changes in the prefrontal cortex (Head, Raz, Gunning-Dixon, Williamson, & Acker, 2002). Executive function is necessary for integrating information and planning a response, therefore is relevant to competent driving performance (K. J. Anstey et al., 2005).

Executive functioning involves the control and coordination of cognitive operations (T. A. Salthouse, 2005). Subtle executive declines in a more cognitively intact group (e.g., older adults) may show a stronger correlation with cognitively demanding driving tasks. The extent to which visual perception and fine motor skills are well coordinated is critical for driving (Schultheis & Manning, 2011). Older drivers experience difficulties to perform effective visual-motor coordination, especially during complex driving tasks (e.g., driving through intersections), largely due to the decline of executive function.

Executive function is responsible for organizing various actions into a goal-oriented behavior, specifically coordinating different brain areas to respond to environmental cues, planning the response, and subsequently carrying it out. Therefore, it is involved greatly in the following tasks and situations: planning and decision making, error correction and troubleshooting, situations requiring sequences of action, situations that are hazardous or technically challenging (Baumann & Krems, 2007; Freund & Smith, 2011; Krems & Baumann, 2009). Given the evidence that the types of crashes in older adults often occur in complex traffic situations such as intersections (McGwin & Brown, 1999), it is logical to infer that driving difficulties are likely occurring at the level of executive function (K. J. Anstey et al., 2005).

2.3. The context of driving assessment in older adults

Since cognition and behaviour are often situational in context, laboratory findings particularly concerning decision-making and related executive functions may fail to predict behaviours in complex and dynamic tasks that people confront in their daily lives. Thus, cognition must be considered in relation to actions and artefacts in the environment. Vehicle driving in real traffic can be regarded as a driver-vehicle-environment interactive system involving the human visual perception, cognition, and locomotion of the driver, vehicle movement and the environment (Hirokazu, Hidetoshi, Nobuhiko, & Tetuya, 2010). Environmental influences are important factors since the driving environment can greatly influence a driver's ability on the road. Age-related declines in the required component functions (vision, cognition, sensorimotor) for driving may quite often be "overloaded" in challenging contextual situations (Justiss, 2005). Integrated research approach to driver safety in recent studies have emphasized on the overlapping and interacting area of the role of driver, vehicle and road environment in driving safety (Coughlin, Reimer, & Mehler, 2011). To detect the state of the drivers, various overt and covert measures, such as driving performance, visual attention, cognitive reaction to the traffic situation, can be collected and interpreted in the driving context (Park & Son, 2010). As movement does not take place by itself, gathering information on the context in which the movement occurs, such as the interactions with the environment and other individuals, can facilitate a better understanding of movement and behaviour (Dodge, Weibel, Ahearn, Buchin, & Miller, 2016).

- *The driver-environment interaction*

In order to keep safe in driving, drivers rely on their situation awareness to correctly perceive and interpret the relevant visual-spatial information in the current traffic situation, so that they would consider the information for planning and controlling their behaviour. Such information can be other drivers, the condition of the street or the traffic signs (Baumann & Krems, 2007). For each elements of the information, drivers must perceive them as well as understand them in term of the relevance to their goals. In addition, drivers must make assumptions about the future states of these elements and actions they need to take (Baumann & Krems, 2007). The theory of situation awareness has caught attention in the psychology field and in driving studies since it describes and integrates different cognitive processes (Gugerty, 1997). Situations that require a driver to adjust the speed or change the direction can be hazardous, the driver has to be able to anticipate these situations in order to take vehicle control actions to avoid any collision (Underwood, Crundall, & Chapman, 2011). Endsley (1995) stressed that the situation awareness is the best theory for encompassing perceptual and comprehension processes, which can be used in driving behaviour analysis and modelling (Salvucci, 2006).

- *The driver-vehicle interaction*

Once in motion, the driver must continuously and actively make adjustments on the steering wheel and pedals not only to attain desired travel objectives, but also to avoid aversive stimuli or situations such as driving off the roadway, or losing control of the vehicle (R. Fuller, 1984; Ray Fuller, 2011; McIlvaine Parsons, 1976). Driving may be described as a control task in an unstable environment faced by the driver's movement on a defined driving track with both stationary and moving objects. The task includes requirements for the route choice and following, coordination between actions, and continuing adjustments of steering and the vehicle speed (Ray Fuller, 2011). In control theory, the driver's control actions are dependent on perceptual processes which select information based on certain standards. The theory implies that drivers act to keep any resulting discrepancies within acceptable limits as the means of control. The target variables in their goal-directed behaviour are space and time margins and mental load specifically relating to control (Summala, 2007).

Smith (1968) described the following discrete phases in driving: to sense a situation and stimulus registered at the perceptual level; to recognize it and stimulus at the cognitive level; to decide how to respond at the cognitive level, and lastly to execute the manoeuver at the motor level. Inputs from sensory and cognitive processes are important in determining what a driver to choose to do and how the movements are organized and adjusted. Therefore, suggested by C. Voelcker-Rehage (2008), for driving assessments, environmental conditions, task requirements, and drivers' states imposing spatial and temporal constraints must be recorded and evaluated in order to interpret what have been done by the drivers.

3. Developing a Psycho-geoinformatics Framework for Investigating Older Drivers' Behaviors and Underlying Cognitive Mechanisms

The framework consists of three components: the conceptual unit (Fig. 1) resembles the interactions between the driver, vehicle and environment, and identify the factors influence driving behaviours, defines the dependent variables and points out the direction of this study; the experimental unit of framework (Fig. 2) presents the protocol of experiments and methods of data collections; and the analysis and assessment unit of framework (Fig. 3) summarizes the key means that will be used in the analysis, the process of the analysis, and the outcome of the study.

3.1. Conceptual unit of the framework

Driving can be conceptualized as a complex system in which the environment, driver and vehicle are influencing factors (A. Rakotonirainy, 2005). The system incorporates drivers' visual patterns, the attribute of traffic environment and vehicle movement that are intertwined in space over time. Fig.1 illustrates the conceptual framework for understanding driver safety. In the center of the unit, we highlight driving as a driver-vehicle-environment interactive system, which is the core of driving assessment.

The second-level circle (in yellow) defines the variables related to driver's cognitive conditions. On the left side, there are the variables related to driver-environment interaction (DE), and on the right, those varaibles are related to driver-vehicle interaction (DV). Driver's perception, visual attention, spatial orientation and spatial visualization are listed as the critical cognitive variables for driver-environment interaction. Psychomotor skill and executive function are the key cognitive abilities for driver-vehicle interaction. The Situation Awareness theory and driver control theory are used to support the notions of the two phases (DE and DV). The two phases are linked by cognitive processes and resulted in driver's locomotion and decision-making in the next circle of drivers' behaviours.

The third-level circle (in blue) groups key parameters of driving behaviours and performance, and the linkage to the drivers' cognitive conditions. Eye fixation and duration, steel wheel and pedal controls are identified as the variables for drivers' vehicle control behaviours and performance.

The outer circle (in grey) presents outcome variables of drivers' behaviours and performance. It is conceptualised as the results of psycho-spatial-temporal interactions including what and how long drivers viewed their surroundings, how gazing behaviour is associated with vehicle control, e.g., lane keeping and speed regulation. The unit is also favour for a vision-in-action paradigm which recognises three factors in the driving model: the driver, the task, the environment and perception-action coupling within driving visual-motor workspaces (Vickers, 2007). The framework employs such vision-in-action paradigm in order to integrate visual-perception with motor action.

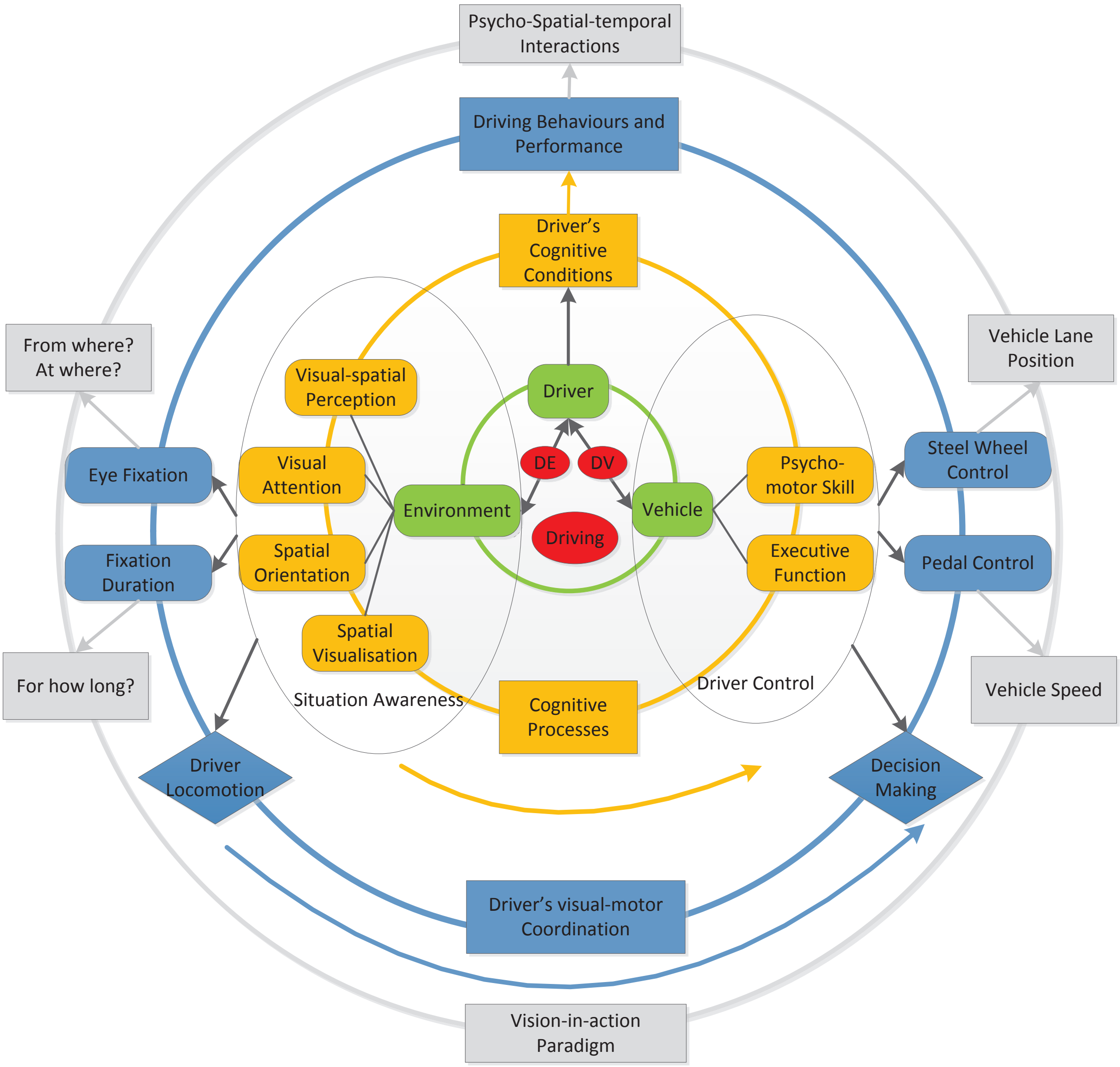

Fig. 1 Conceptual unit of research framework - driving behaviour and cognitive processes

The links between variables of circles would give indications on the underlying neuropsychological mechanisms responsible for the behaviours and visual-motor coordination between individuals and groups. A variety of research questions can be answered via the investigation of the associations. The preliminary implication for older drivers is that the variability in the performance of older drivers may stem from age-related declines in cognitive functioning. Another implication from this presentation is that we must go beyond the single risk factor studies of crashes to identify the multiple factors, which are most highly related and predictive for safe driving (Classen, Awadzi, & Mkanta, 2008).

3.2. Experimental unit of the framework

Based on the variables identified in the conceptual unit, the experiment unit of the framework (Fig. 2) sets out a protocol for exploring a variety of older drivers attributes in a single investigation including the laboratory neuropsychological tests (left side) and the on-road driving assessment (right side). The laboratory neuropsychological tests can provide a window into the specific cognitive deficits presenting in individuals with increased crash risk. This testing is typically sensitive to gross abnormalities and is often used to assess cognitive deficits in the clinic (Lees et al., 2010). Studies have shown relationships between the performance of at-risk drivers on laboratory neuropsychological tests of cognitive function and driving behavior in both simulation and on-road driving (Anderson et al., 2012), and the predictive value of neuropsychological test scores on driving behavior in healthy aging (Bieliauskas, 2005).

Vehicle kinematic profiles in common roadway scenarios may provide specific evidence of driving safety problems in older drivers who experience age-associated declines in visual, cognitive, and motor abilities. Using such data collection procedures with at-risk drivers can provide an abundance of knowledge and a context of low-performance that result in risky behaviours. This data can also verify the assumptions of theoretical models and the results of laboratory studies regarding the role of variables such as reaction time, or lane deviation (Lees et al., 2010).

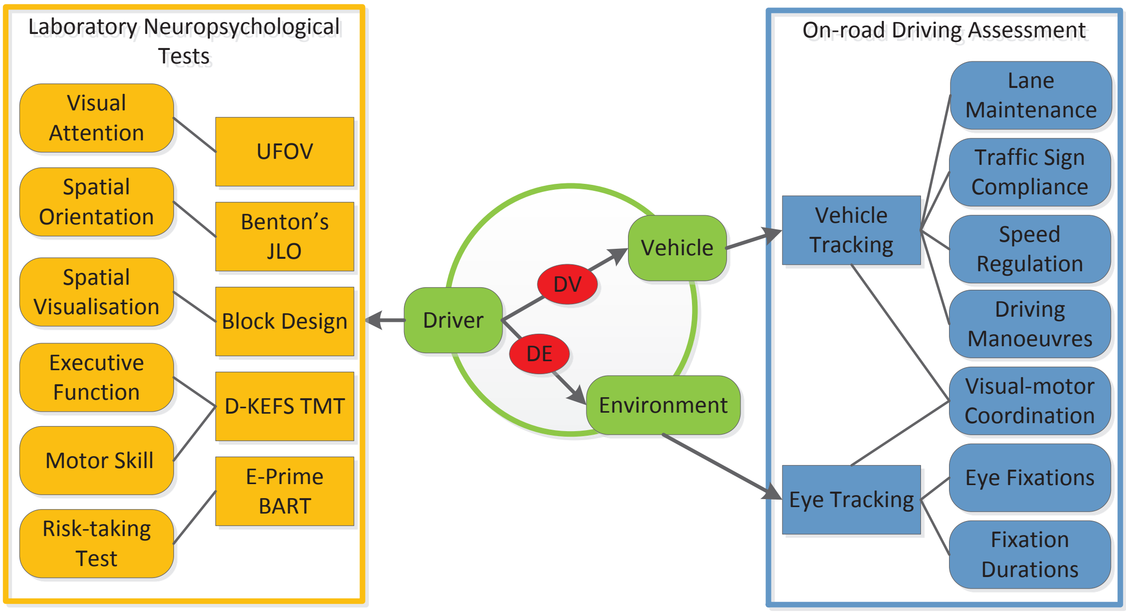

Fig. 2 Experiment unit of research framework – on-road and laboratory assessment

Eye tracking is a widely used technique to measure the eye movement pattern, so that researchers can find where the subject was gazing at a given time and the sequence of eye movement shifting from one location to another (Poole & Ball, 2006). The rationale behind eye tracking research was depicted by Tatler (2014) that human eyes are directed to the locations relevant to the task on a second-to-second basis, the purpose is to obtain the information at the location which allow for the completion of our planned motor actions. When and where drivers look at are critical for the driver's safety (J. D. Lee, 2008; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). As Crundall and Underwood (2011) addressed that eye tracking is eminently suitable for assessing driving tasks. Gaze analysis based on eye tracking is a useful tool to understand the visual behaviours during driving. Analysis of eye movements facilitates the investigation of the driver's visual searching and driver behaviours in dynamic driving situations (Dukic & Broberg, 2012; Falkmer, Dahlman, Dukic, Bjällmark, & Larsson, 2008).

3.3. Analysis unit of the framework

The data analysis and assessment unit (Fig. 3) outlines the methods of data processing and integration, spatial and statistical approaches for assessments, and expected outcomes. Technically, it establishes an analytical platform of psycho-geoinformatics to investigate the driving behaviours and the cognitive mechanisms.

After data collected, a central driving geodatabase (left side) can be created to store and integrate spatial-temporal data of vehicle trajectory and eye movement parameters. The human factor of drivers' demographics and driving habits from a questionnaire survey, and laboratory neuropsychological scores (right side) will be loaded into a spreadsheet. Various spatial-temporal analysis and statistical analysis will be performed across the datasets. The analysis and assessments (middle of Fig. 3) including three subsets: the spatial-temporal patterns of drivers' eye movement and vehicle control parameters will be visualized at both individual and group level to find the distributions of visual attention and vehicle control; the driving assessment will evaluate driving competencies with respect to the level of safety, efficiency and workload; and finally, the comprehensive statistical analysis will be performed to investigate correlations and discriminants between driving behaviours and cognitive abilities.

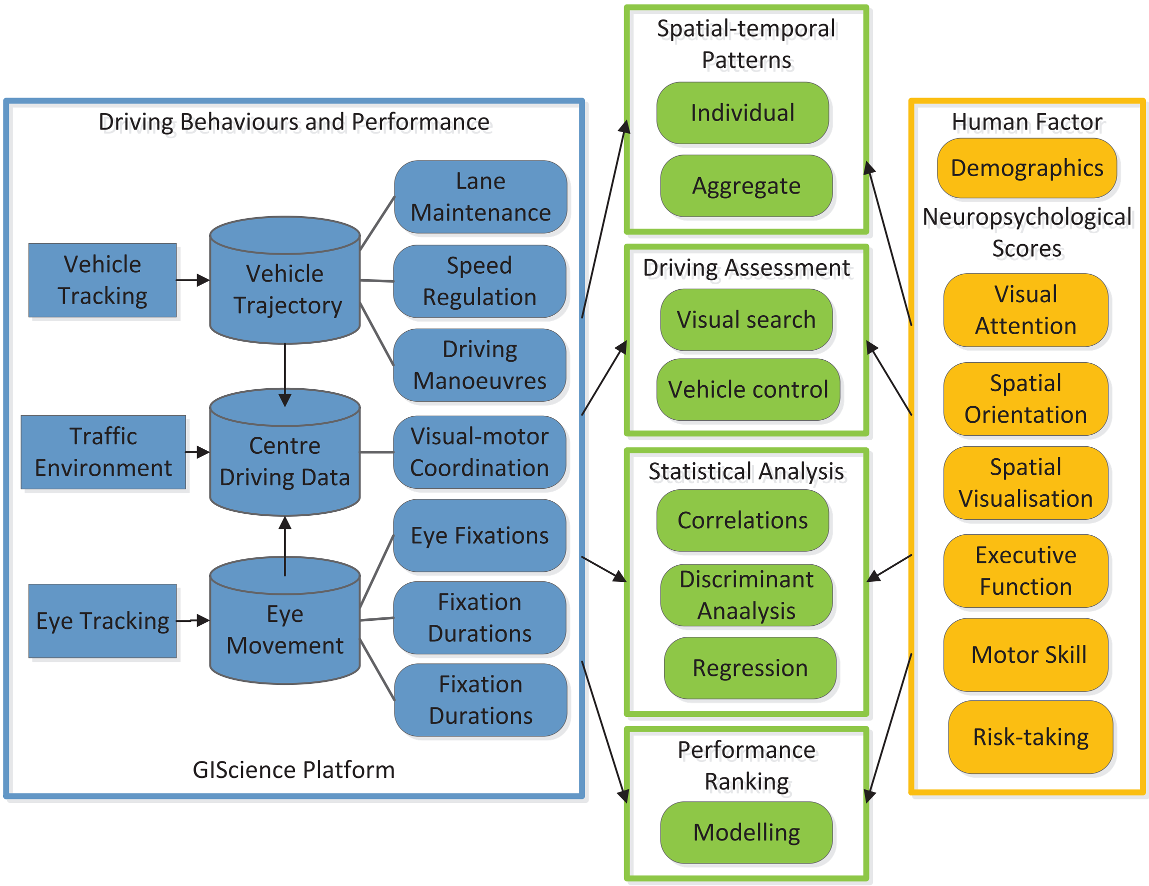

Fig. 3 Analysis and assessment unit of research framework – the analytical platform of psycho-geoinformatics

The expected outcomes are: (1) the correlations between specific measures of older drivers' driving behaviours and performance and cognitive ability measures, the explained variance of these relations to determine the strength of these correlations; (2) the predictors of neuropsychological tests for lane maintenance and visual-motor coordination performance; (3) the discriminant variables associated with good and low-performing driving behaviours in older adults; (4) a series of analyses of visual-motor coordination focusing on specific assumptions and sub-scenarios; and (5) performance benchmarking model for identifying risky drivers and driving behaviours.

4. The Implementation of the Framework and Practical Considerations

4.1. Participants and Recruitment

Fifty older drivers aged from 60 to 81 (mean=69.7yr, SD =0.85) were recruited from the local community. The eligibility of participation also includes: holding a valid Australian driver license and having an insured vehicle, driving at least 3-4 times a week, and having no mental and physical issues affecting driving. Before the assessment, all subjects provided informed consent for participation in compliance with ethics requirements from the Curtin University Human Research Ethics Committee (Approval no. HR68_2014). A mini-questionnaire survey on demographics and driving habits was also conducted prior to the assessment. Visual acuity (Snellen eye chart) and cognitive function by Mini-Mental State Examination (MMSE) were assessed to ensure their basic fitness for on-road driving protect participants and avoid research bias.

4.2. Laboratory neuropsychological tests

A battery of neuropsychological tests was chosen to assess older participants' vision, cognition and motor skills. These tools are standardised tools that have been widely used internationally (Fig. 2) including a set of sub-tests: (1) The Useful Field of View (UFOV) tests evaluate processing speed, divided attention and selective attention (Classen, Wang, Crizzle, Winter, & Lanford, 2013; Wood & Owsley, 2014). (2) The Benton's Judgement of Line Orientation (BJLO) test is used to measure the judgement of visuospatial orientation (Benton, Sivan, Hamsher, Varney, & Spreen, 1983; Emerson et al., 2012); (3) The Block Design (BD) test evaluates the participant's spatial cognition and motor skills (Ferreira, Simões, & Marôco, 2013). (4) The D-KEFS Trail Making (Delis-Kaplan Executive Function System) test measures the visual search, attention, sequencing, executive functions and motor skills (Barrash et al., 2010; Delis, 2010; Mitchell & Miller, 2008); (5) The Balloon Analogue Risk Task (BART) tests the level of risky personality in the participants. The total score on the psychometric tests was used to categorize the neuropsychological status of participants, and to evaluate the relationship between cognitive functioning and driving behaviours. For driving assessment programs, it will be necessary to assess several functional abilities to cover the complexity of the driving task (Cuenen et al., 2015).

4.3. On-road driving assessment

The on-road driving test simultaneously recorded the driver's eye movement and the vehicle movement. The study area was chosen around the campus of Curtin University in Perth, Australia. The test route includes driving manoeuvres through a series of roundabouts, intersections, traffic lights, stop and giveway signs and pedestrian crossings. Posted speed limits along the test route are 10, 40, 60 and 70 km/h. The test route took participants through an urban residential area, taking about 20-minutes to drive covering approximately 10 km.

Participants were asked to drive their own cars with an eye tracker (Arrington Viewpoint^{TM}) mounted on their heads. The eye tracker equipped with an eye camera and a scene camera, was used to collect the participant's eye movement and the view data at the recording frequency of 60 Hz. The eye camera recorded gaze patterns and the scene camera captured the scene in front of the driver. The eye and scene images were superimposed by the eye tracking system and present real-time information about where in the environment the line-of-gaze was located. The data collection required corrected vision, and the eye tracker can be worn with glasses when necessary. The computed eye tracking data includes a number of fixations and fixation durations, which demonstrate the order and length of time a driver directs gaze at any particular object in the visual scene, as well as the visual patterns the driver utilizes while performing any particular driving task (Falkmer et al., 2008).

A pair of Trimble R10 GNSS (Global Navigation Satellite System) receivers was mounted on each participant's car roof to record the vehicle movement trajectory. The receivers can track multi-GNSS systems beyond GPS-only approach, which is essential for recording vehicle movement when precise vehicle positioning and a smooth trajectory are required. The tracking configuration of Trimble R10 receivers was setup at 10 Hz. The Multi-GNSS improves the availability and accuracy of the positioning data used to evaluate the driver behaviors. RTK postprocessing technique was used to achieve centimeter to decimeter level accuracy horizontally by minimizing the effect of error sources transmitted between the satellites and GNSS receivers (Qian Sun et al., 2017; Qian Sun, Xia, Foster, Falkmer, & Lee, 2016). The post-processed data was then mapped to calculate the lane maintenance parameters.

4.4. Driving assessment data integration

The collected eye tracking and vehicle movement data are to integrate and analysed in a GIScience platform as shown in Fig. 4. Prior to the data integration, a team of eye tracking analysts qualitatively analysed the captured video frames as well as the eye movements including gaze direction, distance, background and the object. The processed vehicle movement trajectory was overlaid with other traffic data to calculate the lane deviations from the desired path (e.g., road centrelines). Two datasets were then linked using the participant's ID and the time fields. Since an eye fixation is a period of eye movement, the gaze pattern during this period, e.g., $Fixation_{i+1}$ can be inspected from the vehicle dynamic between the start time at $Vehicle_j$ to the end time at $Vehicle_{j+1}$. The (x, y) coordinates of the start time at $Vehicle_j$ show that from where the eye fixation occurred. The parameters of the $Vehicle_{j+1}$ refer to the results of the motor behaviour of the driver.

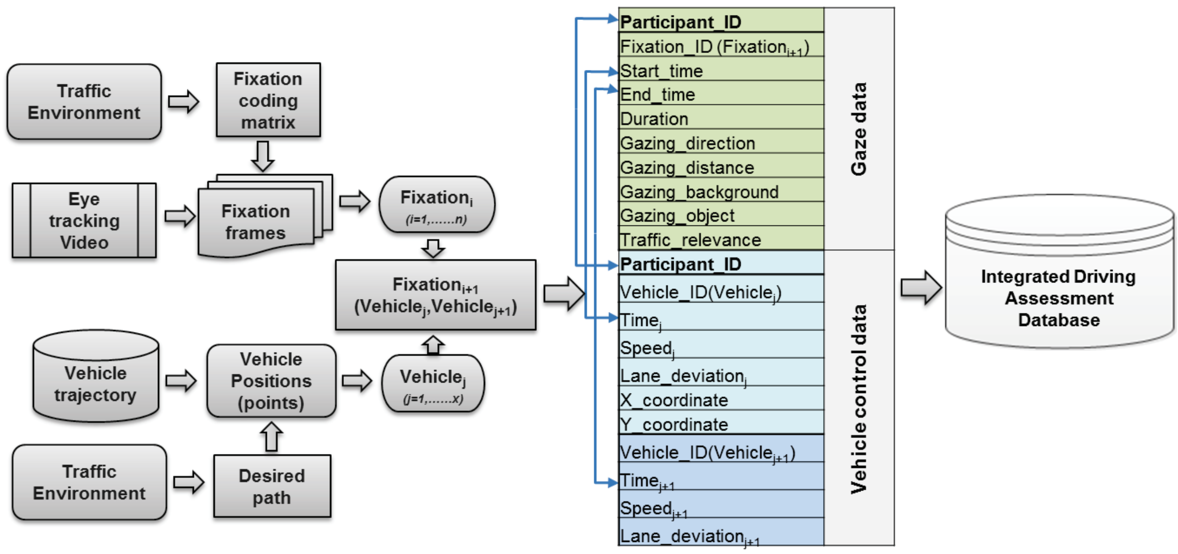

Fig. 4 Visual tracking and vehicle tracking data Integration, adapted from Sun at al. (2016).

From a physics perspective, a driver's eye movement and vehicle movement controlled by the driver appear distinctly different. The eyes typically move in discrete jumps (also called saccades) between fixations which produce irregular movements and a jagged trajectory (Çöltekin, Demšar, Brychtová, & Vandrol, 2014); in contrast, the vehicle moves continuously which produces a smooth movement trajectory. However, the two trajectories moved along which were guided by the same process of the driver's visual searching upon the traffic environment. Geographically, eye movement and vehicle movement are co-located and co-existed in space and time. Thus, it is appropriate to integrate them into a more meaningful format in order to reflect the comprehensive content of driving behaviours. Where, how long and how often the driver gazed at the surroundings during driving are important indicators of the visual perception strategy, which the drivers used to keep the vehicle in an optimal lane position.

4.5. Sample psycho-geoinformatics analyses

Given the complexity of the integrated empirical datasets, full analyses are due to be reported in a series of papers focusing on specific research questions and sub-scenarios. In this paper, analysis of two samples of psycho-geoinformatics approach are briefly presented and the detail will be described in the corresponding papers.

Table 1 presents one example of data analysis: the statistical correlations between participants' neuropsychological test scores and their lane maintenance performance. The results show that that lower visual attention (divided and selective attention) tested in UFOV was significantly associated with higher deviation of lane position from the desired path (p = .000). The deviation of lane position (the stability of lane keeping) was also correlated to spatial visualisation by Block Design test (p = .002) and four subsets of D-KEFS Trail Making Tests (p < .01).

Table 1 Correlations relationship between drivers' the neuropsychological scores and their lane maintenance performance

Neuropsychological tests	Correlation with Lane Deviation (mean)
UFOV 1 (Processing speed)	.055 (.704)
UFOV 2 (Divided attention)	.579** (.000)
UFOV 3 (Selective attention)	.544** (.000)
Block Design (Spatial visualisation)	.432** (.002)
Benton's JOL (Spatial orientation)	.314** (.026)
D-KEFS TMT 1 (Visual Scanning)	.353*(.012)
D-KEFS TMT 2 (Number Sequencing)	.365** (.009)
D-KEFS TMT 3 (Letter Sequencing)	.458** (.001)
D-KEFS TMT 4 (Number-letter Switching)	.370** (.008)
D-KEFS TMT 5 (Motor Speed)	.383** (.006)

**. Correlation is significant at the 0.01 level (2-tailed).*. Correlation is significant at the 0.05 level (2-tailed).

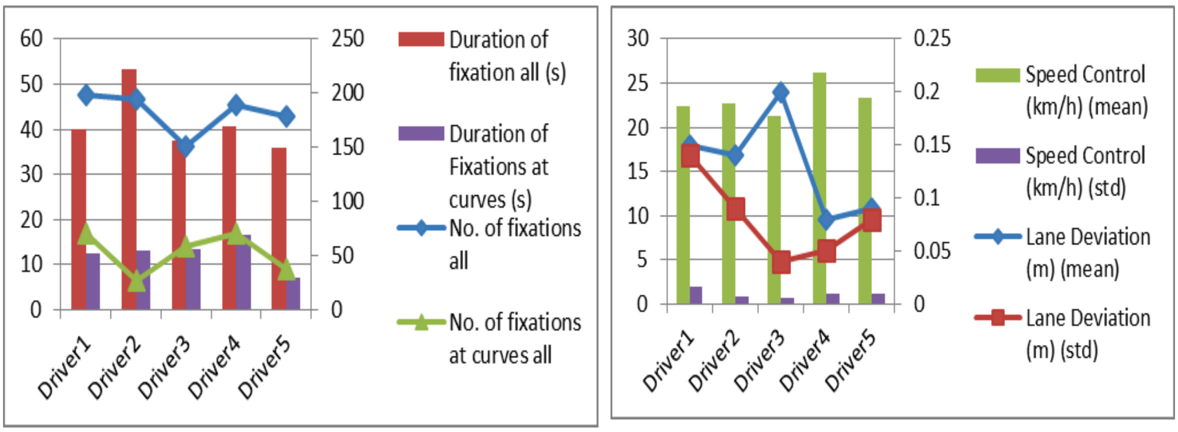

Fig. 5 Variations of visual-motor behaviours among individual older drivers (Q. Sun et al., 2015)

Descriptive statistics in Fig. 5 show the variations of visual-motor behaviours between five older drivers. The detail of this study has been published in a preliminary report of this research (Q. Sun et al., 2015). The left-hand graph shows the frequency and duration of eye fixations among individual drivers; and the right-hand graph plots the mean and standard deviation of speed control and lane deviation for each driver. Individual drivers' visual-motor behaviour can be interpreted and compared, for example, Driver 4 performed the most frequent eye fixations and longest average fixation duration at curves, presented the lowest lane deviation, and slight higher mean speed. Driver 3 had the least frequent eye fixation overall but average eye fixation and duration at curves, this driver demonstrated the highest lane deviation but the lowest standard deviation value of lane deviation, and the slowest mean speed. The other drivers also exhibited different visual-motor behaviours during this particular driving.

5. Discussions

In the past, the on-road vehicle crashes were attributed to the risk-taking behaviour or poorly developed psychomotor skills. More recently, the high crash involvement rate in older drivers has been linked to the relative inability to acquire information in risky situations (Pradhan et al., 2005). Therefore, for the current state of driving safety studies, it can be argued, on both theoretical and methodological grounds, that we must go beyond crashes per see to understand driving behaviour (Ranney, 1994). Additionally, more sensitive measures of driving capacity are needed to identify older adults with functional and cognitive declines related to driving ability (Schultheis & Manning, 2011).

Through developing and describing a psycho-geoinformatics approach, this paper has established a basis to explore a variety of older drivers' attributes and driving behaviour in a single integrated experiment. The process adopted allows for comprehensive data collection and analysis with the advantages of both standard neuropsychological tests and spatial-temporal analysis of GISciences functions. As a result, a broad set of measures from multiple domains including the driver, vehicle, and road environment in the same time period can be obtained. The integration of the driver's visual patterns, vehicle movement and the traffic can not only provide insights into the driver-vehicle-environment interactions in space over time, but also help discover the underlying cognitive processes. The framework is driver centric on an individual basis and the analysis and assessment are based on a scalable multi-dimensional data infrastructure, which is more plausible with respect to the real driving.

The experiment protocol has high ecological validity since the assessment is undertaken in a naturalistic setting. The purpose of the human visual system is not to simply record the image outside, rather give us the necessary information for us to behave appropriately (Snowden, Thompson, & Troscianko, 2012), which explains the rationale that the move from a traditional approach that used to study human vision in laboratory to the natural world. This paradigm shift is required in the study of human cognition and behaviour (Bremond et al., 2014). Technically, both eye tracking and GNSS vehicle movement tracking use high frequency recording, therefore the data collection offers detailed and more reliable visual search and vehicle control data. The assessment is high in discriminant validity, with the data and analysis undertaken at the individual level and sensitive to inherent variability for the behaviour and performance of individuals and groups. The framework reveals links between the driver's visual and motor behaviour and the cognitive process from visual search to vehicle control. It highlights location and time as essential parameters in driving studies, and synthesizes multi-sensory data into a meaningful form and creates a context-aware investigation platform. Such measurement cannot be obtained without geoinformatics tracking and analysis tools, when it comes to the practice of intervention, the assessment feedback for participants can be significantly cheaper than personal interaction with a therapist (Markowetz et al., 2014; Yarkoni, 2012).

Together, the gaze-based integrated driving assessment system has improved our ability to take advantage of previously tracking driving data to improve the quality of analysis and assessment of driving behaviour and performance. While time and resource intensive to establish, future improvement is expected to pay off in terms of the reduced costs and errors of data analysis over multiple projects, greater operational efficiencies, and enriched information for decision-making.

Apart from the above traits, there are some limitations of the approach and framework. First, the complexity of data analysis and data accuracy, the computing of eye fixation and vehicle movement data is time-consuming, the accuracy and quality of vehicle movement data need to be controlled carefully as the satellites' signals are affected by a number of parameters. Secondly, it is hard to detect the participants driving errors due to the short driving assessment duration. Also, the participants have fairly close driving skills due to the recruitment channels, which demonstrate low variations in the driving behaviours and performance. In the future, a design of certain experimental driving scenarios is recommended in combination with the current psych-geoinformatics protocol, such as using distraction in experiments to detect drivers' visual-motor coordination.

6. Conclusions

Driving behaviour assessment, particularly that of drivers with cognitive declines, is a fruitful application area for the proposed psycho-geoinformatics approach. Psychology help explain the mechanisms of cognitive breakdowns that undermine driving safety and mobility. Geoinformatics complements this explanation with the tools to systematically explore the various layers of the complexity which define driving activity. Psycho-geoinformatics provides a multidisciplinary translational approach that merges elements of cognitive psychology, human factors, transport and ergonomics to study the relationships between driving behaviours and cognitive abilities. Driving makes demands on multiple cognitive processes that are often studied in isolation and so presents a challenge in generalizing findings to predict safety outcomes. Applied to the salient example of driving mobility, such an approach with multiple sources of evidence is deemed to provide a deeper understanding of cognition in natural settings.

Using geoinformatics tools in driving behaviours assessment enables an entire range of new options, which do not have to rely on human observations. Instead, it receives clear indicators of the individual driver's interactions with the vehicle and the traffic environment, in a fine spatial-temporal resolution. Researchers can thus observe the continuous changes in driving parameters over time and space, namely the visual-motor coordination patterns. The goinformatics-based framework integrates a set of standard spatial tools and techniques; thus derived products are in a standard GIS based format that leads to interoperable solutions and can be used as an input for any GIS based application.

The potential uses of the system are plentiful since the application is adaptable and adjustable. The framework and data model can be directly used or modified in other studies with larger sample sizes since the data collection of critical experimental data takes less than half an hour to complete for each subject. It can be applied in studies for other cohorts, such as novice drivers, drivers with dementia or other age-related diseases. The framework can be also used to answer other research questions related to distraction in driving behaviour, alcohol/drugs effect in visual-motor coordination in driving, etc. Furthermore, new studies can employ the approach to model driving behaviours and scenarios, such as driving on freeways, bus drivers' behaviours, etc. In conclusion, this paper has set out the feasible and valid practice executed in this study as a basis for others to adapt and develop in exploring the complex driver-vehicle-environment interactions and driver behaviours.

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3

Vehicle Movement Tracking and Driving Behaviour Assessment

CHAPTER 3 VEHICLE MOVEMENT TRACKING AND DRIVING BEHAVIOUR ASSESSMENT

This chapter is covered by the following papers (paper 2, 3 and 4 of the thesis):

Sun, Q., Odolinski, R., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2017). Validating the efficacy of GPS tracking vehicle movement for driving behaviour assessment. *Travel Behaviour and Society, 6*, 32-43. doi:http://dx.doi.org/10.1016/j.tbs.2016.05.001. **(Paper 2)**

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). *Pursuing Precise Vehicle Movement Trajectory in Urban Residential Area Using Multi-GNSS RTK Tracking*. Paper presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. **(Paper 3)**

Sun, Q., Xia, J. C., Falkmer, T., Foster, J., & Lee, H. (2016). *Driving Manoeuvres during Lane Maintenance in Older Adults: Associations with Neuropsychological Scores*. The manuscript was originally peer-reviewed and accepted by WCTRS (14th World Conference on Transport Research). [Revised and submitted to Transportation Research Part F: Traffic Psychology and Behaviour]. **(Paper 4)**

The previous chapter presented a psycho-geoinformatics framework for the current thesis. The heart of the technical section in the framework is a geoinformatics infrastructure, which should consist locational data, and enable the integration of psychological parameters and contextual information. Since this research will investigate driving behaviour with respect to visual search, motor control and the coordination between visual and motor actions, the precise vehicle positioning is essential for the establishment of the data infrastructure.

This chapter seeks to obtain precise and high-resolution vehicle movement trajectories, which are also used as a locational reference to geo-code the eye fixations and construct visual-motor coordination paths and episodes in the later chapters. Through paper 2 to paper 3, this chapter presents the evidence that the advanced surveying technology, namely multi-GNSS (multiple Global Navigation Satellite System) with RTK (Real-time Kinematic), can record precise accurate vehicle trajectories suitable for detecting driving behaviour, e.g., calculation of lane deviations. Various GNSS/GPS devices and positioning techniques are tested and compared aiming to determine an optimal means to record and compute precise vehicle movement trajectories for driving assessment.

Based on the obtained vehicle movement trajectory data, paper 4 of this chapter investigates the lane maintenance performance in older drivers and the associations with their cognitive functioning. Mean Lane Position (MLP), Standard Deviation of Lane Position (SDLP) and manoeuvre time calculated from precise vehicle movement trajectories are used as the lane maintenance parameters.

This chapter also validates the battery of the neuropsychological tests for assessing older drivers' cognitive abilities. A discriminant analysis will be used in paper 4 to investigate the effectiveness of the combined cognitive variables from neuropsychological tests in determining lane maintenance performance in older drivers.

Both the validated vehicle movement tracking and neuropsychological tests are crucial for the implementation of the psycho-geoinformatics framework. On the one hand, the precise vehicle movement trajectory data will serve as the backbone of the central database, all the processed driving behaviour data and analysis will be based on the locational and temporal information of the vehicle positions; on the other hand, the cognitive conditions from the individual drivers' neuropsychological tests scores will play the key part of "psycho" in the framework.

Therefore, this empirical chapter is a critical starting point in the thesis to fulfill all the objectives in the later chapters and achieve the aim of understanding the impact of the age-related cognitive decline in older drivers' driving behaviour and performance.

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Validating the efficacy of GPS tracking vehicle movement for driving behaviour assessment

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ABSTRACT

Vehicle movement trajectory recorded by GPS maps the vehicle's lane position in time sequence, therefore theoretically can be used to assess driving behaviour. However, the data quality level which can be achieved for vehicle movement tracking by different GPS receivers and positioning techniques hasn't been fully explored and documented. This study systematically validated the efficacy of GPS recording vehicle movement using different types of receivers and positioning techniques. The receivers include both recreational and professional devices; the positioning techniques refer to Single Point Positioning (SPP), Differential GPS (DGPS) and Real-time kinematic (RTK) solutions. The field trials tested the positioning accuracy as well as the quality of trajectory tracking by comparing the recorded positions to benchmarks. The study findings indicate that vehicle movement trajectories recorded by recreational-grade GPS receivers can only match other spatial information at low resolution, which is limited to the assessment of wayfinding and navigation behaviour. In contrast, the SPP, DGPS and RTK techniques undertaken by professional receivers can raise horizontal accuracy to the metre, decimetre, and centimetre level respectively. For under open sky road driving, the RTK solution generated accurate and precise vehicle movement trajectories sufficient for extracting vehicle lane position, speed, acceleration/deceleration, so as to detect detailed driving events and quantitatively assess individual driver behaviour. This paper serves as a critical reference for other researchers on the different types of GPS receivers and solutions prior to engaging a GPS in their studies.

1. Introduction

There is a growing trend of using spatial tracking technology to record the patterns of moving objects, such as animal movements, human mobility, and in recent decades to track vehicle movements in transport management and traffic safety studies (Gonzalez et al., 2008; Juang et al., 2002; Kageyama et al., 2001). Within those applications, the most commonly used technology is the GPS (Global Positioning System) or GPS embedded mobile devices tracking (e.g. smartphone with GPS app) (Herrera et al., 2010; Ryan et al., 2004). GPS allows researchers to continuously measure the vehicle speed, acceleration and location (Ogle et al., 2002). It can be comparably low-cost and ecologically valid to assess driving behaviours using GPS tracking vehicle movement. Since many transportation-related problems, including traffic congestion, vehicle collisions and crashes, energy consumption, and vehicle emissions, are directly related to driver behaviours (Jun et al., 2006), GPS tracking can empower the data-driven research in the transport and traffic behaviour studies. The potential of GPS data can be maximized even more when compiled in a GIS (Geographic Information System) to be overlaid with other spatial data, such as built environment (Duncan et al., 2009). Integration of GPS data into a GIS allows researchers to categorize, visualise and model their data based on location. Likewise, other data can be geocoded with the reference of GPS locations to obtain new attributes.

While the majority of the users were excited about the rich datasets of GPS tracking, the accuracy of GPS tracking seems to be neglected in many applications. This is perhaps due to the continuously and comparably more accurate positions and timestamps from GPS recording, compared to which the conventional surveys or retrospective questionnaires can bring about. However, since the GPS positions are determined from the signals transmit-

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ted between the satellites and GPS receivers, multi-factors may cause positioning errors at different levels. GPS recording does raise concerns over accuracy depending on the application requirement. On the other hand, the nature of GPS recording offers possibilities and opportunities to expand its application by enhancing its accuracy level, as Zito et al. (1995) stated earlier that corrections can be applied to the GPS observations when accuracy is a particular concern. With the advent of advanced positioning techniques, such as Differential GPS (DGPS), Real-time kinematic (RTK) and the possibility of multi-GNSS (Global Navigation Satellite System), more accurate and precise data for tracking moving trajectories can be achieved to fit many applications' needs: fleet tracking, lane departure warning, driverless car controlling and on-road driving behaviour assessment, etc.

In previous work, GPS or the combination of GPS plus video recording can provide a means to assess driving behaviours by tracking vehicle movement (Cruz et al., 2013; Grengs et al., 2008; Mudgal et al., 2014; Naito et al., 2009; Porter and Whitton, 2002). While there are a wide range of commercial GPS receivers available, they literally differ in the costs of devices and data collection accuracy. Despite the minimal information regarding the positioning accuracy reported in the manuals by the manufacturers, mostly under optimal static recording, studies on the details of the reliability and capability of GPS tracking vehicle kinematic trajectory are rare. In fact this is particularly important for risky driving detection in order to avoid misleading results caused by GPS errors. Although a few earlier studies investigated the GPS accuracy for such concerns (Ogle et al., 2002; Porter et al., 2004; Zito et al., 1995), the data quality level which can be achieved for vehicle movement tracking by different GPS receivers and positioning techniques hasn't been fully explored and documented. Standing from the users' (but not GPS experts) perspective, we comprehensively looked into some off-the-shelf GPS receivers, both recreational and professional-grade devices, and positioning solutions from different techniques (SPP, DGPS and RTK), aiming to evaluate the GPS capability in tracking vehicle movement trajectory for the application of assessing driving behaviours. Here, we tested five types of receivers: Garmin 76 and 72H, Mobilemapper 100 from Ashtech, Trimble R10 and JAVAD DELTA-3. The positioning techniques were applied to the latter two survey-grade receivers. A field trial for the absolute accuracy evaluation was undertaken by comparing the GPS recordings to the benchmark of a pillar station. The tracking ability was examined by a series of driving trials with the comparisons between GPS/GIS derived vehicle movement trajectories and a benchmark line. The objectives are as follows:

- Tracking vehicle movement using various GPS receivers and positioning techniques and computing the trajectories in GIS.
- Developing methods to evaluate the extent of data quality in GPS tracking vehicle movement, so as to reveal the least and the ultimate accuracy from GPS tracking.
- Validating the efficacy of the GPS recorded vehicle trajectories in driving assessments.

2. Research context

GPS can be used to measure positions through its array of navigational satellites from the 31 current operational satellites (GPS.GOV, 2015). Orbit and clock data are transmitted by each satellite in the GPS receiver's field of view. GPS device receives the satellite signals and computes the receiver position, velocity and time estimates through trilateration between four or more satellites. In theory, GPS can track vehicle movements and detect events on the vehicle trajectories which may imply certain driving behaviours. A number of studies have used vehicle movement data recoded by GPS to classify driver behaviour (Cruz et al., 2013; Jensen et al., 2011; Lotan and Toledo, 2006; Ma and Andréasson, 2007; Rigolli et al., 2005; Wang et al., 2010). Rigolli et al. (2005) integrated video surveillance of daily traffic activity with vehicle trajectory analyse from GPS recording and found that GPS recording offered better performance in terms of accuracy and speed than human observations. Jensen et al. (2011) pointed out that objective data collection can be applied in several different ways, from specific manoeuvre deficiencies such as lane changes to overall driver risk, depending on the precision and details of the collected data.

GPS positioning errors have usually been calculated for stationary positions, examinations of kinematic positions, is more important for the assessment of driving to detect variables like velocity and acceleration (Porter et al., 2004). Zito et al. (1995) firstly reported the reliability and usefulness of GPS data for obtaining information on the position and speed of vehicle movements. By acknowledging the possibilities of using GPS in vehicle monitoring they further suggested that the minimum degree of accuracy needed by the application must be known, therefore the questions like whether the positioning accuracy is required and whether the GPS data can be post-processed should be considered. In a drivers' speeding behaviour research, Ogle (2005) gathered vehicle GPS coordinates and speeds to correlate speeding behaviour to crash rates. As a part of the project, Ogle et al. (2002) tested the reliability of speed and acceleration from four GPS packages with different combinations of receiver setting, both error corrected and uncorrected. They suggested that GPS can be used to obtain results within a reasonable range of the requirements. Porter et al. (2004) noted that GPS tracking could be advantageous in detecting driving behaviours of different types of drivers, they compared corrected (Differential GPS) and raw positions and addressed that error correction should be done if positional information is needed.

To date, most on-road driving assessments have only a pass or fail outcome that was based on driving evaluators' observation and subjective evaluation. In contrast, a standardized on-road driving assessment with a quantifiable score based on the velocity, acceleration/deceleration variables derived from GPS tracking would allow for driving assessment in an objective or blinded fashion (Porter and Whitton, 2002).

Table 1 below presents five categories related to critical driving abilities to test during on-road driving assessments; a series of driving events associated with each category can be scored using vehicle movement trajectories recorded by GPS and computed in GIS, and the variables are extracted from the driving trajectory, e.g. the duration and smoothness (vehicle lane deviations) of the events, the speed changes in the vehicle movement, and the speed at which the manoeuvre was performed.

To provide sufficient parameters for driving behaviour assessments, Table 1 depicts the requirement of GPS data for each category. For example, when turning, it is important to make the turn as accurate as possible, wide turns or cutting a turn too sharply are considered to be inappropriate behaviours. Thus, an accurate vehicle trajectory with precise curvature is required in order to evaluate the quality of turning behaviour. GPS/GIS derived vehicle movement trajectory provides possibilities to quantitatively assess such on-road driving behaviour. However, the GPS observations contain errors and noise, which would affect the validity of assessment. The accuracy of the GPS data depends on many factors, the quality of the GPS receiver, the position of the GPS satellites at the time the data was recorded, and the characteristics of the surrounding landscape which can either block the signals or cause multipath errors as illustrated in Fig. 1. In addition, errors in satellite clocks and orbits, the trips through the layers of the atmosphere, and some other sources contribute to inaccuracies in the GPS signals by the time they reach a receiver. Currently positioning using GPS can be performed through Single Point Positioning (SPP)

Table 1
Requirements of GPS/GIS derived vehicle movement trajectories to assist on-road driving assessment.

Category	Driving events	Driving behaviours assessment variables	GPS/GIS derived vehicle trajectory
Lane maintenance	Turns, straight driving, lane changes	Vehicle lane position	Accurate and precise high resolution vehicle trajectory
Traffic sign compliance	Driving through a STOP, a GIVE WAY, a pedestrian crossings	Speed, acceleration/ deceleration	Vehicle trajectory with accurate speed and acceleration
Speed regulation	Performed speed against the posted speed limits Stable speed control	Speed	Vehicle trajectory with accurate speed
Driving manoeuvres	In a roundabout T-junction with left turn Intersection with right turn	Duration, vehicle lane position, speed, acceleration/ deceleration	Accurate and precise high resolution vehicle trajectory
Navigation and wayfindings	Turning into the correct street	Duration, vehicle location	Low resolution vehicle trajectory can overlay with street maps

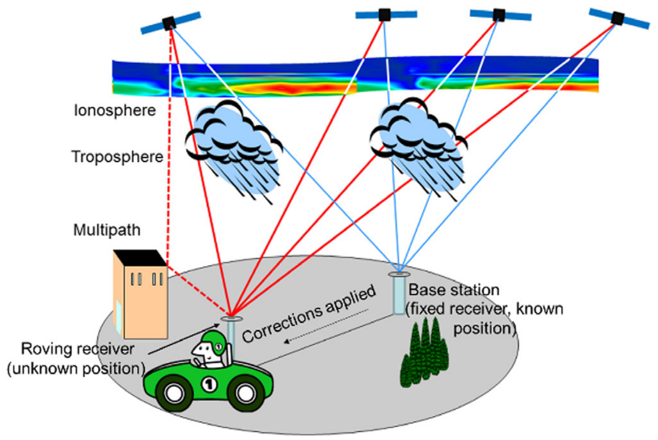

Fig. 1. GPS main source errors and advanced positioning techniques using correcting data from a reference station.

without reference station correction, and Differential GPS (DGPS), Real-time kinematic (RTK) with accuracy enhancement from a reference station (El-Rabbany, 2006; Ragheb and Ragab, 2012). Despite accuracy degradation in unfavourable physical environments (such as under the tree canopies), GPS recording with SPP is only able to provide position solutions with an accuracy level of several metres (Gao et al., 2005), it is unsatisfactory for projects when centimetre-level accuracy is required. For instance, when assessing drivers' lane maintenance and driving manoeuvres through an intersection (Table 1), the drifting of recorded vehicle trajectory between lanes might be related to GPS recording errors rather any inappropriate steering behaviours, such inaccuracy would lead to misinterpreted behaviour detection.

For the above consideration, advanced GPS positioning techniques are introduced to improve the accuracy of vehicle movement tracking by minimising the effect of each error source. Typically, this can be achieved by DGPS and RTK solutions with different measurements. A minimum of four common satellites in view is required for DGPS and RTK; however, tracking more than four common satellites simultaneously would improve the precision of the GPS position solution. Both DGPS and RTK use a known position of a base station to compute the rover position (the receiver with unknown position) (Fig. 1), in this study, a vehicle position. The DGPS technique uses only GPS code pseudo-ranges to compute its position, which are available in many low-cost receivers. The atmospheric errors (ionosphere and troposphere) can either be estimated, or if the rover is within a distance of a few kilometres from the base station, they are similar and can be neglected (El-Rabbany, 2006). This allows for positioning accuracies reaching sub-metre level. The more complex Real-time kinematic (RTK) technique can be adopted by most survey or professional-grade receivers, uses not only code observations for positioning, but also carrier phase measurements which can provide positions that are orders of magnitude more accurate than DGPS. With such an approach, the unknown ambiguities in the phase measurements need to be solved with sufficiently high success rate (probability of correct integer ambiguity resolution) to allow for recording positions at the millimetre to centimetre level accuracy (Teunissen, 2007). Such precision can be adequate for tracking accurate vehicle movement trajectories. The DGPS and RTK solutions can be achieved by both real-time and postprocessing, the postprocessing was used in this study. For real time approach, the user doesn't normally think much about how the position was computed. In contrast, post-processing allows the user to analyse more thoroughly the integrity of computed positions, which could provide a higher level of confidence in the results. For RTK postprocessing, it can be also a cheaper and more efficient approach comparing to the real time kinematic method which requires additional hardware and firmware for real-time communication link (Awange and Kyalo Kiema, 2013).

3. Experimental context

3.1. The test route

The test route was chosen around the campus of Curtin University in Perth, Australia, approximately 1.5 km radius distance from the Curtin GNSS base station (Fig. 2). The base station provides reference data for DGPS and RTK solutions. Fig. 2 provides a schematic of the test route with red arrows showing test segments. The test route includes driving manoeuvres through a series of roundabouts, intersections, traffic lights, Stop and Giveway signs and pedestrian crossings. Posted speed limits along the test route are 10, 40, 60 and 70 km/h. The length of the test route is approximately 7 km, it contains open road segments in most road sections, but also consists of the following conditions expected to affect GPS operations: tree canopies, electrical lines, street signing, buildings and possibly tall passing vehicles along the roads. The study area represents a typical urban residential suburb in Australia.

3.2. GPS receivers and data collection

3.2.1. Summary of experimented GPS receivers

Five types of GPS receivers were tested in this study: Garmin 76 and 72H, Ashtech Mobilemapper 100, Trimble R10, and JAVAD DELTA-3. Table 2 lists the main features of the receivers. Although Mobile mapper 100 and Garmin series are handheld receivers, it is expected that mounting handheld receivers on the car roof will increase the positioning accuracy due to the reduced multipath effect; this will be tested by comparing with the installation on

Fig. 2. The test route and GNSS base station.

Fig. 3. Experimented GPS receivers and the placement for recording vehicle movement (left to right: Mobilemapper 100, Trimble R10, Garmin76, Garmin 72H, and JAVAD DELTA-3. Receivers were aligned in the middle of the car roof; the distances between receivers were measured).

the car dashboard. The Garmin series are recreational-grade receivers that produce positions and speed parameters of the tracks, but not the raw GPS measurement directly. The horizontal accuracy level of Garmin series is between 3 and 15 m according to the specifications. Mobilemapper 100, Trimble R10 and JAVAD DELTA-3 are professional-grade receivers and raw GPS measurements can be logged for post-processing positioning. From their specifications, they can reach sub-metre level horizontal accuracy with the DGPS technique, and centimetre level accuracy with RTK technique.

Fig. 3 presents the placement of the receivers for recording driving data; the magnets and blu-tack were used to mount the receivers on the car roof. One more Garmin 72H was mounted on the dashboard inside the vehicle. All the receivers were set up to use one second GPS tracking interval. The JAVAD DELTA-3 antenna was powered by the vehicle's battery; all other receivers have internal batteries. Tracking configuration for both Trimble and JAVAD receivers were setup as dual frequency (L1 + L2) to give the best possible accuracy. The elevation mask for the receiver antennas was set at a cut-off angle of 15° in order to ward off possible multipath errors (Porter et al., 2004). The Position Dilution of Precision (PDOP) mask value was set to 6, so as to reject satellite geometries that may give rise to large positional errors, e.g. five satellites located on a cone or a line.

3.2.2. Data collection methods

GPS data was collected by a several field trials and each recording lasted for about one hour; the first trial was to collect the GPS data recording on a pillar station with known position. Four receivers (except JAVAD) were experimented due to the limited space of the pillar. The other field trials were on-road driving for kinematic GPS recording: 1) a driving trial using five GPS receivers on the car roof (Fig. 3), and one Garmin 72H on the car dashboard; 2) a driving trial by four different drivers on the same route using same Garmin 72H; 3) a driving trial by the same driver at different times using same Garmin 72H. All the on-road driving trials followed the same route but completed different experiments as above.

GPS data from each receiver was loaded into computer by relevant software after each trial. GPS data elements including GPS time, latitude, longitude, velocity were collected from Garmin series and Mobilemapper 100. Raw GPS measurement data from both Trimble R10 and JAVAD is GPS observation files in RINEX (Receiver independent exchange) format. The satellite observation and navigation files from the base station were obtained from Curtin GNSS Research Centre. Fig. 4 mapped the number of satellites tracked at every vehicle position during one driving trial to illustrate the visibility of GPS satellites, it is noted that more than four satellites are guaranteed during most of the driving except a few small sections with heavy tree canopies, while during the majority of the time driving, more than five up to eight GPS satellites were tracked. For the purpose of validating positioning accuracy, we excluded the records with satellite number less than five as these records can be anomalous, and don't reflect the true objects positions. The base station receiver data including the satellites navigation file and observation file were captured simultaneously as the recording of the experimented receivers, in order to apply positioning techniques to the raw GPS recordings through data postprocessing.

Table 2
Overview of the main features of experimented GPS receivers.

Receiver feature	Garmin 76	Garmin 72H	Mobilemapper 100	Trimble R10	JAVAD DELTA-3
Horizontal accuracy on specifications	3–15 m	3–15 m	DGPS: 0.3–0.01 m RTK: 1 cm	DGPS: 0.25 m RTK: 0.8 cm	DGPS: 0.25 m RTK: 1 cm
Usage	Recreational		Professional		
Character	Handheld			Antenna pole	
Antenna placement	Internal antenna and device integrated				External antenna

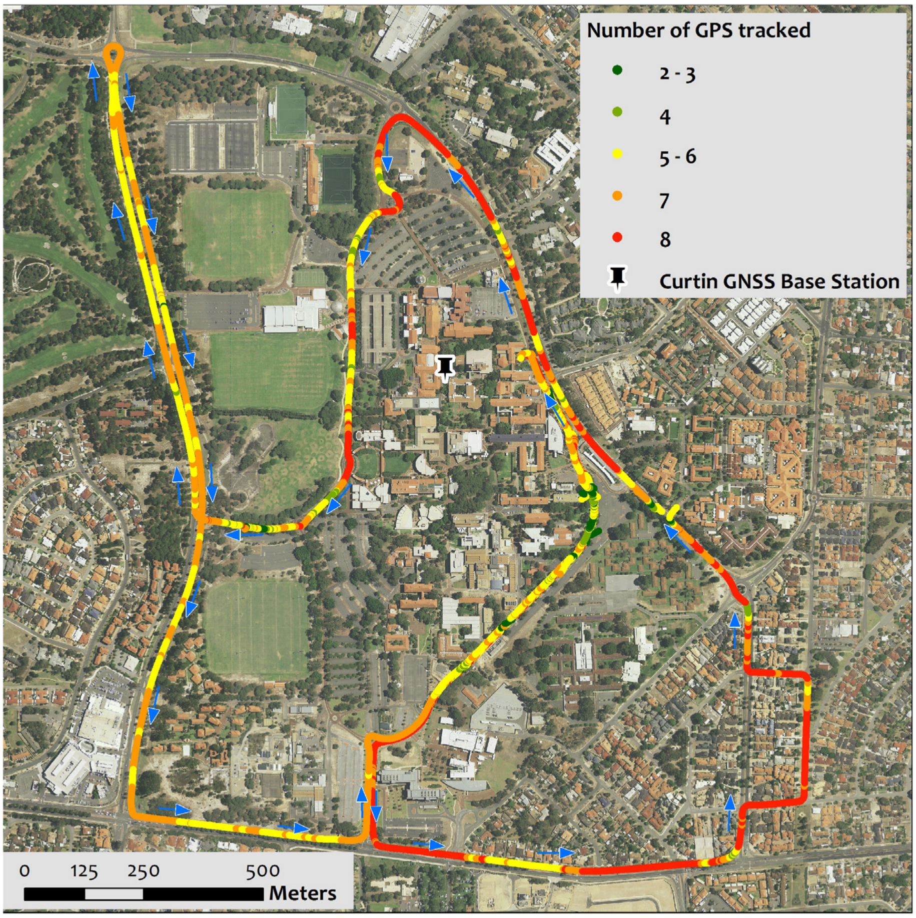

Fig. 4. Number of GPS satellites tracked during one driving trial.

4. Methods

4.1. GPS data postprocessing and positioning techniques

The GPS data postprocessing was conducted in the latest version of RTKlib program downloaded from the application website (RTKlib, 2015). RTKlib is an open source software which supports various postprocessing positioning modes. Since both JAVAD DELTA-3 and Trimble R10 receivers can obtain both code and carrier phase measurements, DGPS and RTK solutions can be produced as separate datasets with the required inputs from the base station reference data. The SPP solutions were processed directly since no corrections are used from the reference station. The procedure improves the navigation attributes, such as positioning accuracy, reliability, and availability through the integration of external information from the base station. A GIS program (ArcMap, 2012) was used to convert GPS text files into GIS shapefile format, and project all data from WGS-1984 Latitude/Longitude to Easting/Northing in MGA (Map Grid Australia) coordinates (GDA94, Zone 50) for linear error measurement, and integration with other local spatial information, such as transport, traffic and environment. Each individual dataset contains about 3600 points resulted from the recording period. Use of a GIS provides a platform and methods to check, measure and visualise the accuracy level of the GPS locations between the recordings, as well as in comparison to other GIS layers. In this study, we used high resolution orthoimagery with accuracy level of ±5 m horizontally as the background spatial information which appears on some figures in this paper.

Fig. 5 visually presents the quality enhancement of data postprocessing: SPP result (green) shows poor smoothness and positioning accuracy of the trajectory. DGPS result (purple) is smoother with less outlier points; however, since DGPS uses pseudoranges code-only measurement, some error effects still exist. The blue dots are the RTK solution, which demonstrates most precise and accurate driving path comparing to others, with taking in addition to code measurements the precise carrier phase measurements into account.

4.2. Data analysis methods

4.2.1. Accuracy comparison of GPS receivers and positioning techniques

A systematic accuracy comparison of GPS recording for the receivers and positioning techniques was conducted by using the pillar station as the static benchmark, and for the driving trials the benchmark using the JAVAD RTK solutions, in order to verify their performance in terms of their positioning and tracking capability in vehicle movement.

Table 3 exhibits the systematic comparison methods. For example, the positioning accuracy comparison of the pillar recordings was conducted between four receivers, but six independent GPS datasets including SPP, DGPS and RTK solutions. The corresponding coordinates of the pillar station was given in the International Terrestrial Reference Frame (ITRF) 2014 at epoch 1st May 2014, which was based on a 14 parameter transformation of the GDA94 coordinates. The trajectory recording comparison used RTK postprocessing solution from JAVAD DELTA-3 as benchmark, although it has

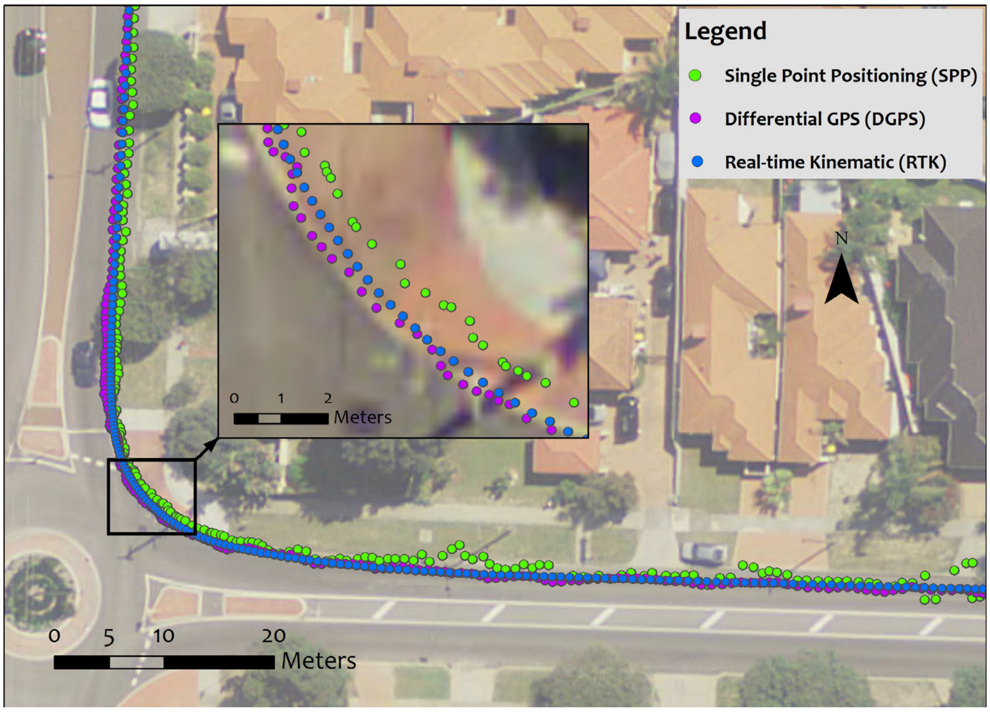

Fig. 5. GPS recording driving paths based on SPP, DGPS and RTK techniques at a left-turn manoeuvre, data was recorded by Trimble R10 receiver.

similar RTK accuracy level, we used it to generate benchmark with the consideration that the receiver's stability and positioning accuracy have been tested by Curtin GNSS centre in their studies.

4.2.2. Accuracy measurements for GPS recordings

4.2.2.1. Accuracy measure for positioning comparisons. Three measures were adopted for positioning comparison: local easting errors (DE), northing errors (DN) and Euclidean distance (D_E) between locations recorded by GPS receivers and the benchmark locations (the pillar station and the RTK solutions).

4.2.2.2. Accuracy measure for trajectory tracking comparison. To investigate the GPS capability for tracking vehicle movement, we generated a perpendicular distance (D_P) layer between GPS recording driving points from different receivers and solutions and the benchmark line in ArcGIS program (ArcMap, 2012). The perpendicular distances demonstrate the deviation of the recorded trajectories from the very precise benchmark line, the lower perpendicular distance (lower mean D_P) indicates less error from recorded vehicle position and thus higher accuracy of the recorded trajectory, while the lower standard deviation of D_P reveals higher precision of the recorded trajectory. For the application of assessing driving behaviours, the more accurate/precise the recorded trajectory demonstrates, the better ability of detecting lane maintenance behaviour the particular receiver has. Fig. 6 illustrates the trajectory deviation from two driving datasets by Garmin recording (Garmin76 and 72H) as examples. The benchmark line was created in ArcGIS using the JAVAD RTK solution data. It is visually inspectable that overall Garmin 72H pursued more accurate and precise trajectory compared to Garmin 76 recording.

5. Results

5.1. GPS positioning accuracy of pillar recordings

Fig. 7 visualises the spatial patterns of the pillar recording results by Garmin 76 and 72H, Mobilemapper 100, and the SPP, DGPS and RTK solutions from a Trimble R10 receiver, which can speak for a range of recreational and professional-grade GPS devices. As can be seen on the map, there were noticeable differences between the performance of different receivers and positioning techniques. Most of the recordings are drifting from the pillar.

Overall Garmin receivers produced more scattered and drifting points while Garmin 76 gave the worst scenario among the six

Table 3
Methods and field trials for validating the tracking abilities between different GPS receivers and positioning techniques ("U " means the receiver was used in the comparison).

Recording and comparisons		Garmin 76	Garmin 72H	Mobilemapper 100	Trimble R10	JAVAD DELTA-3	Benchmark
Recording on a pillar station		U	U	U	SPP, DGPS, RTK		Known pillar position
Recording of on-road driving to compare the tracking abilities	Different series of Garmin	U	U				JAVAD RTK
	Different mounted positions: dashboard vs. car-roof		U				JAVAD RTK
	Different receivers & positioning solutions	U	U	U	SPP, DGPS, RTK	SPP, DGPS, RTK	JAVAD RTK

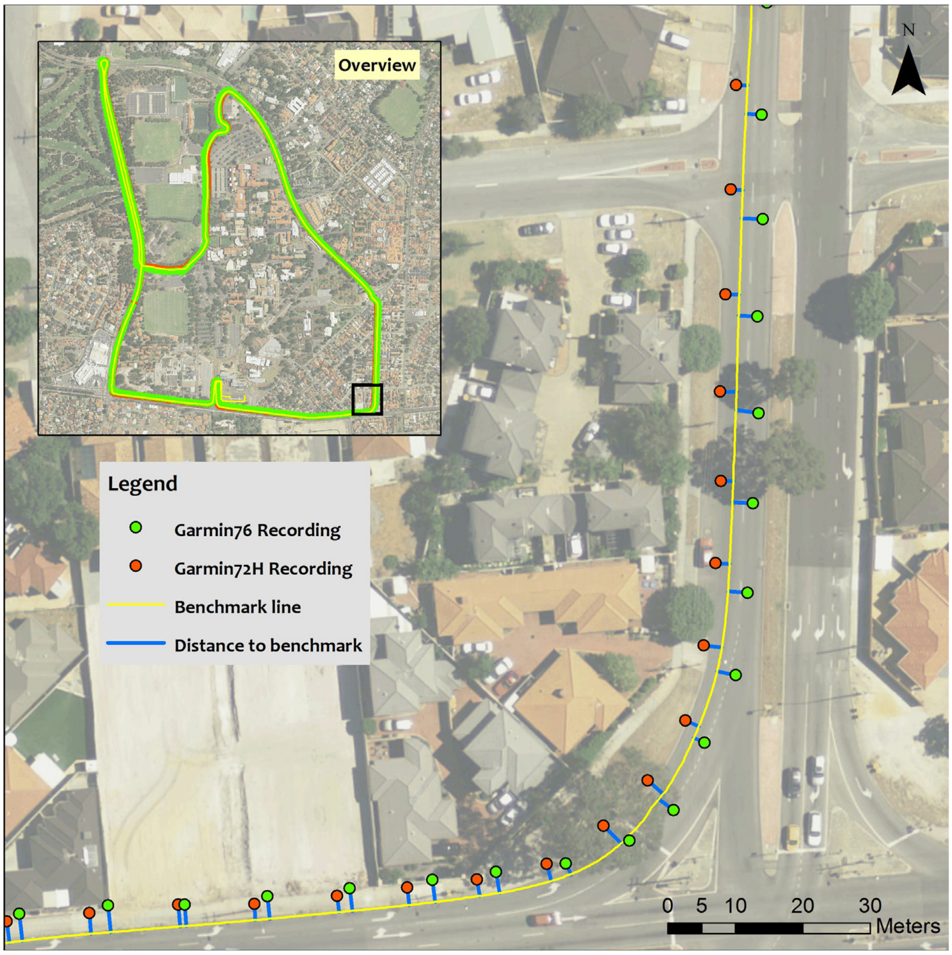

Fig. 6. Perpendicular distances (D_P) (blue) from the benchmark line indicate the accuracy and precision of the trajectory recorded by GPS (Garmin 72H/76). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results. Both Mobilemapper 100 and Trimble R10's recordings show more concentration, and locate in the closer position to the pillar benchmark. This visually implies the higher accuracy and confidence level of professional-grade receivers. The handheld GPS receivers of Garmin series and Mobilemapper 100 present irregular patterns: some points were grouped in Garmin recordings; some points were lined up in Mobilemapper 100 recording.

To inspect the spatial distribution and data quality of between SPP, DGPS and RTK solutions, we plotted Standard Deviational Ellipse (SDE) in ArcMap with a one standard deviation for SPP and DGPS results, and a three standard deviation for RTK results (Fig. 8). It can be noted that the positioning accuracy and the confidence level of SPP solutions are significantly lower than DGPS and RTK solutions with the majority of the SPP recordings drifting north of the benchmark. After DGPS postprocessing, the recordings are much concentrated around the pillar and about 68 percent of points are located within half metre distance of the benchmark. The RTK solution achieved the most precise and reliable results with approximately 99 percent of all points located within 5 cm distance of the benchmark.

The numerical results of accuracy are displayed in Table 4 by comparing the Mean (μ) and Standard deviation (σ) in the variance of Easting (ΔN), Northing (ΔE), Euclidean distance (D_E) between measured GPS location and the benchmark. The accuracy of the Garmin series measured in this study is the lowest compared to other receivers. It is similar to the specifications listed in the manuals at 3–15 m horizontally. The errors in both Mean and Standard

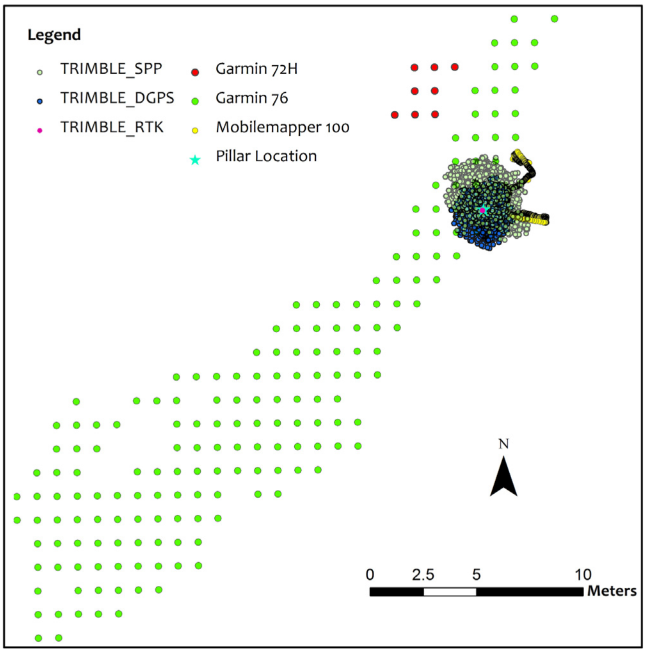

Fig. 7. The drift and spatial distribution of GPS points against the benchmark location (pillar) showing the positioning accuracy of recordings from different receivers and positioning techniques.

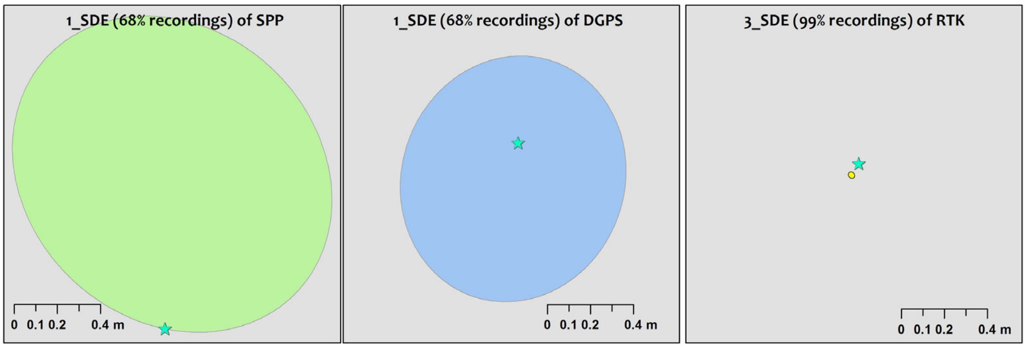

Fig. 8. The one (68%) and three (99%) Standard Deviational Ellipses (SDE) compare the accuracy and confidence level of GPS recordings between SPP, DGPS and RTK solutions.

deviation dramatically drop in the professional receivers, which are also close to the values on the specifications. Data collected by Trimble R10 RTK is much closer to the benchmark than the other receivers and solutions, and the very low Standard deviation (r) gives best confidence level of the tracking ability, which is consistent with the spatial distribution of three Standard Deviational Ellipse on Fig. 8.

5.2. GPS positioning accuracy of driving tracking

In a driving setting (Fig. 3), the Easting and Northing errors between different GPS recordings to the benchmark points would vary due to the changing heading angle of the car along streets. Therefore, it is no point to compare these values for the accuracy validation. However, the Euclidean distance (point to point) between each recording result to the benchmark point can be calculated and compared (with receivers' physical distance excluded). This can be considered to be a relative accuracy comparison in contrast to the absolute accuracy to the known pillar location. Fig. 9 demonstrates the overall relative accuracy levels between the seven GPS recording results to the benchmark of JAVAD RTK.

The recreational GPS receivers achieved slightly better positioning accuracy, while the Trimble R10 obtained less accurate positioning in contrast to the pillar recordings (Table 4). This might be caused by the more complex environment during driving. Nevertheless, the comparison results show that GPS performance in a driving setting is generally consistent with the results of static recordings; both of them are in favour of Trimble R10 RTK results, which pursed centimetre accuracy level in both pillar and kinematic driving tracking.

5.3. Accuracy of GPS recorded vehicle movement trajectories

The accuracy of vehicle movement trajectory is essential for assessing driving behaviour, especially the lane maintenance. Fig. 10 compares the perpendicular distance (D_P) variations (Mean and Standard deviation) from GPS recordings to the very precise driving benchmark line. Difference occurs between Garmin 76 and 72H since 72H is a more advanced version which produced more accurate positioning. The results from different mounting positions prove that more accurate positioning can be achieved under higher and more open sky view because of the reduced multipath effect and more satellites visibility. The results from different drivers using recreational receiver (Garmin 72H) indicate that the driving behaviours of lane maintenance can hardly be detected since the variation could be from GPS errors instead of human driving behaviour, with the receiver's accuracy reaching a few metres or even more. The better positioning result from different times could indicate better satellites visibility and geometry for the lower error recording. Other significant differences are between different receivers and postprocessing techniques. Professional-grade receivers performed better accuracy recording than recreational ones. While both DGPS and RTK results show under-metre level difference, the RTK result at centimetre deviation to the benchmark line is more acceptable for lane maintenance behaviour analysis.

The comparison implies that the more advanced devices and better tracking environment would result in more accurate and reliable vehicle movement trajectories. The Garmin receivers can usually match other spatial information at low resolution, which can be used to assess wayfinding and navigation behaviour. However, the results show that the positioning accuracy is inadequate for assessing lane maintenance behaviours, nor for speed and acceleration detections. The SPP results with just over a metre-level accuracy, could be used in small scale mapping and for travel behaviour study, to obtain the general time of arriving and locations in reference to the streets. It can be an effective choice since no complicated postprocessing involved and available in some cheaper GPS receivers, however, the SPP result isn't able to generate smooth vehicle trajectory with accurate speed and acceleration, therefore, it is not sufficient for detecting behaviours of speed control and driving manoeuvre. The handheld Mobilemapper 100 as a professional receiver obtained similar accuracy results as SPP, but better in the smoothness of vehicle movement trajectory, the cost would be a barrier for some projects. In comparison with DGPS, RTK GPS achieves much more precise positioning with

Table 4
Statistics of absolute positioning accuracy of GPS recordings for different receivers and positioning techniques.

		Mean (l)			Standard deviation (r)		
		Easting (DE) (m)	Northing (DN) (m)	Distance (D_E) (m)	Easting (DE) (m)	Northing (DN) (m)	Distance (D_E) (m)
Garmin 76		10.208	9.789	14.353	7.094	6.170	9.078
Garmin 72H		3.782	4.504	5.975	0.775	0.824	0.412
Mobilemapper 100		0.589	0.950	1.183	0.468	0.699	0.644
Trimble R10	SPP	0.421	0.761	0.942	0.317	0.451	0.418
	DGPS	0.295	0.347	0.505	0.227	0.265	0.272
	RTK	0.033	0.054	0.064	0.003	0.003	0.003

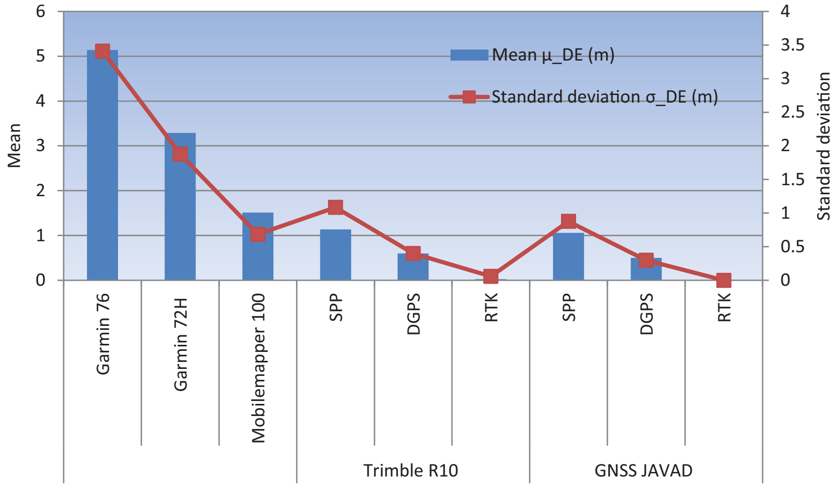

Fig. 9. Statistics of positioning errors (Euclidean distance) from GPS tracking driving using JAVAD RTK results as benchmark (the primary and secondary y-axis show the mean and standard deviation of distance variations from the benchmark line).

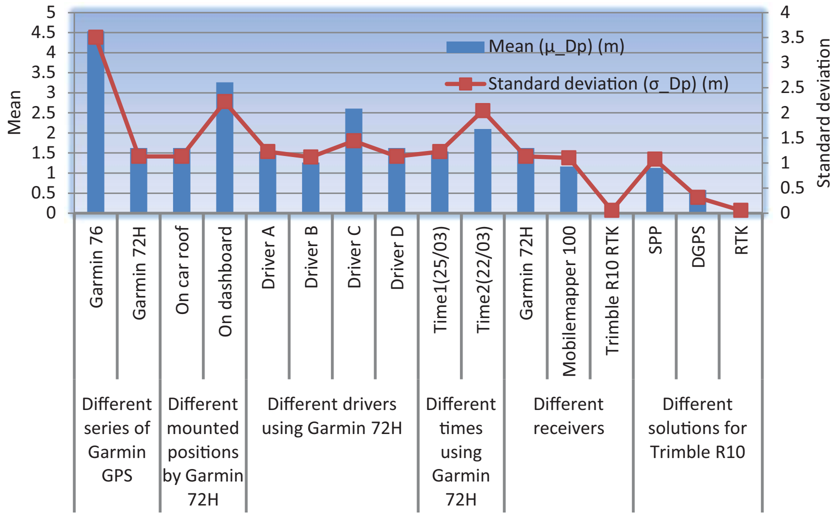

Fig. 10. Mean and standard deviation of perpendicular distances (D_P) from GPS recordings to the benchmark line showing the vehicle trajectory quality (the primary and secondary y-axis show the mean and standard deviation of distance variations from the benchmark line).

similar effort required. In many professional-grade GPS receivers, when both code and carrier phase measurement available, no doubt, RTK approach is the best option to accomplish higher accurate positional data, ultimately the vehicle trajectories with accurate speed and acceleration, which is optimal for inspecting detailed driving behaviours.

During our data analysis, we didn't find any correlations between the satellite numbers tracked (under five records were excluded) and the GPS accuracy. The increasing number of visible satellites would increase the opportunity of obtaining better accuracy, however, the GPS positions are also determined by other factors, such as the geometry of the satellite alignment (geometric dilution of precision), multipath etc. Future study may take the satellite visibility to investigate the accuracy distribution of GPS recordings.

5.4. Sample driving behaviour assessment using RTK GPS recording

A newly conducted field trial assessed driving behaviours using RTK GPS recording. In Fig. 11, both lane keeping and speed control behaviour from four sample drivers are presented and compared at a roundabout manoeuvre. Since the earlier trials in this study have proved that RTK GPS recording by professional receivers can obtain centimetre-level accuracy horizontally with high confidence, the trajectories are reliable to evaluate driving behaviours. In this trial we tested two older drivers (01 and 02) at age of 60 s and two young drivers (03 and 04) at age of 20 s. A road centreline was used as the desired path to evaluate their lane keeping performance.

Here we evaluate the spatial-temporal patterns of the driving behaviour between the four participants: For speed control, all the participants kept safe speed and slowing down when approaching roundabout, and speeding up when exiting the roundabout. For lane keeping, the older drivers performed smoother driving trajectories compared to the young drivers. With the reference of desired path, Driver02 achieved least lane deviation. Driver04 presented least smooth driving path which indicates inexperienced lane keeping skill. Driver01 tended to drive left offset to the road centreline when exiting, Drivers03 drove closer to the roundabout curb, while both were still in the safe zone, however were not good lane positioning.

More sophisticated analysis can be conducted by calculating the duration of the manoeuvres, acceleration/deceleration, and

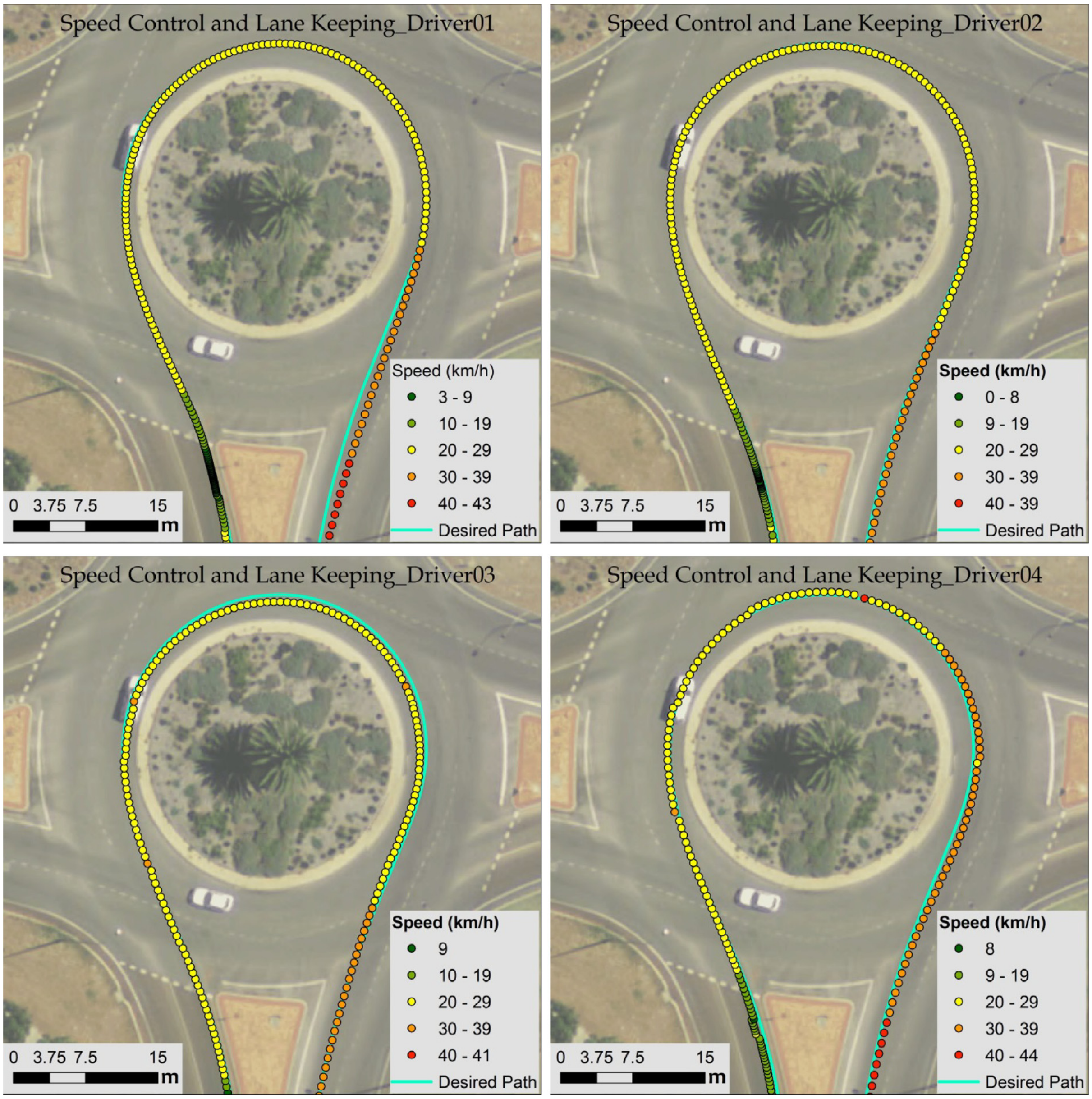

Fig. 11. Individual driving behaviour assessments based on the vehicle movement trajectories using RTK GPS recordings.

lane deviation for statistical analysis base on bigger sample size. Moreover, the accurate driving trajectories can be integrated with other tracking information, such as synchronising with eye movement tracking videos to assess the visual-motor coordination of drivers (Sun et al., 2015; Qian Sun et al., 2016), which localises more driving behaviours in a comprehensive traffic scene.

6. Discussion and conclusions

Driving behaviour assessment has become one of the hottest topics in transport and health studies. Close-to-reality vehicle movement trajectories recorded by GPS (used in combination with other spatial information) may be sensitive to not only driving errors but also to other elements of driving performance. Such data would be useful for discriminant analysis used to evaluate driving behaviours for cohort populations (such as older drivers), especially when raw observation data lack sensitivity to subtle variation of driving manoeuvres. Using GPS to track vehicle movement to quantitatively assess driving behaviours is not practical in the immediate future as raw GPS recording currently involves too great a margin of error. However, future positioning techniques seem promising for obtaining more reliable locational data. The current study developed methods to derive vehicle movement trajectories and systematically validate the capability of GPS recording with the goal of providing a fundamental set of guidelines for GPS users (in particular, non-GPS experts from different fields) in terms of positioning accuracy and behaviour tracking ability in driving assessment.

The measurement of positional errors of a moving object can be difficult, as by definition an error is determined by comparing the estimated position of the mobile unit with some more accurate reference position. This study first tested GPS recordings on a known location (a pillar station) to evaluate the absolute accuracy, which also verified the performance of the device that was reported by each receiver manufacturer. However, the performance of a receiver is not necessarily indicative of its efficacy in tracking vehicle movement. A series of driving tracking tests were therefore undertaken to compare the accuracy of GPS tracking by different receivers and techniques, and to clarify questions concerning GPS operations under different scenarios. With respect to the relative accuracy of measurement in driving tests, a vehicle movement benchmark line was derived via a JAVAD DELTA-3 receiver using RTK postprocessing and modified with reference to the road alignment geometry data. The data accuracy assessment was conducted in a GIS in the context that the GPS tracking data will be overlaid with other spatial information to study driving behaviour.

The realized trials highlight the performance of GPS positioning using different types of receivers and positioning techniques, and provide an overview of their capability of tracking vehicle movement to assess driving behaviours. GPS recorded positions have a high geographical accuracy after applying DGPS and RTK of components of location error in the data recorded by GPS receivers through data from a stationary GPS receiver (base station) with a known position. This study demonstrates the potential of GPS tracking of vehicle movements to obtain a reliable classification of driving behaviours based on the spatial-temporal information provided by GPS.

These findings of this study indicate that recreational-grade GPS receivers usually match other spatial information on low resolution. However, we found that the positioning accuracy resolution can reach ± a few metres horizontally, which is not an adequate resolution for assessing speed control and lane maintenance behaviours. In contrast, the SPP, DGPS and RTK postprocessing techniques applied by professional receivers can achieve a horizontal accuracy at metre, decimetre, and centimetre scale of resolution respectively, and the confidence level of accuracy is significantly high for RTK solution based on the results of the spatial distribution of the 99% in three Standard Deviational Ellipse and 5 mm in the Standard deviation of Euclidian distance from the benchmark, and 5.5 cm as lane deviation to the benchmark line in driving. Taken together, these findings indicate that the RTK GPS recording is suitable for assessing driving behaviours.

It is worth mentioning that the comparison in this study that focused on data from under open sky road driving, on a complex urban road network indicated that multi-GNSS (Global Navigation Satellite System) technique would be a better approach to obtain higher position accuracy with increased number of satellites (compared to GPS-only positioning), particularly in harsh environments (Kubo et al., 2014; Noomwongs et al., 2014). As Odolinski et al. (2014) have pointed out that multi-GNSS positioning (GPS + Galileo + BeiDou + QZSS) will replace GPS tracking in future in order to achieve better accuracy, availability and reliability. In addition, although the RTK solution used in this study is for the short-baseline (the distance between the base station to the rover), techniques of network RTK for long-baseline up to a few hundred kilometres have been successfully researched and the software is under development (Odolinski et al., 2015), in the future, the RTK positioning will be even more promising in the obtaining close-to-reality vehicle movement trajectories.

For practical considerations, in the circumstances when RTK isn't achievable, DGPS can be applied on baseline distances of hundreds kilometres (Landau et al., 2009), however, satellite ephemeris errors and those introduced by ionospheric and tropospheric distortions vary with space. For this reason, the accuracy of DGPS decreases with distance from the reference station. Currently another favourable technology, PPP (Precise Point Positioning), is also increasingly used in the fields of autonomous navigation. PPP solutions are determined by means of a single receiver without recordings from a base station; it can provide centimetre accuracy level recording too with the availability of precise reference satellite orbit and clock products (Li et al., 2015; Ozaki et al., 2015). Therefore, even if a researcher's study area is in a dense urban environment with buildings (particularly in urban canyons) and no access to a reference station, Multi-GNSS with PPP solution can be possible to track precise vehicle trajectories. Unfortunately, the satellite orbit and clocks data normally made available is given at intervals as large as 30 s, whereas kinematic positioning requires sampling frequencies of 1 Hz up to 10 Hz or even higher.

Given other limitations in the experiments, such as relatively smaller sample size in the driving recordings and the type of the car used, the numerical accuracy level calculated in this study can be only used as references. However, this won't affect the above conclusions we draw from the study. The underlying implication of the study also reminds that the questions need to answer prior to engaging a GPS in driving behaviour studies. For example, whether the positioning accuracy is required, whether the GPS data can be post-processed, what is the version of the receivers and the tracking frequency, etc, should be considered or even mandatory in order to collect meaningful data.

This study sought to identify an optimal GPS tracking means for the investigation of driving behaviours. However, we acknowledge that a more thorough investigation into the different aspects of GPS receiver performance is required before a more definitive decision can be made with respect to other fields. Nevertheless, the potential of the GPS/GIS system for driving behaviours assessment has only recently commenced and is likely to offer a more refined analysis of the interactions between driving behaviours, types of driving environment and cognitive abilities.

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Pursuing Precise Vehicle Movement Trajectory in Urban Residential Area Using Multi-GNSS RTK Tracking

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Abstract

Close-to-reality vehicle movement trajectory data can be valuable for many transport and geography studies when precise vehicle localization or timing is required in the application. Vehicle kinematic tracking by GPS (Global Positioning System) varies in the data accuracy depending on the receiver's capability and the tracking environment. Nevertheless, advanced positioning techniques offer potential possibilities to enhance the tracking data quality. In this paper, the high performance of multi-GNSS (multiple Global Navigation Satellite Systems) with Real-time Kinematic (RTK) solution was investigated aiming to pursue precise vehicle movement trajectory in an urban residential area of Australia. This study systematically compared vehicle kinematic recordings between different positioning solutions by multi-GNSS and GPS-only recordings. Various elevation cut-off angles ranging from 5° - 35° were applied to simulate the satellite availability under different sky view conditions. The results show that the multi-GNSS approach outperformed conventional GPS positioning in the satellite availability and the positioning accuracy. The 10 Hz RTK solution proved to generate optimal vehicle movement trajectories for driving behaviours assessment.

Keywords: Vehicle movement trajectory, Real-time Kinematic (RTK), Multiple Global Navigation Satellite Systems (multi-GNSS), GIS

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1. Introduction

Vehicle localization and tracking have many applications in transport-related studies including vehicle navigation, fleet monitoring, traffic congestion etc. In recent years, much attention has been paid to driving behaviour studies through examining vehicle movement trajectories (Greaves & Somers, 2003; Grengs, Wang, & Kostyniuk, 2008; Ren, Xu, & Li, 2014; Wong, 2013). GPS devices receive the satellite signals and compute the receiver position, velocity and time estimate through trilateration between four or more satellites. This provides a fast, accurate, and cost-efficient way to determine the geographical position of an object anywhere on the Earth (Edelkamp & Schrödl, 2012). In theory, GPS can track vehicle movements and detect events on the vehicle trajectories that may imply certain driving behaviours. Vehicle movement trajectories recorded by GPS (used in combination with other spatial information or sensor data) can be sensitive to detect not only driving errors but also the level of driving performance (Sun et al., 2017).

Close-to-reality vehicle movement trajectory data are essential when precise vehicle localization or timing is required in the application. Vehicle kinematic tracking by GPS varies in the data accuracy depending on a number of factors, such as the capability of the GPS receiver and the position of the GPS satellites at the time the data was recorded. In addition, the signal trips through the layers of the atmosphere, and some other sources contribute to inaccuracies and errors in the GPS signals. Various techniques to increase the accuracy have been invented to obtain positioning solutions. Commonly, GPS positioning can be performed through Single Point Positioning (SPP) without correction process, Differential GPS (DGPS) and Real-time kinematic (RTK) with accuracy enhancement using data from a reference station (El-Rabbany, 2006; Ragheb & Ragab, 2012). In driving behaviour studies, the single solution (SPP) with accuracy at the meters level can be acceptable for data analysis at small scales, such as wayfinding. However, for lane maintenance analysis, decimeter or even centimeter level accuracy is needed (Sun et al., 2017). For example, when performing a turning manoeuvre, wide turns or cutting a turn too sharply is considered as a dangerous vehicle control behaviour. To detect that from the vehicle movement recordings, an accurate vehicle trajectory with precise curvature is needed in order to take a quantitative measurement. The RTK positioning solution has attracted much interest in such an application owing to its centimeter-level accuracy achieved (Thitipatanapong et al., 2015).

Even so, in some harsh environments, precisions can be degraded due to the limited satellites tracked by GPS receivers. The lack of where-in-lane level accuracy from GPS positioning has become a barrier to the widespread use of GPS tracking in driving safety research. In this context, more advanced technology, such as multi-GNSS (multiple Global Navigation Satellite Systems) can be a better approach for obtaining a higher positioning accuracy compared to the GPS-only positioning (Kubo, Hou, & Suzuki, 2014; Noomwongs, Thitipatanapong, Chatranuwathana, & Klongnaivai, 2014). The current operating GNSSs include GPS (USA), Galileo (European Union), GLONASS (Russian), QZSS (Japan), Beidou (China). With a good view of the sky, tracking 10 or more satellites is normal and redundancy of observations is easily obtained; whereas more than five satellites are not uncommon even in urban residential areas (Sun et al., 2017). With the advent of new GNSS, multi-system, multi-frequency, precise RTK positioning can potentially be possible anywhere at any time (Quan, Lau, Roberts, & Meng, 2015). A number of pioneer studies in GNSS research domain have developed models, algorithms and tested the performance of multiple constellations. One study proved that additional GLONASS data considerably improved the positioning accuracy especially when there are no sufficient satellites with good geometry available (Alkan, İlçi, Ozulu, & Saka, 2015). The “GPS + GLONASS” combination was also considered in a vehicular test by Angrisano and Gioia et al. (2013), their results showed evident performance improvements relative to GPS only configurations for all the considered parameters including accuracy, integrity and continuity. Similarly, Verhagen and Odijk et al. (2010) presented the improved performance with GPS + Galileo for RTK in a multipath condition in a simulation study.

Furthermore, positioning combining four GNSSs (GPS + Galileo + BeiDou + QZSS) has been proved as a better replacement of GPS tracking for a better accuracy, availability and reliability (Odolinski, Teunissen, & Odijk, 2014). Above studies have established the fundamental theories and proved the feasibility of multi-GNSS tracking. In real practice, Thitipatanapong and Wuttimanop et al. (2015) addressed that the precision from multi-GNSS is the key to detect the risk incident in vehicle driver's behaviour, precise vehicle movement trajectory should be achieved in GPS/GNSS tracking driving behaviours.

The objective of this study is to explore the optimal vehicle movement tracking quality that GPS/GNSS can record. In particular, the performance of multi-GNSS (GPS + Galileo + GLONASS + QZSS + Beidou) with RTK solution will be investigated in an urban residential area of Western Australia. We systematically compared vehicle kinematic recordings by multi-GNSS RTK, GPS RTK, DGPS and SPP techniques, in the obtaining of positioning accuracy and trajectory precision. Various elevation mask cut-off angles were applied to simulate the satellite availability in different sky view conditions. The vehicle trajectory data were computed and compared in GIS in order to fit the applications involving spatial analysis and integration in a Geodatabase. This study will provide insights into vehicle movement tracking for a wide audience including GIS, transportation, and surveying.

2. Related Work

2.1. Positioning solutions

Global Navigation Satellite Systems (GNSS) including GPS positioning can be categorized into several different types (Feng & Wang, 2008), according to the types of measurements used in the positioning estimation, the data epochs required to create a set of solutions, and the number of receivers involved in the positioning operations. SPP produces navigation solutions with pseudorange measurements from a single receiver and a single epoch. Precise Point Positioning (PPP) solutions are obtained using both code and phase measurements from a single receiver, but a period of observations, e.g., tens of minutes to hours. DGPS solutions are based on code measurements from a single epoch, but using the differential corrections from a reference station. The more complex RTK positioning makes use of both code and carrier phase measurements with the differential corrections from a reference station as well from a single epoch.

DGPS and RTK solutions improve the accuracy of GNSS tracking by reducing the effect of error sources. A minimum of four common satellites is required while tracking more than four common satellites simultaneously would improve the precision. Both DGPS and RTK use a known reference position to compute the rover position (the receiver with unknown position). The DGPS technique is available in many low-cost receivers. If the rover is within a distance of a few kilometers from the reference station, the atmospheric errors (ionosphere and troposphere) can either be estimated, or can be neglected since they are similar (El-Rabbany, 2006). This allows for positioning accuracies reaching sub-meter level. The RTK technique can be adopted by most surveying or professional-grade receivers, which can provide positions that are orders of magnitude more accurate than DGPS, and achieve recording positions at millimeter to centimeter level accuracy (Teunissen, 2007). This technology uses carrier phase measurements from two GNSS receivers. The observable of such measurements is the total number of carrier cycles, also called ambiguity integer, plus a fractional cycle part between the satellite and the receiver. This unknown number of cycles must be estimated along with the other unknowns of interest that may include the receiver's coordinates and the velocity of the user's movement (Teunissen, 1995).

Fixing the carrier phase ambiguities to integer numbers is one of the keys to obtain the best accuracy from RTK technique. Normally, this is done through several steps: first the ambiguities are fixed to float numbers using standard least-square techniques; then the set of integer ambiguities are set to the one that optimizes the residuals in the surroundings of the float solution; the carrier measurements can be corrected with the integer ambiguities, and they are used to obtain the relative position of the rover to the reference station. After the floating solutions being achieved, methods such as LAMBDA (Least-squares Ambiguity Decorrelation Adjustment) (Teunissen, 1995), can be used to get the integer ambiguity. Once the ambiguity is fixed, the RTK solutions can provide centimeter level accuracy (Odijk et al., 2010; Teunissen, 1994) for the outcome positions.

Such accuracy level is adequate for tracking precise vehicle movement trajectories in ideal environments (Sun et al., 2017). The RTK solutions can be achieved by both real-time and postprocessing. The latter allows the user to analyse more thoroughly the integrity of computed positions, which could be important to provide a higher level of confidence. It can be also a cheaper approach comparing to a real-time kinematic method that requires additional hardware and firmware for real-time communication link (Awange & Kyalo Kiema, 2013).

2.2. Multi-GNSS technology

GPS/GNSS positioning is a subject to satellite signal reception, hence its performance is related to signal quality, the operational scenario and the geometry between satellites and receivers (Angrisano, Gaglione, & Gioia, 2013). For optimal accuracy, receivers must have an unobstructed line of sight to four or more satellites. Since GNSSs perform better in an open sky when many satellites are in view and the signals are uncorrupted. Having more satellites available may help meet this goal more quickly (Kaplan and Hegarty 2006). Multiple GNSS may have as many as twice the satellites for determining location compared to a single system only such as the standalone GPS tracking. This is particularly helpful for users who need reliable location information in challenging environments, such as urban canyons or environments with foliage blocking portions of the sky (Angrisano, Gioia, et al., 2013).

The combination of different GNSSs guarantees improved satellite availability, thus can provide enhanced accuracy, continuity, and integrity for the positioning. Angrisano, Gaglione et al. (2013) outlined the advantages of multi-GNSS: higher position accuracy and higher success rate of positioning with increased number of satellites compared to GPS-only positioning, and more robustness against interferences by using different frequency bands and more precise timing. With the current 32 satellites in GPS, adding 14 Chinese BeiDou, four European Galileo, one QZSS satellite, as well as some satellites from other systems in orbit (Teunissen 2014), a combination of the satellite systems is possible to be employed to improve the positioning accuracy, reliability and satellite availability. In real practice, with more satellites available, optimal positioning can be also achieved by modifying the receiver configurations to eliminate bad satellites signals but still have sufficient satellites: by increasing the angle of elevation mask for the receiver antennas to ward off possible multipath errors from lower satellites; by reducing the Position Dilution of Precision (PDOP) to reject satellite geometries that may give rise to large positional errors, e.g., five satellites located on a cone or a line (Porter, Whitton, & Kriellaars, 2004).

A recent study in Australia by Odolinski et al. (2014) demonstrated that RTK based single-frequency multi-GNSS data resulted in an instantaneous ambiguity success rate at almost 100 percent with a 35° cut-off elevation. While with standalone GPS, they could not always compute a solution using such high cut-off due to insufficient satellites, and the success rate was only up to eight percent. The fixed positioning accuracy based on the multiple systems (GPS + Galileo + BeiDou + QZSS) data in their study was resolved to the centimeter level. In addition to the benefit of the improved visibility, quicker solutions for the ambiguity fixation can be also achieved in multi-GNSS, which can enhance the real-time application by multiple or dual frequency GNSS receivers compared to single frequency receivers (Imakiire, 2013).

The proliferation of the GNSSs enables a range of applications worldwide using multi-GNSS technology: such as navigation systems, vehicle monitoring, Geographical Information Systems (GIS), Location Based Services (LBS), applications with precision timing (Rizos, 2003), with more potential applications are coming in the near future.

2.3. Vehicle trajectory tracking in transport related applications

The accuracy requirements for vehicle tracking in transport safety applications were classified into three levels in an Australian study (Green et al., 2013): the road level (on which road the vehicle is placed); lane level (in which lane the vehicle is in); and where-in-lane level (where the vehicle is in the lane). The study report also stated that GNSS in vehicles tracking in Australia is only sufficiently accurate for the road level (accuracy better than 5 m). In contrast, in the US and Europe, GNSS augmentation can resolve positioning accuracy to the lane-level (1.5 m or better) (Green et al., 2013). The lack of where-in-lane level accuracy (centimeter to decimeter) from GNSS positioning limits the use of GNSS tracking in driving safety studies in Australia. The applications require a high standard GNSS tracking vehicle kinematic in terms of accuracy, timeliness, availability and reliability that has not always been available on market.

In driving ability studies using GNSS tracking vehicle movement, one category frequently reported is about the direction and lane control. Direction and lane control are related to the ability to control the vehicle heading along the desired route as well as keeping to the lanes (Vichitvanichphong, Talaei-Khoei, Kerr, & Ghapanchi, 2015). To successfully track a vehicle and assess the driving behaviour, vehicle position data should be at the lane level. Conventional GPS at 1 Hz positioning rate provides enough accuracy and update rate to estimate longitudinal speed and acceleration, but not enough for lateral acceleration of turning manoeuvre with large displacement and duration; also data with such accuracy level can't be used to estimate lane changing due to the low accuracy (Thitipatanapong et al., 2015).

Multi-GNSS with RTK positioning solution would be a suitable approach filling the abovementioned gaps (Somers. A., K, Weeratunga, 2015). Increasing visible satellites from GPS and other satellite systems can contribute to a better stable positioning. Driving behaviour study requires information from their on-vehicle sensors to determine the where-in-lane information. RTK system that can provide centimeter level accuracy, is growing in popularity for not only survey purpose but also for many other research fields which require precise positions. It may be possible and the right time to tracking vehicle kinematic even in a challenging area using multi-GNSS RTK technologies.

3. Methods

3.1. Study area and the test route

To test the performance of GPS/GNSS tracking vehicle movement, we chose the experiment area around the campus of Curtin University in Western Australia. It is approximately 1.5 km radius distance from the Curtin GNSS base station, which enables the cost-effective GPS/GNSS data postprocessing using reference data from the base station. The area is located in the suburb with less heavy traffic condition during the day, representing a typical urban residential area in Australia. The test route consists of both two-lane and four-lane roads, and driving manoeuvres through a series of roundabouts, intersections, traffic lights, Stop and Giveway signs and pedestrian crossings. Posted speed limits along the test route are 10, 40, 60 and 70 km/h. The length of the test route is approximately 7 km, it contains open road segments in most road sections, but also consists of the following conditions might affect GPS/GNSS operations: tree canopies, electrical lines, street signing, buildings and tall passing vehicles along the roads.

3.2. Data collections

Trimble R10 was used to collect GPS/GNSS recording data. Both static and kinematic recordings were conducted, the data was collected between May to September 2014. The first trial was to collect the GPS data recording on a pillar station with a known position, the recording lasted one hour. The other field trials were on-road driving for kinematic GPS recording, the driving was conducted to follow the road centerline as close as possible, the duration for driving was usually lasted approximately 30 minutes including a few minutes of warming up time in the car park. A pair of Trimble R10 receivers was mounted on the car roof with two positioning rates: 10 Hz and 2 Hz respectively. Tracking configuration was setup as multi-frequency, for example, L1 + L2 + L5 for GPS. The elevation mask for the rover antennas, which is the angle between the line of sight vector and the horizontal plane, was set at 5 degrees initially, but can be later on simulated to higher angles in the postprocessing software. Five GNSS systems (GPS + Galileo + GLONASS + QZSS + Beidou) were included in the constellation tracking. The Russian GLONASS is included but its ambiguity solution was turned off in RTKlib herein since it tracks a frequency that does not overlap any of the other frequencies used in this study.

Reference data from the base station receiver (Trimble NetR9) including the satellites navigation files and observation files at 10 Hz frequency were captured simultaneously as the recording of the experimented receivers, in order to apply positioning techniques to the raw GNSS recording through data postprocessing. Usually, the sampling frequency of standard reference stations is not higher than 1 Hz, and many stations even deliver data at sampling intervals as large as 30 s. The results from the commonly used output interval (30 s) of publicly available GPS reference stations (IGS, CORS networks, etc.) were a bit too sparse for optimal use in kinematic applications (Schüler, 2007). However, the 1 Hz reference data made available online was also downloaded and used for data comparison process in this study.

3.3. Data postprocessing and computing vehicle movement trajectory

The data postprocessing for raw observables recorded by GNSS receivers was conducted in the latest version of RTKlib program accessed from the application website (RTKlib, 2015). RTKlib is an open-source software that has been developed to support various postprocessing positioning modes (Single, DGPS, and RTK, etc.). The software also supports all major satellite constellations (GPS, GLONASS, Galileo, BeiDou, and QZSS) and major file exchange formats. In this study, we used RINEX (Receiver Independent Exchange Format) which is a standard GPS/GNSS data format. Since Trimble R10 receivers record both code and carrier phase measurements, the DGPS and RTK can be produced as separate datasets with the required inputs from the base station reference data. The SPP solution data were processed directly since no corrections were used from the reference station. The sections of warm-up time at the beginning of trials were deleted from each dataset. For driving trials, it was about 5-minute static recording in the car park so that it won’t affect the usage of the data. The solutions using corrections from reference data aim to improve the navigation attributes, such as positioning accuracy, reliability, and availability through the integration of external information from the base station into the calculation process, thus the procedure is commonly referred to as the GPS/GNSS enhancement.

Table 1 lists the options of GPS/GNSS datasets recorded or simulated for quality comparison and investigation. For example, there are three types of positioning solutions in the datasets: SPP, DGPS, and RTK. In this study, we didn’t investigate the PPP solution due to the unavailability of satellite positions and clocks at high rates (10 Hz or 1 Hz). Also we considered that the main drawback of PPP is that the convergence time is still too long. To reach good quality of positioning measurements have to be taken for over dozen minutes when using a single frequency, this time can extend to tens of minutes or few hours. As Witchayangkoon (2000) stated that it happened that convergence won't be achieved at all. Five different elevation cut-off angles were applied to simulate satellites' availability in different sky view conditions (Table 1). Setting at lower angles of elevation mask can track more satellites; however, signals from satellites at the horizon or at low elevations often experience considerable ionospheric delays and multipath effects. The higher angles can represent the tracking environment with trees or buildings etc., which would block the signals from lower satellites, typically in the urban area.

Table 1. Lists of GPS/GNSS datasets recorded or simulated for quality comparison

Data Recording and RTKlib Simulations	Options for sub-datasets
Recording methods	Static (pillar), Kinematic (driving)
Constellations	GPS+Galileo+GLONASS+QZSS+Beidou, GPS only
Positioning Solutions	SPP, DGPS, RTK
Elevation Mask Angles	5°, 15°, 20°, 25°, 35°
Reference data rates	1 Hz, 10 Hz
Recording data rates	2 Hz, 10 Hz

RTKlib has a compact and portable program library written in C to provide a standard platform for GPS/GNSS data processing applications. The library implements fundamental navigation functions and carrier-based relative positioning algorithms for RTK with integer ambiguity resolution by LAMBDA. In RTKlib, the positioning mode was configured in the "kinematic" when computing RTK solutions, the Integer Ambiguity resolution was set to "continuous" mode to estimate and resolve the ambiguity continuously. For each dataset by RTK solution, RTKlib generates results ranking based the solution status of quality as follows: fixed, float, and SPP (RTKlib, 2015). The "fixed" solution generally inherits a much higher precision than the "float solution", and the "SPP" solution returns values without correction from reference data thus presenting the least precision in the dataset (Teunissen, 2007). The percentage of "fixed rate" indicates the level of success in the ambiguity resolution, therefore, higher "fixed rate" is in the dataset and a better data quality in the positioning results can be inferred. We keep all the positioning results (fixed, float and SPP) in the investigation as every vehicle position (time) plays a role in applications using vehicle movement trajectories.

A GIS program (ArcMap, 2012) was used to project all data from WGS-1984 Latitude/Longitude to Easting/Northing in MGA (Map Grid Australia) coordinates (GDA94, Zone 50) for linear error measurement, and integration with other local spatial information, such as transport and environment. In this study, we used orthoimagery as background spatial information in the maps for visualisation purpose.

3.4. Data analysis

To date, the data quality level that can be achieved for vehicle movement tracking by various GPS/GNSS techniques hasn't been fully explored, especially with the advent of multi-GNSS. Based on the above recorded and simulated datasets, we compared the accuracy and precision of the GPS/GNSS recording with comprehensive options to evaluate the GPS/GNSS capability in tracking vehicle movement trajectory and ultimately achieve close-to-reality vehicle movement trajectory as the main objective of this study.

Euclidean distance between the GPS/GNSS recordings to the benchmark of pillar location was used to verify the positioning accuracy. This was also used to verify the performance of the device that was reported by receiver manufacturer.

When analysing the data quality of kinematic recording in driving, we do not normally know the exact location of the test vehicle at a particular time, thus obtaining an absolute error for each GPS location data is impossible. In this study, we used the across-track error defined as the perpendicular distance from a GPS/GNSS observed positions to the corresponding road centreline (as a benchmark line) the test vehicle was traveling along. The perpendicular distance from GPS/GNSS driving points to the benchmark line was created and measured in ArcGIS program (ArcMap, 2012). The perpendicular distances demonstrated the deviation from the benchmark. The smaller perpendicular distance indicates better trajectory accuracy and precision.

After each calculation, the accuracy and precision of GPS/GNSS recordings were measured and compared using descriptive statistical analysis (mean and standard deviation) of the differences between Euclidean distance and perpendicular distance respectively. A series of maps and tables provide more insight into the efficacy of GPS/GNSS recording vehicle movement trajectories with comprehensive options of setting, configuration and environment. In particular, the vehicle movement trajectory of multi-GNSS with RTK solution will be examined in the study area.

4. Results

4.1. Summary of satellite visibility

Satellite visibility is essential for precise positioning. Satellites that appear near the horizon at low angles can cause signal fading. They also pick up more atmospheric noise than satellites orbiting higher above the horizon. To obtain better positioning results, we may ignore those satellites by increasing the elevation mask angle. However, if the angle is too high, the GPS/GNSS receiver might eliminate satellites that would be useful in determining coordinates. A typical mask angle is between 10-15 degrees. Sometimes lower values can be used (such as 0° - 5°) if the users need to get a reading quickly and don't have time to wait for other satellites to position themselves higher above the horizon. When a low elevation mask angle was chosen, the receiver still reports the location, but the reading might not be as accurate as the one from a higher mask angle setting. During data postprocessing, better results can be achieved through adjusting the elevation mask angles.

Fig. 1 mapped the number of satellites tracked at every vehicle position during one driving trial in order to illustrate the visibility patterns of satellites. We can visually compare the results between the multi-GNSS and GPS-only at two cut-off angles of elevation mask: left side maps present 15° recordings and right side for the 35° recordings; top two maps show the multi-GNSS recording and the bottom two maps for the GPS-only recordings.

Overall, in any circumstance, the number of satellites tracked by the receiver significantly dropped in those narrower streets, streets with tree canopies. There is a big contrast with the satellites visibility between 15° and 35° for both multi-GNSS and GPS-only options. It is noted that, for the lower elevation mask angle of multi-GNSS (top left), only small sections of the route present recordings with less than five satellites. In contrast, for multi-GNSS at a high cut-off angle of 35° (top right), more than five satellites were guaranteed during most of the driving route except a few small sections with heavy tree canopies, which is still promising considering the requirement of positioning. Whereas during the majority of the time on the driving route, recoding on both the two-lane road and four-lane road can track up to 10 satellites. For GPS-only option at an angle of 15° (bottom left), there were more than five up to eight GPS satellites tracked during most time of the trial. However, if the angle increased to 35° (bottom right), all the way only up to five satellites were available, less than four satellites recorded in many sections even on the broad four-lane sections. Furthermore, some sections showed no satellites tracked due to the high elevation angle used.

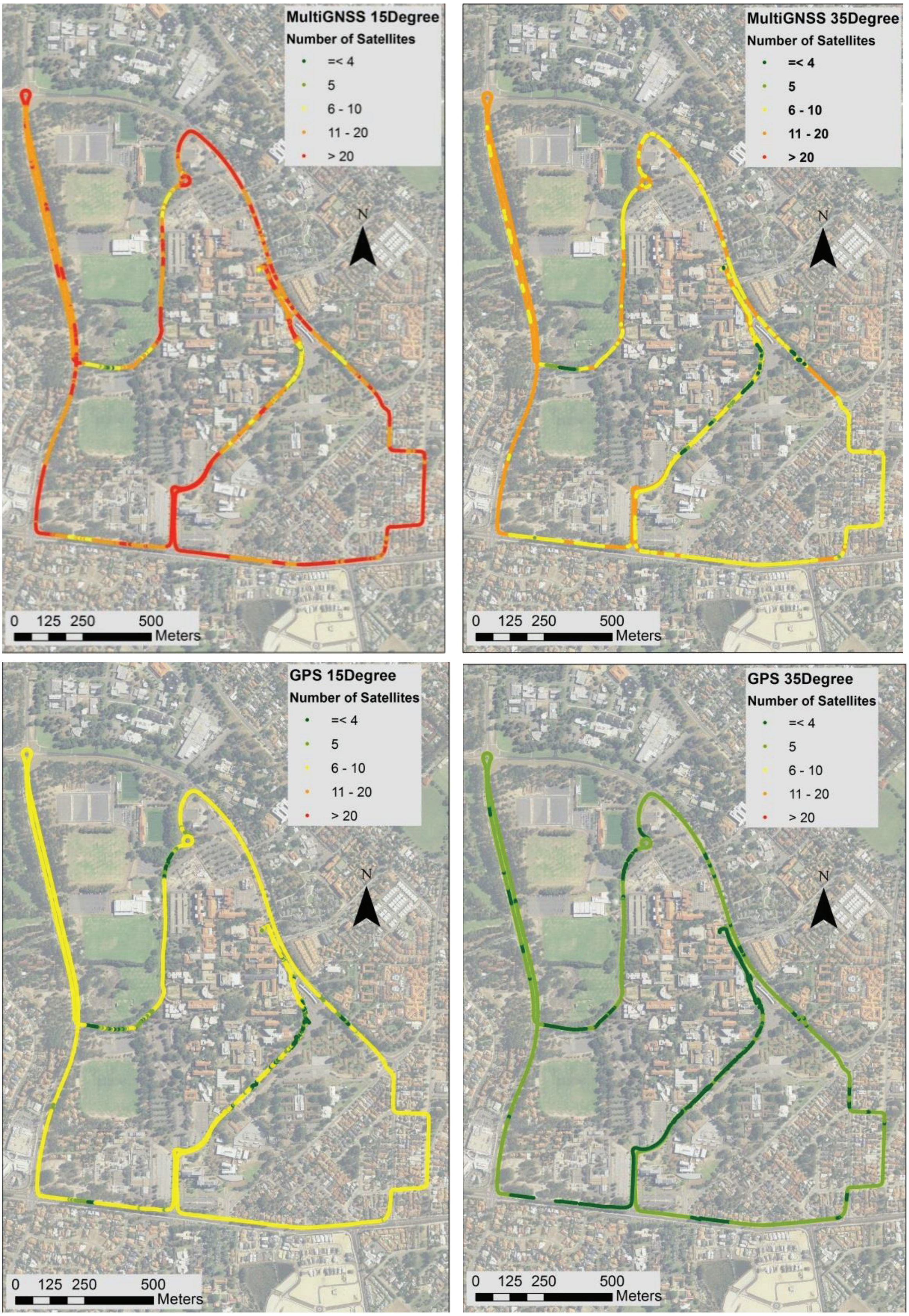

Fig. 1 Number of satellites tracked by GPS/Multi-GNSS with different elevation mask angles during a driving trial

4.2. Positioning accuracy and precision under static recordings

Fig. 2 visualises the spatial patterns of the pillar recording results by multi-GNSS RTK at 25° and GPS at 15° with SPP, DGPS, and RTK solutions. The results can speak for a range of GPS/GNSS devices at different costs, such as recreational receivers with code-phase only measurement, and professional receivers have a carrier-phase measurement as well; the latter can provide RTK solutions.

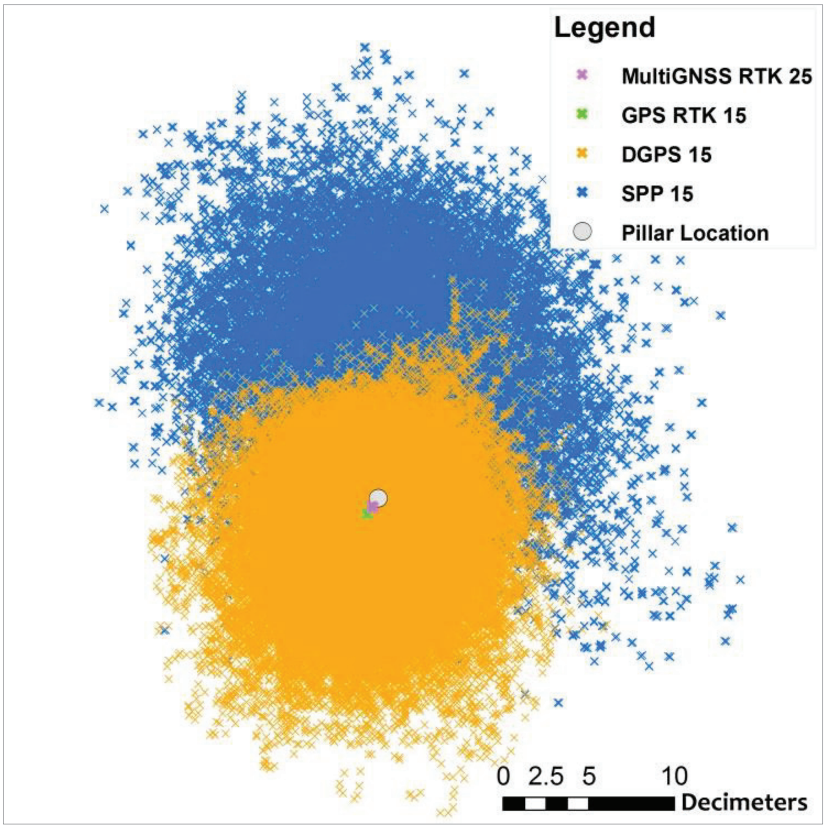

Fig. 2 Static recording by GPS/Multi-GNSS with different positioning solutions

Table 2 Statistics of positioning accuracy of GPS/GNSS recordings with different positioning techniques at static recording

GNSS Recordings for Static tracking	Error distance (m) mean	Error distance (m) STD
Multi-GNSS RTK 25°	0.063	0.001
Multi-GNSS RTK 15°	0.066	0.007
Multi-GNSS RTK 5°	0.071	0.014
GPS RTK 15°	0.065	0.008
DGPS 15°	0.501	0.270
GPS SPP 15°	1.075	0.422

The statistics of the different positioning results for static recordings giving more implication are shown in Table 2. The figures are the error distance calculated using Euclidean distance method. The table presents two more static recordings: multi-GNSS at 15° and 5° of elevation masks. The results from multi-GNSS RTK at 25° achieved the best accuracy at 6 cm (mean) and 0.1 cm (standard deviation) of the error distance, indicating a very high concentration of the recording. For different positioning solutions, RTK demonstrates the best accuracy at centimeter level, DGPS with half a meter and SPP at meter level respectively. This is consistent with the accuracies announced by the manufacturer on the receiver manual. For different elevation mask angles, recording at 25° gives the best accuracy with the smallest mean at 6.3 cm, and best precision with the STD at 0.1 cm.

We can also look at the comparison between multi-GNSS and GPS-only with both using RTK solutions at 15°, the two results are very close; however, the STD of multi-GNSS is slightly lower showing improving precision in the positioning. In conclusion, under current open sky view as an ideal recording environment, GPS/GNSS can obtain optimal results with corresponding settings. However, the multi-GNSS option didn't give a significant difference in the results.

4.3. Positioning accuracy and precision for vehicle movement recording

4.3.1. Visualisation of data quality between different solutions and mask angles in vehicle kinematic recordings

Fig. 3 visually compares the accuracy of the vehicle kinematic recording results by multi-GNSS RTK 15° and 35°, and GPS at elevation mask of 15° with the SPP, DGPS, and RTK solutions, in the ideal recording environment of open sky view with minimum multipath interference.

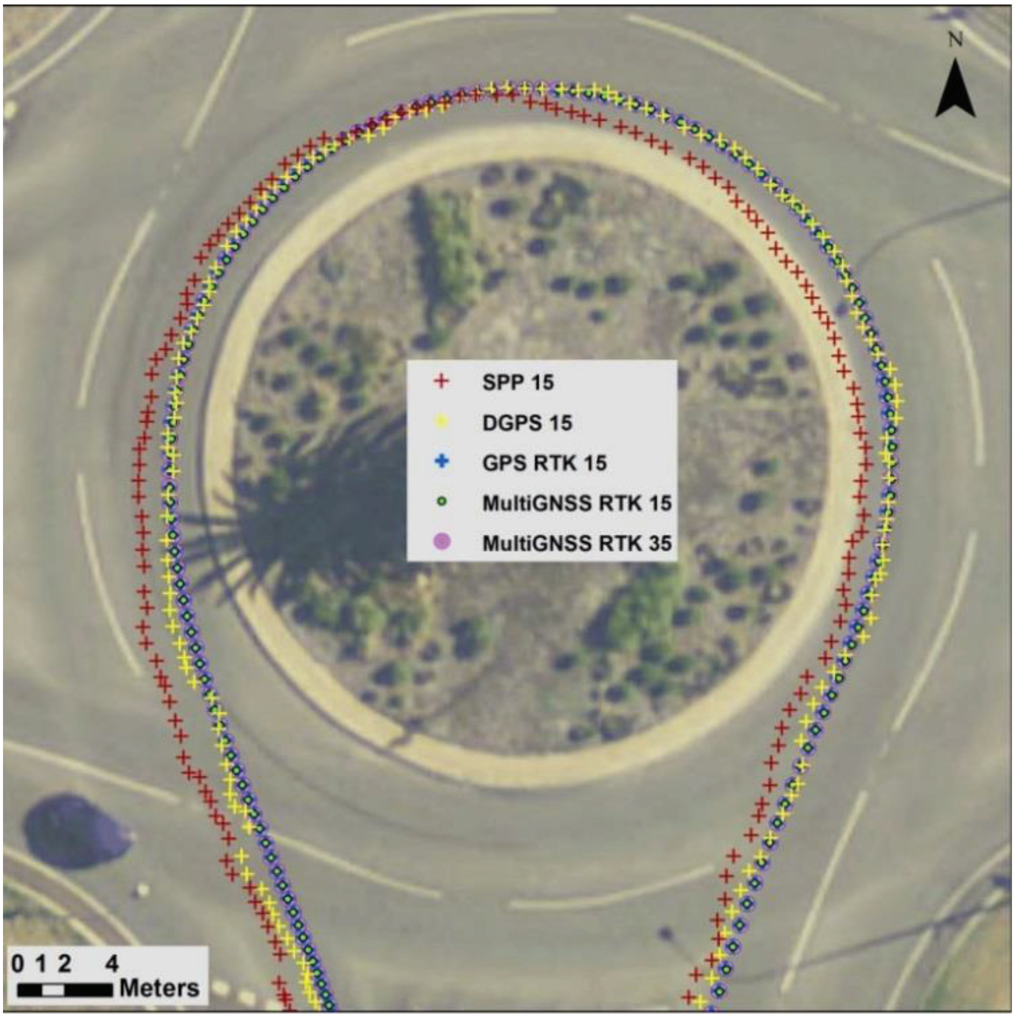

Fig. 3 Comparison of tracking quality of GPS/multi-GNSS with different positioning solutions under open sky view

All RTK solutions result in smooth and accurate trajectory, DGPS result shows the improved accuracy, however, the trajectory is not smooth, and the SPP solution gives the least accuracy and noticeable variation of the trajectory since no corrections for the raw observables. In contrast, the GPS/GNSS recording under a harsh environment (Fig. 4) was greatly degraded by multipath from surroundings and the reduced satellites visibility since the tree canopies can block satellites signals. In this section, both DGPS and SPP trajectories contain considerable errors and noises. There are also a lot of dropping off points from the benchmark in GPS RTK at 15°; while multi-GNSS RTK at 15° presents much improved trajectory indicating increased satellites visibility, however, the trajectory quality was downgraded in the multi-GNSS RTK 35° indicating insufficient satellites visibility.

Fig. 4 Comparison of tracking quality of GPS/multi-GNSS with different positioning solutions in a harsh environment with tree canopies

4.3.2. Statistics of data quality comparisons between different solutions and mask angles in kinematic recordings

The statistics of the different positioning results for kinematic recordings are shown in Table 3. All the listed individual datasets were processed in RTKlib based on one single observables, but using different solutions and elevation angles.

The figures are the offset distances from the benchmark line calculated using the perpendicular distance method. Overall the results using multi-GNSS provide improved accuracy and precision in compared to the GPS-only counterparts, indicating an increased number of satellites affecting positioning performance. With GPS-only, the fixing rate is much lower than multi-GNSS options (see Table 4). A dramatic performance improvement can be observed by combining other GNSSs to GPS, as Verhagen, Odijk et al. (2010) addressed that, due to the larger number of visible satellites, the propagation of the multipath biases is much less compared to the GPS-only case, and successful instantaneous ambiguity resolution is possible nearly all day, obviously even with only Galileo combined to GPS. Interestingly, since we included the results from all the solution status (fixed, float and SPP), the multi-GNSS RTK 20° beats the 35° option and achieved the best accuracy and precision, the latter one gave very high fixed rates but also more SPP results (Table 4). This is because the increased elevation angle eliminated satellites that would be useful in determining coordinates, particularly in a harsh environment (see Fig. 5).

Table 3 Statistics of positioning accuracy of GPS/GNSS recordings positioning techniques in kinematic recording

GNSS Recordings for Vehicle Kinematics (with different solutions and mask angles)	Error distance (m) mean	Error distance (m) STD	Rank mean
Multi-GNSS RTK 35°	0.036	0.090	3
Multi-GNSS RTK 20°	0.028	0.057	1
Multi-GNSS RTK 15°	0.031	0.059	2
Multi-GNSS RTK 5°	0.040	0.065	4
GPS RTK 15°	0.071	0.463	5
Multi-GNSS DGPS 15°	0.266	0.316	6
DGPS 15°	0.404	0.497	7
Multi-GNSS SPP 15°	0.993	0.543	8
GPS SPP 15°	1.087	0.562	9

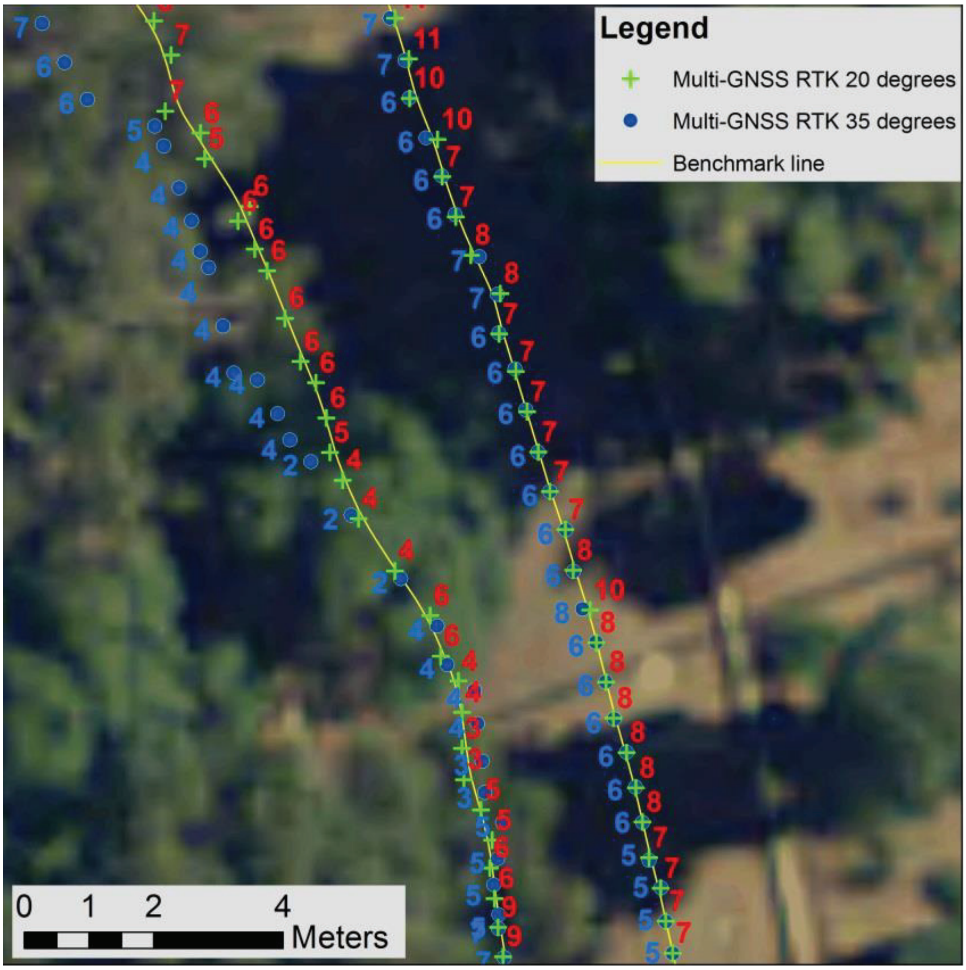

Fig. 5 Comparison of positioning in a harsh environment recorded with different mask angles (The number of tracked satellites at each position, red is for 20°; blue is for 35°.)

Table 4 Quality report of the integer ambiguity solution status: Fixed, float and SPP (percentage of each quality solutions)

GNSS Recordings for Vehicle Kinematics (with different mask angles)	Fixed rates (%)	Float rates (%)	SPP (%)
Multi-GNSS RTK 35°	96.5	3.2	0.3
Multi-GNSS RTK 20°	93.4	6.3	0.3
Multi-GNSS RTK 15°	84.8	14.9	0.2
GPS RTK 35°	72.5	24.6	2.8
GPS RTK 20°	86.6	11.1	2.2
GPS RTK 15°	74.9	24.0	1.1

4.3.3. Comparisons of GNSS data quality with different frequency rates

Recording data at different frequency rates show the density of vehicle trajectories. We tested 10 Hz and 2 Hz simultaneously and applied RTK solution for both data processing. 1 Hz or even lower rates can be too coarse for computing trajectory in kinematic applications.

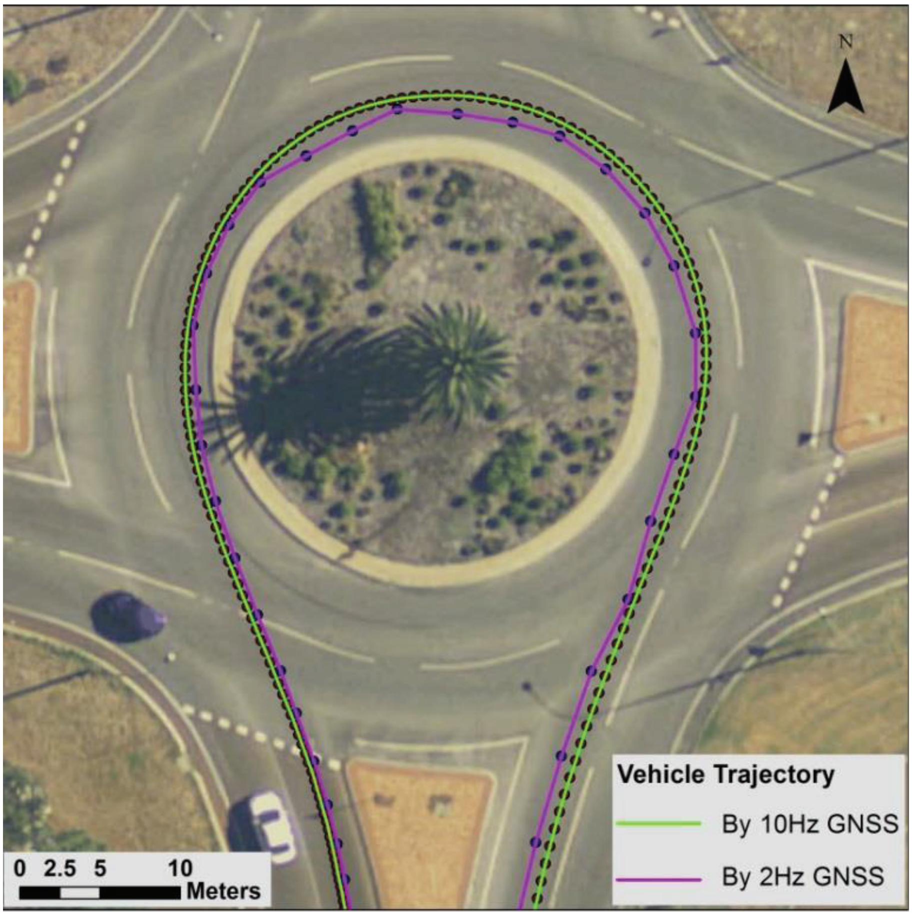

Fig. 6 Comparison of tracking accuracy between different positioning rates using RTK solution

Fig. 6 shows that the positioning at 10 Hz update rate (ten times per second) creates more detailed and higher resolution in vehicle tracking capabilities. Trails of the vehicle can be recorded with five times the resolution compared with the 2 Hz positioning update rate, and ten times to the more traditional rate of once a second. By updating the positions 10 times per second, vehicle trajectory can be scrolled more smoothly. For driving behaviour assessment, in the event of abrupt steering, braking or a collision while driving, the detailed position where such events take place can be accurately recorded. Even while driving on the express highway, the trajectories of the vehicle can be recorded in second detail to ensure accurate and complete data analysis capabilities. This is of particular important when the vehicle movement recording needs to synchronized with other sensor recording at high rates, such as video recording.

As for the frequency rates from the reference station, we compared the results using reference data at 1 Hz and 10 Hz rates. Since the rover recording is still at 10 Hz, a single correction data will be applied to every five recordings on rover data. For vehicle movement tracking, it might smooth out some variations of the positioning along the trajectory. Fig. 7 presents the positioning discrepancies using base station data at 10 Hz and 1 Hz at one section; there are several points where the 1 Hz reference data gave less accurate and precise positions than the 10 Hz ones.

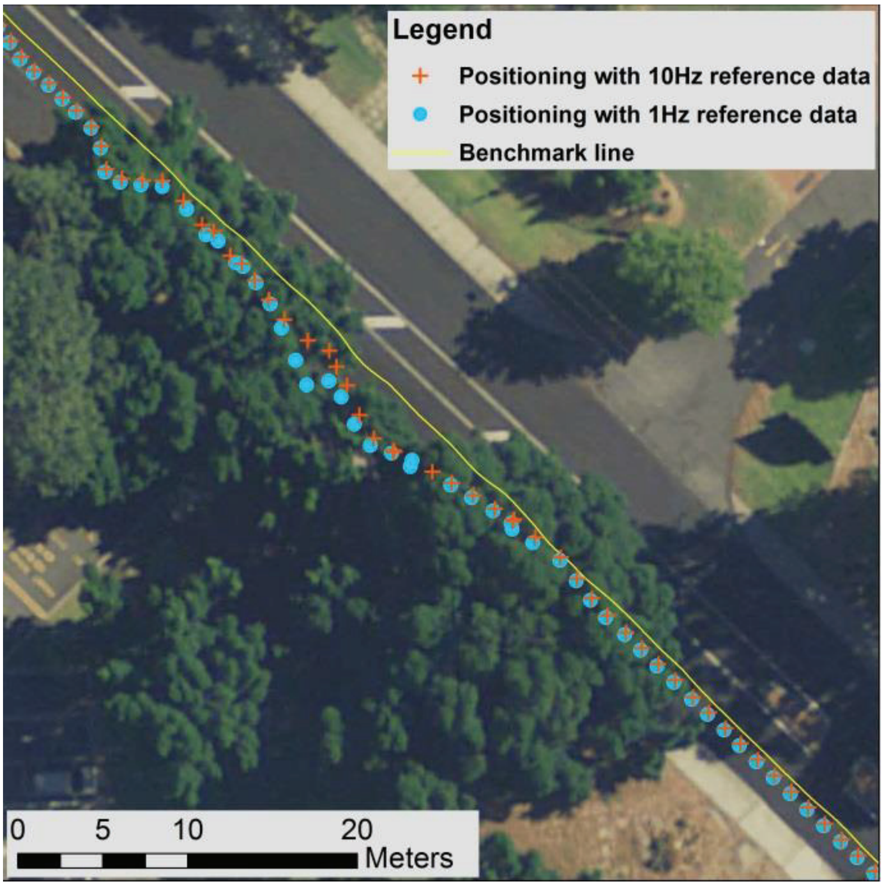

Fig. 7 Comparison of positioning with reference data at different rates

Table 5 Quality report of the integer ambiguity solution status with reference data at different frequencies

GNSS Recordings for Vehicle Kinematics	Fixed rates (%)	Float rates (%)	SPP (%)
Multi-GNSS RTK with 1 Hz reference data	92.8	5.2	2.0
Multi-GNSS RTK with 10 Hz reference data	96.5	3.2	0.3

Table 5 reports the data quality based on the percentage of solution status from two datasets, both are multi-GNSS RTK solutions but using reference data at different rates. Positioning with the same frequency rates from reference station recording presents higher percentage at “fixed” and lower “SPP”, indicating better accuracy and precision with 10 Hz reference data.

With these extensive experimental results, we conclude that in the tested urban residential area, the multi-GNSS RTK solutions can provide horizontal accuracy and precision up to centimeter level, and ambiguity-fixed solutions for over 90% at 35 degrees of elevation angle. Such data was further enhanced in GIS to modify positioning with "float" and "SPP" solutions, a series GIS spatial analysis functions in ArcMap, e.g., snapping, smooth and interpolation, were used to provide proposed positions for those results.

5. Discussions

The main practical issue of obtaining precise vehicle movement trajectory is the cost and the complexity of data processing. The receiver that is suitable for vehicle kinematic tracking with carrier-phase measurement enabled and has the capacity to track multiple GNSS can be comparably expensive even among the professional-grade GNSS devices. The postprocessing of multi-GNSS RTK at high rates usually takes long hours to complete**,** knowledge and skills from both surveying and GIS are needed to execute the procedure. Also, the logistics management can be complicated since data recording the base station needs to simultaneously operate at high rates. The RTKlib program was found to be an inexpensive tool that allows performing a broad variety of postprocessing of gathered data.

PPP (Precise Point Positioning) solutions are determined by means of a single receiver without recordings from a base station; it can provide centimeter level accuracy too with the availability of precise reference satellite orbit and clock products. However, the satellite orbit and clocks data normally made available is given at intervals as large as 30 s, whereas kinematic positioning requires sampling frequencies of 1 Hz up to 10 Hz or even higher.

Although the multi-GNSS is a promising approach and its efficacy for tracking vehicle movement trajectories has been proved in this study, precautions should be always taken for those recording sections where the satellite signals can be degraded.

Recommendation for pursuing precise vehicle movement trajectory is to test the receiver with a range of options, once the optimal results achieved, experiments should be undertaken with the same receiver. Metadata form should be always filled for every experiment with sufficient information on the receiver and vehicle setting that would affect the quality of recordings.

The performance of these methods is compared in terms of the mean and standard deviation of error distances for the horizontal position. Other parameters of GNSS recording quality, such as the integrity and continuity presented in maps are for illustrative purpose, should not be construed as a direct definitive comparison between different positioning options. The aim of this study sought to produce a close-to-reality vehicle movement trajectory for the investigation of driving behaviours. We thus acknowledge that a more thorough investigation into the different aspects of multi-GNSS tracking performance is required before more definitive decisions can be made with respect to other fields.

6. Conclusions

GNSS are worldwide, all-weather navigation systems able to provide three-dimensional position, velocity and time. The best known among these GNSSs is GPS, followed by Russian GLONASS. With the European Galileo positioning system, China BeiDou system, and more other systems coming to the operation, it appears that multi-GNSS data processing would become the norm in the near future. It is now an opportune moment to evaluate and develop the potential benefits that may accrue from processing multi-GNSS data.

In this paper, vehicle movement tracking using GNSS was tested with comprehensive positioning options. We simulated satellites' availability in different sky view conditions using different elevation cut-off angles ranging from 5° - 35°. The vehicle trajectory data was computed and compared in GIS to suit applications involving spatial analysis and integration in a spatial database. Based on the results, multi-GNSS configurations show evident improvements with respect to stand-alone GPS in terms of solution availability and accuracy, the parameters that are usually considered to be critical in urban scenarios. It is concluded that multi-GNSS data considerably improved the position accuracy especially when there are no sufficient satellites with good geometry available.

As results, in the tested urban residential area, the RTK solution with 10 Hz multi-GNSS using 20 elevation mask angle presented ideal vehicle movement trajectory. Such data can be integrated with other spatial information and used in applications when precise vehicle localization or timing is required. Integration of high-resolution vehicle movement trajectory data into a GIS allows researchers to segment, visualize and model their data based on location. Moreover, other data can be geo-coded with the reference of vehicle locations to obtain new spatial attributes. In many movement and behaviour studies, a good quality GPS/GNSS dataset will lay the essential foundation of the project database. In the following contributions, multi-GNSS RTK tracking vehicle movement trajectories will offer comprehensive and reliable data for investigating driving behaviour and performance in older drivers; and the high rates vehicle trajectories can be linked to eye tracking data, so that a more contextual and realistic driving behaviour dataset can be obtained (Sun, Xia, Falkmer, & Lee, 2016; Q. C. Sun et al., 2016) for investigating visual-motor coordination performance in older drivers.

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Driving Manoeuvre during Lane Maintenance in Older Adults: Associations with Neuropsychological Scores

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Abstract

Older drivers experience difficulties in lane maintenance under challenging driving sections due to age-related cognitive declines, yet there is little comprehensive evidence on associations between cognitive functions and the lane maintenance in this population. In this study, fifty older drivers completed an on-road driving assessment and a battery of standard neuropsychological tests. Mean Lane Position (MLP), Standard Deviation of Lane Position (SDLP) and manoeuvre time calculated from precise vehicle movement trajectories were used as the lane maintenance parameters. The GNSS tracking vehicle movement presents comprehensive and reliable vehicle position data, which is more sensitive for detecting subtle variations of lane maintenance in older drivers. Statistical analysis results show that lower visual attention (selective and divided attention) was associated with higher MLP and SDLP; MLP was also correlated to spatial abilities, executive function, and motor speed; manoeuvre time was negatively correlated with drivers' risk-taking personality (all p <.01). Selective attention was found to be the best predictor of MLP in lane maintenance. A combined eight variables from three neuropsychological tests, UFOV 2 and 3, BD and BJLO, D-KEFS TMT 1, 2, 3, and 4, correctly classified 80.4% of participants with good versus low-performing lane maintenance.

Keywords: Older Drivers, Cognitive Abilities, Lane Maintenance, Neuropsychological tests, GNSS tracking

1. Introduction

Older drivers have higher crash rates per distance driven compared with most other age-group drivers, and these crashes result in greater morbidity and mortality (Molnar et al., 2007). Various aspects of cognition, particularly visual attention and executive function, were found to link with crash risk among older drivers (Cynthia Owsley & McGwin Jr, 2010; Richardson & Marottoli, 2003). According to previous studies, older drivers were over-involved in angle collisions, crashes at intersections, turning, and changing lanes (Charlton et al., 2006; Clarke, Ward, Bartle, & Truman, 2010; Marmeleira, Ferreira, Melo, & Godinho, 2012; McGwin Jr, 1999). Maintaining lateral control within the driving lane is a key aspect of safe driving for older adults (Johnson, Dawson, & Rizzo, 2011). Drivers normally adopt safety margins to avoid the consequences of their errors (Ranney, 1994). Effective safety margins need preservation from the entire distribution of responses, involving neuropsychological capacities that are mediated by multiple areas of the brain, e.g., visual, attentional, perceptual, cognitive and psychomotor abilities (Anstey, Wood, Lord, & Walker, 2005; Dawson, Uc, Anderson, Johnson, & Rizzo, 2010). The occurrence of crashes with respect to increasing steering variability in older drivers indicates inadequate safety margins performed during lane maintenance (Ranney, 1994). Understanding the critical cognitive abilities underpinning older drivers' lane maintenance would provide insights into older drivers' behaviour and safety.

One category frequently reported in driving assessment is about the direction and lane control, which is related to the ability of the driver to control the vehicle heading along the desired route in the correct lane (Vichitvanichphong, Talaei-Khoei, Kerr, & Ghapanchi, 2015). A driver on road, as the position controller at the stabilisation level, keeps the vehicle as near as possible to the desired position along the given path (Evangelou, 2004). To describe dynamic steering characteristics of a driver, the control theory is mostly appropriate to use

(Jürgensohn, 2007). Maintaining a car in the right position and with proper speed are typically regulation tasks which the driver is the centre and controller. Inattention to the road ahead while driving has been identified a primary cause of unsafe behaviours and a factor leading to vehicle accidents (Neale, Dingus, Klauer, Sudweeks, & Goodman, 2005). When turning, the driver should make the manoeuvre as accurate as possible, wide turning or cutting a turn too sharply can be risky due to the reduced safe margins on the road (Phondeenana, Thitipatanapong, Klongnaivai, Noomwongs, & Chantranuwathana, 2014; Ren, Xu, & Li, 2014).

Lane maintenance in driving tests generally assesses the lateral (side to side) positioning of the vehicle during turning, straight ahead driving and lane changing. A typical error in lane maintenance is drifting out of the driving lane (Sherrilene Classen, Shechtman, Awadzi, Joo, & Lanford, 2010; Justiss, 2005), while some performance, such as zigzagging, cutting corners and wide turns indicating inappropriate behaviour or poor car control of the drivers. Lane maintenance performance of a driver can be examined with traditional measures of the central tendency, using mean and standard deviation of lane position, together with performance criterion measures, such as lane exceedance counts or time in and out of the lane (Cooper, Medeiros-Ward, & Strayer, 2013). These measures present intuitive links with lane departure crashes (Ball, Edwards, & Ross, 2007). The most commonly used measure of lateral control in is the standard deviation of lane position (SDLP), since all the factors contributing to lane departures have an influence on the standard deviation of lane position (Green, 2013; Verster & Roth, 2011). Studies by Green (2013) have measured SDLP with an on-road and some driving simulator experiments, the typical values and likely variation provided a practical implication for data collection in future studies.

Lateral position can be measured as the deviation in meters from the center of the driving lane. Since the increment of mean lane position (MLP) and SDLP may ultimately cause lane crossings onto the road shoulder or the adjacent traffic lane, measurements of MLP and SDLP have been used as potential indexes of driving behaviour and safety, which ensures the construct validity of the study observed (Verster & Roth, 2011). Moreover, on-road driving tests with lane position measure demonstrate a higher content and ecological validity when compared to closed road tests, driving simulators, and clinical psychometric tests (Odenheimer et al., 1994). A measure of lateral lane maintenance can also be used an index of road-tracking precision for individual driving performance (Wester, Böcker, Volkerts, Verster, & Kenemans, 2008) and can provide a sensitive measure for detecting drivers' impairment (Cuenen et al., 2015). Ben and Frank et al. (2008) stipulated that the parameters of time-in-lane and SDLP are both indices of driving related visual performance by the ambient visual system, which involves both central and peripheral portion of the visual field for movement control (Schmidt & Wrisberg., 2008). Sandberg et al. (2013) investigated the relationship between SDLP and the drivers' physical conditions, found a significant difference in the average lane position for sleepy and alert drivers. Verster and Roth (2011) addressed that the SDLP measure with its high test-retest reliability, can be used as an index of "driving weaving" for a measure of stability in driving.

Older drivers experience difficulties in lane maintenance under challenging driving sections, such as urban conditions at intersections or at roundabouts (Gstalter & Fastenmeier, 2010). Although many studies showed that age-related cognitive declines are correlated to decreased driving performances in older adults, there is little comprehensive evidence on associations between cognitive functions and the lane maintenance in this population, especially in real-world driving conditions (Ott, Papandonatos, Davis, & Barco, 2012).

In parallel to on-road and simulated driving tests, assessing drivers' level of functioning has been used as a clinical approach to determine the risk of vehicle crashes in older adults. Static visual acuity, visual fields, visuospatial skills, processing time, selective attention (the ability to focus on a particular object while simultaneously ignoring irrelevant information), divided attention (the ability to maintain attention in multiple stimulus) all decline with age and may adversely affect driving skills (Anstey et al., 2005; Cynthia Owsley, Wood, & McGwin, 2015). The functional visual field or "useful field of view" (UFOV) measure has been found to correlate with crash data in older drivers (Cynthia. Owsley, Ball, & McGwin, 1998). So far a variety of cognitive abilities declines with increasing age have been well-researched, including attention, processing speed, and problem-solving (executive function) (Mathias & Lucas, 2009). Although these findings can be important when considering the established links between basic cognitive abilities and everyday functional abilities (Ball et al., 2007), no single cognitive test is able to provide sufficient sensitivity and specificity to discriminate safe drivers from unsafe older drivers (Bedard, Weaver, Dārzin, & Porter, 2008). For predicting fitness-to-drive among older drivers, cautions should be taken when using those cognitive tools (Bédard, Campbell, Riendeau, Maxwell, & Weaver, 2016). Driving places demands on multiple cognitive abilities for the driver to accurately perceive the constantly changing traffic environment, make quick decisions, and effectively control the vehicle (Dawson et al., 2010). Therefore, the strongest predictor of age-related decline in driving performance can be a composite measure that takes into account a range of cognitive abilities. Generally, composites are broader and more reliable than individual variables (Salthouse, 2005). Few study has yet examined relationships between cognitive functions and on-road lane maintenance performance among older drivers. In particular, there is lacking of studies that use an accurate measure of MLP and SDLP for driving behaviour assessment.

The relationship between cognitive factors and the specific lane maintenance competence in older drivers has not been adequately explored, such as which lane maintenance parameters can be compromised by the decline of cognitive functions in older drivers, and whether the neuropsychological assessment can assist in the determination of this competency in this population. Knowledge about the cognitive characteristics associated with the driving behaviour of older people has important implications for the improvement of safety and mobility in older adults. Findings from such studies may inform educational efforts to help drivers understand the risks of age-related cognitive declines and the inadequacies of compensatory driving strategies (Dawson et al., 2010; He, McCarley, & Kramer, 2014). In addition, transport management and driving assessments need to observe the multiple factors that discriminate those who have a higher crash risk from the lower ones. Once they are identified, some intervention strategies can be put in place in order to enhance their driving competencies.

In order to explore more thoroughly the role of older adults' cognitive functions in driving ability, the present study investigates which measures in a neuropsychological battery are predictive of older participants driving ability determined by on-road lane maintenance performance. Mean Lane Position (MLP), Standard Deviation of Lane Position (SDLP) and manoeuvre time calculated from precise vehicle movement trajectories are used as the lane maintenance parameters. It is hypothesized that spatial ability, executive, and visual attention measures would be critical determinants of lane maintenance competencies in older drivers. The objectives of this study are to:

- Assess the lane maintenance performance of older drivers based on the parameters of lateral positioning, lane deviation, and manoeuvre time derived from precise vehicle movement trajectories.
- Assess the cognitive functions of older drivers using a selected battery of neuropsychological tests.
- Investigate the relationship between the neuropsychological scores of older drivers and their lane maintenance performance, so as to identify the cognitive variables associated with driving competencies.

2. Methods

2.1. Participants

Fifty older drivers aged from 60 to 81 were recruited from the local community. The participants were conscripted from clubs and a retirement village. They first received a participant information form indicating the procedure of the experiment. The benefit of participation is gaining knowledge on driving behaviour; they also received a small gift as compensation. The eligibility of participation also included: holding a valid driver license and having an insured vehicle, driving at least 3-4 times a week, and reported no mental health or physical impairments that could impact their driving performance. Participants were excluded from the study if they had a comorbid diagnosis that would interfere with their driving ability such as dementia, and severe cognitive or physical impairment, and no sedative medication was taken prior to the assessment. Before the assessment, all subjects provided informed consent for participation in compliance with ethics requirements from the University Human Research Ethics Committee (Approval no. HR68_2014). Visual acuity (Snellen eye chart) and cognitive function by Mini-Mental State Examination (MMSE) were assessed as screening tools to ensure their basic vision and cognitive fitness for on-road driving. All participants met the criteria for screening tests of visual acuity and MMSE, 20/50 and 24/30 respectively. A mini-survey on demographics and driving habits was also conducted prior to the assessment.

2.2. Data collection

An experimental protocol for exploring a variety of older driver attributes in a single investigation was conducted including laboratory neuropsychological tests and the on-road driving test. The neuropsychological assessment took place either before or after on-road driving, all the assessment were done in one session lasting about one and a half hours in total.

2.2.1. On-road driving assessment using GNSS tracking

The study area was chosen around the campus of Curtin University in Perth, Australia. The driving route (Appendix A) was designed as a loop route circling around the university campus which contains a series of roundabouts and intersections. It is approximately 1.5 km radius distance from the Curtin GNSS base station. This enables postprocessing techniques for precise vehicle movement data using the base station reference data. The driving test lasted about 20 minutes for about 10 km distance under normal traffic. Participants were instructed to drive their own car as they normally do and choose their preferred position within the traffic lane.

A pair of Trimble R10 GNSS (Global Navigation Satellite System) receivers was mounted on each participant's car roof to record the vehicle movement trajectory. The receivers can track multiple satellite systems (multi-GNSS) beyond GPS-only approach, which is essential for recording vehicle movement in an urban area when the precise vehicle positioning and completed trajectory are required. Using multiple satellite systems achieved higher position accuracy with an increased number of satellites compared to GPS-only positioning, particularly in harsh environments (tree canopies etc.) where the GPS-only positioning becomes difficult (Kubo, Hou, & Suzuki, 2014; Noomwongs, Thitipatanapong, Chatranuwathana, & Klongnaivai, 2014). The tracking configuration of Trimble R10 receivers was setup at 10Hz, so the vehicle movement trajectory of each driving contained the following attributes every 0.1 seconds: time, x-coordinate, y-coordinate. The multi-GNSS improves the availability and accuracy of the positioning data, and the Real-time kinematic (RTK) positioning solution was used to achieve the accuracy at centimeter-level horizontally (Sun et al., 2017; Sun et al., 2016). The vehicle trajectory data of each older driver were computed in GIS (Geography Information System) and integrated with other local spatial information, such as transport and environment.

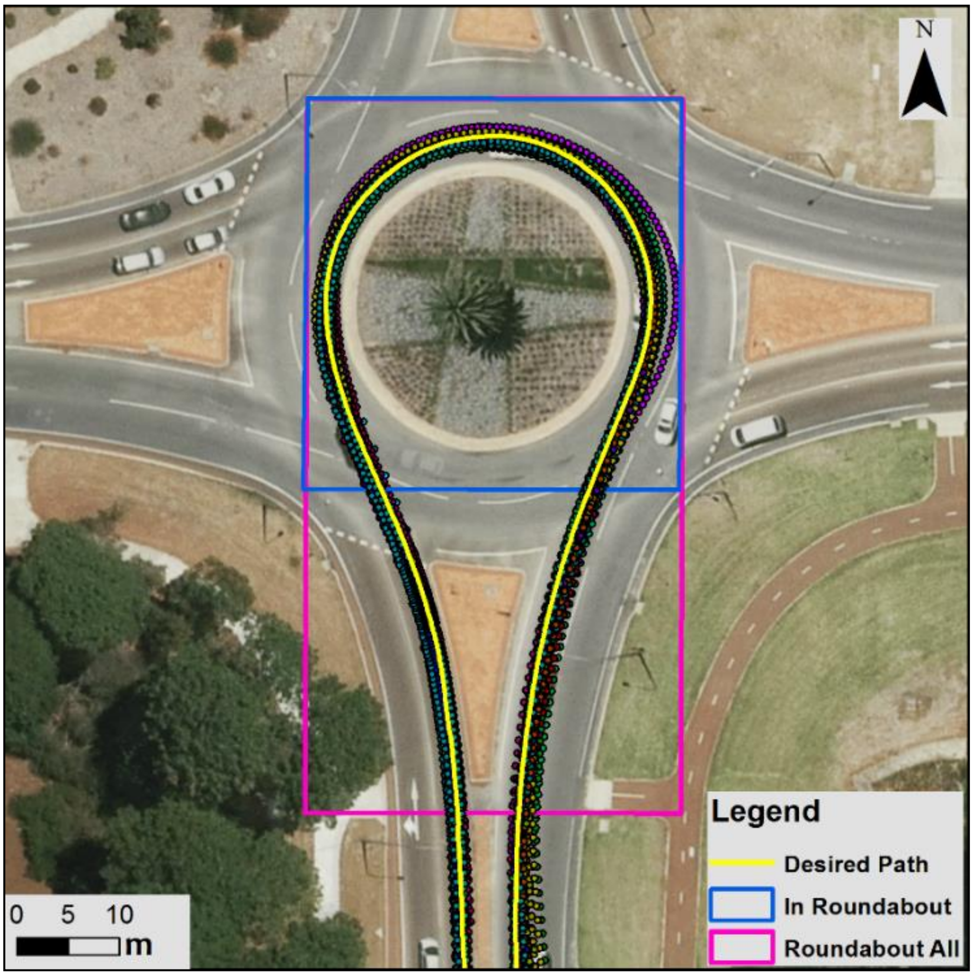


Fig. 1 Precise vehicle movement trajectories recorded by multi-GNSS RTK positioning.

The investigation of older drivers' lane maintenance focuses on roundabouts and intersections at 12 critical sections along the driving route (Appendix A). Fig. 1 presents the vehicle movement trajectories of the participants making a U-turn at a roundabout. The desired path here was derived from the road centreline and modified with the centre of the mean path driven by all drivers; used as benchmark line to calculate the lane deviations of driving behaviour. The purple line defines the study area of this particular manoeuvre, so the vehicle movement trajectory of each driver can be extracted for calculations. The blue line delineates the manoeuvre time at this section inside the roundabout since individual drivers might have different waiting time before entering into the roundabout due to different traffic.

2.2.2. Laboratory neuropsychological tests

A battery of neuropsychological tests was chosen to assess older participants' vision, cognition and motor skills and the level of risk-taking personality. These tools are standardised tools that have been widely used internationally. For driving assessment programs, it is of necessity to assess several functional abilities to cover the complexity of the driving task (Cuenen et al., 2015). The neuropsychological tests would provide a window into the specific cognitive deficits present in individuals with increased crash risk (Lees, Cosman, Lee, Fricke, & Rizzo, 2010). Assessments of aging drivers should take into account possible changes across a range of different cognitive abilities, and a battery of tests is, therefore, likely to be more effective than any single test (Dawson et al., 2010).

The Useful Field of View (UFOV) tests evaluate processing speed, divided and selective attention (S. Classen, Wang, Crizzle, Winter, & Lanford, 2013; J. M. Wood & Owsley, 2014). The test determines the speed of processing abilities quantified by display speed threshold for central target identification alone in Subtest One, central target identification with peripheral target localization in Subtest Two, and central target identification with peripheral target localization in the presence of distractors in Subtest Three (Ball et al., 2007). Scores are expressed in milliseconds, representing the exposure duration required for a participant to perform. For each subtest, possible scores range from 13 to 500 ms. Lower scores correspond with better visual attention. An association has been found between low UFOV scores and speed processing deficits (Anstey et al., 2005; J. M. Wood & Owsley, 2014).

The Benton Judgement of Line Orientation (BJLO) test is used to measure the judgement of visuospatial orientation, which was developed to be as pure a measure of one aspect of spatial thinking, as could be conceived (Benton, Sivan, Hamsher, Varney, & Spreen, 1983; Emerson et al., 2012). Participants are presented with a pair of lines and asked to match the angular positions to the referenced lines. This test uses subtle differences in line slope to accurately detect participants' visual-spatial perception and scored according to the number of correct responses.

The Wechsler's Block Design (BD) test (Wechsler, 1981) evaluates the participant's spatial cognition and motor skills (Ferreira, Simões, & Marôco, 2013; Kaplan, 1988). This task is a measure of the visual-spatial perception and organisation; it examines essential components of nonverbal intelligence and requires that participants use bicoloured cubes to reproduce designs or models (Ferreira et al., 2013). BD has been used to test the visual-spatial problem-solving and motor abilities in everyday activities (Groth-Marnat & Teal, 2000), it was found as an individual significant predictor of more safety errors in older drivers (Dawson et al., 2010).

The Delis-Kaplan Executive Function System Trail Making test (D-KEFS TMT) measures the visual search, attention, sequencing, executive functions and motor skills (Barrash et al., 2010; Delis, 2010; Mitchell & Miller, 2008). The D-KEFS TMT test specifically isolates these processes in its five testing conditions (Vasilopoulos et al., 2012): Trails 1 (visual scanning), Trails 2 (number sequencing), Trails 3 (letter sequencing), Trails 4 (number-letter switching, or called set shifting) and Trails 5 (motor speed). In essence, the D-KEFS TMT measures rapid visual search, psychomotor speed and cognitive flexibility in a visual-motor task in all the TMT conditions while Trails 4 is considered an index of executive function (Homack, Lee, & Riccio, 2005; Vasilopoulos et al., 2012). The test is completed in the shortest time possible and scored by seconds to completion.

The Balloon Analogue Risk Task (BART) tests the level of risky personality in the participants. The test is designed to mimic realistic risk-taking behavior by presenting the choice between reward and loss. The scoring method is based on the average number of pumps the participant makes on unexploded balloons. High scores predict higher risk-taking behavior. Previous research has demonstrated that various forms of risky behavior are highly associated among individuals, and such personality traits are correlated with risk-taking. The average number of pumps on successful trials were sensitive to impulsive sensation seeking and risk-taking in the real world (Ba, Zhang, Peng, Salvendy, & Crundall, 2015). The BART was observed as a real-world risk-taking behavior related to traffic safety (Mishra & Lalumière, 2011; Vaca et al., 2013).

2.2.3. Lane deviation calculations and spatial statistical analysis

Fig. 2 illustrates the lane maintenance performance at a roundabout between two older drivers as an example of the data analysis. To quantitatively measure the lane deviations, the perpendicular distances between vehicle movement trajectories to the benchmark line were created and the lengths were calculated (Fig. 2). A GIS tool (ArcMap, 2012) was used to compute the perpendicular line and calculate the distance between each point of vehicle positions at 0.1 seconds interval recorded by GNSS receivers to a benchmark (the desired path). It is visually noticeable that the Driver B presented significantly larger lane deviation, especially in the second part of the roundabout.

Based on the perpendicular lines, two parameters of lane maintenance can be generated for each driver at the particular scenario: the MLP (mean lane position) and SDLP (standard deviation of lane position). The manoeuvre time was directly extracted from the GNSS recordings defined by the start/end time in the blue area in Fig. 1. The three parameters (MLP, SDLP and manoeuvre time) for individual drivers at 12 sections were loaded into the database and integrated with neuropsychological scores for further statistical analysis.

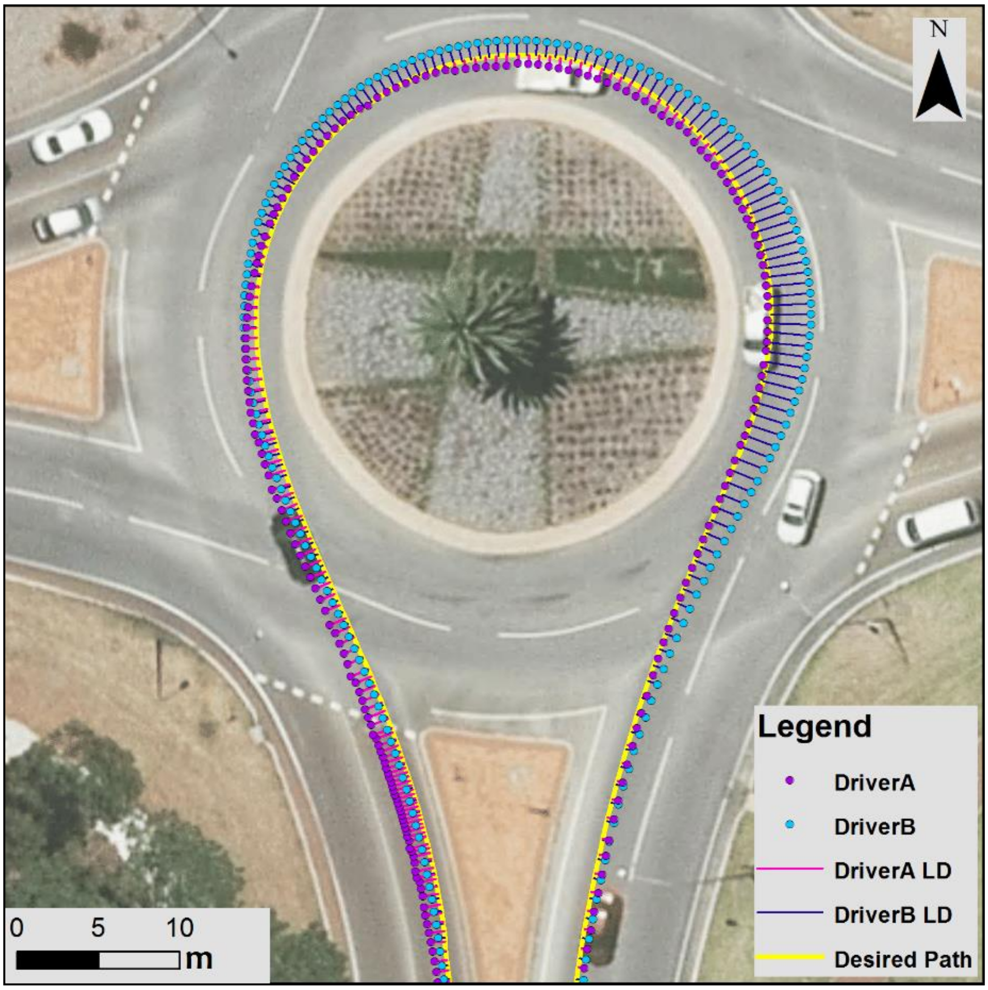


Fig. 2 Perpendicular distances created for lane deviation calculations

The SPSS® statistical package was utilized for all statistical analyses. Pearson's Correlations were computed across drivers' age and neuropsychological scores, driving measures (MLP, SDLP and manoeuvre time), and the relationship between driving measures, and age and neuropsychological scores. Multiple linear regression was used to investigate the possible influence of cognitive abilities on older drivers' lane maintenance, and most predictive neuropsychological test/s for their driving performance. Discriminant Analysis (DA) was conducted to identify variables from the cognitive tests which discriminate between good and poor lane maintenance in older drivers.

3. Results

3.1. Descriptive statistics of study variables

In total, there are 15 study variables used including participants' age, lane maintenance performance and neuropsychological tests scores. Descriptive statistics for each study variable are presented in Table 1. It can be seen that there is considerable variation in the distribution of performance on manoeuvre time, UFOV 2 and 3, BD, D-KEFS TMT 2, 3 and 5. Most of the study variables except SDLP and UFOV 1 demonstrated acceptable levels of normality, reflected in skewness parameters less than an absolute value of 2 (George, 2011).

Table 1 Descriptive Statistics of study variables

Variables	Min	Max	Mean	Std. Deviation	Skewness	Kurtosis
Age	60	81	69.58	5.88	0.27	-0.97
MLP (m)	0.11	1.78	0.57	0.30	1.64	4.84
SDLP (m)	0.10	2.18	0.37	0.31	4.43	24.92
Manoeuvre time (x0.1s)	330	507	438	34.27	-0.84	1.88
UFOV 1	13	23	13.59	1.85	3.92	16.14
UFOV 2	13	160	47.50	44.98	1.16	0.10
UFOV 3	20	390	107.90	71.94	1.59	3.60
BD	22	58	42.32	10.66	-0.39	-1.04
BJLO	13	30	24.78	4.41	-1.23	0.58
D-KEFS TMT 1	14	42	24.61	7.06	0.61	-0.25
D-KEFS TMT 2	16	88	40.06	15.95	0.84	0.37
D-KEFS TMT 3	15	82	38.68	16.41	0.92	0.42
D-KEFS TMT 4	12	65	27.47	11.20	1.25	1.72
D-KEFS TMT 5	31	234	89.03	40.31	1.74	4.23
BART # Saved Balloons	8	30	24.32	4.20	-1.35	3.05

Note. Abbreviations: MLP = mean of lane position; SDLP = standard deviation of lane position; UFOV = Useful Field of View; BD = Block Design; BJLO = Benton Judgement of Line Orientation; D-KEFS TMT = Delis-Kaplan Executive Function System Trail Making test; BART = Balloon Analogue Risk Task

3.2. Drivers' age and the performance on the neuropsychological tests

Statistical correlations between the performances on individual neuropsychological tests along with drivers' age, in total 12 variables, are presented in Table 2.

In this particular cohort of older adults, participants' age was found to be correlated with four conditions of D-KEFS TMT except the TMT 4. However, there were no correlations between age and all of three UFOV subtests, BD, BJLO and BART. This indicates that chronological age was not a good predictor of participants' cognitive functions with respect to visual attention (UFOV 2 and 3), spatial abilities (BD and BJLO), executive function (D-KEFS TMT 4) and risk-taking test scores (BART). Three tests, UFOV 1 (processing speed), BJLO (spatial orientation) and BART's risk-taking test had no correlations with any other cognitive tests. In contrast, the selective attention (UFOV 3) was correlated with seven cognitive functions including UFOV 2, BD, BJLO, D-KEFS TMT 1 (Visual Scanning), 2 (Number Sequencing), 3 (Letter Sequencing), and 4. Likewise, the divided attention test (UFOV 2), spatial visualisation (BD), executive function (D-KEFS TMT 4) and motor speed tests were also associated with seven other cognitive variables. The TMT 1, 2, and 3 of D-KEFS were associated with eight other cognitive variables. All five conditions of D-KEFS TMT measures were correlated with each other.

Table 2 Correlations relationship between drivers' age and the neuropsychological scores
(Pearson Correlation Coefficients and Significances)

	Age	UFOV1	UFOV2	UFOV3	BD	BJLO	TMT1	TMT2	TMT3	TMT4	TMT5	BART
Age	-											
UFOV 1	.006 (.967)	-										
UFOV 2	.242 (.109)	.155 (.277)	-									
UFOV 3	.251 (.097)	.012 (.933)	.598** (.000)	-								
BD	-.235 (.121)	-.055 (.700)	-.468** (.001)	-.627** (.000)	-							
BJLO	.067 (.662)	-.090 .532)	-.272 (.053)	-.303* (.031)	.259 (.066)	-						
TMT 1	.583** (.000)	.042 (.769)	.277* (.049)	.376** (.007)	-.402** (.003)	.155 (.277)	-					
TMT 2	.511** (.000)	.068 (.635)	.428** (.002)	.585** (.000)	-.582** (.000)	.007 (.964)	.640** (.000)	-				
TMT 3	.543** (.000)	.035 (.806)	.438** (.001)	.445** (.001)	-.575** (.000)	-.037 (.794)	.738** (.000)	.749** (.000)	-			
TMT 4	.275 (.067)	.091 (.527)	.305* (.030)	.443** (.001)	-.475** (.000)	-.190 (.181)	.473** (.000)	.503** (.000)	.627** (.000)	-		
TMT 5	.568** (.000)	-.012 (.934)	.335* (.016)	.188 (.187)	-.375** (.007)	-.202 (.155)	.598** (.000)	.452** (.001)	.674** (.000)	.389** (.004)	-	
BART	-.102 (.503)	.225 (.112)	-.260 (.065)	-.106 (.460)	.046 (.746)	-.019 (.897)	.013 (.927)	-.247 (.081)	-.190 (.182)	.102 (.474)	-.056 (.697)	-

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

3.3. Correlations between lane maintenance measures and neuropsychological scores

Table 3 provides the statistical correlations between participants' lane maintenance performance and individual neuropsychological test scores.

Table 3 Correlations relationship between the drivers' age, neuropsychological scores, and their lane maintenance performance

Age/Neuropsychological scores	Correlation with MLP	Correlation with SDLP	Manoeuvre time
	Correlation Coefficient (Sig. (2-tailed)		
Age	.041 (.777)	.101 (.489)	.020 (.894)
BART (Risk-taking)	-.125 (.381)	-.068 (.636)	.297* (.036)
UFOV 1 (Processing speed)	.059 (.683)	.002 (.989)	.072 (.614)
UFOV 2 (Divided attention)	.581** (.000)	.408** (.003)	-.034 (.815)
UFOV 3 (Selective attention)	.544** (.000)	.370** (.008)	-.034 (.815)
BD (Spatial visualisation)	-.431** (.002)	-.283 (.050)	.092 (.521)
BJLO (Spatial orientation)	-.323* (.021)	-.153 (.285)	.118 (.410)
D-KEFS TMT 1 (Visual Scanning)	.361** (.009)	.177 (.213)	.109 (.445)
D-KEFS TMT 2 (Number Sequencing)	.365** (.008)	.331* (.019)	.098 (.492)
D-KEFS TMT 3 (Letter Sequencing)	.467** (.001)	.327* (.019)	.148 (.301)
D-KEFS TMT 4 (Number-letter Switching)	.392** (.004)	.223 (.115)	.207 (.146)
D-KEFS TMT 5 (Motor Speed)	.390** (.005)	.150 (.295)	.157 (.271)

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Note. Abbreviations: UFOV = Useful Field of View; BD = Block Design; BJLO = Benton Judgement of Line orientation; D-KEFS TMT = Delis-Kaplan Executive Function System Trail Making test; BART = Balloon Analogue Risk Task.

Similar to the correlations summary in the age and neuropsychological tests (Table 2), variables of age, processing speed (UFOV 1) and BJLO were not associated with lane maintenance performance. The same applies to the visual scanning (D-KEFS TMT 1), together with UFOV 1, BJLO. These tests demonstrated less difficulty for participants, therefore, could hardly detect the variation of cognitive functions between individual participants.

Both UFOV 2 and 3 tests, Block Design and D-KEFS TMT 2 to 5 tests were associated with MLP; UFOV 2 and 3 also correlated with SDLP indicating that visual attention predicted the level of lane maintenance well. The risk-taking test of BART was associated with the manoeuvre time, and it was the only predictor for this variable. It can explain the fact that the high risk-taking participants took less time manoeuvreing through the roundabout. Overall, the divided attention was the best predictor of lane maintenance performance based on the strength of the correlation. Likewise, the selective attention showed a stronger relationship with MLP than with SDLP.

With regard to the correlations across lane maintenance measures, only MLP and SDLP correlated strongly with each other (r =.639, p <.001). No relationship between manoeuvre time and other two measures.

3.4. Regression analysis to predict lane maintenance using neuropsychological tests scores

A multiple regression with enter method was run to predict lane maintenance from a selection of neuropsychological tests including UFOV 2, UFOV 3, BD, D-KEFS TMT1 and D-KEFS TMT3. These variables statistically predicted MLP, $F\,(5, 45) = 4.695, p < .005, R^2 = .343$. UFOV 3 for testing selective attention presented a significant p-value for the individual coefficient in the model ($\beta = .360, p < .05$).

3.5. Predictive variables to discriminate lane maintenance behaviour

Discriminant Analysis (DA) was used to predict the lane maintenance performance of participants based on a linear combination of the interval variables from a set of neuropsychological tests. A linear function that separates date into two groups, can be obtained as the result of a discriminant analysis of a set of data. The obtained discriminant function contains parameters of cognition with an associated weight factor. Larger weight factors indicate that the associated parameters are of greater importance to explain the classification of good versus poor lane maintenance.

3.5.1. Category and covariate variables in discriminant analysis

The participants were divided into two groups (category variables) based on the median of the combined measures of MLP and SDLP to represent their overall lane maintenance performance. The lower scoring participants comprised the group of good performance whereas the higher scoring ones were defined as the low-performing group. The DA resulted in a way to “predict” events as the discriminant scores for better lane maintenance performance showed a deviation from the worse ones.

Eight variables from three neuropsychological tests were used as the covariate variables for DA including UFOV 2, UFOV 3, BD, BJLO, D-KEFS TMT1, 2, 3 and 4. Technically, DA will find coefficients for the input variables that creates a value that can be used to distinguish between groups of datasets. The formula below describes the mathematical form of the resulting discriminant score and how it relates to the coefficients for each variable. In general, in the two-group case, a linear equation of the type was fitted:

$$\text{Group} = a + b_1 * x_1 + b_2 * x_2 + \ldots + b_8 * x_8$$

In the above equation, where a is a constant and b_1 through b_8 are regression coefficients for variables x_1 to x_8. The interpretation of the results of a two-group problem is straightforward and closely follows the logic of multiple regression: those variables with the largest standardized regression coefficients are the ones contributing most to the prediction of a group membership.

3.5.2. Discriminant analysis results

The DA provides the summary of canonical discriminant functions to report the validity of the analysis. The canonical relation is a correlation between the discriminant scores and the levels of the dependent variable. A high correlation indicates a function that discriminates well; the correlation was 0.663. Wilks’ Lambda (0.561) had a significant value (p = .001). In DA, the value of the variance proportion of discriminant scores that were explained by the discriminant function is determined subtracting Wilk's Lambda from 1.00 (Meyers, Gamst, & Guarino, 2006), which is 0.439.

Table 4 shows the tests result of equality of group means for each variable. There were seven variables that were significant, while three variables of divided and selective attention and letter sequencing perform even better with significant Wilks's lambda values ≤ .001.

Table 4 Tests of equality of group means for each variable.

Neuropsychological variables	Wilks' Lambda	Sig.
UFOV 2 (Divided attention)	.771	.000
UFOV 3 (Selective attention)	.798	.001
BD (Spatial visualisation)	.921	.045
BJLO (Spatial orientation)	.841	.004
D-KEFS TMT 1 (Visual Scanning)	.881	.013
D-KEFS TMT 2 (Number Sequencing)	.905	.028
D-KEFS TMT 3 (Letter Sequencing)	.811	.001
D-KEFS TMT 4 (Number-letter Switching)	.937	.075

Table 5 Standardized and structure canonical discriminant function coefficients for each variable

Neuropsychological variables	Standardized Coefficients	Structure Coefficients
UFOV 2 (Divided attention)	.438	.617
UFOV 3 (Selective attention)	.313	.568
BD (Spatial visualisation)	.495	-.332
BJLO (Spatial orientation)	-.582	-.492
D-KEFS TMT 1 (Visual Scanning)	.361	.416
D-KEFS TMT 2 (Number Sequencing)	-.020	.365
D-KEFS TMT 3 (Letter Sequencing)	.512	.545
D-KEFS TMT 4 (Number-letter Switching)	.027	.294

Note. Abbreviations: UFOV = Useful Field of View; BD = Block Design; BJLO = Benton Judgement of Line Orientation; D-KEFS TMT = Delis-Kaplan Executive Function System Trail Making test

The standardized discriminant function coefficients in Table 5 indicate the relative importance of the independent variables in predicting the dependent. Coefficients with large absolute values correspond to variables with greater discriminating ability. The standardised coefficients show predictions after controlling for other predictors; divided attention, spatial abilities (BD and BJLO), and letter sequencing presented higher discriminant function coefficients. The structure coefficients present predictions without controlling for other predictors, it shows the correlations of each variable with the discriminant function, and only one discriminant function is in this study. The cognitive abilities of divided and selective attention, spatial orientation, and letter sequencing demonstrated higher discriminant function coefficients in determining the two groups of good versus poor lane maintenance performance.

Using the combined tests, the DA had a canonical correlation with the participation of 80.4% of original grouped cases and 70.6% of cross-validated group cases correctly classified.

4. Discussion and Conclusions

In this sample of 50 community-dwelling older adults with valid driving license, we investigated the relationship of the lane maintenance performance on an on-road assessment with their cognitive functions. The participants had not driven on the pre-determined testing route and they were unfamiliar with the traffic conditions in the campus area. The driving assessments were performed in ecologically valid contexts. Although participants had to follow certain instructions while driving, and a driving instructor accompanied the participants, the lane position measures (MLP and SDLP) are the closest representations of normal driving performance. Since the speed variability usually has fewer consequences for traffic safety than the waving of the vehicle's lane deviation (Verster & Roth, 2011), lane position deviations are better parameters associated with risky driving compared to speed parameter. The data collected by the GNSS vehicle movement tracking system on vehicle control is comprehensive and reliable, which is more sensitive in detecting subtle variations of driving manoeuvres in evaluating driving behaviours for older populations (Sun et al., 2017).

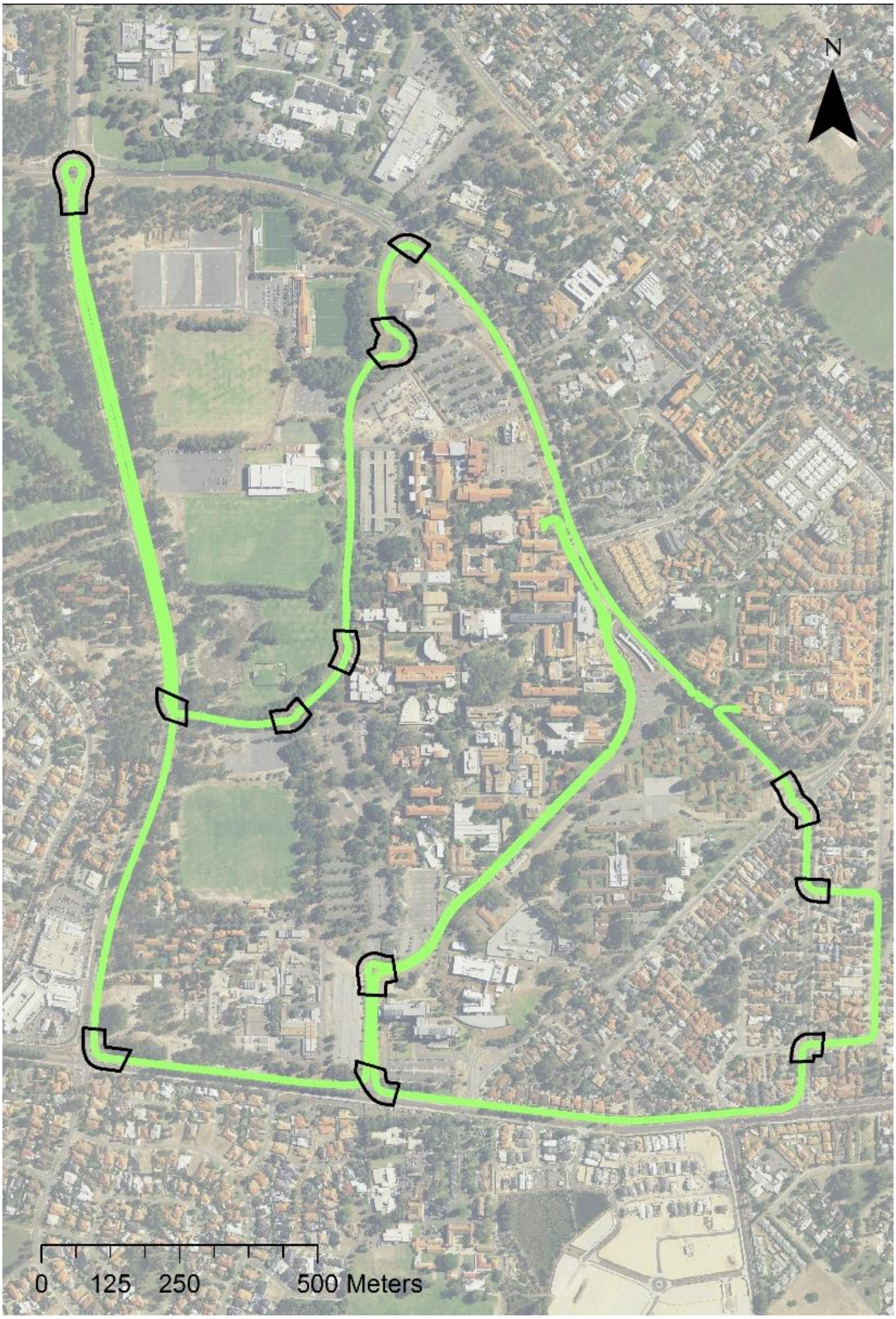
Some of the cognitive variables: divided and selective attention, spatial visualisation, number sequencing, letter sequencing, number-letter switching, and motor speed, was correlated with MLP parameter (p <.01). Divided and selective attention were also positively correlated with SDLP (p <.01). However, manoeuvre time is only negatively associated with the risk-taking factor (p <.05). The current study indicates that age alone was not associated with older drivers' lane maintenance performance, whereas, visual attention and executive function of older drivers demonstrate were strongly correlated to lane maintenance performance. The result is consistent with studies in car crash epidemiology of older drivers (Baldock, Mathias, McLean, & Berndt, 2007; Ott et al., 2012; Richardson & Marottoli, 2003; Joanne M. Wood, Horswill, Lacherez, & Anstey, 2013). Overall, UFOV 2 and 3, all D-KEFS TMT subsets and Block Design tests had significant correlations with lane maintenance parameters in older drivers. The decline in cognitive functions would not affect driving performance alone since some cognitive performances are tightly coupled in affecting the driving actions, visual-spatial and visual-motor abilities required in multiple tests of the battery appear to be particularly associated with the low performance of lane maintenance. However, selective attention tested by UFOV 2 could be used as an independent predictor for lane maintenance in older drivers.

The discriminant analysis results revealed that age-related cognitive functions: divided and selective attention, spatial abilities, and letter sequencing can categorise older drivers with different ability to control their lane position in driving. The better of the cognitive function, the better their ability to control their lane position in driving. This research showed that the discriminant analysis has the potential to find the best parameters related the neuropsychological tests in predicting drivers' performance in lane maintenance.

The present study has several limitations. First, this group of participants is a sample of independent, healthy older drivers who have maintained active mobility and lifestyle, and results may not be generalizable to all older drivers (Rapoport et al., 2013). Apart from age, other variables, such as educational and professional background, could be factors affecting their cognitive performances. In the future, more detailed demographic information should be considered in the analysis. Results of discriminant coefficients are sensitive to the definition of groups of drivers, and further analysis should be undertaken to improve the prediction of the model. One alternative to improve the model could be to separate lane maintenance performance into three groups with more samples to avoid the bias between good and risky drivers. Nevertheless, the methodology presented in this paper yielded the probability of distinguishing the risky drivers from good drivers. The main limitation of this study is that it only considered lane deviation in the driving manoeuvre. However, there are many other attributes that enable older people to remain proper lane position, such as visual search and the coordination of visual and motor movements. More research is needed to understand how drivers using visual information to control their steering and operate a car to main in proper land position. The influence from the environment and the interactions of the drivers on the road also needs to be examined. To combine eye tracking in the driving behaviour recording and evaluation would provide valuable information on how the drivers behave in relation to the vehicle control and to interact with the environment.

In conclusion, this study provides useful information how cognitive functions affect the ability of older drivers in maintaining lane position, and has identified some variables specifically associated with lane maintenance competencies. Based on these findings, simple substitution rules can be proposed for designing more efficient fitness-to-driver assessment. Specific measures of visual attention, spatial ability, executive functions, psychomotor speed and global cognitive functioning can be useful for predicting unsafe driving.

Appendix A: Study area and sections (Green dots show the GNSS tracked vehicle movement trajectory)



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4

Integrating Vehicle Trajectory and Eye Movement Analysis

CHAPTER 4 INTEGRATING VEHICLE TRAJECTORY AND EYE MOVEMENT ANALYSIS

This chapter is covered by the following papers (paper 5 and 6 of the thesis):

Sun, Q., Xia, J. C., Nadarajah, N., Falkmer, T., Foster, J., & Lee, H. (2016). Assessing drivers' visual-motor coordination using eye tracking, GNSS and GIS: a spatial turn in driving psychology. *Journal of Spatial Science*, 61(2), 299-316. doi:10.1080/14498596.2016.1149116 **(Paper 5)**

Sun, Q., Xia, J. C., Falkmer, T., & Lee, H. (2016). Investigating the Spatial Pattern of Older Drivers' Eye Fixation Behaviour and Associations with Their Visual Capacity. *Journal of Eye Movement Research, 9*(6). doi:10.16910/jemr.9.6.2 **(Paper 6)**

Previous chapters have defined the psycho-geoinformatics framework and computed precise vehicle movement trajectories. To understand the driving behaviours through driver-vehicle-environment interactions, eye movement tracking data can be used to investigate older drivers' visual search patterns and the visual-motor coordination in the further stages. This chapter integrates visual patterns with lane keeping data, the eye fixations of eye movement are geocoded and linked to the vehicle movement trajectory to represent the visual-motor coordination of drivers in a GIS platform. The techniques are described in paper 5. A spatial-temporal data model of visual-motor coordination (VMCM) is constructed. The integration extends the dimensions of eye movement tracking by adding the location of where each gaze originated and visualising the pattern of older drivers' oculomotor behaviour in a traffic environment. The methods of identifying and extracting eye fixations from eye tracking videos are introduced in paper 6.

Based on the geocoded eye fixation data, paper 6 will investigate older drivers' eye movement in various driving sections. And the associations between older drivers' visual capacity (processing speed, divided and selective attention) and their eye fixations corresponding to different driving manoeuvres. The influence of different driving scenarios on the associations between older drivers' eye movement and visual ability will be explored via both spatial and statistical analysis.

The assessment of visual-motor coordination will be conducted in the next chapters based on the visual-motor coordination data model in this chapter.

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Assessing drivers' visual-motor coordination using eye tracking, GNSS and GIS: a spatial turn in driving psychology

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ABSTRACT
Vehicle-driving in real traffic can be considered as a human-machine system involving not only the attribute of the vehicle movement but also the human visual perception, cognition and motion of the driver. The study of driving behaviours, therefore, would integrate information related to driver psychology, vehicle dynamics and road information in order to tackle research questions concerning driving safety. This paper describes a conceptual framework and an integrated GIS data model of a visual-motor coordination model (VMCM) to investigate drivers' driving behaviour via the combination of vision tracking and vehicle positioning. The eye tracker recorded eye fixations and duration on video images to exhibit the driver's visual search pattern and the traffic scenes. Real-time kinematic (RTK) post-processing of multi-GNSS (global navigation satellite system) tracking generated the vehicle movement trajectory at centimeter-level accuracy, which encompasses precise lateral positioning and speed control parameters of driving behaviours. The eye fixation data were then geocoded and linked to the vehicle movement trajectory to represent the VMCM on the GIS platform. An implementation prototype of the framework and the VMCM for a study of older drivers is presented in this paper. The spatial-temporal visualisation and statistical analysis based on the VMCM data-set allow for a greater insight into the inherent variability of older drivers' visual search and motor behaviours. The research framework has demonstrated a discriminant and ecologically valid approach in driving behaviour assessment, which can also be used in studies for other cohort populations with modified driving scenarios or experiment designs.

KEYWORDS
Driving behaviour; eye tracking; multi-GNSS RTK; visual-motor coordination model (VMCM)

1. Introduction

Driving is an important activity which underpins personal mobility and autonomy in our society. As an activity, driving involves neuropsychological capacities that are mediated by multiple areas of the brain, including visual, attentional, perceptual, cognitive and psycho-motor abilities (Anstey *et al*. 2005; Molnar *et al*. 2013). Vehicle-driving in real traffic can be

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considered as a human-machine system involving not only the attribute of the vehicle movement but also the human visual perception, cognition and motion of the driver (Hirokazu *et al*. 2010). The study of driving safety, therefore, would integrate information related to the driver, vehicle dynamics and road information in order to tackle research questions concerning driving safety and the driver's competence. Theorising about driving safety has suggested that errors associated with the inherent variability of human behaviour in drivers may be more important to vehicle crash causation than systematic errors which are attributable to the known limits of the human information-processing system (Ranney 1994). To date, many driving studies in the traffic safety literature have undertaken error assessments of driver behaviour. Few studies have been able to analyse the detailed individual visual-motor behaviours largely due to the lack of reliable data and available applications. Thus little is currently known about the inherent variability of drivers' visual-motor coordination involving the use of visual information to regulate their physical movements, particularly in naturalistic driving.

Several reviews of driving research have reached the same conclusion: when and where drivers look is of vital importance to driver safety (Underwood *et al*. 2003; Lee 2008). The information that a driver uses is predominantly visual (Sivak 1996). Crundall and Underwood (2011) examined the driving task as eminently suited to the application of eye-tracking methods: from navigation to anticipation of hazards, a wide range of specific driving behaviours are predominantly dependent on the optimal deployment of attention through overt eye movements. Gaze analysis based on eye tracking is a useful tool in understanding the visual behaviours underlying driving, such as the optimum fixation on the tangent point when negotiating a curve (Land & Lee 1994; MacDougall & Moore 2005). Since fixations are periods of relative stability during which the eyes focus on something in the visual scene, eye fixations most often reflect the fact that the brain is processing the fixated information (Crundall & Underwood 2011). Therefore, the use of eye-tracking measures has offered useful information to understand what strategies drivers employ to ensure a safe journey (Underwood *et al*. 2003).

The visual scene and the fixated information are tightly linked to driving manoeuvres and result in vehicle positions on the road. Donges (1978) earlier described that the driver's task in steering a vehicle is to extrapolate from the complex information of the driver's environment, where the vehicle's desired path served as guidance information, and at the same time to deduce the vehicle's actual motions related to its desired path, which serves as stabilisation information. Having received both types of information, the driver needs to intervene and coordinate in order to keep the vehicle's position continuously in its desired path. Donges (1978) further postulated that steering a vehicle is a control process with the desired path as forcing function (e.g. the road centreline) and the vehicle's actual position and attitude as output variables. Therefore, visual searching and steering behaviour should be tightly connected during driving (Chattington *et al*. 2007), thus the speed control and lane alignment would reflect the driver's capability to use visual information to control their physical movement, namely the capability of visual-motor coordination. Since vehicle speed and lane position are two of the many possible factors that lead to crashes on the road, especially on horizontal curves (Fitzsimmons *et al*. 2012), understanding the visual-motor coordination of drivers becomes important to promote safe driving, in particular for the cohort population of older drivers, who have been an area of high priority related to the increasing elderly population and higher involvement in car crashes (Lee 2003, Rakotonirainy *et al*. 2012), since ageing might cause functional decline in vision, motor skill and executive functioning, adversely affecting driving behaviours and performance (McKnight 1999; Fancello *et al*. 2013; Wood *et al*. 2013; Sun *et al*. 2016b).

Previously, on-road testing, computerised tasks, driving simulation and clinical measures (physical, visual, cognitive) have all been used to estimate driving competence (Odenheimer *et al*. 1994). While the on-road driving test is the universal 'criterion standard' for licensing new drivers and has been the most widely accepted method for determining driving competence, it generally lacks standardisation and data on reliability or validity (Odenheimer *et al*. 1994). Many on-road driving assessments have only a pass or fail outcome that was based on the driving evaluators' clinical reasoning and not on a quantifiable, numerical test score (Shechtman *et al*. 2010). As Porter and Whitton (2002) noted, a standardised on-road driving assessment with a quantifiable score using global positioning system (GPS) tracking would allow for greater objectivity in determining whether a driver is fit to drive. Using electronic data-collection methods was also recommended by Vlahodimitrakou *et al*., (2013) as a future effort for the DOS (Driving Observation Schedule) approach.

Nevertheless, on-road driving assessments have not scrutinised detailed individual vision and motor behaviour (such as speed and acceleration patterns in conjunction with visuospatial skills), which raises challenges and opportunities for researchers to develop appropriate applications and collect reliable data, so as to understand drivers' visual-motor coordination in different manoeuvres and investigate the underlying neuropsychological mechanisms. For such consideration, we hypothesise in this study that eye-tracking technology when coupled with vehicle movement tracking would provide a more meaningful assessment of individuals' driving behaviour than the standard on-road test. The goal of this research is to study visual-motor coordination in driving, thereby forming a bridge between the literature on visual searching and motor control in driving behaviour and psychology research.

In this paper we propose a conceptual framework for driving behaviour assessment and an integrated GIS data model of visual-motor coordination (VMCM) using the combination of eye movement tracking and GNSS vehicle movement tracking in naturalistic driving. The on-road driving was recorded and modelled using eye tracking synchronised with multi-GNSS (global navigation satellite system) tracking, and geographic information system (GIS) technologies. The eye-tracking equipment recorded eye fixation on video images to analyse the visual patterns of the driver (Figure 2), and multi-GNSS tracking and the real-time kinematic (RTK) postprocessing technique recorded and processed the precise vehicle movement trajectory, from which we detected lane-keeping and speed-control parameters of driving behaviours in GIS. Earlier in an explorative pedestrian navigation study, ETHZ (Kiefer *et al*. 2012) combined GPS positioning with a gaze-overlayed video, concerns about GPS accuracy presented in the data were addressed. Another similar study was a simulation study by Nakayasu *et al*. (2011). The current contribution is the first attempt in the research using precise surveying technology combined with eye tracking to study human behaviours in a naturalistic setting. We investigated the visual perception pattern of the drivers and linked it to their speed control and lane-keeping, and analysed the inherent variability in individuals and groups. The objectives of this paper are as follows:

- to set up a conceptual framework which combines vision tracking and vehicle positioning to investigate the visual-motor coordination of drivers;
- to develop an integrated GIS data model of visual-motor coordination (VMCM) to represent eye movement and vehicle movement during driving over space and time;
- to implement the above methods in a prototype: investigating the visual-motor coordination of roundabout manoeuvres in older drivers.

2. A conceptual framework for visual-motor coordination assessment in driving psychology

Our eyes and hands move in coordination to execute many everyday tasks; this coordination has been widely studied in psychology and cognitive science (Crawford *et al*. 2004). Weiten (2007) defined psychology as referring to the scientific study of behaviour and underlying mental and physiological processes in acquiring knowledge. While cognitive psychology focuses on higher mental process such as reasoning, information-processing, problem-solving and decision-making. James (1997) depicted three domains of driving behaviour in driving psychology: affective, cognitive, sensory-motor. When trying to understand automobile driving, it is important to realise that driving is a complex task that involves visual, motor and cognitive abilities. The vision (the sense of sight) and motor (movement using motor neurons) behaviours are integral for vehicle driving. Moreover driving involves higher mental abilities called executive functions that supervise these movements and decisions taken by the driver (Daigneault *et al*. 2002).

Safe driving is dependent on efficient coordination between vision and motor behaviours by the drivers, who execute the function of using visual information to regulate their physical movements. A number of types of in-vehicle equipment allow researchers to collect behaviour data on drivers' vison and motor activity, including the speed and position of the vehicle via GPS, and the driver's physiology and cognitive state by video camera or eye-tracker device. In this study, we combine eye tracking with precise vehicle positioning in order to tackle the visual-motor behaviour of drivers and discover the underlying psychological mechanisms.

2.1. Tracking eye movement in driving assessment

Eye tracking is a technique whereby an individual's eye movements are measured so that the researcher knows both where a person is looking at any given time and the sequence in which the eyes shift from one location to another (Poole & Ball 2006). Over the past decade, eye tracking with highly specialised eye wear equipment has been used to record detailed and accurate eye movements and visual direction in many psychology studies (Gilland 2008), and is especially widely used in the studies of spatial cognition, visual searching and reading. Kiefer and his colleagues from ETHZ studied self-localisation and human wayfinding using location-aware mobile eye tracking (Kiefer *et al*. 2012), which looked at the gazing patterns on the map to determine the participants' critical decision points. Analysis and recording of eye movements have also been an important tool in the investigation of the driver's visual awareness and driver behaviours in dynamic driving situations, particularly a driver's spatial cognition and fixation (Falkmer *et al*. 2008; Dukic & Broberg 2012). Eye tracking enables the researcher to collect quantitative data relating to the cognitive processes employed while undertaking any particular task such as turning; these processes may include the order and length of time a viewer directs their gaze at any particular object in a visual scene (Falkmer *et al*. 2008). Fixation is a central aspect of eye-tracking analyses, and can be defined as the length of time the eye ceases movement and remains set on any particular focal point (Green 2002). Since fixation is relatively 'stationary' eye behaviour, it allows eyes to focus the gaze on the objects being looked at, and to extract this information (Yang *et al*. 2012). Psychologically, it is during these fractions of a second that the brain is able to receive visual information which has been acquired from the focal point (Gilland 2008). Therefore, eye tracking may provide a resourceful data-set of a driver's visual pattern and can be used to evaluate driving behaviour and performance in a variety of driving manoeuvres (Mourant & Rockwell 1970; Victor 2005; Mars & Navarro 2012; Tivesten & Dozza 2014).

2.2. GPS/GNSS tracking vehicle movement in driving assessment

It can be comparatively low-cost and ecologically valid to assess driving behaviours using GPS tracking. GPS provides a feasible way to continuously measure the position, velocity and acceleration of a vehicle under typical driving conditions. In previous work, GPS or the combination of GPS plus video recording has provided a means to assess driving behaviours by tracking vehicle movements (Porter & Whitton 2002; Grengs *et al*. 2008; Naito *et al*. 2009; Cruz *et al*. 2013; Mudgal *et al*. 2014). A multi-GNSS (global navigation satellite system) receiver is a system able to calculate position, velocity and time by receiving satellite signals from multiple satellite systems. Currently, there are a number of GNSS systems operating, including GPS, GLONASS, Galileo, QZSS and Beidou (Kubo *et al*. 2014; Noomwongs *et al*. 2014). Using multiple satellite systems can achieve higher position accuracy with the increased number of satellites compared to GPS-only positioning, particularly in harsh environments where GPS-only positioning becomes difficult (Kubo *et al*. 2014; Noomwongs *et al*. 2014; Odolinski *et al*. 2014). Due to the nature of satellite signals, GNSS raw data contain errors and noises. The accuracy of GNSS data depends on many factors: the position of the satellites at the time the data were recorded, the journey through the layers of the atmosphere and many other sources contribute inaccuracies to satellite signals by the time they reach a receiver. The relative GNSS techniques can be introduced to improve the accuracy by minimising the effect of each error source, in the search for more realistic vehicle positions and trajectories (Sun *et al*. 2016a). The RTK (real-time kinematic) solution uses the known position of a base station to computethe moving receiver position based on code and carrier phase measurements. By having the base station over a known position, the errors produced by atmospheric effects can be estimated and referenced to the observed position of the receiver (El-Rabbany 2006). RTK post-processing is a further technique in that the algorithms applied to the raw data are essentially the same as would be applied in real time. Yet the post-processing can use more sophisticated approaches which usually result in more precise positioning (Awange & Kyalo Kiema 2013), which allows for relative positioning accuracies at the sub-meter to centimeter level. This can be achieved under most critical sections of a road network with a clear open-sky view (e.g. roundabouts, T-junctions, etc.). From there, precise vehicle speed, acceleration/deceleration and lateral position data can be generated for driving behaviour assessment.

2.3. Combining eye movement and vehicle movement in driving behaviour assessment

From the physics perspective, the driver's eye movement and the vehicle movement controlled by the driver seem distinctly different. The eyes typically move in discrete jumps (saccades) between fixations, producing irregular movement and a jagged trajectory (Çöltekin *et al*. 2014), while the vehicle moves continuously, producing a smooth trajectory. However, the two trajectories run alongside and are guided by the same process of the driver's visual searching of the surroundings. Geographically, eye movement and vehicle movement are co-located in space and time. Therefore, it is appropriate to investigate eye and vehicle movements using methods from trajectory analysis and visualisation. Where and how long and how often the driver gazed during driving are indicative of the visual perception strategy of the driver to keep the vehicle in an optimal lane position; as a matter of fact, cognitive resources involving visuospatial and motor coordination are constantly required for safe driving. To investigate the visual-motor coordination in driving, eye movement tracking can be integrated with vehicle movement tracking by simultaneously recording the two movements; the two movements can be then synchronised based on the recording frequency and time for further analysis. Figure 1 illustrates the conceptual framework of such an approach and explains the rationale in a psychological context.

The tracking of the vehicle trajectory should use precise and high-rate kinematic vehicle recording. In this study, the multi-GNSS RTK method is employed in the search for precise vehicle movement trajectories and accurate positioning, and importantly the precise time reference for eye movements. Based on the time recorded in both systems, the eye-tracking data can be synchronised with the GNSS vehicle recording. The eye movement data, including the fixation objects and duration of visual searching behaviour, can be then geo-coded using the vehicle position reference, and linked to the parameters of the vehicle movement trajectory, such as speed, acceleration/deceleration and vehicle lateral position in relation to the road centreline. Such a data model contains spatial and temporal attributes for both visual pattern and vehicle movement, while the latter reflects how the driver controlled the steering wheel and brake and accelerator pedals. The streamlining of the data integration reveals the cognitive processes of the driver: how the driver searched and processed the surrounding information and made decisions, and eventually executed the physical movements in the vehicle. An integrated data model derived from this framework can be accomplished on a GIS platform.

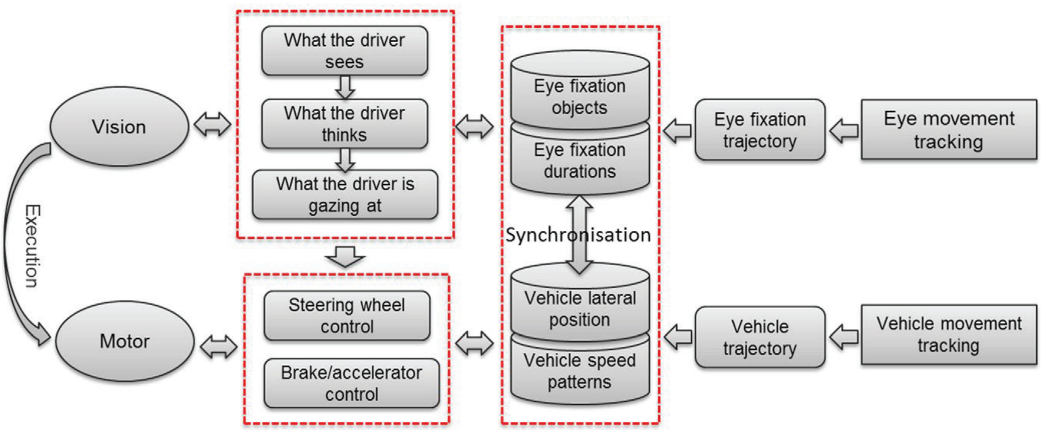

Figure 1. The conceptual framework of visual-motor coordination assessment in a psychological context.

2.4. Developing a visual-motor coordination model (VMCM) for driving behaviour assessment in GIS

In essence, GIS data models allow the user to create a representation of how the world looks (Goodchild 1992), and a good model requires sound theories, reasonable estimates of parameters, and supporting data (Bian 2004). Referring to Li *et al*. (2014), we defined a fixation-driven spatial-temporal data model which integrates eye movement data and vehicle movement data, namely the visual-motor coordination model (VMCM) (Figure 2). The VMCM has the following merits: (1) it segments and integrates the complex eye movement trajectory and vehicle movement trajectory into eye fixation-based events; (2) it exhibits spatial distribution and temporal change of vision and motor behaviours of the driver; (3) it describes essential parameters of visual searching and motor behaviours of the driver; (4) it can be used for analysing cognitive reasons behind the spatiotemporal changes; (5) it uses real-time observation data; and (6) it can also simulate future driving manoeuvres.

Figure 2 displays the development and the main parameters of VMCM. The eye fixation frames were extracted from the eye-tracking video and analysed based on a predefined fixation coding matrix, which classifies the gazing behaviour into the categories of direction, distance, background and the object, and whether the gazing is traffic-relevant. The processed vehicle movement trajectory containing speed and acceleration parameters was overlaid with other traffic data to calculate the lane deviations from the desired path (e.g. road centrelines) and classify the stages of the manoeuvre. The two datasets were then integrated using the participant's ID and the time fields; since an eye fixation is a period of eye movement, the visual-motor coordination during this period, e.g. Fixation_{i+1}, can be inspected from the vehicle dynamics between the start time at Vehicle_j to the end time at Vehicle_{j+1}. The (x, y) coordinates of the start time at Vehicle_j show the point from where the eye fixation occurred, and the parameters of the Vehicle_{j+1} refer to the results of the motor behaviour of the driver. The actual VMCM data can be overlaid with other environment and transport information on the GIS platform and, by visualising and analysing the

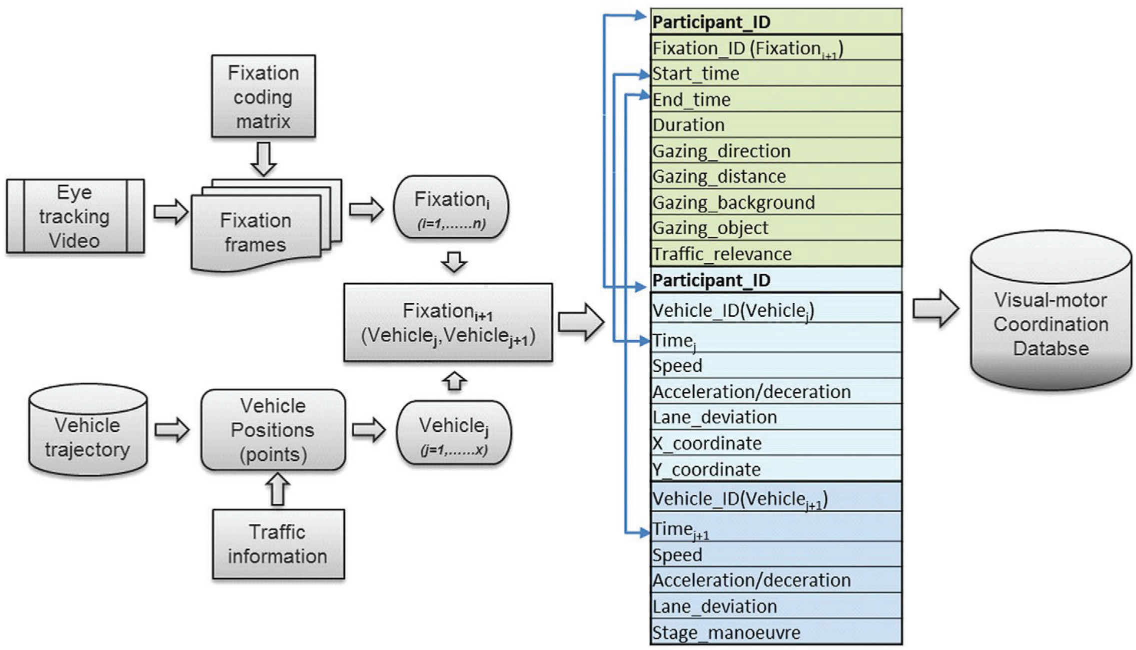

Figure 2. Fixation-driven spatial-temporal data model of visual-motor coordination model (VMCM).

spatial-temporal patterns of the VMCM data, the characteristics of the driver's visual-motor coordination can be investigated in depth. In the next section we use older drivers as a focus group to implement the framework and the VMCM.

3. An implementation prototype of the framework: older drivers' visual-motor coordination in a U-turn manoeuvre at a roundabout

3.1. Participants and recruitment

Previous studies found that older drivers were over-represented in angle collisions, and crashes at intersections, turning and changing lanes (McGwin 1999; Clarke *et al*. 2010; Marmeleira *et al*. 2012). These findings indicate that the age-related decline in particular functions leads to unsafe driving (Dobbs *et al*. 1998; McKnight 1999; Fancello *et al*. 2013; Wood *et al*. 2013). Even so, not all older drivers are unsafe; the statistics don't reflect the driving abilities of individuals; age itself is not a predictor of fitness for driving (Anstey *et al*. 2005). Worldwide, the ageing population has brought the issue of older drivers into a sharper focus. While there is a strong emphasis around the world on older adults maintaining their mobility for as long as possible, the challenge is to develop appropriate evaluation methods to identify those older drivers with hazardous driving behaviours and to provide intervention as early as possible (Lee 2003). Since most driving studies of older adults have looked at error assessments of drivers' behaviours, there has been little research with respect to their vison and motor behaviour and coordination, which can be the primary concern in age-related functional decline in elderly drivers. In this case study, we set up an on-road driving experiment with older drivers and created a VMCM data-set to investigate their visual-motor coordination behaviour.

Three female and two male older drivers aged from 60 to 79 (mean = 67, SD = 7.2) participated in the assessment. The participants were conscripted from clubs and a retirement village. They first received a participant information form indicating the procedure of the experiment. The benefit of participation is gaining knowledge on driving behaviour; they also received a small gift as compensation. The eligibility for participation also included holding a valid Australian driver's licence and having an insured vehicle, driving at least 3 or 4 times a week, and having no mental or physical issues affecting driving. Before the assessment, all subjects provided informed consent for participation in compliance with the ethics requirements of the Curtin University HREC (Human Research Ethics Committee), followed by an eye acuity check and the Mini-Mental State Examination (MMSE) to ensure their basic vison and motor fitness for on-road driving. A mini-survey on demographics and driving habits was also conducted prior to the assessment.

3.2. On-road driving test and data collection

The driving route was chosen around the campus of Curtin University in Perth, Australia, approximately 1.5 km radius distance from the Curtin GNSS base station. This enables cost-effective RTK postprocessing techniques for precise vehicle movement data using the base station reference data. The primary purpose of the on-road driving assessment was to track the driver's visual-motor coordination, with the focus on the complex roundabout manoeuvre in this implementation. This was achieved by simultaneously recording the driver's eye fixation and the vehicle movement trajectory when driving round a roundabout.

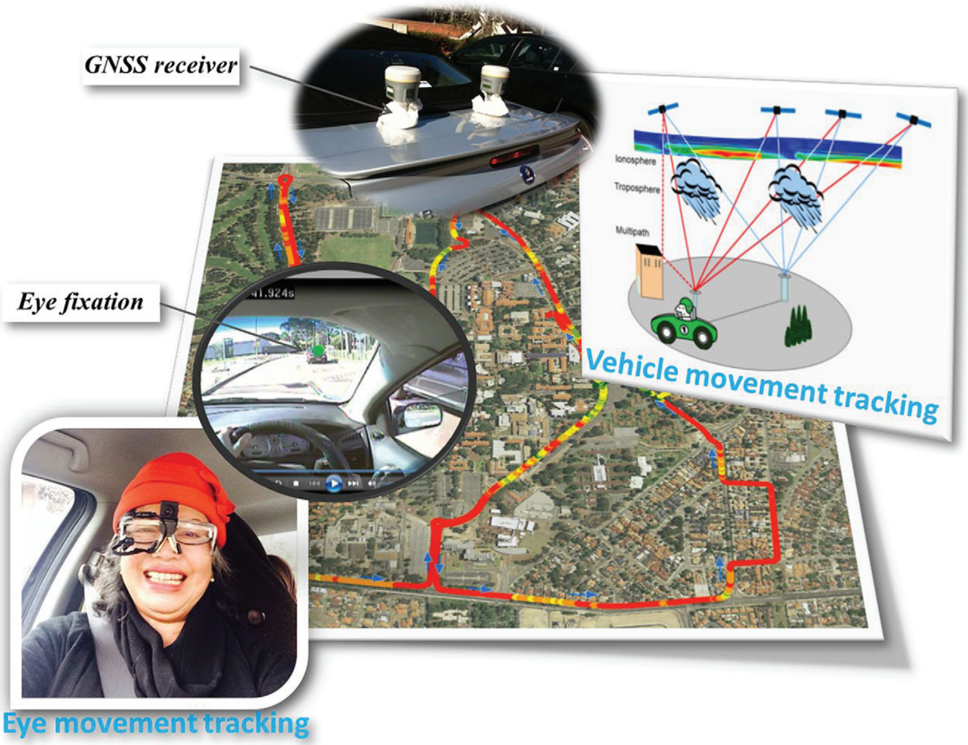

Figure 3. Apparatus and on-road driving setting.

During the on-road driving test, each participant was asked to drive their own car with the eye tracker (Arrington Viewpoint^{TM}) mounted on her/his head (Figure 3). The eye tracker is infrared, video-based with a 60 Hz frequency. A 16-point calibration procedure was carried out prior to the on-road test; the accuracy of the gaze position can be resolved to 0.25–1.0° approximately. Corrected vision was required and the eye tracker can be worn with glasses when necessary. The eye tracker consists of a pair of optics with two cameras mounted on it: eye and scene cameras. The eye camera measures gaze behaviour and the scene camera captures the scene in front of the participant. The eye and scene images are superimposed by the eye-tracking system and give real-time information about where in the environment the line-of-gaze is located. Data collected, including number of fixations and fixation durations, a proxy for the driver's attention to and reaction to external stimuli from the environment, are captured by the eye-tracker system. These processes may include the order and length of time a driver directs their gaze at any particular object in a visual scene, as well as the visual patterns the driver utilises while performing any particular driving task (Falkmer *et al*. 2008).

The sequential video clips of driver's view and eye fixation objects (the green dots) in Figure 4 show the visual pattern of one driver on the roundabout. From left to right and top to bottom, we categorise the roundabout manoeuvre into four stages, ① before roundabout; ② entering roundabout; ③ in roundabout; and ④ exiting. The driver looked at the passing cars before and entering the roundabout, looked frequently at the edge line of the curves and looked further when exiting in order to coordinate the vehicle positions. The edge lines of curves play a critical role in the visual-motor strategy of steering (Land & Lee 1994; Coutton-Jean *et al*. 2009). To analyse the data and capture the eye movement attributes, the video footage was divided frame by frame and viewed in fixation clusters. Each cluster was analysed

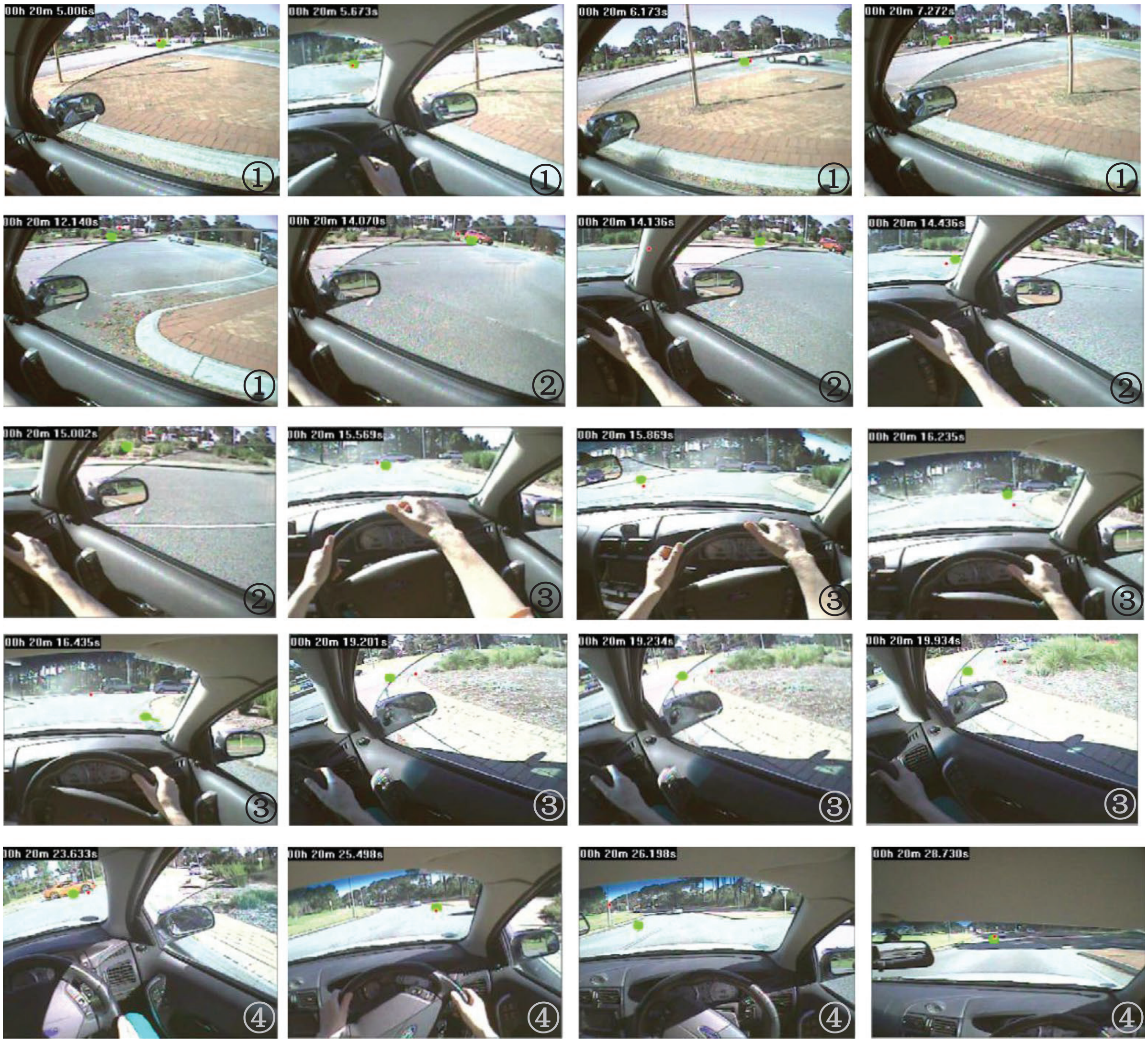

Figure 4. Video clips of one driver's view and eye fixation objects recorded by eye tracker (left to right and top to bottom): the sequence of eye movement when taking a U-turn through a roundabout. The green dots refer to the recorded fixation locations of the right eye pupil. The video clips show different manoeuvre stages: ① before roundabout; ② entering roundabout; ③ on roundabout; ④ exiting.

and the duration of the fixation was noted. Each fixation was then labelled with a code from two categories, the background and the exact object the driver gazed at.

A pair of Trimble R10 GNSS receivers was mounted on each participant's car roof to record the vehicle movement trajectory (Figure 3). The receivers are able to track multi-GNSS systems beyond the GPS-only approach; this is essential for recording vehicle movements in an urban residential area when precise vehicle positioning and the smoothest trajectory are required. The tracking configuration of the Trimble R10 receivers was set up at a frequency of 10 Hz in order to record the car positions at a high resolution. The RTK postprocessing technique was used to achieve centimetre- to decimetre-level accuracy horizontally by minimising the effect of error sources transmitted between the satellites and the GNSS receivers (Sun *et al*. 2016a). The post-processed data were then mapped to calculate the lateral position, speed and acceleration. Figure 5 shows one diver's speed control (left) and lane-keeping (right) at the roundabout manoeuvre: slowing down to stop when approaching the roundabout, keeping a moderate speed on the roundabout and accelerating to exit the

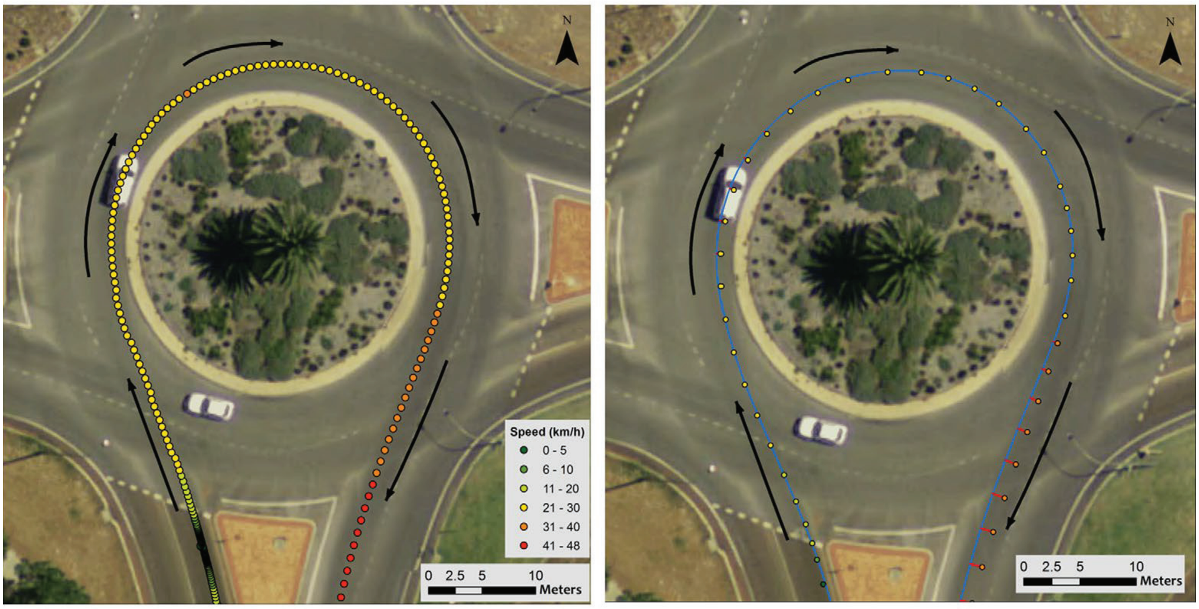

Figure 5. Patterns of speed control (left) and lane-keeping (right) at a roundabout based on the multi-GNSS tracking vehicle movement trajectory. The blue line in the right map is the road centreline used as benchmark (the desirable path) to calculate the lane deviation. The accuracy of the underneath orthoimagery is +/− 5 m horizontally.

roundabout; the perpendicular red lines between the car position and the road centreline generated in GIS demonstrate the lane deviations of the manoeuvre in reference to the road centreline: in the case of this driver, the exit of the roundabout gave more lane deviation, followed by the stage when entering into the roundabout (west side of the roundabout).

The eye-tracking data including the fixation objects and duration of visual searching behaviour can be geo-coded using the vehicle position reference, and linked to the parameters on vehicle movement trajectory, such as speed, acceleration/deceleration and vehicle lateral position relative to the road centreline (Table 1). The geocoding was carried out using the synchronised temporal attribute from both datasets: the resultant data include spatial and temporal attributes for both visual pattern and vehicle movement, while the latter reflects how the driver controlled the steering wheel and brake and accelerator pedals. The geocoding was accomplished using GIS software (ArcMap 2012). The geocoding positioned eye fixation in the environment by adding the vehicle location to the drivers' viewpoints, and the vehicle speed and acceleration for vehicle control information were appended to the driver's oculomotor behaviour. Although the eye tracking has a higher frequency (60 Hz) than the vehicle tracking (10 Hz), the speed and acceleration of the vehicle in 0.1-s intervals should remain very closely monitored; therefore, little spatial uncertainty would be introduced into the VMCM data-set.

3.3. Spatial-temporal visualisation of the visual-motor coordination model (VMCM) in individual drivers

The five older drivers' roundabout manoeuvres were analysed on the GIS platform. The core data-set of VMCM combining both the eye movement behaviours and speed control and lane deviation was overlaid with road centrelines and orthoimagery in order to visualise the spatial-temporal patterns of visual-motor coordination in individual drivers.

Table 1. Sample data-set of VMCM in GIS.

FID	Partici-pant_ID	Fixation_no	Duration (second)	Gazing direction	Gazing distance	Back-ground	Object	Traffic	Speed (km/h)	Acceleration/ deceleration (m/s)	Lane Devia-tion (cm)	Stages at roundabout	*X*_coordi-nate	*Y*_ coordi-nate
1	9	4082	0.2999	Left	1	126	2891	1	25.28	7	42	Before	394830.7	6459224
2	9	4084	0.2001	Left	1	126	2892	2	24.65	6.9	40	In	394830.6	6459224
3	9	4086	1.5992	Left	3	126	259	1	24.01	6.7	36	In	394830.5	6459224
4	9	4088	0.1666	Middle	2	126	243	2	23.25	6.5	30	In	394830.3	6459225
5	9	4090	0.2332	Right	2	129	2892	2	23.01	6.4	25	In	394830.2	6459226
6	9	4092	0.1667	Right	1	126	2892	2	23	6.4	22	In	394829.9	6459226

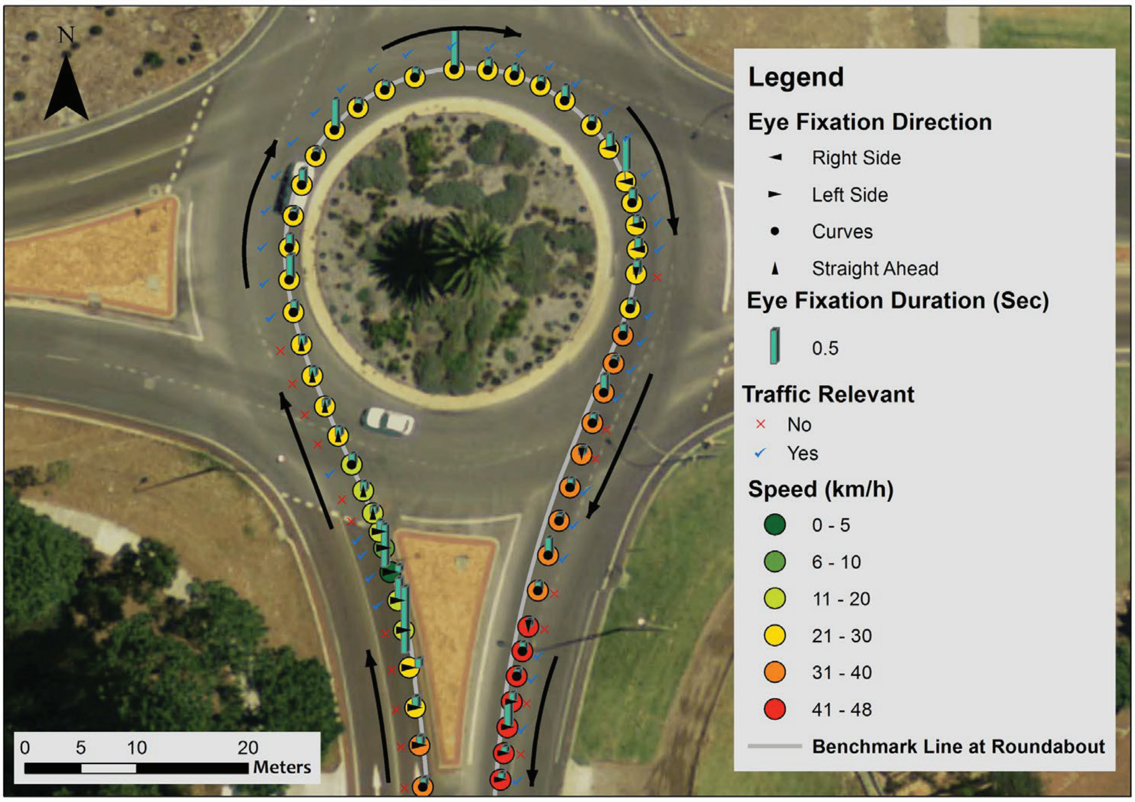

Figure 6. Spatial-temporal visualisation of VMCM data-set at U-turn roundabout manoeuvre by an older driver.

As shown in Figure 6, one driver smoothly decelerated when approaching the roundabout from 31–40 km/h to 21–30 km/h then to 11–20 km/h to prepare to enter the roundabout and steadily accelerated through the roundabout and while exiting the roundabout to 41–48 km/h. Eye-tracking data show that the driver looked right and looked into the curve while preparing to enter the roundabout, specifically at line markings, and other objects. While travelling through the roundabout the participant primarily looked into the curve, the right rear view mirror, trees/shrubs, and line markings. When exiting the roundabout the participant looked right at the right rear view mirror, looked straight ahead, looked into the curve and line markings, and looked to the left side to align the vehicle position. The participant showed adequate preparation while entering the roundabout and active scanning patterns while travelling through the roundabout, with the majority of fixations being traffic-relevant objects. The visualisation of the spatial-temporal patterns of visual-motor coordination will give more insight into the understanding of how the drivers used visual information to control their physical movement in particular manoeuvres, in order to identify hazardous behaviours, and provide intervention to the risky drivers.

3.4. Statistical analysis of thevisual-motor coordination model (VMCM) in older drivers

To further investigate the characteristics of older drivers' visual-motor coordination, Figure 7 statistically demonstrates the inherent variability of visual-motor coordination through roundabout manoeuvres among the five older drivers. The left graph shows the

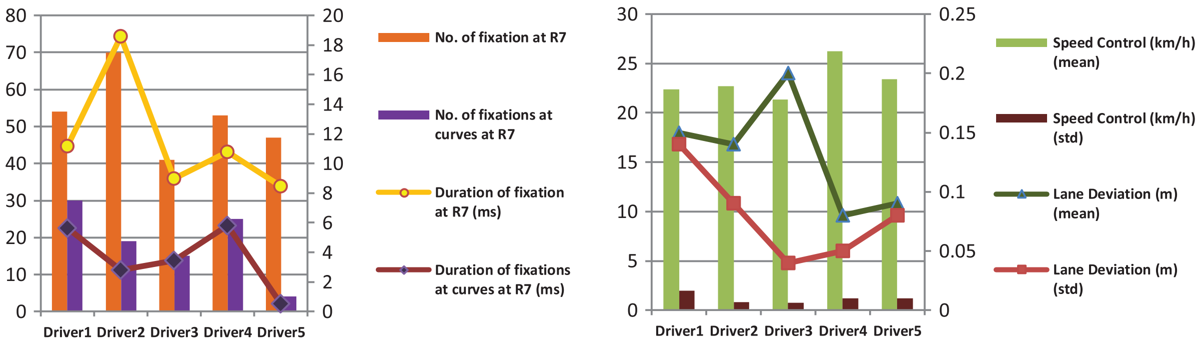

Figure 7. Visual-motor coordination at roundabout manoeuvres among older drivers (left: the duration and numbers of fixations in total and at curves; right: the mean and std of speed control and lane deviation).

duration and frequency of fixations within individual drivers, which refers to their visual searching strategies; the right plots their motor behaviour (speed control and lane keeping) through the mean and std (standard deviation) of vehicle speed and lane deviation from the desired path. As can be seen, Driver4 had the most frequent eye fixation and longest duration at roundabout curves, presented the lowest lane deviation, and slightly higher mean speed. Driver3 had the least frequent eye fixation overall but average eye fixation and duration at roundabout curves; this participant demonstrated the highest lane deviation but the lowest std value of lane deviation, and the slowest mean speed. Other drivers also used different strategies of visual-motor coordination when negotiating roundabouts. The eye fixation at roundabout curves seems associated with lane-keeping and speed control, but there might be other conditions affecting driving performance at roundabouts.

The descriptive statistical analysis in this case study shows that older drivers with a better visual searching strategy achieved slightly less lane deviation and higher mean speed at roundabout manoeuvres. The visualisation of spatial-temporal patterns of visual-motor coordination when entering, passing and exiting the roundabout gives more insight into the understanding of how the drivers used visual information to control their physical movement in particular manoeuvres. The findings of this study indicated that those individuals at inflated risk of road crashes could be identified using the combination of eye tracking and vehicle movement tracking. Such an approach is able to detect the detailed behaviours and subtle variations between individuals which are hard to obtain by other methods, such as observation by instructors, clinical assessments or driving simulations, etc.

In summary, this case study showed that combining eye tracking and precise vehicle movement tracking can detect variations in the visual-motor coordination in older drivers. The combination also allows for the determination of age-related driving differences and inherent variability of individuals, which has discriminant validity in older adults. This prototype has also presented a cost-effective and ecologically valid approach in driving behaviour assessment, which can be used in studies with a larger sample size in the future. Further advanced statistical analysis methods, such as DFA (discriminant function analysis), can be used to predict variables affecting visual-motor coordination in older adults with higher discriminant validity.

4. Discussion and conclusions

The behaviour of drivers is one of the main subjects of safety research; much attention has been focused on the perception and cognition of drivers. Based on the assumption that more detailed but comprehensive individual data are needed for understanding the underlying psychological mechanisms of driving behaviours, this paper presented a conceptual framework and a GIS data model (VMCM) for investigating drivers' visual-motor coordination in naturalistic driving using some advanced spatial tracking technologies. We simultaneously recorded drivers' eye movements and precise vehicle movements, and linked both datasets via a GIS platform using sequential time and position information in order to obtain complete attributes of vision and motor behaviours of individual drivers. We attempted to investigate how visual perceptual information is processed with respect to changes in driving patterns due to age or different cognitive conditions, and how these factors altered driving behaviours and vehicle manoeuvres. To address this question we set up a case study to collect detailed individual data to compute the VMCM, and investigated age-related changes in visual exploratory and driving behaviours associated with visual-motor coordination. The prototype implementation of these methods demonstrates how this approach can be used to tackle research questions concerning driving-related spatial problem-solving in a novel way. The implications for visual-motor coordination modelling are evaluated via the spatial-temporal visualisation and statistical analysis of the VMCM.

The framework presented an innovative approach to measure human mobility by taking advantage of high-frequency tracking of eye movement and vehicle kinematics, and spatial statistical analysis. The complexity of the datasets and their integration have raised concerns about the data accuracy and uncertainty, such as that GNSS has variable performance under certain conditions, and the eye-tracking analysis model also has uncertainty – all of which will impact on the overall performance achievable. To mitigate the accuracy issues and reconcile any uncertainty introduced in the datasets, for data collection the same frequency of eye tracking and vehicle tracking can be used and synchronised in real time, so as to mininise the spatial uncertainty when geocoding. For data analysis, great caution needs to be taken when processing the raw data: for example, the noise in GNSS data should be filtered out and modified; a calibration parameter can be used when determining the objects on eye-tracking video frames.

As an implementation prototype, we only have a small sample size, which limited the data analysis on visual-motor coordination and for investigating the associations between driving behaviour and cognitive abilities. More proper correlation analysis can be performed using a large-scale experiment. In addition, more qualitative aspects of driver behaviour assessment can be obtained and integrated with quantitative results, such as conducting in-depth interviews with participants and clinical driving observations to gather information on drivers' driving habits as supplementary attributes.

To conclude, our attempt to investigate the visual-motor coordination behaviour of drivers in a naturalistic (rather than laboratory) setting successfully collected detailed visual and vehicle control data for individuals using eye tracking and vehicle movement positioning. The advanced surveying technology (multi-GNSS RTK) that was used ensures the precision of vehicle kinematic positions, which were linked to the visual search behaviour fixation by fixation (or, in other words, the visual behaviour was geo-coded, integrated with the vehicle movements). The GIS platform then provides the analytical and visualising tools to examine the spatial-temporal patterns of the data. This approach offers more insight into how the drivers used visual information to control their physical movement in particular manoeuvres. We are able to analyse not only what a driver is viewing in their surroundings and from where, but also how gazing behaviour is associated with vehicle control. The statistical analysis undertaken reveals the relationship between visual searching and driving manoeuvres, and differences between individuals or groups. The preliminary findings obtained suggest that variability in the performance of older drivers may stem from age-related declines in cognitive functioning. It is important that further research effort is directed toward understanding in greater detail the cognitive behavioural variability in drivers using more samples and cognitive data. Moreover, the findings obtained in the current study underline the potential value of studies in different populations into particular driving or traffic situations, such as how distraction affects the visual-motor coordination of the driver.

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Investigating the Spatial Pattern of Older Drivers' Eye Fixation Behaviour and Associations with Their Visual Capacity

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Visual capacity generally declines as people age, yet its impact on the visual search patterns along sections of different road during actual driving still remains undocumented. This on-road driving study simultaneously recorded 30 older drivers' eye movement and precise vehicle movement trajectories. The vehicle positions were linked to every identified eye fixation for each individual driver, so that the locations of the driver's gaze origin in geo-spatial coordinates were obtained. Spatial distribution pattern of drivers' eye fixations were then mapped and analysed. In addition, the associations between older drivers' visual capacity (processing speed, divided and selective attention) and their eye fixation patterns in various driving manoeuvres were investigated. The results indicate that driving scenarios have a significant impact on older drivers' visual patterns. Older drivers performed more frequent eye fixations at roundabouts, while they tended to fixate on certain objects for longer periods during straight road driving. The key findings show that the processing speed and divided attention of older drivers were associated with their eye fixations at complex right-turns; drivers with a lower capacity in selective attention performed less frequent eye fixations at roundabouts. This study has also demonstrated that visualisation and spatial statistics are effective and intuitive approaches to eye movement analysis.

Keywords: Eye fixation, visual attention, older drivers, driving manoeuvres, GIS (Geographic Information System)

Introduction

Background

Older drivers have one of the highest vehicle crash rates in comparison with other population groups, largely due to the functional effects of the accumulation, and progression of age-related deterioration in visual, cognitive and motor conditions that impact on fitness to drive (Molnar et al., 2007). Numerous studies indicate that the predominant casualty crash type for older drivers involved complex road environments or high cognitive workload situations (Charlton et al., 2005). Statistically, older drivers are less likely to be involved in crashes caused by fatigue, high speed, weather condition, or alcohol than younger drivers. Conversely, older drivers are more likely to be involved in crashes in certain scenarios, such as manoeuvres through intersections; failure to yield the right of way; failure to identify hazards, or to heed stop signs/traffic signals; and problems involving turning and changing lanes (Clarke, Ward, Bartle, & Truman, 2010; Marmeleira, Ferreira, Melo, & Godinho, 2012; McGwin & Brown, 1999).

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The decline in visual capacity appears directly related to the above crash scenarios in older drivers (Wood & Owsley, 2014). Several changes occur in the human eye with age making the visual system operate less efficiently. Visual search inefficiency may prevent the driver's attention returning quickly to the already searched locations (Bedard et al., 2006). Driving in traffic typically requires the ability to differentiate between relevant and irrelevant information in often complex and challenging visual scenes, where potential hazards may occur in any part or in direction of the visual field (Lees, Cosman, Lee, Fricke, & Rizzo, 2010). For older adults, their mental and physical condition and their ability to concentrate behind the wheel deteriorate (Fancello, Pinna, & Fadda, 2013). Even in the normal ageing process there is a decline in various aspects of visual attention including selective attention, divided attention, sustained attention, and switching attention (Glisky, 2007). For example, the ability to divide their attention between a central location and the periphery experiences a sharp decline with ageing (Boot, Stothart, & Charness, 2014). Smither, Mouloua et al. (2004) stressed that it would take an older driver 1.5 to 1.7 times longer on average than a younger driver to scan for information. Apparently, for older drivers, visual attention ability is an important factor associated with accident risk (B. Sekuler, 2000; C. Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Richardson & Marottoli, 2003). Older people decline in visual capacity at different rates and in different ways, however, the impact of these declines on visual search in driving remains undocumented. In addition, how older drivers' oculomotion responds to the different driving manoeuvres hasn't been fully explored owing to the difficulty in obtaining quantitative measurement of the drivers' behaviours, especially in naturalistic settings.

Previous studies have shown that drivers' physical and cognitive conditions, and driving habits result in different behaviours and performance on road at both the individual and group levels (Rapoport et al., 2013; Sagberg, Selpi, Bianchi Piccinini, & Engstrom, 2015). The investigation into the eye movement pattern of older drivers would help understand the characteristics of the oculomotor behaviour in this age cohort. At the individual level, such investigation may offer early detection of risky behaviour, such as excessive or insufficient gazing in certain scenarios, which can cause missed visual information (Nakayasu, Miyoshi, Kondo, Aoki, & Patterson, 2011). Underwood et al. (2003) found different sequences of visual patterns between experienced and novice drivers, suggesting that it may be of benefit to provide suitable intervention on visual search strategies for novice drivers. Konstantopoulos et al. (2012) investigated whether showing people where to look can provide information on why it is important to look in these locations. Such training interventions would have a great chance of improving visual processing, situational awareness, and ultimately driving behaviour. Thus, it is important to investigate the visual search behaviour in older drivers and identify the spatial distribution patterns.

To date, the common trends in eye movement research include attempts at understanding gaze patterns, e.g. where we look at and for how long (Schütz, Braun, & Gegenfurtner, 2011). For driving, visual activity is vital for steering since it provides spatial-temporal information about the desired travel path and general movement within the environment (A. S. Cohen & Studach, 1977; Cooper, Medeiros-Ward, & Strayer, 2013; Lee, 2008; Underwood et al., 2003). Gaze position measures can be a valuable source of information in cognitive studies of driving (Lappi & Lehtonen, 2013). For example, a landmark study by Land and Lee (1994) found that the tangent point as a guiding gaze fixation location is relevant for steering in curve driving. Wann and Swapp (2000) added explanation for the future path model, pointed out that gaze behavior during locomotion is to fixate points on the road ahead. Lappi (2013) drew a conclusion based on three experiments, that the drivers fixated on target points on the future path beyond the tangent point, and pursuit eye movements were used to track the points. The types of guiding and look-ahead fixations were reported in Lehtonen et al. (2013). Despite that, few studies have examined gaze patterns from the perceivers' positions, rather the locations eyes fixated on as recorded by the eye tracking device. In fact, *from where* and *when* the driver was fixating at a given object in driving are equally important as this allows human oculomotor behaviour to be revealed. Lappi and Lehtonen (2013) related eye movements to the vehicle trajectory, and presented the first on-road data where gaze stability was analyzed quantitatively at the level of individual fixations. Also by locating visual information, Lehtonen and Lappi (2014) continued to provide evidence for the effect of experience on visual scanning during different curve driving.

Thanks to the advanced tracking technologies and analytical applications, it is possible to record high resolution vehicle movement data, and further link the eye movements with the vehicle trajectories to demonstrate the spatial variation of the drivers' visual behaviour. Such spatial patterns may be related to the older drivers' visual capacity to scrutinize human oculomotor behavior responding to cognitive workloads, which may in turn be utilized in safety studies and to develop intervention strategies for older drivers (Hamel et al., 2013). To achieve this, drivers' eye movement using an eye tracker and precise high-resolution vehicle trajectories using an advanced GNSS (Global Navigation Satellite System) were synchronously recorded. The eye fixations were analysed and geo-coded in a GIS (Geography Information System) environment with reference to the vehicle positions, so that every eye fixation was given a (x, y) coordinate of the driver's origin of view. Individual drivers' oculomotor path can be then recreated in GIS and overlaid with other spatial information, such as the driving route. In addition, drivers' visual attention ability (processing speed, divided and selective attention) was evaluated using UFOV® (Useful Field of View) test. Spatial and statistical analysis were applied to investigate the gaze pattern and the correlations with older drivers' visual capacity.

Research Aim

Eye movement measures provide useful information to investigate behavioral performance. This study introduces a new measurement of driving behaviour and examine eye fixations across a variety of driving tasks involving different visual and cognitive workloads. Tsai and Viirre et al. (2007) stressed that the attention capacity is limited and task dependent, so the oculomotor range is an important measure of driving performance.

While a great deal is known about the objects which the eyes fixate on and the temporal attributes of the fixations, less is known about spatial pattern of the entire oculomotor behavior during various driving manoeuvres. Considering that eye movement reflects changes in attention states, this investigation focuses on the effects of driving tasks on the oculomotor behavior for 30 older drivers. Going one step further from traditional eye movement study in driving, this paper extends the dimensions of eye movement tracking by recording from where (the vehicle positions) the driver started gazing at a certain object. This approach enables various spatial analysis and interpretation to be used in the current investigation.

This study is therefore aiming to provide insight into the oculomotor behaviour of older drivers by segmenting the driving route into different scenarios and understanding the impact of the visual capacity decline on their visual searching patterns. Additionally, eye fixation behaviour patterns in older drivers that could potentially lead to road crashes may be observed. Future research on older drivers' eye movement in relation to driving behaviours, as well as the shortcomings of the study are discussed in this paper.

Methods

Subjects

In this paper, 30 participants aged from 60 to 80 (mean = 68.7, SD = 5.6) were selected as research subjects from the original PhD research project (Sun, Xia, Foster, Falkmer, & Lee, 2016) with 50 older drivers. The selection was based on the completeness of analysed eye tracking and vehicle tracking data. The eligibility of participation also included: holding a valid driver license and having an insured vehicle, driving at least 3-4 times a week, having no known mental and physical issues affecting driving, and no sedative medication taken prior to the assessment. Before the assessment, all subjects provided informed consent for participation in compliance with ethics requirements from the University Human Research Ethics Committee. All participants passed screening on visual acuity, and on Mini-Mental State Examination (MMSE) to smooth out any mental and cognitive functional deficits which would affect normal on-road driving.

Data Collections

Visual Capacity Test. This study utilized a PC version of UFOV® (Useful Field of View) test to evaluate the performance of processing speed, divided attention, and selective attention of subjects (Classen, Wang, Crizzle, Winter, & Lanford, 2013; Wood & Owsley, 2014). The test determines speed of processing abilities quantified by display speed threshold for central target identification alone in Subtest One, central target identification with peripheral target localization in Subtest Two, and central target identification with peripheral target localization in the presence of distractors in Subtest Three (Ball, Edwards, & Ross, 2007). Scores were expressed in milliseconds, representing the exposure duration required for a participant to perform. For each subtests, possible scores range from 13 ms to 500 ms. Lower scores correspond with better visual capacity. Edwards and Ross et al. (2006) stated that UFOV is a better predictor of vision problems in everyday life than standard visual field assessments, which detect sensory losses across the visual field. In addition, an association was found between low UFOV scores and speed processing deficits in older adults; UFOV performance also predicts important indices of mobility (Anstey, Wood, Lord, & Walker, 2005; Ball et al., 2007; Wood & Owsley, 2014). Since the UFOV test relies on the integrity of visual sensory information as well as the subject's higher order processing abilities (Cynthia Owsley, Ball, & Keeton, 1995), it demonstrates reliable data regarding older adults' visual capacity.

On-road Driving and Eye Tracking. The on-road driving experiments simultaneously recorded the vehicle movement and the driver's eye movement (Sun, Xia, Nadarajah, et al., 2016). Participants were instructed to drive their own car through the campus of Curtin University in Perth, Australia, for about 10 km distance under normal traffic avoiding peak hours. The on-road driving lasted about half an hour. The driving route (Figure 6) contains a series of roundabouts and intersections.

A head-mounted Arrington Viewpoint™ eye tracker (Figure 1) was used to record the eye movements of each participant during driving. The eye tracker consists of an eye camera and a scene camera, capturing gaze behavior and the scene in front of the driver respectively. The eye and scene images are superimposed by the eye tracking system and give real-time information about when and where in the environment line-of-gaze is located. The recording frequency is 60 Hz. A 16-point calibration procedure was carried out prior to the driving experiment. The eye tracker's precision can be resolved to 0.25-0.5 degrees of the visual arc, when the recording resolution is 0.15 degrees in the visual field (Arrington, 2010).

Figure 1. Arrington viewpoint head-mounted eye tracker.

The vehicle trajectory of each participant was recorded using a professional-grade GNSS receiver (Trimble R10) with 10 Hz tracking rates. The receiver was installed and initialized on the participant's car roof prior to the on-road driving to warm up. Real-time kinematic (RTK) positioning technique was used to obtain precise vehicle trajectories and with methods described in detail in earlier publications (Sun et al., 2017; Sun, Xia, Foster, et al., 2016).

Data Analysis and Visualisation

Segmentation of Driving Manoeuvres. We created a set of 16 driving scenarios (see Figure 6) including two sections of left-turn, three sections of right-turn, seven sections of roundabouts and in between four sections of straight road driving. The driver workload varies in the different sections. For example, cognitive resources involving visuospatial and motor coordination are required for making turns (Schweizer et al., 2013). Driving through intersections and roundabouts thus requires precision in visual-motor coordination to complete the turning manoeuvre. This skill can sometimes be challenging for older adults. The curvature of roads plus moving cars in different directions places high demands on perception, attention, orientation and motor control that often decline with age. Measuring the shift of visual attention in older drivers in these tricky sections can predict their driving behaviours (Min, Min, & Kim, 2013). While those sections of straight road driving between turnings were meant to represent the relatively easy, less risky driving conditions.

Eye Tracking Data Analysis: Dispersion Centroid Mode Algorithm. Eye movements were analysed through the use of eye tracking video recording for each participants. The main purpose of this analysis was to separate saccadic eye movements, and noise, from fixations (periods where the gaze location is spatially relatively stable), in order to focus on conscious perception. Dealing with measures of fixations rather than the unfiltered raw data simplifies the analysis and interpretation, as every fixation was uniquely associated with a particular spatiotemporal location (Frederick, Katarzyna, & Brian, 2008), namely what that perceiver's visual attention was focused on.

The tracking equipment records raw gaze data (x_i, y_i, t_i), giving the gaze coordinates (x_i, y_i) at the time of t_i, where clusters of gaze points can be potentially identified as fixations (Blignaut, 2009). To achieve this, a computational algorithm is needed to efficiently extract fixations from the original large dataset discarding noises and saccades.

This study employed the dispersion centroid mode algorithm for eye tracking data analysis; originated and validated by Falkmer et al. (2008). Fundamentally, the algorithm identifies the fixations as sets of consecutive points within a particular dispersion distance (Salvucci & Goldberg, 2000). Two parameters were defined for the algorithm: the duration threshold and the dispersion threshold. The minimum duration was set to 100 ms since fixations rarely have a shorter period (Amos S Cohen, 1977); and the maximum dispersion threshold was defined at 1° of visual angle in the field of view. A fixation defined by 100 ms and 1° will encompass all consecutive eye movements that occurred within 1° distance from each other for at least 100 ms.

The fixation identification algorithm utilizes a weighted procedure in accord with the fact that, in human oculomotor behaviour, our eyes first land close to the object of interest and then for micro saccades to adjust the eye position to the fixated object. Technically, the algorithm identifies fixations using a window that extends across consecutive data points (Salvucci & Goldberg, 2000). The weighting of the fixation generation takes the standpoint that humans want to maximize the fixation duration on any object and hence the window moves according to the combined weight of the previous fixation and the current one, in order to include as many gaze sampling points into a series of fixations as possible. The moving window was initialized to cover a minimum of three chronologically consecutive sampling gaze points, which all lasted at least 100 ms to meet the duration threshold. Next, the dispersion (maximum separation) of the sampling points was calculated by summing the distances from the centroid of the sampling points in the window. If the dispersion is lower than 1° of visual angle, the centroid point in the window was consequently noted as a fixation with the given start time and duration. Otherwise, the window moves to the next area to cover new points until the window's dispersion is above the threshold. This dispersion dimension giving a spacing that allows for pursuit tracking to be classified as a fixation (Falkmer & Gregersen, 2005). The algorithm carried on with the window moving and fixation identification repeated to the end of the raw eye tracking data.

The actual identification of fixations can be quite challenging, particularly in a naturalistic setting (Falkmer & Gregersen, 2001; Lappi, 2015), due to the fact that all perceived objects are in relative motion. When driving around roundabouts or through intersections, the fixations are likely to represent pursuit movements. When turning, a fixation can be determined to have ended although in fact the driver was still looking at the same location in the environment (Itkonen, Pekkanen, & Lappi, 2015; Lappi, Pekkanen, & Itkonen, 2013). In order to ensure such eye movement is classified as a "fixation", the speed the gaze rotates should be slow enough relative to the chosen dispersion threshold and the actual fixation durations to avoid breaking fixations. Based on the finding in Lappi et al. (2013) that the horizontal pursuit speed is half the rate of rotation of the vehicle. In this study, participants drove at an average speed between 20 to 30 km/h when manoeuvreing through roundabouts; the smallest roundabout radius is 14 m, where no participants drove over 25 km/h. Thus the required maximum horizontal pursuit speed is about 14 deg/s. Therefore, the fixation identification algorithm parameters works properly because the suggested fixations did not produce dispersion that would cause the identification method to break a fixation. Similarly, the threshold allows individual optokinetic nystagmus smooth pursuits included in fixations.

A post manual identification was also carried out to minimize errors and misclassifications from the data analysis program. To do this the raw data (eye tracking video footage) was divided frame by frame and viewed in fixation clusters. Each cluster was visually validated and additional attributes of eye fixations can be recorded.

Visualizing and Spatial Statistics of Geo-coded Eye Movement. The eye fixation data and vehicle trajectory were synchronized using time stamp as the common link, so each fixation has a (x, y) coordinates assigned from the vehicle position, in order to represent "from where" the driver started gazing; and the fixation duration from the eye tacking analysis gives the period of the gazing. The geo-coded eye fixations data was then overlaid with driving route in a GIS environment. Accurate spatial gazing pattern analysis can be conducted by statistically reporting eye fixations in various driving sections.

To visualize eye movement patterns, the eye fixation positions were superimposed along with the vehicle trajectories for individual drivers A and B (see Figure 2 to 5). The frequency, durations and the spatial distribution of drivers' gaze behaviour vary significantly between two drivers; driver B performed more frequent eye fixation during both manoeuvres than driver A demonstrated. The spatial patterns indicate that driver B tended to shift his fixations to different objects during the manoeuvres, which might cause excessive work load. Nevertheless, both drivers performed more frequent eye movement in the second part of the roundabout, indicating their different visual strategies when getting information in order to exit the roundabout.

Figure 2. The spatial distribution of eye fixation behaviour at roundabout U-turn from driver A

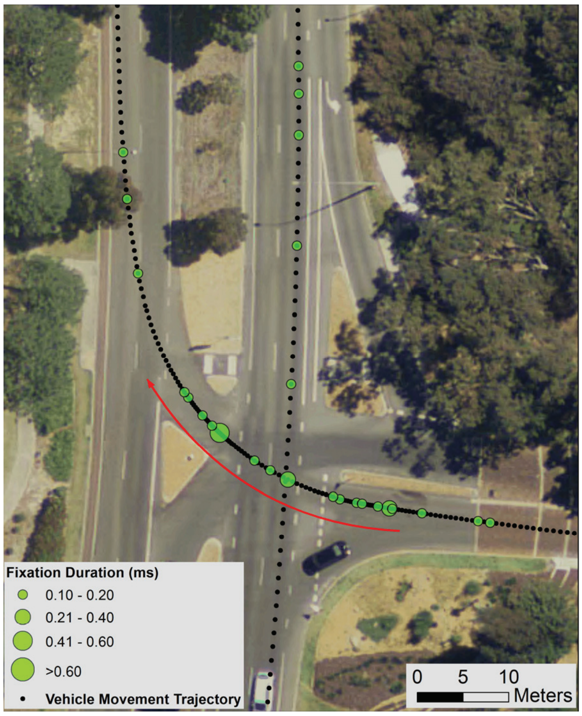

Figure 4. The spatial distribution of eye fixation behaviour at right-turn from driver A

Figure 3. The spatial distribution of eye fixation behaviour at roundabout U-turn from driver B

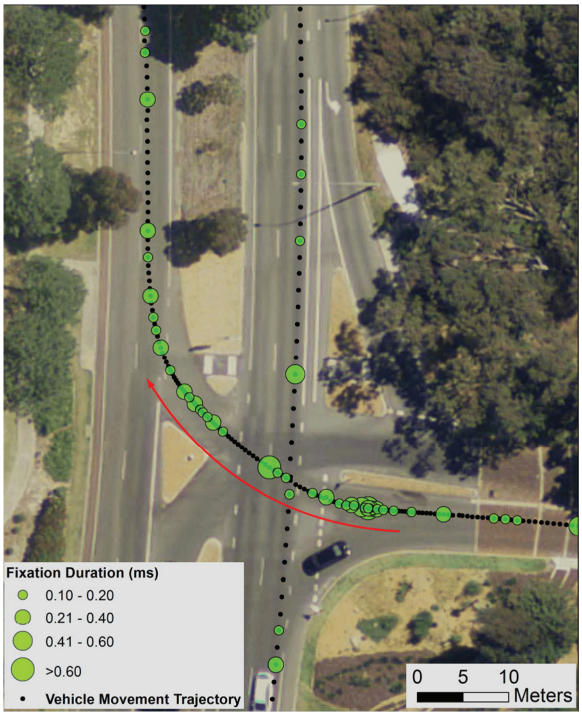

Figure 5. The spatial distribution of eye fixation behaviour at right-turn by driver B

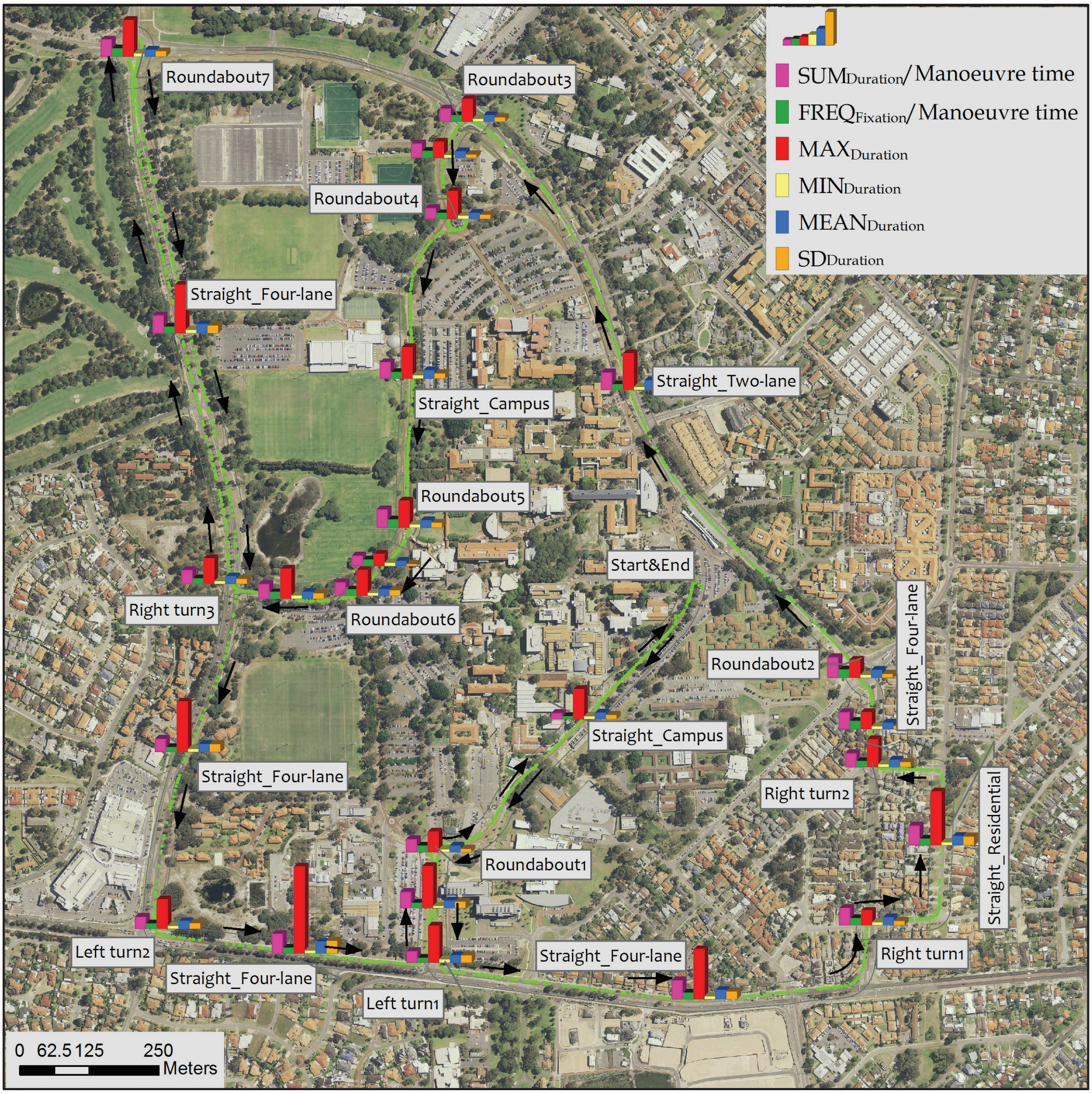

Figure 6. The spatial distribution of eye fixations for different driving manoeuvres and sections by an individual driver (driver C) using statistical parameters of the driver's eye fixations. The green dots are the driver's viewpoints related to eye fixation behaviour, namely the locations of the driver's gaze origin on the driving trajectory. Black arrows show the driving direction along the route.

Figure 6 focuses on the statistical distribution of eye fixation in different driving sections from an individual driver (driver C). Six statistical parameters of eye fixations were generated and mapped to the corresponding driving sections. The parameters include the following magnitude and statistics of eye fixation duration and frequency:

- $SUM_{Duration}$/Manoeuvre time (the ratio of total fixation duration to manoeuvre time)
- $FREQ_{Fixation}$/Manoeuvre time (the ratio of eye fixation count to the manoeuvre time)
- $MAX_{Duration}$ (the maximum fixation duration)
- $MIN_{Duration}$ (the minimum fixation duration)

- $MEAN_{Duration}$ (the mean of fixation duration)
- $SD_{Duration}$(the standard deviation of fixation durations)

The statistical distribution of eye fixations in Figure 6 gives an example for analyzing individual drivers' visual search behaviour in different driving sections. Some characteristics of the driver's eye movement can be identified, for example during straight road driving, the maximum and standard deviation of fixation duration are higher than those observed driving at turning manoeuvres. No significant variations were observed for the other parameters in the different manoeuvres and sections. Moreover, the visualisation of the individuals' gazing pattern is intuitive and graphically understandable for inspecting drivers' oculomotor behaviour.

The aggregate spatial and statistical distribution of the eye fixation behaviour for the whole group, associated with their visual capacity were examined using statistical correlation methods. This exploration is to identify critical driving sections underpinning older drivers' oculomotor behaviour due to their declined visual capacity. The potential factors related to driving situations can be investigated, such as the geometry of roundabouts or the complexity of driving scenes.

Results

Visual Capacity on UFOV Test

Table 1 summarizes the UFOV scores of the 30 subjects. The higher scores indicate lower visual capacity and poorer performance on the test. Subset 3 (Selective attention) presents the highest variation range (20-390 milliseconds); while subset 1 (Processing speed) has the lowest range (13-23 milliseconds). In terms of the associations between participants' age and their visual capacity, we have previously reported for the total 50 older drivers that there were low positive correlations between age and processing speed, divided and selective attention (r was .006, .242 and .251 respectively).

Table 1
Descriptive statistics of UFOV scores (unit as milliseconds).

UFOV Subsets	Min	Max	Mean	Std.
Processing Speed	13	23	13.7	2.067
Divided Attention	13	157	41.62	41.34
Selective Attention	20	390	102.56	79.061

Statistical Parameters of Eye Fixations in Relation to Driving Manoeuvres.

We present the summary of participants' eye fixation performance in different driving manoeuvres and sections in Figure 7 and 8. Five statistical parameters of eye fixations ($SUM_{Duration}$/Manoeuvre time, $FREQ_{Fixation}$/Manoeuvre time, $Max_{Duration}$, $Mean_{Duration}$ and $SD_{Duration}$) were used to examine the oculomotor behaviour for this cohort. Of the total 16 sections, Figure 7 shows that, the in-campus straight road driving demonstrated the lowest values in both the total fixation duration ($SUM_{Duration}$/Manoeuvre time) and fixation frequency ($FREQ_{Fixation}$/Manoeuvre time). The highest total fixation duration ($SUM_{Duration}$/Manoeuvre time) was found in the two-lane straight road driving, and in general, the roundabout manoeuvres possessed slightly more frequent eye fixations ($FREQ_{Fixation}$/Manoeuvre time), followed by turns manoeuvre, and the straight road driving.

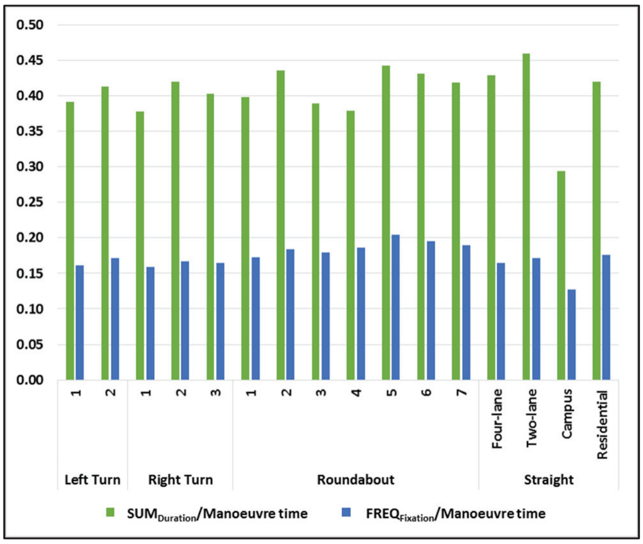

Figure 7. The statistics of $SUM_{Duration}$/Manoeuvre time, and $FREQ_{Fixation}$/Manoeuvre time at different driving manoeuvres and sections.

Figure 8 compared the statistics of the maximum, mean and standard deviation of fixation durations for the 16 driving sections. The maximum fixation durations ($Max_{Duration}$) of participants during straight road driving are significantly higher than both turns and roundabout performance. However, the mean ($Mean_{Duration}$) and standard deviation of fixation durations ($SD_{Duration}$) are similar with the slightly lower values observed for roundabout driving.

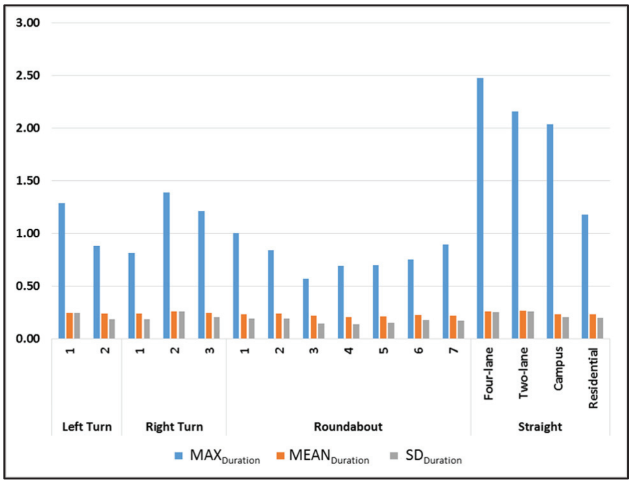

Figure 8. The statistics of the maximum, mean and standard deviation of eye fixations durations at different driving manoeuvres and sections.

Figure 9. The spatial distribution of eye fixation behaviour at a roundabout U-turn and straight road driving from one driver.

For visually exploratory inspection, Figure 9 illustrates a sample of spatial distribution of eye movement at a roundabout U-turn and straight road driving. The difference in visual search patterns is obvious, with the driver exhibiting larger fixation durations and larger variation of fixation durations (standard deviation of fixation duration), but less frequent fixations on the straight-driving, compared to the U-turn manoeuvre at the roundabout.

Correlations between Visual Capacity and Oculomotor Behaviour in Older Drivers.

Pearson's Correlations (SPSS®) were computed to investigate the relationship between participants' oculomotor behaviour (eye fixation movements) and their UFOV subsets' scores during different driving manoeuvres and sections. The five statistical parameters of eye fixations ($SUM_{Duration}$/Manoeuvre time, $FREQ_{Fixation}$/Manoeuvre time, $Max_{Duration}$, $Mean_{Duration}$ and $SD_{Duration}$) were examined against three UFOV scores (processing speed, divided and selective attention). Table 2 to 6 list all the correlation coefficients for the 16 driving sections. The objective was to compare the relationships between older drivers' eye fixations and their visual attention abilities at different segmented driving sections. Then any hot spots of the relationships can be identified for further in-depth investigation.

Table 2
*Correlation coefficients between visual capacity and fixation duration ($SUM_{Duration}$/Manoeuvre time) at different driving scenarios (*p<.05; **p<.01, 2-tailed).*

Eye Fixations of Driving Scenario	Processing Speed	Divided Attention	Selective Attention
LeftTurn1	0.184	-0.158	-0.121
LeftTurn2	0.237	-0.157	-0.159
RightTurn1	0.469*	0.178	0.164
RightTurn2	-0.024	-0.163	-0.166
RightTurn3	0.026	-0.428*	-0.170
Roundabout1	0.062	-0.447*	-0.275
Roundabout2	0.250	0.045	-0.218
Roundabout3	0.249	-0.309	-0.296
Roundabout4	0.081	-0.338	-0.030
Roundabout5	0.198	0.043	0.262
Roundabout6	-0.104	0.179	0.286
Roundabout7	0.038	-0.173	-0.152
Straight Four-lane	0.251	-0.152	-0.059
Straight Inside Campus	0.145	-0.201	-0.022
Straight Residential	0.001	-0.041	0.265
Straight Two-lane	0.108	-0.153	-0.042

Table 3
*Correlation coefficients between visual capacity and fixation frequency and manoeuvre time at different driving scenarios (*p<.05; **p<.01, 2-tailed).*

Eye Fixations of Driving Scenario	Processing Speed	Divided Attention	Selective Attention
LeftTurn1	0.105	-0.119	0.012
LeftTurn2	-0.011	-0.045	-0.126
RightTurn1	0.065	-0.018	-0.032
RightTurn2	0.021	0.201	0.161
RightTurn3	0.315	0.008	-0.082
Roundabout1	0.151	0.073	0.126
Roundabout2	0.168	-0.012	-0.116
Roundabout3	0.181	-0.098	-0.106
Roundabout4	0.190	0.063	-0.203
Roundabout5	0.266	-0.064	-0.428*
Roundabout6	0.366	-0.163	-0.424*
Roundabout7	0.284	0.002	-0.077
Straight Four-lane	0.202	0.037	-0.028
Straight Inside Campus	0.187	-0.08	-0.139
Straight Residential	0.169	-0.09	-0.218
Straight Two-lane	0.014	-0.166	-0.126

Table 4
*Correlation coefficients between visual capacity and mean fixation duration at different driving scenarios (*p<.05; **p<.01, 2-tailed).*

Eye Fixations of Driving Scenario	Processing Speed	Divided Attention	Selective Attention
LeftTurn1	0.166	-0.145	-0.101
LeftTurn2	0.232	-0.188	-0.185
RightTurn1	0.461*	0.191	0.186
RightTurn2	-0.003	-0.135	-0.151
RightTurn3	0.021	-0.461*	-0.184
Roundabout1	0.069	-0.424*	-0.240
Roundabout2	0.243	0.014	-0.263
Roundabout3	0.246	-0.28	-0.270
Roundabout4	0.083	-0.361	-0.064
Roundabout5	0.225	0.016	0.262
Roundabout6	-0.095	0.174	0.272
Roundabout7	0.028	-0.148	-0.125
Straight Four-lane	0.264	-0.143	-0.05
Straight Inside Campus	0.169	-0.191	-0.013
Straight Residential	0.037	-0.013	0.292
Straight Two-lane	0.125	-0.181	-0.066

Table 5
*Correlation coefficients between visual capacity and standard duration of fixation duration at different driving scenarios (*p<.05; **p<.01, 2-tailed).*

Eye Fixations of Driving Scenario	Processing Speed	Divided Attention	Selective Attention
LeftTurn1	0.163	-0.231	-0.217
LeftTurn2	0.175	-0.184	-0.04
RightTurn1	0.413*	0.07	0.16
RightTurn2	-0.014	0.06	-0.031
RightTurn3	-0.012	-.468*	-0.323
Roundabout1	0.175	-.415*	-0.249
Roundabout2	0.117	0.008	-0.134
Roundabout3	0.231	-0.253	-0.081
Roundabout4	0.137	-0.318	-0.024
Roundabout5	0.395*	-0.034	0.124
Roundabout6	0.117	0.257	0.337
Roundabout7	0.035	-0.239	-0.128
Straight Four-lane	0.403	-0.118	-0.039
Straight Inside Campus	0.308	-0.244	0.144
Straight Residential	0.27	-0.072	0.259
Straight Two-lane	0.141	-0.021	0.111

Table 6
*Correlation coefficients between visual capacity and maximum fixation duration at different driving scenarios (*p<.05; **p<.01, 2-tailed).*

Eye Fixations of Driving Scenario	Processing Speed	Divided Attention	Selective Attention
LeftTurn1	0.084	-0.111	-0.215
LeftTurn2	0.35	-0.143	-0.223
RightTurn1	0.334	-0.017	0.002
RightTurn2	-0.043	-0.076	0.192
RightTurn3	-0.012	-0.228	-0.176
Roundabout1	0.387*	-0.309	-0.199
Roundabout2	0.303	0.062	-0.209
Roundabout3	0.209	-0.242	0.435*
Roundabout4	0.217	0.195	0.032
Roundabout5	0.485**	0.088	0.174
Roundabout6	-0.122	0.026	0.490**
Roundabout7	0.199	-0.154	-0.184
Straight Four-lane	0.288	-0.043	0.094
Straight Inside Campus	-0.169	0.005	-0.289
Straight Residential	0.092	-0.07	0.287
Straight Two-lane	-0.089	0.04	-0.127

In order to identify the hot spots where the eye fixation behaviours are associated with certain visual capacity in older drivers from all the correlation coefficients in able 2 to 6, the following tables (Table 7, 8 and 9) summarize the critical sections with significant correlations between processing speed, divided attention and selective attention with statistical parameters of eye fixations respectively.

Table 7
Significant correlations (r, p-value) summary between processing speed and eye fixations parameters.

	SUM_D/M	MAX_D	$MEAN_D$	SD_D
Right-turn1	.469; .012		.461; .012	.413; .026
Roundabout1		.387;.038		
Roundabout5				.395; .034

Table 8
Significant correlations (r, p-value) summary between divided attention and eye fixations parameters.

	SUM_D/M	MAX_D	$MEAN_D$	SD_D
Right-turn3	-.428; .021	.485; .008	-.461; .012	-.468; .010
Roundabout1	-.447; .015		-.424; .022	-.415; .025

Table 9
Significant correlations (r, p-value) summary between selective attention and eye fixations parameters.

	$FREQ_F/M$	MAX_D
Roundabout3		.435; .018
Roundabout5	-.428; .020	
Roundabout6	-.424; .022	.490; .007

The results in Table 7 show that older drivers' processing speed was positively correlated to three statistical parameters of eye fixations at the right-turn 1 manoeuvre. The divided attention (Table 8) was associated with four statistical parameters of eye fixation at right-turn 3, and with three statistical parameters at roundabout 5. The selective attention (Table 9) was found to be negatively correlated with the frequency of eye fixations at some roundabout manoeuvres, but positively correlated to the maximum duration at roundabout 5 and 6.

Discussion and Conclusions

In this study, the vision-in-action paradigm was applied in the data collection and analysis, eye fixations were linked to vehicle trajectory so that the driver's eye movement can be examined in different types of motor behaviour. The driving route was segmented into 16 sections containing four categories of driving manoeuvres (left turn, right turn, straight road and roundabout driving), in order to quantitatively assess older drivers' oculomotor behaviour at the aggregate level. Eye fixation data were used since fixations reveal optimal placement of fovea, and hence the attention the perceiver intended to demonstrate. Both spatial and statistical analysis were performed to investigate older drivers' oculomotor behaviour in relation to driving manoeuvres and their visual capacity scores.

The visualisation of individuals' eye fixation movement presents intuitive and graphical understanding of older drivers' oculomotor behaviour. It demonstrates an exploratory analysis of the main characteristics of drivers' eye movement in actual driving. Since eye fixations were mapped along the vehicle trajectory, the spatial-temporal variation of individual drivers' visual attention allocation can be viewed in detail, or compared with each other. Hazardous behaviour, such as excessive or insufficient eye fixations of individual drivers can be detected, so as to provide advice on the visual searching strategies. In the next phase of research, focus can be given on how oculomotion and locomotion intertwine in space over time (Sun, Xia, Foster, et al., 2016), and on identifying older drivers with underperforming visual-motor coordination.

The results of statistical parameters of eye fixations in different manoeuvres indicate that older drivers performed more frequent eye fixations when manoeuvreing through turns and roundabouts than during straight road driving, as these sections imposed higher visual load and demand on the perceptive and cognitive skills in the driver (Dukic & Broberg, 2012). According to the multiple resource theory (Wicken, 1984), visual workload is associated with the number and complexity of visual information sources (Wickens, 1991), which can explain the reason that typical car crashes for older drivers occur at intersections and turns (Scheiber, 1999). This is also consistent with findings in other studies (Mourant & Rockwell, 1970; Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967; Wilkie, Kountouriotis, Merat, & Wann, 2010). Participants tended to fixate on certain objects for longer durations during straight road driving. When driving in campus straight ahead, the least frequent fixation was performed, suggesting less active visual activity due to less traffic and easier manoeuvreing. However, there were no significant variations for the other statistical parameters, such as the mean and standard deviation of fixation durations under different manoeuvres and sections. This was also reflected on the individual driver's eye movement pattern presented in Figure 6.

As for the associations with older drivers' visual capacity, the correlation coefficients (Table 2 to 6) didn't point out general correlation directions (positive or negative) of relationships in turns, roundabouts and straight driving roads. However, the data indicate stronger correlation strength for relationships between older drivers' eye movement and visual capacity at roundabouts and intersections than the relationships during straight road driving. Significant correlations were observed in some sections (Table 7, 8 and 9), those driving manoeuvres and sections were identified in which certain visual abilities played more important roles during the driving. The results showed that older drivers' processing speed and divided attention were associated with their eye fixations at the complex right-turns: right-turn 1 and 3. The processing speed was positively correlated to three statistical parameters of eye fixations at the right-turn 1 manoeuvre (Table 7), indicating older drivers taking longer fixation time to process visual information at this section, especially for the older drives with a slower processing speed, and they also have higher mean and standard deviation of eye fixation durations.

Figure 10 shows the traffic feature at right-turn 1, the manoeuvre occurs at the intersection without stop or give-way signs, therefore requires quick and more frequent response for information processing (Cynthia Owsley, 2013), which would affect drivers' eye movements. Anstey et al. (2005) stated that the speed at which visual information processed is an important factor for successfully negotiating difficult or dangerous traffic situations. Similar findings of older drivers processing speed impacting on driving can be also found in Leversen et al. (2013). Driving passing right-turn 3 is another complex manoeuvre (Figure 4 and 5), with turning into the four-lane road at an intersection presenting multiple and complex visual information in the driving scene. In this section, older drivers' divided attention (Table 8) was found to be negatively correlated to $SUM_{Duration}$/Manoeuvre time, $Mean_{Duration}$ and $SD_{Duration}$, and positively associated with $Max_{Duration}$. These results infer that older drivers with better divided attention took a longer period of eye fixation, and demonstrated higher mean and deviation values but shorter maximum duration was observed. Similar correlations were found between divided attention and eye fixation at roundabout 1, which is the first turning manoeuvre in the entire driving route. Although it is not a very complex manoeuvre, drivers might have paid more attention driving through.

Figure 10. The driving manoeuvre at right-turn 1 and the eye fixation movement by an individual driver as an example.

Selective attention is the visual ability to select the relevant information around the observers and to focus on the objects that require our attention. The results (Table 9) show older drivers' selective attention to be negatively correlated with the frequency of eye fixations at roundabout 5 and 6. These two roundabouts are of smaller size and located in-campus with a lot of surrounding buildings and trees, which can interfere with driving attention. The correlations indicate that older drivers with poorer selective attention took less eye fixations during these two roundabout manoeuvres. The positive correlations between selective attention and the maximum duration parameter were found at roundabout 3 and 6. Overall, older drivers with lower capacity of selective attention performed less frequent of eye fixations at certain roundabout manoeuvres, they might have compensated with longer durations as their visual search strategy.

Despite the above key findings of both spatial and statistical analysis of eye movement, this study has some limitations: First is the discriminant validity of UFOV® test in the evaluation of visual capacity. Although UFOV has well-recognized reliability and validity in assessing older drivers' fitness to drive, subset 1 (processing speed) showed small variation in the 30 subjects' performance, suggesting a low discriminant validity of the subset 1. Secondly some assumptions were not identified in the study perhaps due to the moderate sample size. No significant correlations were found at right-turn 2 and the U-turn at roundabout 7 even though both are manoeuvres requiring high visual workload. Lastly, as a driving behaviour study in general, it tended to address the key eye movement type related to their visual attention: the fixations, yet the fixation identification algorithm simplifies the eye movement types, it was thought that the 16-points calibration before eye tracking and the frame by frame manual identification would minimize the errors and misclassifications in the output.

Future study would investigate more on the sequence of eye movement and integrate the attributes of fixated objects, the distance between the positions of perceiver and the fixated objects can be extracted as an additional spatial attributes. Other driving performance parameters, such as speed and lane control can also be used to examine the effect of older drivers' oculomotor behaviour. Nevertheless, the spatial and statistical analysis of older drivers' eye movement presented in this study provide a clear spatial link between older drivers' oculomotor behaviour and their visual capacity under different driving manoeuvres and sections. It has added to the understanding of how vision is adjusted to regulate locomotion in older drivers. This paper is part of an ongoing investigation into the driving behaviour of older adults with focus on visual scanning behaviour. More in-depth investigations on visual-motor coordination of older drivers will be described in the next contributions.

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Conflict of Interest. The authors declare that there is no conflict of interest regarding the publication of this paper.

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5

Assessing Older Drivers' Visual-motor Coordination

CHAPTER 5 ASSESSING OLDER DRIVERS' VISUAL-MOTOR COORDINATION

This chapter is covered by the following papers (paper 7, 8 and 9 of the thesis):

Sun, Q., Xia, J. C., He, J., Foster, J., Falkmer, T., & Lee, H. (2016). Towards Unpacking Older Drivers' Visual-motor Coordination: A Gaze-based Integrated Assessment System. Manuscript. [Revised and resubmitted to *Accident Analysis & Prevention*]. **(Paper 7)**

Sun, Q., Xia, J. C., Falkmer, T., Foster, J., & Lee, H. (2016). Unpacking Older Drivers' Mobility at Roundabouts: Their Visual-motor Coordination through Driver-vehicle-environment Interactions. Manuscript. [Submitted to *International Journal of Sustainable Transportation*]. **(Paper 8)**

Sun, Q., Xia, J. C., Falkmer, T., Foster, J., & Lee, H. (2016). Unpacking Older Drivers' Manoeuvre at Intersections: Their Visual-motor Coordination and Underlying Neuropsychological Mechanisms. Manuscript. [Submitted to *Journal of Gerontology: Medical Sciences*]. **(Paper 9)**

In order to better describe a nuanced image of older drivers, the investigation is of necessity to look at their operational-level behaviour and performance. This level of behaviours relies on the second-to-second decision-making, e.g., using the visuospatial information to guide their steering. Based on a comprehensive literature review and the investigation of lane keeping and visual search in older drivers in previous chapters, it is clear that the fundamental concern of older drivers is the declined cognitive abilities which adversely impact on their driving behaviours. In particular, the decline in visual capacity investigated in Chapter 4 and the executive function investigated in Chapter 3, are challenging older adults' driving competencies.

From a time-geography perspective, this chapter introduces the concept of visual-motor coordination path and episodes in driving mobility and comprehensively examines the visual-motor coordination of older drivers. The time-space concept explains how time and space interact as resources and constraints for human action. Based on the visual-motor coordination data model developed in paper 5, paper 7 further integrates more visual search parameters from a qualitative coding and proposes a gaze-based integrated driving assessment database in order to undertake an assessment of older drivers' visual-motor coordination through comprehensive driver-vehicle-environment interactions.

Paper 8 and 9 focus on assessing older drivers' visual-motor coordination and identifying low-performing older drivers and indicators of risky behaviours. Paper 8 measures older drivers' visual-motor coordination at a series of roundabouts. Their visual scanning pattern and lane keeping are aggregated and benchmarked. Data Envelopment Analysis (DEA), an optimization model for measuring the relative performance, combined GIS analysis is used to develop a visual-motor coordination composite indicator (VMCCI) for individual drivers. Low-performing drivers and their risky driving behaviours, and problematic road sections will be identified through the DEA modelling. The impact of the roundabout geometrics on older drivers' visual-motor coordination will be explored.

Further investigation will look at older drivers' visual-motor coordination performance at intersection driving, which is the most challenging section for older drivers. The associations of visual-motor coordination in older drivers with their cognitive performance will be investigated to explain neuropsychological mechanisms underlying visual-motor coordination.

This chapter acts as a sub-thesis concentrating on the older drivers' visual-motor coordination. It sits on all the other techniques and analysis developed in the previous chapters, but complements the measurement of visual-motor coordination with an in-depth investigation of older drivers' driving behaviour. Over the whole thesis, it highlights the link between psycho and geoinformatics in the framework, since the *coordination* itself is a primitive topic in psychology. This chapter also highlights the significance of the older adults' characteristics in the driving mobility and behaviour investigation. It upholds the research rationale described in Chapter 1 that investigation of visual-motor coordination through quantitative measurements is reliable for investigating older drivers driving mobility and behaviours.

Towards Unpacking Older Drivers' Visual-motor Coordination: A Gaze-based Integrated Assessment System

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Abstract: The linking of drivers' visual search patterns with motor behaviour data can reveal how the individual drivers perceived spatial and hazardous information to regulate their physical movements. Such investigation may provide insight into driving behaviour resulted by distractions or cognitive deficits. It is yet challenging to quantitatively measure the visual-motor coordination of the driver owing to the complexity of the human mobility behaviour. In this paper, we first comprehensively reviewed the critical role of vision guiding motor action in driving. A gaze-based integrated driving assessment system was then introduced. The experimental data were from 38 older adults' on-road driving recorded using high frequency tracking of eye movement and vehicle trajectory. The gaze behaviour and visual search attributes were extracted and analysed from the eye tracking video frames and linked to the vehicle positions. The performance of visual-motor coordination in individual older drivers was examined based on multiple visual search and vehicle control parameters. The effectiveness and properness of the gaze-based integrated driving assessment system in driving behaviour assessment were discussed followed by implications and suggestions for further research.

Keywords: older drivers, visual pattern, visual-motor coordination, gaze-based integrated assessment system.

1. Introduction

Vehicle driving is a complex human mobility which requires agile psychomotor ability and intact cognitive functions in areas of visual perception, attention and executive function, etc (Dukic & Broberg, 2012). Previous studies have identified that inattention, visuospatial deficits, and low cognitive awareness were associated with poor driving performance, especially in older drivers (Anstey, Wood, Lord, & Walker, 2005; Charman, 1997; Matas, Nettelbeck, & Burns, 2014; Owsley & McGwin Jr, 2010; Wilson, Chattington, & Marple-Horvat, 2008). The results of these studies also indicated that visuospatial perception and cognition were frequently employed in driving to ensure safe and effective operation of a vehicle. Since cognitive processes and the visual search strategies greatly influence driving behaviour (Falkmer, Dahlman, Dukic, Bjällmark, & Larsson, 2008), cognitive and visual abilities of drivers should be accurately monitored and tested.

For decades, researchers have undertaken many studies aiming at providing insight into the cognitive processes involved in driving and seeking novel assessments of fitness to drive. Those studies usually examine driving behaviour in the area of vision, motor and cognition individually or with focus on one or another aspect of driving skills, few results have measured the interaction between vision and motor, and consider the driving behaviour and performance as a whole process, owing to the lack of tools to monitor the complexity of human mobility behaviour. Very little is thus known about the dynamic patterns of drivers' cognitive processes including visual search reflecting on their driving abilities (Qian Sun, Jianhong (Cecilia) Xia, Nandakumaran Nadarajah, et al., 2016). In the current paper, we introduce a gaze-based integrated driving assessment system for the investigation of driving behaviour in older adults, in order to unpack their visual, locomotion and the coordination performance. Considering vehicle driving is one kind of human mobility with visual search and vehicle control as the main activities, such activities are tightly linked and limited by various constraints over space and time, the constrains, such as the road curvature, the posted speed limits and traffic, would shape the visual pattern of the driver and her/his driving path as well. This system incorporates drivers' visual patterns, the traffic environment and the driving behaviours in a space-time context organized by a GIS (Geographic Information System) platform. The gaze patterns are conceptualized as a sequence of eye fixations and their durations synchronizing with the vehicle movement trajectory in traffic scenes, and conducted by the individual drivers. Gaze distances and traffic relevant gazing objects were identified and noted from the eye tracking video frames. Advanced GNSS (Global Satellite Navigation System) was used to obtain high rates and precise vehicle positions, which provide an accurate locational reference for the gaze behaviour. We argue that the integrated system sets-up a scalable multidimensional data infrastructure which can offer significantly more definitive information relate to the driver's visual search strategies, motor planning, intentions and actions. Such gaze-based visual-motor events exhibit spatial distribution and temporal change of vision and motor behaviours of the driver, thus would build a much detailed model for the cognitive processes of the individual drivers and their interactions with the traffic. And from here, the driving competencies can be accurately evaluated and potentially we can provide effective feedback to the drivers, in terms of the efficiency of their visual-motor coordination.

The objectives of this paper were as follows:

- To establish a gaze-based integrated driving assessment system for quantitative examination on visual-motor coordination in driving.
- To extract and analyse older drivers' gazing behaviour in relation to the surrounding environments.
- To investigate older drivers' visual-motor coordination performance.

2. Related Works

2.1. Visual Requirements to Control the Vehicle in Driving

In general, gaze behaviour and visual patterns are shaped by visual ability, spare visual capacity, workload, and involuntary tendency to fixate on details with high information content (Hughes, 1989). In driving situations, the visual perception, and the attentional process can be explained in Lansdown's model (Lansdown, 1996) in Figure 1. The driver initially samples the roadway peripherally to locate a feature of interest. Some information processing may occur at this point to prioritize the information. This can be weighted according to the road and surrounding situation, eye position, experience, and/or situational workload. To assess their relevance, the diver directs foveal vision to the features identified to extract the details required to the vehicle safely. Normal drivers have a single foveal resource, the only way the driver can gather detailed visual information from sources at difference positions is to move the foveal resources about in time, that is, to sample or time-share (Wierwille, Antin, Dingus, & Hulse, 1988). If the displays require that the driver extracts detailed information, then they will create a demand on the driver's foveal visual resource (Lansdown, 1996).

Visual search patterns reflect human information processing strategies. A driver with cognitive decline would face increased problems in adopting flexible visual strategies (Falkmer & Gregersen, 2001). The visual sampling by a driver is based on cognitive processes and the sampling process is dependent on his/her eye movements. Eye movements are directed under the individual schema of the driver and updated with information gathered by both peripheral and foveal sampling, so that the driver can identify certain features in the traffic environment in order to operate the vehicle properly (Figure 1). Hughes (1989) suggested that variations of eye fixation durations are dependent on task type, task importance, the nature of the information processing, and the overall workload. Visual properties (e.g., visual clutter density or certain information per area per unit time) and driver information goals are both important determinants in the distribution of attention in visual scanning.

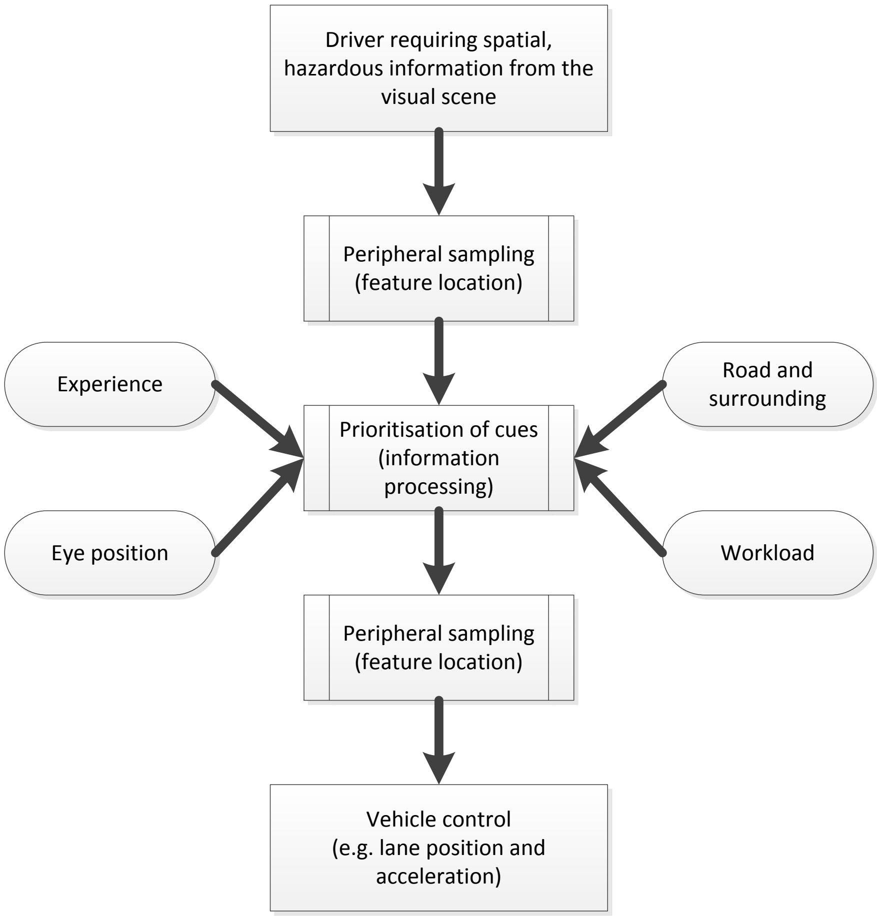


Figure 1. A model of the drivers' visual information processing, adopted from Lansdown (1996)

2.2. Eye Tracking of Gaze Behaviour in Driving

Eye tracking is one of the widely used technique to measure eye movement so that researchers would find both where the person was looking at a given time, and the sequence of eye movement shifting from one location to another (Poole & Ball, 2006). The rationale behind eye tracking research was depicted by Tatler (2014) that human eyes are directed to the locations that are relevant to the task on a moment-to-moment basis, and at each moment we need to gaze at the locations that convey information allowing us to act upon the surrounding environment in order to complete our current motor acts. Tatler (2014) further addressed that individuals' behavioural goals and the allocation of overt visual attention are tightly connected. This is because, when engaging in a natural task, human rarely gaze at objects irrelevant to our overall behavioural goals (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003). During vehicle driving, the information that a driver uses is predominantly visual (Sivak, 1996), such visual information is vital to motor planning, therefore, tracking eye movement allows the researcher to collect an abundant source of information on the driver's visual attention and patterns. When and where drivers look is of importance to driver safety (Lee, 2008; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), a number of specific driving behaviours are mainly dependent on the optimal deployment of attention through overt eye movements (Crundall & Underwood, 2011), for example, when negotiating a curve, the fixation on the tangent point is optimum; while when exiting a bend road, the fixation should be directed on the future path (M. F. Land & Lee, 1994; Lappi, 2014; MacDougall & Moore, 2005; Ren et al., 2014).

Eye movement study involves two processes, data collection and analysis. Analysis of eye movements facilitates the investigation of the driver's visual awareness and behaviour, particularly visual-spatial cognitive abilities, in dynamic driving situations (Dukic & Broberg, 2012; Falkmer et al., 2008). Eye tracking enables the data collection with respect to cognitive processes for undertaking any particular task. These processes may include the order and length of time a person directs gaze at any particular objects in a visual scene (Falkmer et al., 2008). Eye fixation has been widely considered as the core aspect of eye tracking analyses. It can be defined as a period that the eye 'ceases movement and remains set on any particular focal point' (Falkmer et al., 2008). Yang and McDonald et al. (2012) further explained that a fixation is relatively 'stationary' eye behaviour in contrast to saccadic eye movement, which allows eyes to focus their gaze on the objects being looked at, so as to extract this information (Gilland, 2008). During those relative stable periods, the eyes focused on a certain object in the visual scene. Therefore, eye fixations often reflect the matter of fact that the brain was processing and paying attention to the fixated information (Crundall & Underwood, 2011). Extracting eye fixations from eye movements and the use of fixation-based eye tracking measurement have offered useful visual behaviour information and extensively promoted the understanding of what strategies drivers employed to make a safe journey (Underwood et al., 2003).

2.3. Positioning Eye Fixation of Gazing Bahviour in Driving

Eye tracking examines driving ability by charting fixation points and durations, so we would find out where and for how long the driver was gazing at in the traffic environment. The frequency and duration of eye movements are affected by the viewer's vision-environment interaction. Found in a study conducted by Shinar et al. (1977), patterns and tendencies in a driver's eye movement were dependent on the driving situation of the environment. For example, in the countries with right-hand traffic, the dominant eye fixation location is simply on the right-hand side of the road. While the visual scanning patterns were very inactive for a straight-road driving, and the main fixation location is on the front section of the road before the vehicle. This is due to the fact that drivers may rely on peripheral vision without using active scanning on a straight-road driving (Gilland, 2008). In contrast, on a bendy road, the driver's eye movement was following the curve geometry, with the fixations shifting into the curve a few seconds before entering into the bend. This was explained by Gilland (2008) that navigating a curve tends to be more demanding than a straight road, and higher workload was needed in visual search since the fixations must be actively focused in order to maneuver safely. Therefore, by knowing from where the driver performed gazing, a meaningful attribute of visual pattern can be obtained for investigating drivers' visual strategies and attention allocation.

Vision-motor interaction also plays a critical role in shaping a driver's visual patterns as well as keeping motion stability. Oculomotion and locomotion are different but co-existed in actions with common spatial-temporal parameters (Goodale, 1998). However, traditionally research on vision has focused on visual perception and human cognitive life, which is regarded as a different enterprise from studies on motion behaviour. For example, discussions on drivers' visual search usually separate from those on how drivers steering. In fact, eye movement in driving is an information-seeking action used to control a broad range of goal-directed motor actions (Goodale, 2011), motor behaviour reveals some effects of visual searching. Thus, a robust research on vision shall be integrated with the study of motor action planning and controlling (Goodale, 1998, 2011).

A technical framework was presently for assessing on-road visual-motor coordination in driving that combines eye tracking, vehicle kinematic surveying using RTK (Real-time Kinematic) multi-GNSS and GIS technologies (Qian Sun, Jianhong (Cecilia) Xia, Nandakumaran Nadarajah, et al., 2016). The eye fixation objects were geo-coded using accurate vehicle locational reference and linked to the parameters on vehicle movement trajectory, such as speed and vehicle lateral position to the road centerline (Qian Sun, Jianhong (Cecilia) Xia, Nandakumaran Nadarajah, et al., 2016). Such data model constitutes spatial and temporal attributes for both visual pattern and vehicle movement, the vehicle movement reflects how the driver controlled the vehicle. Multi-GNSS RTK approach is capable of tracking precise vehicle positioning and trajectories, with better precision than the GPS only tracking, which significantly enhances the possibility to extract more attributes from the vehicle movement data

(Malik, 2011; Malik, Rakotonirainy, & Maire, 2009). The accuracy of vehicle movement tracked by multi-GNSS RTK can resolve to centimetre level horizontally, which also offers precise reference positioning to the eye fixations once two tracking datasets are integrated.

The vehicle positioning data linked to eye movement defines a driver-centred human mobility, and such context- and location-aware mobile eye movement tracking can be further used to trigger new kinds of interactions (Giannopoulos, Kiefer, Raubal, Richter, & Thrash, 2014; Kiefer, Straub, & Raubal, 2012). So we are able to obtain more spatial attributes for each eye fixation: the position of the driver and the direction of the gaze; and the space of the traffic environment. In addition, positioning of eye fixation of eye tracking in driving enables: 1), conceptualising driving behaviour as two activities patterns (vision and motor) with visual pattern as the guidance; 2), mapping spatial distribution and temporal change of driving behaviours; 3), describing the visual search and motor behaviour and the environment as a whole. With all of these attributes, driving behaviour can be investigated in a scalable multi-dimensional platform, such as a GIS program.

3. A Gaze-Based Integrated Driving Assessment System and Experimental Data

3.1. 3D Gaze Patterns Tracked by Eye Tracking Technologies

Eye gaze pattern is a fundamental parameter for a driving assessment system. Gaze pattern is guided by the interplay of top-down and bottom-up control in visual search affecting eye movement during driving. The top-down strategies developed over driving experience can influence the bottom-up visual process. Crundall (2005) and Underwood et al. (2003) studied the key top-down factors in driving and recognized a phenomenon of tunnel vision: top-down search plays a vital role for narrowing down the functional visual field resulting in less information extracted from peripheral vision and improving the efficiency of the information process. This could explain why experienced drivers release attentional resource faster than the novice ones (Underwood et al., 2003). The bottom-up visual search could stimulate the objects viewed by drivers into distractors or attractors for driving (Crundall, 2005), such as eye fixation on the tangent point when negotiating a curve was found to be beneficial for driving (M. F. Land & Lee, 1994; MacDougall & Moore, 2005); while billboards on the road were found to be some sort of distractions for driving (Wallace, 2003), these kinds of objects tend to take drivers' attention away from driving. Ady (1967) also identified that a section with a large size sign and bright lights, located in a sharp bend road, presented a significant association with vehicle accidents.

The type of objects, the numbers and duration of eye fixation on the objects recorded by eye trackers can also be important metrics for understanding visual search. For example, fixation durations driving along the curve are more likely to be shorter as drivers increase their frequency of fixation on objects, such as lane markers and road edges when negotiating a curve (Land and Lee 1994). In addition, the timing of eye fixation and the distance between fixation and road markers could affect steering performance. For example, drivers tended to fixate their eyes on tangent points about 0.8-0.9s before the steering, which would give them enough time to acquiring information feeding into steering calculation (M. F. Land & Lee, 1994; Michael F Land & Tatler, 2001). They also found that the increased distance between fixation and road markers is associated with the decreased steering performance. Based on above literature, we propose to capture 3D gaze patterns attributes including gaze area (background), object, direction, distance and whether it is traffic relevant.

The traffic environment include not only static objects (e.g., signposts), but also dynamic objects (e.g., moving cars in a space). Appendix B illustrates an example of object coding matrix for eye tracking related road surface. The matrix was prepared prior to the eye tracking data analysis. The fixation area (background) and the object in the area are two attributes for coding drivers' gaze patterns.

3.2. Vehicle Control Tracked by GNSS Technologies

The vehicle control is the primary outcome of on-road driving performance, which influenced by the gaze patterns and road environment information. As Land and Horwood (1995) stated that peripheral vision is vital to lane maintenance between two peripheral markers which are usually the road edges or lane markings. The vehicle control, more precisely vehicle movement trajectories tracked by multi-GNSS RTK technologies can be used to assess driving performance from the following perspectives: lane maintenance, straight driving and lane changing; and speed regulation for both performing speed control against the posted speed limit and stable speed control (Qian Sun et al., 2017). One quantitative measure of driver performance is the amount by which a vehicle's path deviated from the centre of the lane as safety margins are an important factor in avoiding collisions. The Mean Lane Position (MLP), Standard Deviation of Lane Position (SDLP) calculated from precise vehicle movement trajectories were used as the lane maintenance parameters.

3.4. Experimental Data

Thirty-eight older drivers between the age of 60 to 81 (mean = 68.7, SD = 5.6) participated in the assessment. The eligibility of participation also included: holding a valid driver license and having an insured vehicle, driving at least 3 times a week, having no mental and physical issues affecting driving, and no sedative medication was taken prior to the assessment. All participants provided an informed consent for participation in compliance with ethics requirements from the University Human Research Ethics Committee. All participants passed screening on visual acuity, and on Mini-Mental State Examination (MMSE) to smooth out any mental and cognitive functional deficits which would affect on-road driving.

3.4.1. Apparatus and data collections

The on-road driving experiments simultaneously recorded the vehicle movement and the driver's eye movement as described in detail in Sun et al. (2016). Participants were instructed to drive through an urban residential area about 20 minutes for about 10km distance under normal traffic avoiding peak hours. The driving route (Appendix A) contains a series of roundabouts and intersections. We predefined the seven roundabout manoeuvres and five turns (three right and two left turns) at intersections as critical sections for analysis. This is based on a comprehensive literature review that the high vehicle crashes involvement of older drivers occurred at these sections (Clarke, Ward, Bartle, & Truman, 2010; Marmeleira, Ferreira, Melo, & Godinho, 2012; McGwin & Brown, 1999). We conducted frame by frame manual eye tracking video analysis for these twelve sections.

Eye movements of the drivers were recorded by a head-mounted eye tracking system (Arrington Viewpoint™) at 60 Hz with a spatial resolution of 0.5 degree, controlled by a laptop which managed the timing of the experiment and collected data. The corrected vision was required and the eye tracker can be worn with glasses when necessary. The horizontal and vertical eye movements of participant's right eyes were recorded using an infrared camera. At the same time, the scene from the driver's perspective was recorded by a second camera as video clips. All eye movement data were analysed off-line by a computer program to calculate the number of fixations and durations based on a dispersion centroid mode algorithm (Qian Sun, Xia, Falkmer, & Lee, 2016). A pair of Trimble R10 GNSS receivers was mounted on each participant's car roof to record the vehicle movement trajectory. The tracking configuration of Trimble R10 receivers was set up at 10 Hz for the frequency so the car positions can be recorded every 0.1 seconds.

The eye tracking records the sequence and duration of time a driver directly gaze at any particular objects in a visual scene, and the visual patterns the driver utilizes while performing a driving task (Falkmer et al., 2008). The sequential video clips of a driver's view and eye fixation locations (green dots) are presented in Figure 2 (left) as an example of eye tracking data, which shows the visual pattern of the driver during the roundabout: from left to right and top to bottom, the driver looked frequently at the passing cars and edge line of the curves in order to avoid the hazards and coordinate the vehicle positions.

The video-based eye movement data were then analysed frame by frame manually to capture more visual search attributes. Each fixation was given one of three categories to note the focus of attention of the subject while driving. The first category was related to the particular object that was fixated, the second category was the area or the background of the object that was fixated, and the third category was the distance between the object and the driver's location. The classification of fixations was based on a pre-defined classification matrix comprising 78 different categories of objects, 11 of them being classified as non-traffic relevant; and 82 different categories of areas or backgrounds, 29 of them being classified as non-traffic relevant. A traffic-relevant object would typically be a car the driver is following, whereas a not traffic relevant object would typically be a commercial sign or a bird in the sky. Additionally, three different gazing distances (inside vehicle; outside vehicle < 5 m; outside vehicle ≥ 5 m) were visually interpreted and recorded. The rationale is that the objects within 5 m distance were possible to be verified as such using the eye parallax of the subjects related to the fixated objects (Falkmer & Gregersen, 2005). The principles for scoring and categorizing eye fixations were adopted from the "object–space–time" relations scoring system (Falkmer & Gregersen, 2005). In total, 13,695 eye fixations were noted and identified from 38 older drivers on 12 driving sections (Appendix A).

Figure 2. Sample eye fixation video frames at a U-turn manoeuvre from one participant (left) and vehicle movement trajectories from five participants (right), adapted from (Qian Sun, Jianhong (Cecilia) Xia, Nandakumaran Nadarajah, et al., 2016)

For vehicle data collection, RTK postprocessing technique was used to achieve centimetre to decimetre level accuracy horizontally by minimizing the effect of error sources transmitted between the satellites and GNSS receivers (Qian Sun et al., 2017; Qian Sun, Xia, Foster, Falkmer, & Lee, 2016b). Figure 2 (right) shows the overlay of vehicle movement trajectories of five participants generated by multi-GNSS RTK. The post-processed data was then mapped to calculate the lateral maintenance parameters.

In this paper, we also used older drivers' cognitive condition score from D-KEFS TMT 4 (Delis-Kaplan Executive Function System Trail Making Test), which measured the participants' set shifting (number-letter switching) speed, namely the time the participant finished the trail making task. This test is considered an index of executive function, in particular, related to visual-motor coordination efficiency (Delis, 2001; Vasilopoulos et al., 2012).

3.4.2. Gaze-based integrated driving assessment database

The collected eye tracking and vehicle movement data were integrated into a GIS platform. Figure 3 displays the data integration and modelling for the gaze-based integrated driving assessment system. Gaze data (e.g., duration, gaze direction, distance, background, and the object) were captured from the eye tracking video frames. The processed vehicle movement trajectory was overlaid with other traffic data to calculate the lane deviations from the desired path (e.g., road centrelines). Two datasets were then linked by the participant's ID and the time fields. Since an eye fixation is a period of eye movement, the gaze pattern during this period, e.g., $Fixation_{i+1}$ can be inspected from the vehicle dynamic between the start time at $Vehicle_j$ to the end time at $Vehicle_{j+1}$. The (x, y) coordinates of the start time at $Vehicle_j$ give a location of the origin where the particular eye fixation occurred, and the parameters of the Vehiclej+1 refer to the results of the motor behaviour of the driver. The driving scenario features were linked to the visual-motor dataset by a Roundabout_ID or Turns_ID.

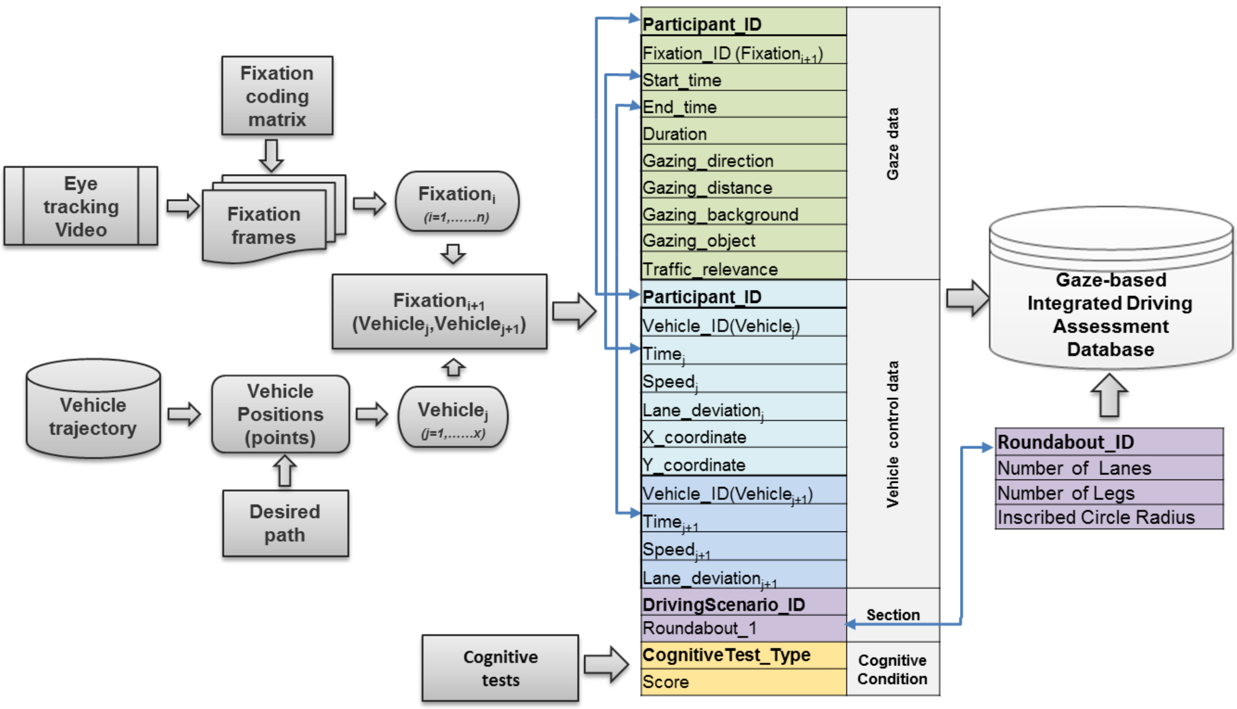


Figure 3. Data integration and modelling for gaze-based integrated driving assessment system, extended from the visual-motor coordination data model (Qian Sun, Jianhong (Cecilia) Xia, Nandakumaran Nadarajah, et al., 2016)

3.5. Data Analysis and Visual-Motor Coordination Assessment

The integrated system exhibits multi-sensory information acquired from the vehicle, driver, and environment, the raw data were analysed, linked and segmented with spatial, temporal and categorical attributes, which enables analysis on drivers' visual, motor behaviour and coordination performance at both individual and group level in a variety of driving sections and scenarios.

The SPSS® statistical package (version 20) was utilized for all statistical analyses. Pearson's Correlations were computed across drivers' gaze performance measures, and the relationship between gaze behaviour, the cognitive condition of visual-motor coordination and driving measures (MLP, SDLP). A composite score was then calculated to aggregate ranks across all categories for individual older drivers.

3. Results

3.1. Statistics of older drivers' gaze behaviour

We summarized the gaze distributions of 38 participants in terms of the following four categories: 1) traffic relevant/non-traffic relevant; 2) gaze distances; 3) gaze objects; 4) gaze background. Gaze frequency count on the traffic relevant objects was slightly lower than on the non-traffic relevant objects. Figure 4 shows the gaze distribution of participants with respect to three different distances, and compares gaze behaviour between roundabout and intersection manoeuvres. The number of gaze frequency outside the vehicle farther than 5 m was as much as three times that of the gaze frequency closer than 5 m. Both roundabout and intersection manoeuvres demonstrated similar patterns of distance distribution ratio, where drivers performed more gaze fixations at roundabouts.

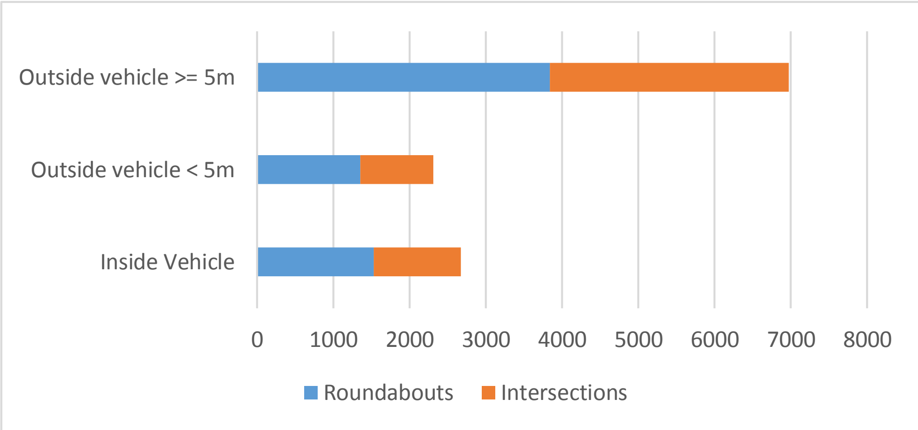
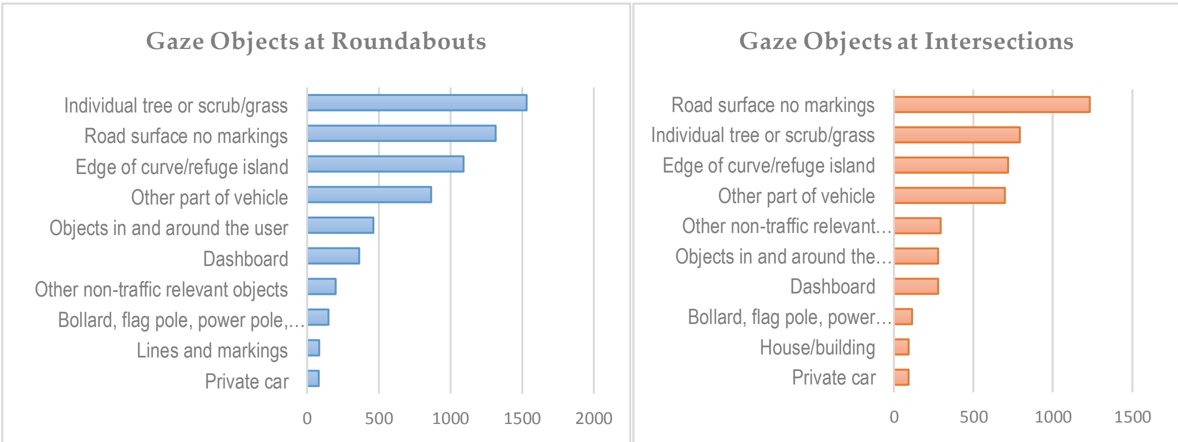
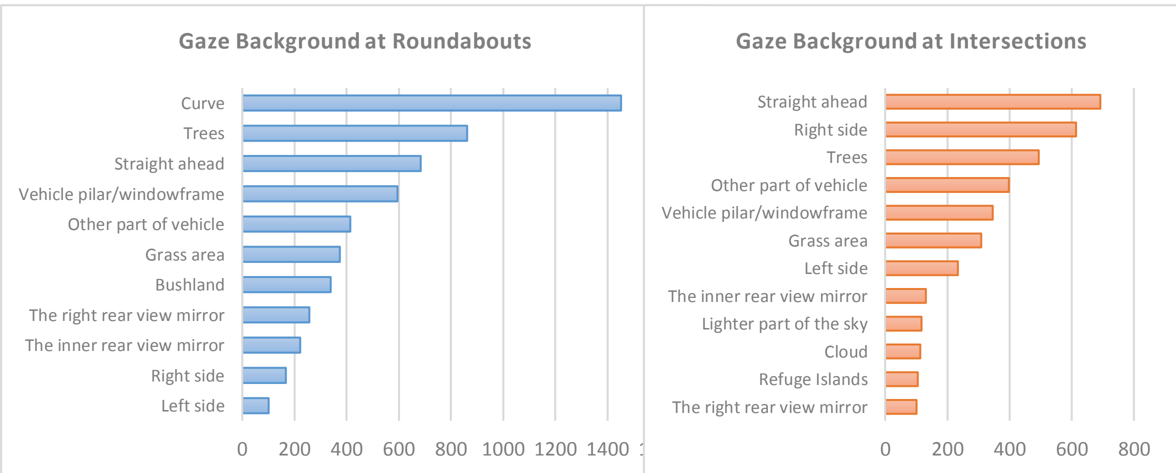


Figure 4. Gaze frequency count related to gaze distances between roundabout and intersection manoeuvres (x-axis shows the gaze frequency count).



(a) (b)

Figure 5. Gaze frequency count related to gaze objects between roundabout and intersection manoeuvres (x-axis shows the gaze frequency count).



(a) (b)

Figure 6. Gaze frequency count related to gaze background comparison between roundabout and intersection manoeuvres (x-axis shows the gaze frequency count).

To identify the focus of attention of the driver while driving on-road, another classification category in this study concerns the particular object (see Figure 5) that the driver was fixated at, also the background (see Figure 6) of the object that was fixated at. In total, the most frequent gaze object is "Road surface with no markings", followed by "Individual tree or scrub/grass" and "Edge of curve/refuge island". However, the gaze distributions were greatly affected by the surrounding environments. When turning through intersections, the drivers fixated more frequent on objects of the road surface, whereas when driving through roundabouts, the drivers gazed more frequently on individual trees or scrub/grass.

Other objects that the older drivers frequent gazed at were in the similar distribution between roundabout driving and turns.

Overall, the most frequent gaze background the drivers fixated on is "Curve", followed by the classes of "Straight ahead" and "Trees". However, the descriptive statistics show different visual search strategies and visual patterns in roundabout manoeuvre and turning at intersections. The "Curve" is the dominating background guiding drivers' maneuver at roundabouts, whereas "Straight ahead" road surface obviously was the most important background to fixate on when turning at intersections. Other noticeable gaze behaviours were: the drivers gazed more frequent on the mirrors at roundabouts than they did at intersections; whereas they paid much more visual attention to the "Right side" at intersections. Therefore, the driving tasks become important contributors in the visual search strategies and patterns of older drivers.

3.2. Correlation matrix of gaze input and vehicle control parameters

This investigation shows how the older drivers' gaze behaviour affect their vehicle control performance, and helps understand which parameters played more important roles in the visual-motor coordination. We performed statistical correlation analysis and report the matrix of Pearson Correlation coefficients and significances values.

Statistical correlations between the older drivers' visual search variables and vehicle control parameters are presented in Table 1. In this particular cohort of older adults, their executive function condition was associated with "Gaze at Curves" and "Look inside vehicle". It can be noted from the data that drivers with better visual-motor coordination skills (higher D-KEFS TMT 4 scores) performed more frequent gazes on the curves and inside vehicle features.

Some interesting associations were found between the gaze behaviour parameters. For example, for the fixation frequency, "Gaze at Mirrors" was positively correlated to "Look inside vehicle" and "Look outside < 5 m", but negatively correlated to "Look outside ≥ 5 m". "Gaze at Curves" was negatively associated with "Look inside vehicle" and "Look outside < 5 m"; but positively associated with "Straight ahead" and "Look outside ≥ 5 m". Also noticeably there is a high correlation between "Gaze at Curves" and "Traffic relevant objects". "Straight ahead" gaze behaviour was positively correlated to "Look inside < 5 m" and "Traffic relevant objects". "Look inside vehicle" was positively correlated to "Look outside < 5 m", but negatively correlated to "Look outside ≥ 5 m". "Look outside < 5m" was negatively associated with "Look outside ≥ 5 m", but positively associated with "Traffic relevant objects". There were no significant correlations found between gaze behaviour variables and lane maintenance parameters of MLP and SDLP. This will be discussed further it in the next section.

Table 1. Correlations relationship between gazing behaviour and vehicle control (Pearson Correlation Coefficients and Significances)

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

SDLP	MLP	Traffic relevant objects	Look outside ≥ 5 m	Look outside < 5 m	Look inside vehicle	Straight ahead	Gaze at Curves	Gaze at Mirrors	D-KEFS TMT 4	
									-	D-KEFS TMT4
								-	-0.170	Gaze at Mirrors
							-	-0.194	.409*	Gaze at Curves
						-	.550**	0.240	0.170	Straight ahead
					-	-0.222	-.400*	.624**	.422**	Look inside vehicle
				-	-.702**	.610**	-.523**	.362**	0.249	Look outside < 5 m
			-	-0.269	-0.304	0.243	0.313	-0.138	0.267	Look outside ≥ 5 m
		-	0.256	.646**	-0.140	.816**	.637**	0.271	0.085	Traffic relevant objects
	-	0.106	0.154	-0.080	-0.087	-0.200	0.121	0.083	.320*	MLP
-	.623**	0.229	0.035	-0.016	0.199	0.000	0.117	-0.020	0.077	SDLP

3.4. Overall Visual-motor Coordination Performance of Individual Drivers

We developed a composite score to rank the overall visual-motor coordination performance of individual older drivers. In total, 13 performance indicators were used for the ranking. The gaze behaviour indicators are: gaze on mirrors, gaze on curves, Straight ahead, look inside vehicle, look outside ≥ 5 m, traffic relevant, non-traffic relevant, fixation frequency/manoeuvre time ratio, fixation duration/manoeuvre time ratio. The vehicle control indicators are: MLP and SDLP, which demonstrate lane maintenance performance. The D-KEFS TMT 4 scores were used as participants' executive function condition indicating their visual-motor coordination ability.

Indicators were benchmarked and normalized in order to calculate a composite score for individual older drivers. The overall visual-motor coordination performance ranks are shown in Figure 7. It is generally consistent with the drivers' lane maintenance performance of SDLP. Driver 26 performed best with more curve, traffic relevant fixations, the driver also demonstrated high fixation frequent per manoeuvre time, resulted in low MLP and SDLP. In addition, his executive function score is also high. The worst performance from Driver 23, on the contrary, showed poor visual search strategies in the gaze pattern, with comparably very inadequate fixations on mirrors (8), curves (16), look outside ≥ 5 m (99), traffic relevant (133) but performed 279 fixations on non-traffic relevant objects, this driver did a high SDLP (Standard deviation of lane position). This driver also performed poorly in the D-KEFS TMT 4 test, indicating lower executive function condition.

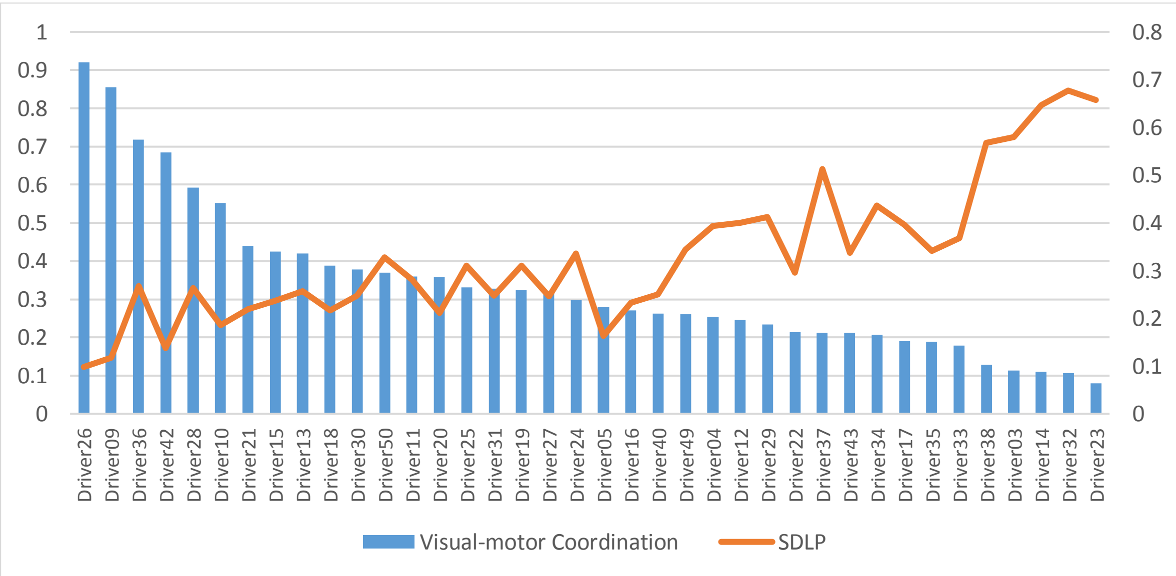


Figure 7. Overall visual-motor coordination performance ranks and lane maintenance of SDLP between older drivers (left y-axis: drivers' visual-motor coordination ranks, right y-axis: drivers' performance of SDLP).

4. Discussion

Visual-motor coordination in driving is complex since it requires the visual guidance of both the eyes and vehicle control, while simultaneously using eye movements to optimize vision. This makes understanding the cognitive abilities underpinnings of visual-motor coordination rather difficult, even if we consider it to be only the sum of its parts. In the end, though, the purpose of visual-motor coordination is using vision to guide locomotion. Such fundamental fact led the construction of our gaze-based integrated driving assessment system in driving behaviour assessment.

In this sample of 38 community-dwelling older adults with the general eligibility of on-road driving, we performed quantitative measurements and analysis on gaze pattern, correlations between gaze behaviour and vehicle control, and the overall efficiency of visual-motor coordination of individual participants.

The gaze pattern analysis results show that the environment, the driving tasks (such as roundabout manoeuvre vs. turning at intersections) have a significant impact on older drivers' visual search behaviour. There were no significant correlations found between gaze behaviour variables and lane maintenance parameters. In this paper, the proposed gaze-based integrated driving assessment system has been implemented and its primary functionality for evaluating driving competency has been demonstrated.

The present study has several limitations that must be acknowledged. The limitations can explain part of the non-significant values obtained in the correlations between gaze behaviour and lane maintenance parameters. Furthermore, such acknowledgement has useful implication for future studies.

- Subjects in this study were comparatively young with a mean age of 68.7. The decline in visual information processing ability is minimal (see their processing speed score in (Q. Sun et al., 2016)). Hence, it is challenging to examine the variations of visual-motor coordination in this cohort of older drivers.
- We only used MLP and SDLP for the correlations analysis. More vehicle control parameters can be used in the future studies, such as incorporating speed and acceleration in the assessment. In addition, the correlations analysis was conducted for the entire driving route. The investigation can be improved on task segmentation, such as different stages of roundabout manoeuvres, left and right turns, etc.
- We used a basic matrix for calculating the composite scores of visual-motor coordination performance in this paper. Sophisticated mathematical methods are needed for benchmarking and ranking and identifying risky drivers and their underperformed tasks, and better indicators of visual-motor coordination assessment can be determined through enhanced matrix.
- One cognitive condition variable was used in this paper, namely the executive function from D-KEFS TMT 4. The older drivers' cognitive conditions can help discover the underlying cognitive processes in visual-motor coordination. It moves one step further from knowing where and for how long the driver gazed at, to why and how the driver performed the visual search. In future, we may incorporate more psychological data in the investigation, in order to fulfill the framework of psycho-geoinformatics approach in driving assessment (Qian Sun, Jianhong (Cecilia) Xia, et al., 2016a).

5. Conclusions

In this paper, we introduced a gaze-based integrated driving assessment system to investigate older drivers' visual, motor behaviour and coordination. The integration of the driver's visual patterns, vehicle movement and the traffic environment in GIS enables the comprehensive examination of driver-vehicle-environment interactions and performance. The system is individual driver-centred and the analysis and assessment based on the scalable multi-dimensional data infrastructure, in a sense, is more plausible with respect to the real specific driving situation.

The gaze-based integrated driving assessment system is a noteworthy improvement to the eye tracking alone approach, it maximizes the usage of eye tracking data by extracting various gaze behaviour attributes, and linking to the motor behaviour and the traffic scenes, so we would know the locomotor action resulting from the visual search. In addition, the gaze-based integrated driving assessment system has improved our ability to take advantage of previously driving tracking data to enhance the quality of analysis and assessment of visual-motor coordination.

The system and data model can be directly used or modified in many other studies, such as medication effects on visual-motor coordination in driving; modelling driving behaviours and scenarios, etc. While time and resource intensive to establish, our future improvement is expected to pay off in terms of reduced errors of data analysis over multiple studies, greater data analysis efficiencies, and enriched information for decision making.

In short, this paper demonstrated the opportunities and possibility of visual-motor coordination study. With richer raw data and secondary data, questions on how individual drivers perceived spatial and hazardous information to regulate their physical movements can be investigated in details. It has also brought out the challenges of developing methods to examine the hypothesis on age-related cognitive decline affecting visual-motor coordination. In conclusion, this study provides useful information on older drivers' gaze behaviour and visual-motor coordination, and has identified some specific variables associated with visual search strategies in driving. Based on these findings, simple substitution rules can be proposed for designing more efficient fitness-to-driver assessment. Specific measures of visual attention, vehicle control and global cognitive functioning may be useful for predicting unsafe driving.

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Appendix A: Driving route and the twelve significant driving sections

Appendix B: Road related object coding matrix for eye tracking (part only)

10	Road	11	T-junction/Intersection (give way)	12	Roundabout
100	Straight ahead	110	oncoming vehicle on right side	120	oncoming vehicle right side
101	left side	111	oncoming vehicle on left side	121	oncoming vehicle opposite side
102	right side	112	oncoming vehicle opposite left side (slip road)	122	vehicle infront exiting same side
103	Opposite direction right track	113	vehicle infront going left	123	vehicle exiting left side
104	Opposite direction left track	114	vehicle infront going right	124	oncoming vehicle right side left lane
105	Opposite direction middle track	115	oncoming vehicle opposite coming straight ahead	125	oncoming vehicle right side right lane
106	road bump	116	oncoming vehicle opposite U-turn	126	Vehicle same direction right side
107	road behind driver's car	117	Vehicle same direction left side	127	Vehicle same direction left side
		118	Vehicle same direction right side	128	Curve
13	**Pedestrian crossing**	**14**	**Footpath/Cycleway**	**15**	**Refuge Islands**
130	to the left - before pedestrian crossing	140	footpath to the left	150	traffic refuge, island
131	to the right - before pedestrian crossing	141	footpath to the right	151	Same direction corner/tip
132	middle of pedestrian crossing	142	footpath infront	152	Same direction side
133	start point of pedestrian crossing	143	Cycleway to the left	153	Same direction in the middle
134	exit point of pedestrian crossing	144	Cycleway to the right	154	Opposite direction-corner/tip

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Unpacking Older Drivers' Mobility at Roundabouts: Their Visual-motor Coordination through Driver-vehicle-environment Interactions

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Abstract

While the mobility and safety of older drivers are challenged by age-related cognitive changes, the increasingly complex road environment places a higher demand on their adaptability. Older drivers experience difficulties in regulating their operational level behaviours which rely on the second-to-second decision-making, e.g., using the visuospatial information to guide their steering. The roundabout manoeuvre is one of the critical scenarios for older drivers which requires efficient visual-motor coordination. Understanding older drivers' visual-motor coordination at roundabouts can provide insights into the mobility and safety of the older driver population, which is important yet to be explored. This paper contributes to new measurements in driving behaviour through quantitative examinations on driver-vehicle-environment interactions. The drivers' visual-motor coordination is conceptualized as a sequence of eye fixations coupling with the vehicle trajectory in a space-time path. The experimental data were from 38 older adults' on-road driving recorded using context and location-aware enabled eye tracking and precise vehicle movement tracking. A visual-motor coordination composite indicator (VMCCI) was developed to measure the efficiency of visual-motor coordination in GIS based on the aggregate multiple parameters of visual and motor behaviours, such as eye fixation frequency and duration, lane keeping and speed control. The results show that the VMCCI is a sensitive indicator to identify the risky drivers, problematic road sections, problematic behaviours. This study has set out the concept of visual-motor coordination in driving mobility as a basis and provided a useful model for evaluating driving behaviour and thus potential interventions for older drivers.

Key Words: Older drivers; Vehicle movement trajectory; Visual search; Context and location-aware enabled eye tracking; Visual-motor Coordination Composite Indicator (VMCCI).

1. Background

The older population is living longer also driving longer, age-related changes and the increasing complexity of traffic put this group at a rising risk for unsafe driving behaviours and crashes (Baldock & McLean, 2005; Dellinger, Langlois, & Li, 2002; Eberhard, 2000). The older drivers group has the second highest fatality rates from vehicle crashes after teenage drivers (Classen et al., 2007). In fact, due to their frailty and fragility, this group has the highest risk for injuries among all the adult driver groups (Oxley, Langford, & Charlton, 2010). Statistics also show an over-representation of older drivers in angle collisions, crashes at intersections, crashes when turning and changing lanes (Clarke, Ward, Bartle, & Truman, 2010; Marmeleira, Ferreira, Melo, & Godinho, 2012; McGwin & Brown, 1999; Staplin, Lococo, Byington, & Harkey, 2001; Staplin, Lococo, Martell, & Stutts, 2012). Consistent with the crash statistics, older drivers also report having increasing difficulties in reading, computing and comprehending road signs when under time pressure; and maintaining a constant speed at the speed-limit (Musselwhite & Haddad, 2010).

In general, drivers take three levels of hierarchical decisions towards driving actions (Michon, 1985): strategic (high-level plans such as choosing the route), tactical (moment-to-moment judgments such as overtaking), and operational (second-to-second behaviours such as braking or steering). The operational level decision involves vehicle controlling or executive behaviours which complete the actions decided at the tactical level. This level actions should be performed with little conscious thoughts due to the time constraints (Glaser, Rakotonirainy, Gruyer, & Nouveliere, 2007). Older drivers are most able to make strategic and tactical decisions, but that they may experience difficulties in conducting their operational behaviours, such as using visuospatial perception to guide their steering and brake (Hong, Kurihara, & Iwasaki, 2008), in particular at challenging driving scenarios with a higher workload.

Strong relationships were found between crashes, roadway-based geometric inconsistency, and driving workload (Green, Lin, & Bagian, 1994; Krammes & Glascock, 1992; Messer, 1980). The complexity of the road environment places increasing demands on drivers' adaptability, older drivers become doubly disadvantaged on the road since aging can diminish their capacity to accommodate the increasing workload (Oxley et al., 2010). Therefore, older drivers are often operating the vehicle under pressure, and if it exceeds their attentional and cognitive capacities, risky behaviours would happen on road leading to crashes.

Managing the problem of older drivers demands approaches at multiple geographical and multi-scalar levels, to address on the road design, the road user and the vehicle interaction (Oxley et al., 2010). A complete understanding of aging and mobility is required for many aspects of research in older drivers. Schwanen & Páez (2010) stated that the context and interactions affecting the ability of old people to travel should be raised to the top priorities. Many crashes were caused by failures in the interactions between the driver, vehicle, and road environment (Violence, Prevention, & Organization, 2013). A driver's mistake characterises the outcome of an action, rather than being the cause of a crash (Hong et al., 2008), and human error was found to be a contributing factor for over 90% of crashes, and be the sole cause in about 57% of total (Treat, Tumbas, McDonald, Shinar, & Hume, 1979). In recent years there has been a growing interest in understanding driving performance through studying complex perceptual-motor skills (Drew & Waters, 1986; Elander, West, & French, 1993; Lajunen, Corry, Summala, & Hartley, 1998; Martinussen, Sømhovd, Møller, & Siebler, 2015; Müller, Brenton, Dempsey, Harbaugh, & Reid, 2015). Drivers' ability to perceive cognitive resources involving visuospatial and motor coordination are critical for making turns or passing through intersections (Schweizer et al., 2013), yet, little research has been done regarding coordination between visual and motor actions in driving. Visual-motor coordination (VMC) can be construed as the extent to which visual perception and fine motor skills are well coordinated (Beery, 2004). The ability to perform efficient and precise movements is an essential part of functioning in everyday activities. However, the advance in aging can cause decrements in speed and accuracy of motor control (Rodrigue, Kennedy, & Raz, 2005; Spirduso & MacRae, 1990), as well as the visual processing and attention in driving (Smither et al., 2004). VMC in older drivers requires the operational level decision can become most problematic due to their reduced cognitive functioning.

The visual information for a driver is predominant (Sivak, 1996), when and where a driver look is of vital importance to the driving safety (Lee, 2008; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). While negotiating a roundabout, the driver's eye movement and steering are closely linked (Chattington, Wilson, Ashford, & Marple-Horvat, 2007). The ability to control over vehicle speed and alignment at roundabouts indicates the strength of the driver's visual-motor coordination. Inappropriate vehicle speed and lane position were reported as factors contributing to crashes on horizontal curves (Fitzsimmons, Nambisan, Souleyrette, & Kvam, 2012). Pilot studies have attempted to detect risky drivers by coupling drivers' gaze behaviour and vehicle operation behaviour (Mori, Miyajima, Hirayama, Kitaoka, & Takeda, 2013; Yekhshatyan & Lee, 2013). Yet, mostly the data collected at the section-scale level, the nature and underlying mechanisms of the older drivers' behaviour behind the wheel have not been fully defined in publications to date.

The use of modern roundabouts is meant to improve the safety at intersections by minimising conflicts and reducing drivers' speed. However, roundabout performances can be degraded if precautions were not taken during either the design or the operational stage (Montella, 2011). Geometric design deficiencies were identified as contributory factors in roundabout crashes (Montella, 2011). Knowledge and findings on the safety of the roundabouts are helpful for planners and designers in refining the design criteria. For road users, the information sampling requirement increases with the increasing road curvature, more frequent information and corrective steering input are therefore needed, which leads to an increased eye-steering correlation and more efficient coordination (M. Land & Horwood, 1995; Miall & Reckess, 2002; Tsimhoni & Green, 2001). Understanding older drivers' visual-motor coordination while they negotiating roundabouts becomes particularly important for older drivers' mobility and safety.

We, therefore, structure this paper, from a geographic perspective, to allow an interdisciplinary approach that all above literature (older drivers, visual-motor coordination, and roundabouts) can be incorporated into a comprehensive model to evaluate and ultimately improve older drivers' behaviour and performance at roundabouts.

2. Visual-motor Coordination (VMC) in Time-geography

Time-geography has long been regarded as "an instructive approach to the study of time, space and human activities" (Duncan, 1984). Time-geography provides an effective environment to chart the backbone of movement patterns and can be extended to the representation of complex movement process in various applications, such as human activity modelling and microsimulation (Gugerty, 1997). Time-geography is an elegant perspective for analyzing the interrelationships among individual activities in space and time (Miller, 2004).

Hägerstrand (1970) emphasized the importance of time in human activity and the constraints that can limit the performance of human activities in physical space and time, which eventually shape the human movement patterns. Fundamental physical restrictions on abilities and resources are summarized as capability constraints, such as a person's ability to trade time for space (Kiefer, Raubal, & Schlieder, 2010). The coupling constraint is the need for a person to present at a particular location at a certain time or during a specific time interval. Authority constraints set the limit for a person's access to either spatial locations or time periods (Miller, 2005). The space-time context of a physical activity can be explicitly represented through its space-time path, and potential physical activities that are available to an individual in physical space and time can be depicted by space-time prisms (Hägerstrand, 1970, 1989). To understand human spatial behaviour, mobility should be treated as a path "which orders events as a sequence, which separates cause from effect, which synchronizes and integrates" (Mozer & Vecera, 2005).

Placing driving mobility in a space-time context and using constraints concept and the space-time path model would facilitate the understanding of the driver-vehicle-environment interactions. Different from other human mobility and behaviours, such as commuters' travel behaviour, tourists' movement, the driving behaviour presents unique characteristics in time-geography of which we need to be aware during investigation: 1), two activities (vision and motor) are intertwined in space over time, active gaze guides and shapes locomotor trajectories (Wilkie, Wann, & Allison, 2008); 2), multiple spatial-temporal dimensions are demonstrated in the manifold of vision and motor behaviour; 3) spatial-temporal patterns of both visual search and vehicle control are at micro scale level.

Gaze pattern is a crucial component for executing skilled actions, in particularly, when controlling of locomotion (M. F. Land & Lee, 1994; Wilkie et al., 2008). Driving, according to Gibson and Crooks (1938), is a locomotion through a terrain by means of a vehicle to reach a destination. The basic activity is to achieve a path (a vehicle trajectory) determined by its proper speed and direction, so as to agree to the spatial constraints (the road infrastructure) and avoid collisions with any obstacles (other vehicles, pedestrians). Driving is guided mainly by the vision, which enables the driver to acquire environmental information from a distance, in order to anticipate the future situation and to take control actions in time (Cavallo & Cohen, 2001). There is a dependent relationship between visual search and vehicle control behaviours, which needs to be considered in driving assessment.

Vehicle driving in a certain manoeuvre results in two space-time paths as eye movement path and vehicle trajectory. The visual patterns and vehicle trajectory reflect how the driver dealt with the constraints and operate the vehicle, therefore, one approach to assess driving behaviour is to examine the efficiency of visual search guiding vehicle control in the traffic environment. Eyes typically move in discrete jumps as saccades between fixations which produce an irregular trajectory (Çöltekin, Demšar, Brychtová, & Vandrol, 2014), while the vehicle moves continuously producing a smooth trajectory. Two trajectories are guided by the same process of the driver's visual search on surroundings. Geographically, eye movement and vehicle movement are co-located in space and time.

Driving activity is one kind of visually-guided locomotion forms an evolving visual-motor coordination path in the space-time context, which is shaped by individuals' cognitive conditions and traffic situation. For older drivers, multiple constraints will be imposed on their visual-motor coordination performance at roundabouts. The eye tracking integrated with vehicle positioning would lead to interest in processing, analysing and interpreting older drivers' behaviour in geographic space with more detailed visual-motor control patterns. In this paper, the visual-motor coordination episodes will be constructed in order to effectively measure the participants' performance of visual-motor coordination in a very fine scale. Specifically, the objectives of this paper are to:

- Develop a visual-motor coordination measurement for assessing individual older drivers' visual-motor coordination performance at roundabouts.
- Investigate the relationships between older drivers' visual-motor coordination and visual search parameters at roundabouts.
- Investigate the impact of the roundabout features on older drivers' visual-motor coordination.

3. Data Collection and Analysis

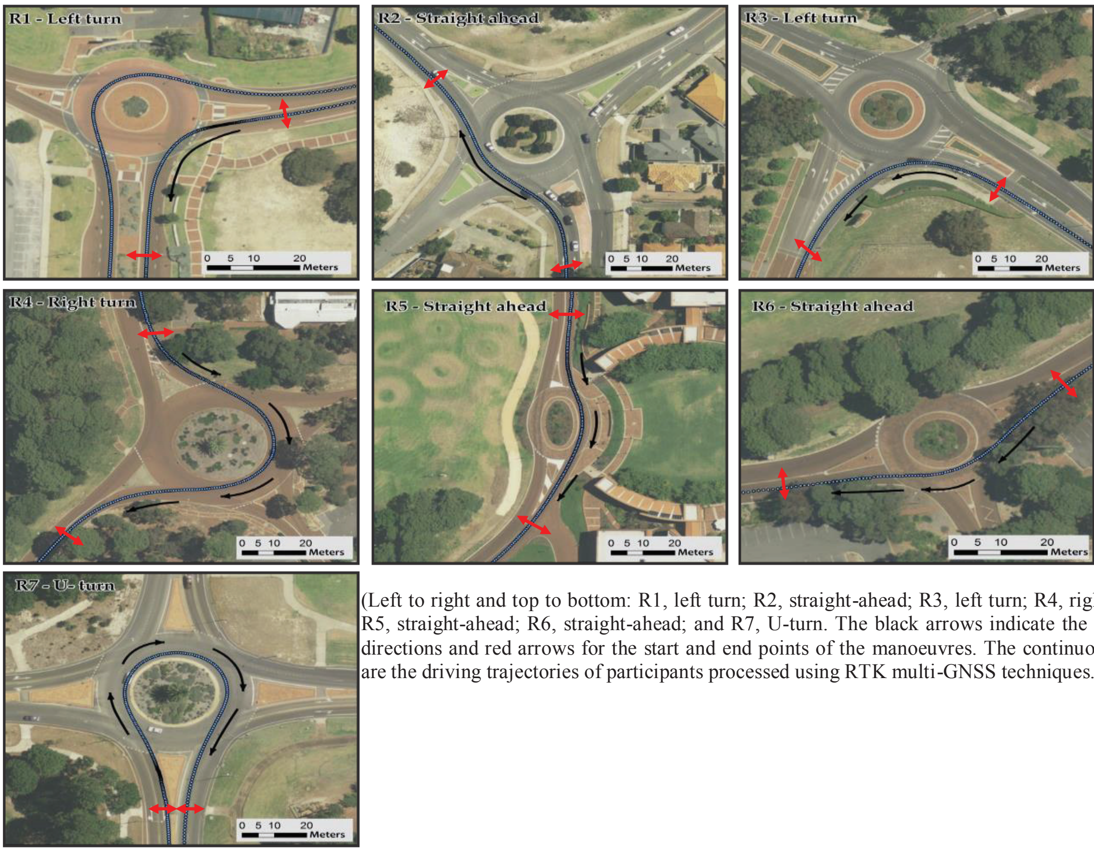
3.1. Participants

Thirty-eight older drivers between the age of 60 to 81 (mean = 68.7, SD = 5.6) were recruited from the local community. Participants were eligible for inclusion if they held a valid full driver's license for a non-commercial motor vehicle; drove at least 3-4 times/week. Participants were excluded from the study if they have a cognitive or physical impairment that would interfere with their driving ability. Participation in the study was voluntary and informed written consent was obtained from each participant. Ethics approval was granted by the university Health Research Ethics Committee (Approval no. HR68_2014).

3.2. Study area and site features

The study area of the road network was chosen around the campus of Curtin University in Perth, incorporating seven roundabouts from Roundabout1 (R1) to Roundabout7 (R7), approximately 1.5 km radius distance from the Curtin GNSS (Global Navigation Satellite System) base station. The base station provides simultaneous reference satellite navigation files which enable the cost-effective techniques for processing precise vehicle movement trajectories of the participants (Sun, Xia, Foster, Falkmer, & Lee, 2016).

Fig. 1 below illustrates the layouts of roundabouts and the entry/exit points of negotiating path at each roundabout. The entry/exit points were carefully defined based on the physical feature of the roundabouts.



(Left to right and top to bottom: R1, left turn; R2, straight-ahead; R3, left turn; R4, right turn; R5, straight-ahead; R6, straight-ahead; and R7, U-turn. The black arrows indicate the driving directions and red arrows for the start and end points of the manoeuvres. The continuous dots are the driving trajectories of participants processed using RTK multi-GNSS techniques.)

Fig. 1. Study sites incorporating with various roundabout manoeuvres: entry/exit points and negotiating paths

In order to understand the complexity of the above roundabouts that would impact on drivers' visual-motor coordination, we construe the geometrical features for each roundabout and the negotiating path in a particular. The parameters are illustrated in Appendix 1 for a left turn as a sample and reported in Appendix 2 for the total seven roundabouts. Inscribed circle radius, the number of exit legs and number of lanes were used to represent the dimension and complexity of each roundabout. The bigger size of a roundabout could indicate bigger capacity. However, the inscribed circle diameter was found to be positively related to the frequency of vehicle crashes (Mahdalova, Krivda,

& Skvain, 2013). An entry angle is used to describe the complication of each manoeuvre passing the roundabout. Entry angle is the angle between the tangential line to the median line on the roundabout and the tangential line to the negotiating path. Too large angles could lead to visibility problem at the entry and severe neck turning for drivers. Typical value is between 20 - 40 degrees (Dahl & Lee, 2012).

3.3. Vehicle movement tracking and eye tracking

The on-road driving assessment simultaneously recorded each driver's eye movement and vehicle movement trajectory as Fig. 2 exhibits. It took participants through an urban residential area about 10 km long, and about 20 minutes to drive. GNSS (Global Navigation Satellite Systems) was used to track precise vehicle movement trajectory, which formed the basis of individual movement data and enabled spatial and temporal analysis. Eye tracking recorded human spatial perception and cognition context information, as well as the human-environment interaction. GIS (Geographic information System) provides a platform for data integration and management and facilitated mapping of data and results for exploration and analysis.

- *Precise vehicle movement tracking*

GNSS receiver (Trimble R10) was mounted on the participant's car roof to record the vehicle movement trajectory. The receiver is able to track multi-GNSS beyond GPS-only approach in the satellite visibility and reliability, this is essential for recording vehicle movement in an urban area when the precise vehicle positioning and smoothest trajectory are required (Kubo, Hou, & Suzuki, 2014; Noomwongs, Thitipatanapong, Chatranuwathana, & Klongnaivai, 2014). The tracking configuration was setup at 10 Hz to record the car positions at every 0.1 seconds. Real-time kinematic (RTK) postprocessing technique was used to achieve centimeter to decimeter level horizontal accuracy by minimizing the effect of error sources transmitted between the satellites and GNSS receivers (Sun et al., 2017). The processed data was then mapped to calculate the vehicle lane position and speed for assessing driving motor skill, and linked to the eye fixation data which establishes the core dataset of visual-motor coordination of the drivers. The vehicle lane position refers to the distance between the vehicle positions to a benchmark (road center) line. The Mean Lane Position (MLP) and Standard Deviation of Lane Position (SDLP) of vehicle lane position were used as the lane maintenance parameters.

Fig. 2. GNSS tracking, eye tracking, driving path and the context of on-road driving assessment

- *Context and location-aware enabled eye tracking*

Participants were asked to drive their own car with eye tracker (Arrington Viewpoint™) mounted on their heads. Eye movements were recorded using a contactless eye movement video system with a time resolution of 60 Hz, which is based on reflection of infrared light from the cornea and allows the coordinates of gaze direction to be measured. Eye movement data was first processed by the system including extracting eye fixations and fixation durations, a proxy to driver's attention and reaction to external stimuli from the environment (Falkmer, Dahlman, Dukic, Bjällmark, & Larsson, 2008). This study employed the dispersion centroid mode algorithm for eye tracking data analysis; originated and validated by Falkmer et al. (2008). The algorithm separated saccades from fixations (the period of time when the eyes remain relatively still) in order to focus on conscious perception and attention. Each eye fixation was then manually labeled in three qualitative categories to identify the focus of attention of the subject while driving: the object that was fixated; the background of the object that was fixated, and the distance of the object from the driver. Three different gazing distances (inside vehicle, outside vehicle < 5 m, and outside vehicle ≥ 5 m) were noted. In addition, individual eye fixations were classified as either traffic-relevant or non-traffic relevant objects (Sun, Xia, Falkmer, & Lee, 2016). Apart from these context information, we also captured the start time of each fixation from the eye tracking video. Eye fixations were then synchronized with the vehicle trajectory recorded by the GNSS receivers, by doing so; each eye fixation was geo-coded with reference coordinates of the vehicle position, and the resulted database accommodates where the exact location is at the roundabout when the eye fixation happened.

- *Visual-motor coordination data integration*

The geo-coded eye fixation data and the vehicle movement data were integrated into a visual-motor coordination geodatabase in GIS. Fig. 3 briefly shows the steps of VMC data capturing and integration, as well as the construction of visual-motor coordination episodes. The VMC data model has been described in an earlier publication (Sun, Xia, Nadarajah, et al., 2016). Based on the visual-motor coordination data model, visual-motor coordination episodes were constructed in order to effectively measure the participants' behaviour and performance. Each episode contains one eye fixation and the corresponding segment of vehicle trajectory, with a series parameters of visual search and vehicle control. The reasons for doing this since it attempts to use the natural breakpoints in the dataset itself to create order within the trajectory history. Individual VMC episode represents a discreet time period for the driver's visual-motor coordination. The intention is to split up the huge dataset into sets of points that can be analysed more effectively (Mountain & Raper, 2001). The (x, y) coordinates of the vision-motor coordination episodes can be overlaid with other environment and transport information in GIS for further analyzing individual drivers' behaviour and performance (Sun, Xia, Nadarajah, et al., 2016).

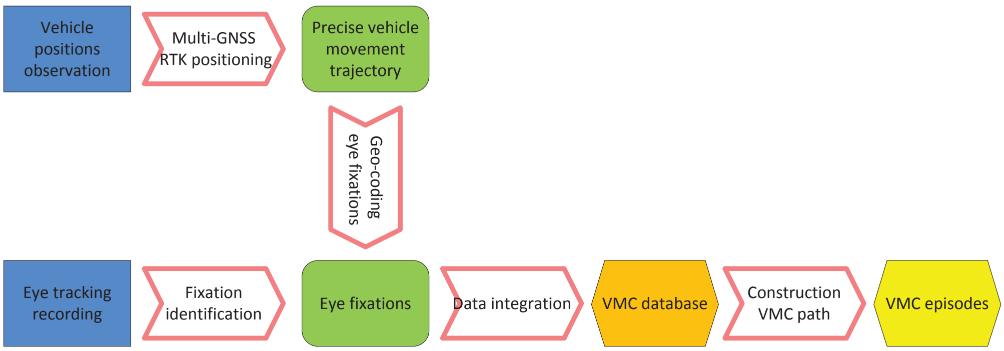


Fig. 3. Data processing flow of constructing visual-motor coordination episodes

3.4. Creating a visual-motor coordination composite indicator (VMCCI)

To evaluate the VMC performance of each driver, an output-oriented Data Envelopment Analysis (DEA) model (Chen, 2004; Cooper, Seiford, & Zhu, 2004; Zbranek, 2016) that evaluates multiple inputs and outputs of VMC episodes was used. All the visual search and vehicle control information (Table 1) at the three stages of each roundabout was combined by using the concept of composite indicators. DEA is an optimization model for measuring the relative performance of a set of DMUs (decision making units), the older drivers in this study. In the basic DEA model, by solving a linear programming problem, the best possible indicator weights can be determined.

The method involves the creation of a "virtual" perfect driver for benchmarking (Cherchye et al., 2008), which has the best performance of inputs and outputs. The visual search parameters for the virtual driver were adapted from the driver who performed the lowest MLP and SDLP, and the vehicle control parameters were given zero value for the MLP and SDLP. Considering one perfect driver's influence on other drivers makes the model more comprehensive and effective. A recognized strength of DEA modeling is that it looks for internal (possibly constrained) weights for individual parameters, then produces an overall score that depicts the analyzed decision making unit in its best possible light relative to the other observations (Cherchye et al., 2006). This study investigates the relative performance of older drivers at the individual level, based on specific measures of visual-motor coordination efficiency. Inputs, in this model, are visual search parameters. Vehicle control parameters were included as outputs. Parameters were benchmarked and normalized in DEA to calculate a composite score for individual older drivers.

Table 1 Parameters for calculating participants' visual-motor coordination performance

	VMCCI parameters
Visual search	Gaze at curve
	Straight ahead gaze
	Look inside vehicle
	Look outside <5m
	Look outside ≥5m
	Traffic relevant gaze
	Fixation frequency
	Fixation duration
Vehicle control	Mean Lane Position (MLP)
	Standard Deviation of Lane Position (SDLP)

Since the visual search behaviour varies between different stages of the roundabout, to get precise weights and generate the DEA input and output parameters for benchmarking, we segmented each roundabout into three stages in GIS: entering, in and exiting. Each stage contains a series of visual-motor coordination episodes, Fig. 4 exhibits the visual-motor coordination episodes on VMC path in relation to roundabouts. The VMC at each stage will be calculated based on the aggregated visual pattern and vehicle control parameter from VMC episodes at that section of the roundabout. The visual search and vehicle control parameters at each stage of seven roundabouts for individual drivers were loaded into the DEA model for benchmarking and calculating the VMCCI.

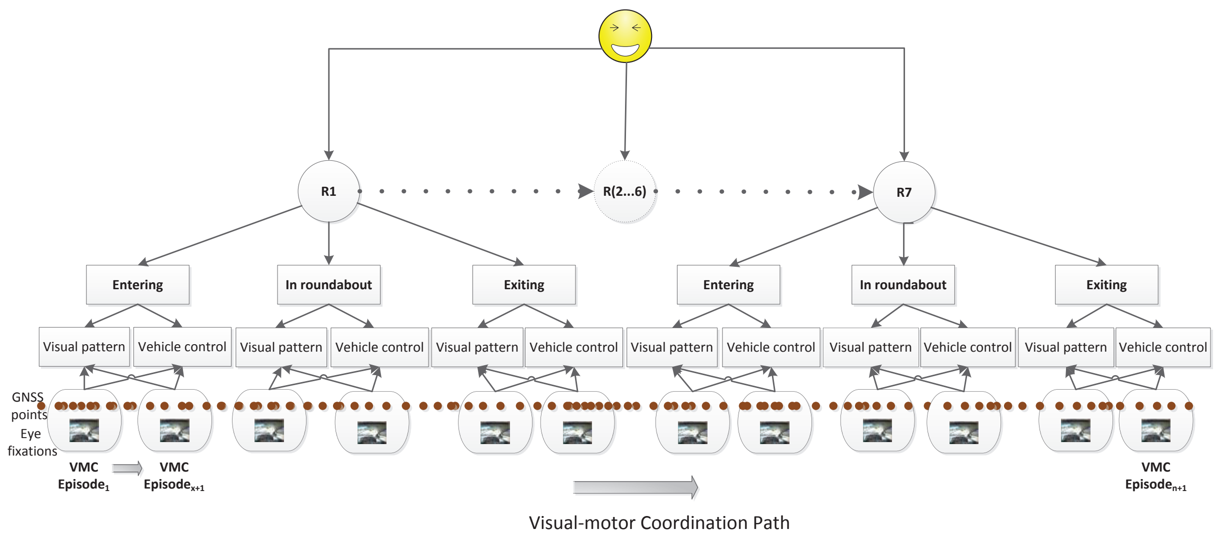


Fig. 4. Visual-motor coordination at different stages of roundabouts based on the visual pattern and vehicle control parameter from VMC episodes on VMC path

The process of DEA linear programming task is to solve the constrained optimization problem, which minimizes the index value of the driver and satisfies the imposed restrictions (Cherchye et al., 2008). The restriction guarantees an intuitive interpretation of the composite indicator and the VMCCI can be formulated as follows:

Objective function:

$\mathrm{VMCCI_j}$: A set of DMUs (decision making units), here the older drivers

$$\mathrm{VMCCI_j} = \min \sum_{r=1}^{s} \lambda_r y_{rj} \qquad r = 1, \dots, s; j = 1, \dots, n$$

subject to:

$$\sum_{i=1}^{m} \omega_i x_{i_j} - \sum_{r=1}^{s} \lambda_r y_{r_j} \geq 0 \qquad i = 1, \dots, m$$

$$\sum_{i=1}^{m} \omega_i x_{i_j} = 1$$

$$\omega_i > 0 \qquad \lambda_r > 0$$

where

x_{i_j} = as “input” refers to the gazing behaviour (aggregated visual search parameters)
y_{r_j} = as “output” refers to the vehicle control behaviour (aggregated vehicle control parameters)
ω_i = internal weight associated with indicators for input parameters
λ_r = internal weight associated with indicators for output parameters

The result of above process is the optimized score of evaluated driver $\mathrm{VMCCI_j}$, which is defined as the ability to achieve minimum outputs (vehicle control) by optimizing the inputs (visual search). The model output ranks the participants from the best, with the ignorance of the virtual perfect driver ($\mathrm{VMCCI_0}$ = 1), to low performance drivers in terms of their visual-motor coordination at one of the three stages of the seven roundabouts. This study also calculated the mean VMCCI at each roundabout for individual drivers, and the mean VMCCI for seven roundabouts for each driver.

4. Results

4.1. Overall VMCCI scores and individual older drivers’ VMC performance

The overall visual-motor coordination performance ranking for 38 older drivers is shown in Fig. 5. In comparison to other drivers, driver 26 performed best with more gaze on curves and straight ahead fixations at roundabouts; the driver also demonstrated high fixation frequent per manoeuvre time, resulted in low MLP and SDLP. The worst performance from Drive 23, on the contrary, showed poor visual search strategies in the gaze pattern, with comparably very inadequate fixations on curves but performed more frequent fixations on non-traffic relevant objects, this driver had a high SDLP in vehicle control at roundabouts.

Fig. 6 demonstrates an example VMCCI pattern at three stages of seven roundabouts from a low-performance driver. Overall the VMCCI values from this driver are very low. All the values are lower than 0.20 except exiting at roundabout 7, indicating that poor visual search and vehicle control behaviours performed by the driver. The problematic driving behaviours can be identified for each stage at individual roundabouts, such as inadequate eye fixations at curves at the exiting at roundabout 3. Corresponding eye tracking video footage and GNSS tracking vehicle trajectory can be reviewed for intervention recommendation.

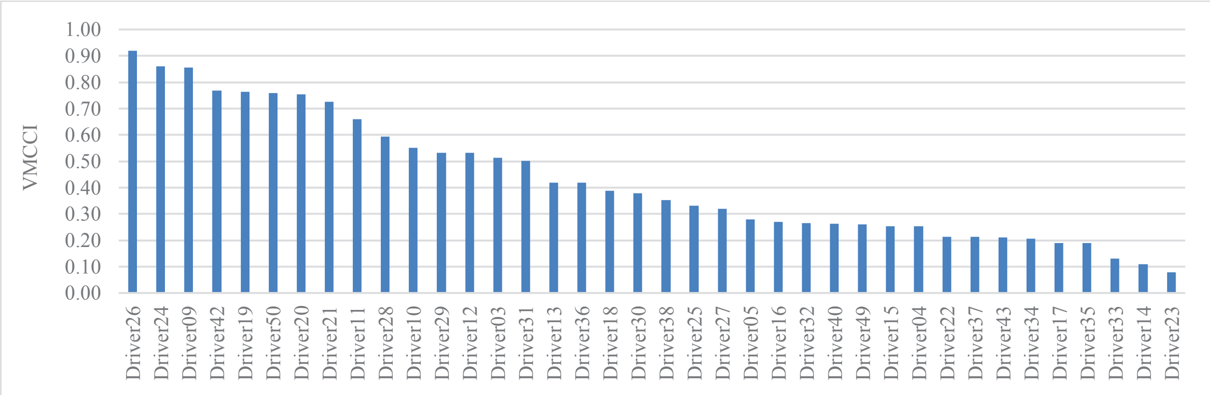


Fig. 5. Rank of visual-motor coordination composite indicators (VMCCI) among participants

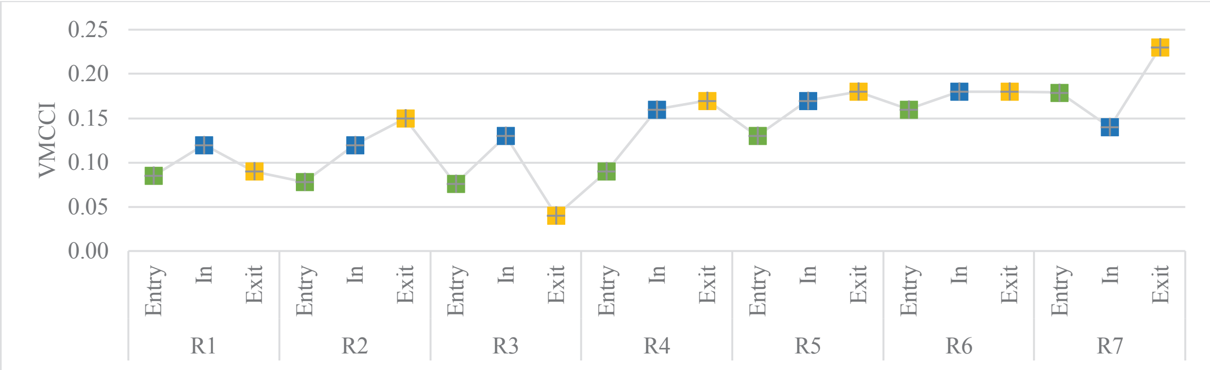


Fig. 6. A sample distribution of individual driver's VMCCI at the entry, in-roundabout and exit stages along seven roundabouts

4.2. The associations between VMCCI and visual search parameters

For the group, Table 2 demonstrates the associations between visual search and VMCCI scores. Gaze at curves and fixation duration presented positive associations with visual-motor coordination scores (p <.01). Straight ahead gaze and fixation frequency were also positively associated with VMCCI scores (p < .05). A negative but not significant correlation is observed between the category of "Look inside vehicle" and VMCCI. No other significant correlations were found between VMCCI and other visual search parameters, and the correlation coefficients were very low.

Table 2 Correlations relationships between VMCCI and visual search parameters

Visual search parameters	Pearson Correlation Coefficients and Significances
Gaze at curves	.435**
Straight ahead gaze	.322*
Traffic relevant	.248
Look inside vehicle	-.320
Look outside < 5m	.029
Look outside ≥ 5m	.283
Fixation frequency	.411*
Fixation duration	.495**

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

4.3. Spatial pattern of older drivers' VMC performance in roundabout driving

Fig. 7 presents the statistics of average VMC performance in the group at the entry, in-roundabout and exit stages for individual roundabouts. Overall, the highest VMCCI is found at the roundabout 5 and the lowest value at the roundabout 3. The group performed a lowest VMC at the entry of roundabout 3 and a best VMC in the roundabout 1. The in-campus roundabouts (R1, R5, and R6) returned higher value of VMCCI perhaps due to the low traffic. Table 3 summarizes the overall performance of VMC at different stages for the seven roundabouts, in total the group performed best in roundabouts and worst at the entry of roundabouts. At roundabout 2 and 5, however, the VMC at the exit stages presented the highest, both of the manoeuvres are straight ahead at roundabouts.

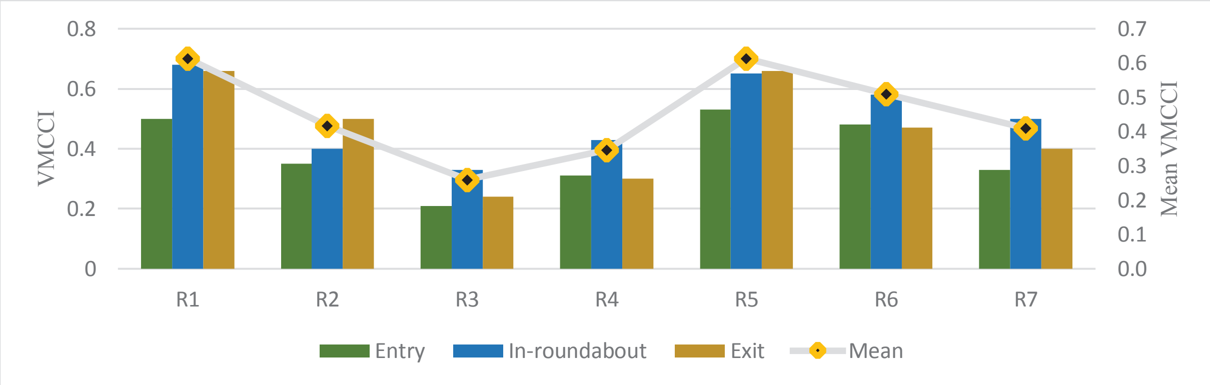


Fig. 7. The group average VMC performance at the entry, in and exit stages of roundabouts and the total mean value of VMCCI at individual roundabouts (the primary and secondary y-axis show the VMCCI values)

Table 3 Overall performance of VMC at different stages of roundabout

Stage	Entry	In-roundabout	Exit
$VMCCI_{mean}$	0.39	0.51	0.46

4.4. Visual, motor behaviours in relation to the complexity of roundabout manoeuvres

Tables 4 presents the roundabout features and the complexity of the manoeuvres in relation to visual search parameters, average speed and visual-motor coordination in older drivers. The roundabout 4 right-turn roundabout required most frequent eye fixation at curves. Entry speed into the roundabouts also impacts on the eye fixation frequency and duration. As a group older drivers demonstrated longer eye fixations at roundabout 5 and 6 (speed limits = 40 km/h) than roundabout 2 and 3 (speed limits = 60 km/h). Roundabout 5 demanded the longest duration and the most frequent eye fixations. Interestingly, roundabout 5 has the smallest inscribed circle diameter of the roundabouts, but the lowest passing speed. Our data suggests that passing speed had more influence on the duration and frequency of eye fixations than the size of the roundabout. R1 and roundabout 3 involved a left turn maneuver. Although negotiating roundabout 3 involved similar duration and number of eye fixations as roundabout 1 and they both involved a left turn maneuver; roundabout 3 demanded almost three times higher duration and a number of eye fixations at curves than roundabout 1. Roundabout 3 is a multi-line roundabout; with the entry speed limit of 60 km, entry angle of 40 degrees, the average passing speed of 31 km/h. Roundabout 1 is a multi-line roundabout, with entry speed limit of 40 km, entry angle of 24 degrees, and average passing speed of 20 km/h.

According to Rodegerdts (2010), the recommended fastest path speed for single-lane roundabouts is 32 to 40 km/h and that for a multilane roundabout is 40 to 48 km/h. In the current study, participants' average passing speed was 20 km/h for single-lane roundabouts and 20 - 31 km/h for multilane roundabouts. This means that older drivers as a group drove with caution. A variety of factors including the geometry of the roundabout, operating tasks in the roundabout and the entering speed into a roundabout affect speed through it. For example, as shown in Table 4, lower entry angle into a roundabout allows better capacity and higher speed; while higher entry speed into a roundabout enables higher manoeuvre speed through the roundabout. In the case of the current sample, the left-turn and straight-ahead roundabouts were associated with higher manoeuvre speed than right-turn or U-turn roundabouts.

A relationship can be observed between the entry angle and the average VMCCI for the seven roundabouts. The largest entry angle at roundabout 3 (Appendix 1) returned a lowest VMCCI due to the more complex to manoeuvre than other roundabouts. In contrast, manoeuvre through the roundabout 5 required the smallest entry angle, where the group performed a best visual-motor coordination.

Table 4 Roundabout features and manoeuvres in relation to visual search parameters, average speed and visual-motor coordination in older drivers

	R 1	R 2	R 3	R 4	R 5	R 6	R 7
Inscribed Circle Radius (m)	16	22	19	25	Oval: 10/14.5	13	25
Number of Lanes	1	2	2	2	1	1	2
Circulating Length (m)	29	55	49	60	32	28	81
Entry Angle (°)	24	15	40	25	10	20	30
Manoeuvre	Left-turn	Straight-ahead	Left-turn	Right-turn	Straight-ahead	Straight-ahead	U-turn
Average duration of eye fixation (s)	3.81	3.87	3.47	8.15	5.48	5.43	12.25
Average duration of eye fixation at curves (s)	0.43	1.05	1.13	2.47	2.11	0.98	3.99
Average passing speed (km/h)	20	30	31	26	20	20	24
Average VMCCI	0.50	0.35	0.21	0.31	0.53	0.48	0.33

5. Discussion and Conclusions

Drivers respond to various stimuli from the environment and the multiple visuospatial perception inputs should be effectively processed so as to generate the appropriate driving reaction in a time frame compatible with their cognitive and physical conditions (Pinna, 2015). In this paper, we first defined driving mobility as a visually-guided locomotion which forms an evolving visual-motor coordination path in the space-time context. For older drivers, multiple constraints will be imposed on their visual-motor coordination performance at roundabouts. A visual-motor coordination composite indicator (VMCCI) with taking consideration of different stages of roundabout manoeuvres was developed using comprehensive visual and motor behaviour parameters from individual older drivers. All participants were successfully ranked based on their calculated VMCCI scores, and their performance respecting to different roundabouts was attained. In addition, critical sections of roundabouts with low VMC performance for both individual and group were detected.

Roundabouts are known to result in fewer traffic crashes than traditional intersections, particularly fewer crashes with fatal or serious injuries. Nonetheless, vehicle crashes still occur at roundabouts (Polders, Daniels, Casters, & Brijs, 2015). Design including geometric variables, however, will greatly enhance the level of safety (Harper & Dunn, 2003). The geometry of modern roundabouts is thought to compensate for the cognitive limitations of older drivers. For example, by lowering the speed through the roundabout, older drivers are afforded more processing time to make the appropriate decision and enter the roundabout at an entry angle, which provides better visibility. However, a study conducted in Netherlands demonstrated that older drivers have difficulties in driving through roundabouts which have more than one lane (Mesken, 2002). The current study presented a more comprehensive investigation and provided insights into the relationships between complex roundabout manoeuvres and visual-motor behaviors of older drivers. For example, we found that entering into roundabouts with a sharp angle would cause coordination problems in older drivers' visual, motor behaviours.

The correlation results between visual search parameters and VMCCI scores showed that some strategies can be recommended to older drivers to improve their visual-motor coordination. More frequent fixations and longer fixation durations, in general, would improve VMC performance; similarly, gaze at curves more frequent along roundabout driving and looking straight ahead when exiting increase the accuracy of vehicle control leading to better VMC. Older drivers performed poorer when entering into a roundabout than manoeuvring in or exiting, which indicate that more visual workload at entering and exiting adversely contribute to the lower performance in the visual-motor coordination. The entry angle of roundabouts thus plays a critical role in older drivers' VMC performance. These findings reveal the importance of locating the optimal environmental location (e.g., curves) at an optimal time (entering or exiting).

A major strength of the current study is that the very special human mobility of driving behaviour was investigated through the examination of driver-vehicle-environment interactions. Older drivers visual and motor behaviours were recoded, linked and the coordination was assessed. This paper is part of research exploring various ways to investigate the complexity of older drivers' behaviour through the sentient movement in space and time. This paper makes an important contribution by demonstrating the possibility and value of considering the coupling of steering and eye movements over time and space. This provides a new set of indicators that can be incorporated into driving assessment and intervention program.

The VMCCI methodology is valuable for older drivers' assessment at the individual level and for detecting problematic aspects of driving behaviours, which in turn can be helpful for more customized training purposes; older drivers can be trained in specific sub-tasks, according to each driver's weakness in terms of visual search and vehicle control, thereby improving driving abilities and the level of road safety. It is important to recognize what critical driving abilities are deteriorated with aging, and identify the drivers who need intervention, so they can continue to use their vehicle in safe conditions. It is also important to acknowledge the influence of environment factors on these critical driving abilities, for example, the geometric aspects of road sections are visible to the drivers and affect their driving performance (Hong et al., 2008).

Despite above contributions and implications, there are limitations existing in this study which should be improved in the future. The primary limitation of this research has been the complexity of raw data processing. An important consideration in generalizing the results of this paper concerns its reliance on data quality. The complex of datasets and the integration have raised concerns about the data accuracy and uncertainty, such as GNSS has variable performance under certain conditions, eye tracking analysis algorithm also has uncertainty, all of which could have affected the overall performance achievable. The centimeter-level vehicle movement data is more reliable in areas under open sky since GNSSs perform better when many satellites are in view and the signals are uncorrupted. This has little impact on this study since the critical areas (intersections and roundabouts) are all under open-view, however, analysis on the entire route needs to conduct data accuracy assessment and control prior to using the data. Eye tracking data accuracy might be caused by calibration issues and lighting issues. Glare is a continuing problem in studies on the road. The fixation identification algorithm simplifies the eye movement types. The 16-points calibration before eye tracking and the frame by frame manual identification have improved the errors and misclassifications in the output. However, the automatic program should be introduced in the future to minimize any errors by manual processes.

This paper has been permeated by time-geography perspective, which in general concerns people's use of time and place, the resources they have and the constraints they face in order to carry out activities. Time-geography concepts can be transferred into driving mobility and behaviour studies since it includes activities, projects, contexts, resources and constraints. Those elements are theoretically and empirically important to understand how mobility strategies and experiences of mobility are intertwined in everyday life. In this study, the power of time-geography has been enhanced tremendously by the combination of GIS, GNSS and eye tracking, while basic time geographic principles have proven to be useful in travel behaviour and transportation research (Miller, 2004). GNSS and eye tracking together collected accurate and detailed space-time trajectories at the individual driver level, and allowed more detailed representation of space-time environments, and computationally scalable methods for discovering new knowledge from driving behaviour datasets. Moreover, this research extended the scope of time-geography by adding individual cognitive conditions into the constraints. A new time-geography is emerging which shows potential as well as challenges for imperative and fascinating research.

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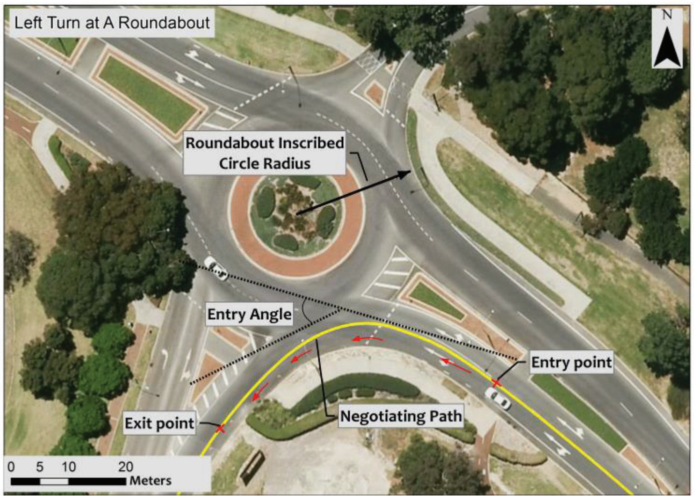
Appendix 1 Illustration of geometrical features of a roundabout and the driving negotiating path and angle



Appendix 2 The geometrical features and driving manoeuvres between seven roundabouts

		R 1	R 2	R 3	R 4	R 5	R 6	R 7
Roundabout Features	Number of Lanes	1	2	2	2	1	1	2
	Number of Legs	3	4	4	4	2	3	4
	Inscribed Circle Radius (m)	16	22	19	25	Oval: 10/14.5	13	25
Manoeuvre Features	Manoeuvre	Left-turn	Straight-ahead	Left-turn	Right-turn	Straight-ahead	Straight-ahead	U-turn
	Exit Leg	First	Second	First	Third	First	Second	Fourth

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Unpacking Older Drivers' Manoeuvre at Intersections: Their Visual-motor Coordination and Underlying Neuropsychological Mechanisms

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Abstract

Background: Negotiating intersections is one of the principal concerns for older drivers as it requires precision and efficiency in visual-motor coordination (VMC). The complex intersection manoeuvre places high demands on visual perception, attention, motor control and executive functioning. Understanding the relationship between VMC and cognitive abilities in older drivers is important, but is yet to be systematically explored. Consequently, little is known about the cognitive factors impact the VMC in older drivers.

Methods: This study examined 38 older drivers' manoeuvres at intersections recorded by eye tracking and advanced surveying technologies. Visual-motor coordination for each participant was measured using multiple parameters of visual (e.g., frequency and duration of eye fixations) and motor (e.g., lane keeping) behaviours using a Data Envelopment Analysis (DEA) model. Participants also performed a battery of cognitive tests of visual attention, spatial abilities, visual-motor speed and executive functions. Statistical correlations between participants' age, cognitive abilities and their VMC were computed; multiple linear regression was used to investigate the possible impact of cognitive abilities on VMC performance.

Results: Eye fixation frequency was negatively correlated with lane maintenance parameters and VMC performance. Traffic relevant eye fixation was also negatively associated with VMC. Significant correlations were noted between VMC and performance on eight measures: UFOV 2 and 3, Block Design, Benton's JLO, D-KEFS TMT 1, 2, 3 and 4. Performance on this combination of cognitive tests explained a significant amount of the variance in VMC ($R^2_{Adjusted} = .53$, $p = .00$). Tests measuring selective attention, spatial ability and executive function were noted to be the best predictors for VMC performance (β =.29; .39; .30 and p = .04; .01; .02 respectively).

Conclusions: Specific elements of cognitive ability in older drivers was associated with poorer VMC at intersections. It appears that eye fixation frequency presented insufficient information in participants with low VMC scores, which resulted in poor lane maintenance. Lower VMC also reflected inadequate traffic relevant fixations. Spatial ability, executive functioning, and selective attention strongly influenced older drivers' VMC during intersection manoeuvres.VMC assessment is potentially able to identify risky older drivers and their problematic behaviours. It is suggested based on these findings that tailored driving evaluation and intervention programs should be developed for older drivers.

Key Words: Older drivers; Intersections; Visual-motor coordination (VMC); Neuropsychological tests.

The older population around the world is increasing rapidly (Matas, Nettelbeck, & Burns, 2014) as is the complexity of the traffic environment. Statistics reveal a rising rate of car crashes in older drivers, aged 65 years and older (Evans, 1988; Fildes, 2006; Rakotonirainy, Steinhardt, Delhomme, Darvell, & Schramm, 2012). There is also an over-representation of older drivers in angle collisions, crashes at intersections, turning and changing lanes (Clarke, Ward, Bartle, & Truman, 2010; Marmeleira, Ferreira, Melo, & Godinho, 2012; J. G. McGwin & Brown, 1999). In a study of a series of left turn (equivalent to right-turn in Australia) road collisions in Denmark, Larsen and Kines (Larsen & Kines, 2002) revealed that over 35% of collisions involved a driver over 74-year-old, and within all of these collisions, the older drivers were at-fault when turning. In Australasia, Oxley et al. (Oxley, Langford, & Charlton, 2010) investigated the patterns of on-road vehicle crashes and found that 97% of all high crash locations amongst older drivers were at intersections.

Age-related reductions in cognitive and visual motor operation lead to unsafe driving behaviours in the older drivers (Maltz & Shinar, 1999; Sivak, 1996; Sivak, Olson, & Pastalan, 1981; Warabi, Noda, & Kato, 1986; Welford, 1968). They have been shown to underperform younger drivers in a number of neuropsychological tests associated with driving performance (Andrews & Westerman, 2012; Owsley, Ball, & McGwin, 1998; Shanmugaratnam, Kass, & Arruda, 2010). Older drivers experience difficulties in driving scenarios requiring divided attention and decision making under time pressure which was reflected by their high involvement in intersection crashes (Dotzauer, Caljouw, de Waard, & Brouwer, 2013). Indeed, the primary concern in older drivers is the decline in executive functioning, which encompasses the higher order operations to organize information and regulate one's behaviour, such as prioritizing, planning ahead and following rules (Salthouse, 2004; Salthouse, Atkinson, & Berish, 2003). Also of concern is the decline in speed of processing as one ages (Salthouse, 1996), for example, older adults have been observed to take twice as long than younger adults for information processing, involving perceptual, cognitive and motor processing operations (Jastrzembski & Charness, 2007), this became even more distinct with increased cognitive workload (Cantin, Lavallière, Simoneau, & Teasdale, 2009). Our previous publication (Sun, Xia, Falkmer, & Lee, 2016) has also demonstrated the impact of intersections on the relationship between older drivers eye fixation movement and their visual capacity. Maneuvering a vehicle through an intersection requires sophisticated physical and mental workloads to make simultaneous decisions on lane choice, vehicle alignment, and continuous vehicle positioning relative to other vehicles in the intersection (Morena, Wainwright, & Ranck, 2007). The drivers need to control the speed and steering angle to keep the car in optimal lane positions. Intersections not only exhibit conflicts between vehicles coming from different directions but also require most of the driver's cognitive resources (Hong, Kurihara, & Iwasaki, 2008). Cognitive resources involving visuospatial and motor coordination are particularly demanded for making smooth turns (Schweizer et al., 2013). Visual-motor coordination (VMC) usually refers to the extent to which visual perception and fine motor skills are well coordinated (Beery, 2004), which can be construed as the ability involving the use visual information to generate motor commands (Vickers, 2007) with appropriate motor actions.

With more older adults on road and their greater susceptibility to injury from vehicle crashes, many researchers and professionals from occupational rehabilitation have been seeking methods to improve the safety of older drivers (Classen, Awadzi, & Mkanta, 2008). However, clinical measures have not been proved as reliable predictors of driving behaviour, the identification of risky drivers is challenging (G. McGwin, Sims, Pulley, & Roseman, 2000) even with simulated driving (Yuan, Du, Qu, Zhao, & Zhang, 2016). Older drivers experience problems in regulating their operational level behaviours which rely on the second-to-second decision-making (Hong et al., 2008), e.g., using the visuospatial information to guide their steering to achieve effective visual-motor coordination. Since specific age-related cognitive declines can affect drivers' visual, motor behaviours, understanding the relationship between the visual-motor coordination and cognition in older drivers is important yet to be explored. In order to do that, a critical challenge is to obtain detailed data on visual search and oculomotor behaviour, which are needed for the VMC assessment. Several attempts have been made to detect risky drivers by coupling gaze behaviour and vehicle operating behaviour (Itkonen, Pekkanen, & Lappi, 2015; Mori, Miyajima, Hirayama, Kitaoka, & Takeda, 2013; Ramon et al., 2008; Yekhshatyan & Lee, 2013), mostly the data collected at the section-scale level. Recent studies have rarely integrated visual and motor behaviour into a meaningful data model that allows a dynamic representation and analysis of visual-motor coordination in driving. Consequently, the nature and underlying mechanisms of the older drivers' behaviour behind the wheel have not been fully defined in publications to date (Park & Son, 2010; Sun, Xia, et al., 2016b).

A recent Australian study presented a precise framework for assessing on-road driving behaviour that combines eye-tracking, multiple Global Navigation Satellite System (multi-GNSS) and Geographic Information Systems (GIS) technologies (Sun, Xia, et al., 2016a). The pilot study quantitatively analysed drivers' gaze behaviour at the level of individual fixations using real on-road data (Sun, Xia, Falkmer, et al., 2016). The integration of vehicle kinematics and gaze behavior makes the investigation of visual-motor coordination possible. In the current paper, a further elaborate method was developed in order to measure older drivers' VMC performance at intersections. A Data Envelopment Analysis (DEA) model (Chen, 2004; Cooper, Seiford, & Zhu, 2004; Zbranek, 2016) with multiple inputs (visual search parameters) and multiple outputs (vehicle control parameters) was used to calculate the relative VMC performance of 38 older drivers. The relationships between the VMC and older drivers' cognitive ability scores were observed, and predictors of VMC performance amongst older drivers at intersection driving were also investigated and discussed. Specifically, the aims of the current study are to:

- Assess the overall visual-motor coordination performance of individual older drivers at intersections.
- Investigate the associations between older drivers' visual-motor coordination and their cognitive abilities.
- Identify the cognitive predictors for VMC performance in older drivers.

METHODS

Participants

Data were collected for 38 older drivers (m =68.7, range 60-81) from Perth, Western Australia. Participants were eligible for inclusion if they held a valid full driver's license; drove at least three times per week, and reported no mental health or physical impairments that could impact their driving performance. Preliminary screening was conducted with all participants to ensure compliance with inclusion criteria using Snellen Visual Acuity Chart and Mini Mental State Examination (MMSE). Ethics approval for the study was obtained from the Health Research Ethics Committee of Curtin University. The data collection included an on-road driving test and a battery of laboratory neuropsychological tests, all the assessments have been done in one session.

On-road driving assessment

The on-road driving assessment simultaneously recorded the driver's eye movement and the vehicle movement (Sun, Xia, et al., 2016a). It took participants through an urban residential area in Perth, about 10 km long including five intersections (Supplementary 1), and took about 20 minutes to drive. The design of the experiment employed a vision-in-action paradigm, which recognizes that activity task, environment, the person, and perception-action are within a perceptual-motor workspace (Vickers, 2007), and human gaze guides the motor action (Land, 2009).

Eye movement tracking and visual search parameters

Participants were asked to drive their own car (standard size) with an eye tracker (Arrington Viewpoint ™) mounted on each driver's head (Supplementary 2). Drivers' gaze points and eye movement, which reflect their visual attention and reaction to stimuli from the traffic environment, were captured by the eye tracker system. Eye movements on eye tracking video were analysed for each participant, the analysis process separated saccades from fixations (the period of time when the eyes remain relatively still) in order to focus on conscious perception and attention (Falkmer, Dahlman, Dukic, Bjällmark, & Larsson, 2008). Based on an eye tracking analysis matrix (Supplementary 3), each eye fixation was coded manually in three categories to capture the attention focus of the driver during driving: the object that was fixated; the background of the object that was fixated, and the distance of the object from the driver. Three different gazing distances (1: inside vehicle; 2: outside vehicle < 5 m; 3: outside vehicle ≥ 5 m) were noted. In addition, individual eye fixations were classified as either traffic-relevant or non-traffic relevant objects referring to the pre-defined analysis matrix (Sun, Xia, Falkmer, et al., 2016).

GNSS vehicle movement tracking and vehicle control parameters

The vehicle movement trajectory was recorded by a Trimble R10 GNSS receiver installed on the car roof. The receiver is able to track multi-GNSS with enhanced satellite visibility and reliability beyond the GPS (Global Positioning Systems) only approach, so as to resolve high-resolution and precise vehicle positioning at the current urban residential area (Kubo, Hou, & Suzuki, 2014; Noomwongs, Thitipatanapong, Chatranuwathana, & Klongnaivai, 2014). The tracking configuration was setup at 10 Hz so the car positions were recorded every 0.1 seconds. Real-time kinematic technique was used to achieve centimeter-level accuracy by minimizing the effect of error sources transmitted between the satellites and the GNSS receiver (Sun et al., 2017). Mean Lane Position (MLP) and Standard Deviation of Lane Position (SDLP) calculated from vehicle trajectories were used as the vehicle control parameters.

The eye fixations and vehicle trajectory were synchronized and converted into a visual-motor coordination dataset (Sun, Xia, et al., 2016a) (Supplementary 4), so a driver's visual search and vehicle control parameters were integrated at individual fixation level with a specific time and vehicle location. The dataset was then loaded into a DEA model to calculate the scores of VMC performance for individual drivers.

Laboratory neuropsychological tests

A battery of neuropsychological tests was chosen to assess participants' cognitive functions. These tools are standardised and have been widely used internationally. The tests have also been evaluated to be ecologically valid to measure visual and cognitive capacities that are likely to impact upon daily functioning in older adults (Barrash et al., 2010; Hoggarth, Innes, Dalrymple-Alford, & Jones, 2013).

The Useful Field of View (UFOV®) subtests assess the participants' perceptual processing speed (ms), perceptual level of divided and selective attention (ms) (Classen, Wang, Crizzle, Winter, & Lanford, 2013; Wood & Owsley, 2014). In previous studies, divided attention function of a brain was found to have influences on driving speed and lane keeping (Lengenfelder, Schultheis, Al-Shihabi, Mourant, & DeLuca, 2002), selective attention was related to safe driving in an age-related manner, especially with vehicle crashes at intersections (Duchek, Hunt, Ball, Buckles, & Morris, 1997).

The Benton Judgement of Line Orientation (BJLO) test measures the judgment of visuospatial orientation (Emerson et al., 2012). The test uses subtle differences in the line slope to accurately detect the visual-spatial perception in subjects.

The WAIS-R (Wechsler, 1981) Block Design (BD) tests participant's spatial cognition (Ferreira, Simões, & Marôco, 2013). Participants were asked to arrange a set of multi-colored blocks to match a specifically given pattern. The test provides a reliable measure of the participant's spatial visualisation ability (Groth-Marnat & Teal, 2000). BD performance has been found as an individual significant predictor for driving errors in older adults (Dawson, Uc, Anderson, Johnson, & Rizzo, 2010).

The Delis-Kaplan Executive Function System Trail Making (D-KEFS TMT) subtests (Delis, 2001) measure the visual search, attention, sequencing, executive functions and motor skills. The test specifically separates these processes in five conditions (Vasilopoulos et al., 2012): TMT 1 (visual scanning), TMT 2 (number sequencing), TMT 3 (letter sequencing), TMT 4 (number-letter switching, or called set shifting) and TMT 5 (motor speed). TMT 2 and 3 are commonly used as measures of processing speed while TMT 4 has been used as an index of executive function (Vasilopoulos et al., 2012).

The Balloon Analogue Risk Task (BART) (Lejuez et al., 2002) tests the level of risky personality based on the average number of pumps that the participant made on unexploded balloons. The test was designed to mimic realistic risk-taking behaviour by demonstrating the choices between reward and loss. It was considered as a valid predictor for risky driving behaviours causing crash injury (Mishra & Lalumière, 2011; Vaca et al., 2013).

Analysis

A Data Envelopment Analysis (DEA) model (Chen, 2004; Cooper et al., 2004; Zbranek, 2016) was developed to calculate the VMC performance scores for 38 older drivers. DEA is a linear programming technique used to evaluate the relative performance of decision-making units, here the older drivers, where multiple inputs and outputs are involved. In this study, six visual search parameters were used as the inputs, and three vehicle control parameters represented the outputs. Typical DEA inputs can be the sources used and outputs reflect the level of products, although these features do not necessarily represent inputs and outputs in practice (Seiford & Zhu, 2002). The model identifies the optimal ways to benchmark the VMC performance rather than calculate the averages (S. Babaee et al., 2014; Babaee, Shen, Hermans, Wets, & Brijs, 2014; Cherchye et al., 2006). A recognized strength of DEA modeling is that it looks for internal (possibly constrained) weights for individual parameters, then produces an overall score that depicts the analyzed decision-making unit in its best possible light relative to the other observations (Cherchye et al., 2006). The details of the DEA formula is presented in the supplementary file (Supplementary 5).

Pearson's correlations in SPSS were executed to identify the associations between visual search and motor control parameters; as well as the relationships between visual search and VMC scores; relationships between age, cognitive abilities and their VMC performance. Multiple linear regression was used to investigate the possible influence of cognitive abilities on VMC, and the most predictive neuropsychological test/s for VMC performance.

RESULTS

VMC performance at intersections in older drivers

By applying DEA model, an overall index score for each driver was calculated based on multiple visual search and vehicle control parameters. The overall visual-motor coordination performance of participants is shown in Supplementary 6. It can be seen that Driver26 performed best. The visual-motor coordination dataset shows that the driver demonstrated relatively high fixation frequent per manoeuvre time (5.83/s), resulted in a low MLP (0.14 m) and SDLP (0.10 m), a high percentage of traffic relevant fixations (58%) was also performed by the driver. In contrast, Driver32, with the lowest VMC score, showed poor visual search strategies in the gaze pattern, with comparably inadequate fixations on mirrors (9 records), eye fixation frequency (1.18/s) and duration (1.93/s), and low percentage of traffic relevant fixations (37%), which were resulted in a high MLP (0.93 m) and SDLP (0.68 m).

Table 1 Correlations relationships between visual search and vehicle control parameters

	Correlation with MLP	Correlation with SDLP
Gaze at mirrors	.027	-.087
Traffic relevant	.037	.092
Fixation frequency	-.332*	-.397*
Fixation duration	-.300	-.297
Gaze inside vehicle	.201	.001
Gaze outside vehicle < 5m	.264	.083
Gaze outside vehicle ≥ 5m	-.282	-.056

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 2 Correlations relationships between VMC score and visual search parameters

Visual search parameters	Pearson Correlation Coefficients and Significances
Gaze at mirrors	.087
Traffic relevant	.554**
Fixation frequency	.364*
Fixation duration	.287
Gaze inside vehicle	.018
Gaze outside vehicle < 5m	-.187
Gaze outside vehicle ≥ 5m	.116

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

For the older drivers' group, Table 1 demonstrates the associations between visual search and vehicle control parameters; and Table 2 presents the associations between visual search parameters and VMC scores. Eye fixation frequency was negatively correlated to MLP and SDLP. Both eye fixation frequency and traffic relevant gaze were positively associated with VMC scores. No other significant correlations were found between other visual search parameters and the correlation coefficients were very low.

Associations between older drivers' VMC and cognitive abilities

Significant correlations (Table 2) have been identified between VMC score and eight neuropsychological tests: UFOV 2 (divided attention) and 3 (selective attention); BD (spatial visualisation); BJLO (spatial orientation); D-KEFS

TMT 1 (visual scanning), TMT 2 (number sequencing), TMT 3 (letter sequencing), and TMT 5 (Number-letter Switching). The variable of spatial visualisation has the highest positive correlation with VMC. No correlations were found between VMC and participants' age, processing speed by UFOV 1, motor speed by D-KEFS TMT 5, risk-taking behaviour by BART.

Table 3. Correlations relationship between older drivers' cognitive abilities, age, and VMC

		Processing speed	Divided attention	Selective attention	Spatial visualisation	Spatial orientation	Visual scanning	Number sequencing	Letter sequencing	Motor speed	Number-letter Switching	Risk-taking	Age
VMC	Pearson Correlation	.122	-.416**	-.568**	.595**	.389*	-.349*	-.509**	-.485**	-.312	-.496**	.186	-.134
	Sig. (2-tailed)	.465	.009	.000	.000	.016	.032	.001	.002	.057	.002	.262	.421

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Cognitive predictions for older drivers' VMC performance

A multiple regression was conducted to determine which cognitive abilities predicted the value of VMC. Using the enter method it was found that the combination of selective attention, spatial visualisation ability, and executive function explain a significant amount (57%) of the variance in the value of visual-motor coordination (F (3, 34) = 14.69, $p < .00$, $R^2 = .57$, $R^2_{Adjusted} = .53$).

The regression analysis revealed significant predictions for VMC by the three cognitive abilities: selective attention (β = -.29, t (37) =-2.15, p =.04), spatial visualisation ability (β = .39, t (37) =2.7, p =.01), and executive function (β = -.30, t (37) =-2.43, p =.02). The β value, also known as standardized regression coefficient, can be used to compare the strength of the coefficient of this variable to the coefficient of another variable, so the relative strength of the various predictors within the model can be obtained. In this example, spatial visualisation ability by BD test has the largest β coefficient of -0.39, and selective attention has the smallest β coefficient of 0.29. Therefore, a one standard deviation increase in spatial visualisation ability leads to a 0.39 standard deviation increase in predicted VMC, with the other variables held constant; whereas a one standard deviation increase the completing time in executive function leads to a decrease of VMC score by a 0.30 standard deviation, with the other variables in the model held constant.

DISCUSSION AND CONCLUSION

In this paper, the VMC performances at intersections in 38 healthy older drivers were examined. The results demonstrated that the VMC assessment is able to identify risky drivers and their problematic behaviours at intersections. Eye fixation frequency was insufficient in participants with low VMC scores, which resulted in poor lane maintenance performance. The lower VMC scores also reflected the inadequate traffic relevant fixations.

The primary objective of this paper was to determine which tests, from a clinical battery, are correlated with VMC performance in older drivers at the most challenging driving section of intersections. Significant correlations were found between VMC score and eight neuropsychological tests: UFOV 2 and 3, Block design, Benton's JLO, D-KEFS TMT 1, 2, 3 and 4. It is clear that decline in multiple aspects of cognition can contribute to poor VMC, therefore, unsafe driving. In this study, no correlations were found between VMC and participants' age, UFOV 1, D-KEFS TMT 5, and BART. The BD has the highest positive correlation with VMC performance.

The combination of cognitive test scores explains a significant amount of the variance in the value of VMC ($R^2_{Adjusted} = .53$, $p = .00$). Selective attention (UFOV 3), spatial ability (BD) and executive function (D-KEFS TMT 4) are the best predictors for VMC (β =.29; .39; .30 and p = .04; .01; .02 respectively). These three neuropsychological tests are comparatively more difficult than other tests among the battery. Block design can be used as a measure of everyday spatial abilities in young people (Groth-Marnat & Teal, 2000). The ecological validity of BD for older adults has been tested by Farley, Higginson, Sherman, and MacDougall (2011), the ability to reason about space is important for many aspects of daily functioning, such as navigating. The results indicated that the spatial ability parameters in conjunction with each other are stable indicators of VMC.

To the authors' knowledge, these findings present the first documentation of the relationships between cognitive abilities and visual-motor coordination in driving. It is strongly recommended that visual-motor coordination is a sensitive and effective measure for driving assessment in the older population. The VMC measure can help determine how deficits in the operational level an older driver performs. In turn, one's VMC performance can be used to develop coping strategies and rehabilitation programs tailored towards individual's profile of strengths and weaknesses in driving mobility and safety. The results are informative regarding the importance of visual search guiding vehicle control and the mechanisms towards safe driving in older drivers.

It is acknowledged that several limitations may affect the interpretation of above findings. First, the participants are comparatively young with a mean age of 68.7. They are reported as very experienced drivers. Therefore it is hard to detect the driving errors or assess their performance levels by observing only during the on-road tests. In addition, since no highway included in the experiments due to the safety concerns, it was difficult to evaluate their speed control due to very close speed data in this cohort. The experiments provided moderate traffic situation, hence it was not possible to determine the visual-motor coordination in the face of dangerous driving situations.

Despite the limitations, the findings demonstrate the underlying mechanisms of visual-motor coordination in older drivers and indicate the potential of cognitive functions as modifiable factors for risky driving behaviours in healthy aging. These relations can be used to guide future development of cognitive interventions tailored to an individual by specifically targeting those driving functions. It is worth noticing that any single neuropsychological test will not be adequate for predicting older drivers' driving competency, rather, a brief battery of tests that provides coverage of the key domains of cognition necessary for safe driving. Continued research in the cognitive mechanisms for older drivers' visual-motor coordination will lead to a standardized cognitive battery with robust scoring algorithms, which will ideally provide empirically derived cut-off scores for determining driver safety in terms of visual-motor coordination.

When it comes to the practice of intervention, the assessment feedback using VMC measurement for participants can be significantly cheaper than personal interaction with a therapist (Markowetz, Błaszkiewicz, Montag, Switala, & Schlaepfer, 2014; Yarkoni, 2012). The preliminary recommendation can be made regarding older adults' fitness to drive using the VMC scores. Educational and training programs based on the findings can be developed to improve mobility related cognitive abilities and promote safe driving.

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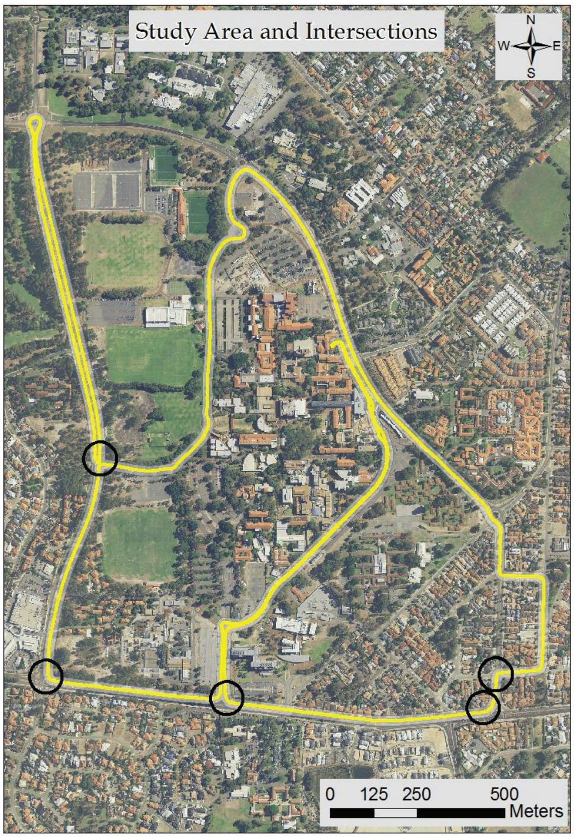
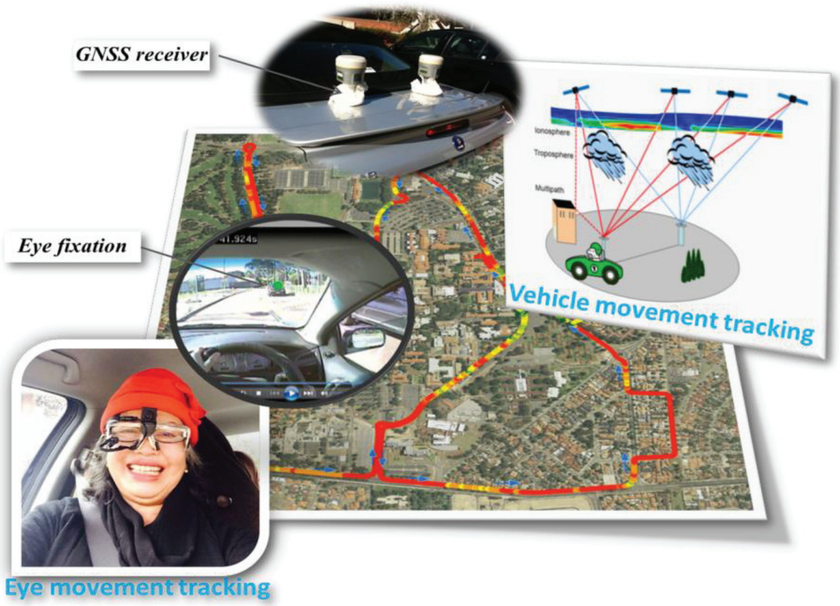
Supplementary 1: Map of study area and intersections



Supplementary 2: Apparatus and driving assessment setting, adapted from Sun et al. (2016).



Supplementary 3: Eye tracking analysis matrix

1. Surface (area) to object

10	**The Road**	**11**	**Intersection (Stop sign, give way)**
100	**vehicle on coming right side**	110	**oncoming vehicle right side**
101	**vehicle oncoming left side**	111	**oncoming vehicle left side**
102	**vehicle oncoming opposite side**	112	**oncoming vehicle opposite left side (slip road)**
103	**vehicle direction right side the road**	113	**oncoming vehicle across straight ahead**
104	**vehicle direction left side the road**	114	**oncoming vehicle opposite straight ahead**
105	**Direction straight ahead**	115	**oncoming vehicle opposite U-turn**
106	**Opposite direction right track**	116	**Vehicle same direction left side**
107	**Opposite direction left track**	117	
108	**Opposite direction middle track**	118	
109	**Bump**	119	

Supplementary 4: Visual-motor coordination dataset

FID	Participant_ID	Fixation_no	Duration (second)	Gazing direction	Gazing distance	Background	Object	Traffic	Speed (km/h)	Acceleration/deceleration (m/s)	Lane Deviation (cm)	Stages at Roundabout	X_coordinate	Y_coordinate
1	9	4082	0.2999	Left	1	126	2891	1	25.28	7	42	Before	394830.7	6459224
2	9	4084	0.2001	Left	1	126	2892	2	24.65	6.9	40	In	394830.6	6459224
3	9	4086	1.5992	Left	3	126	259	1	24.01	6.7	36	In	394830.5	6459224
4	9	4088	0.1666	Middle	2	126	243	2	23.25	6.5	30	In	394830.3	6459225
5	9	4090	0.2332	Right	2	129	2892	2	23.01	6.4	25	In	394830.2	6459226
6	9	4092	0.1667	Right	1	126	2892	2	23	6.4	22	In	394829.9	6459226

Supplementary 5: VMC formula

Objective function:

VMC_{j} : A set of DMUs (decision making units), here the older drivers

$$VMC_{\mathrm{j}} = \min \sum_{r=1}^{s} \lambda_r y_{rj} \qquad r = 1, \dots, s; j = 1, \dots, n$$

subject to:

$$\sum_{i=1}^{m} \omega_i x_{i_j} - \sum_{r=1}^{s} \lambda_r y_{r_j} \geq 0 \qquad i = 1, \dots, m$$

$$\sum_{i=1}^{m} \omega_i x_{i_j} = 1$$

$$\omega_i > 0 \qquad \lambda_r > 0$$

where

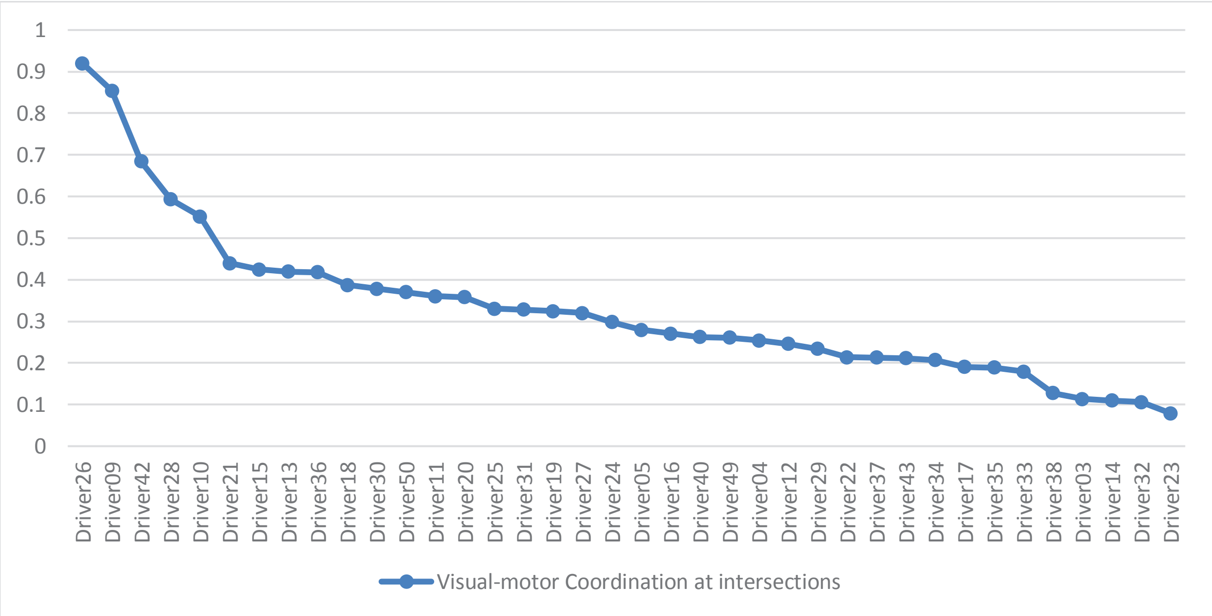
x_{i_j} = as "input" refers to the gazing behaviour (aggregated visual search parameters)

y_{r_j} = as "output" refers to the vehicle control behaviour (aggregated vehicle control parameters)

ω_i = internal weight associated with indicators for input parameters

λ_r = internal weight associated with indicators for output parameters

Supplementary 6: Visual-motor Coordination performance at intersections



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General Discussion and Conclusions

CHAPTER 6 GENERAL DISCUSSION AND CONCLUSIONS

As has been highlighted throughout this thesis, previous studies have identified the issue of older drivers' mobility and safety and urged more focused health and technological research (Coxon, 2015; Owsley, 2002; Owsley, McGwin, & Searcey, 2013). Consequently, this thesis developed a variety of measures to assess older drivers' behaviour, and examined their cognitive abilities in order to identify the cognitive mechanisms underlying the visual searching, lane keeping and visual-motor coordination performance. In brief, this PhD research has examined the impact of aging on the specific measures of older adults' driving behaviours.

This chapter first summarises the empirical results obtained from three main sub-studies, followed by a review of the thesis objectives and evaluating the methods and outcomes, with a particular emphasis on the assessment of vision-motor coordination. The practical and theoretical implications, and the main contributions to the research fields are then presented. Lastly, the limitations of this research are discussed with recommendations for future research.

1. Summary of Empirical Results

This research has provided insights into the impact of the age-related cognitive decline in the driving mobility and behaviour of the older population. Several complementary studies were undertaken towards achieving the specific objectives, with the analysis conducted and outcomes discussed in substantive Chapters 3 to 5. These three chapters consist of eight papers that, taken together, focused on the investigation of the visual, motor behaviour and coordination of older drivers, and the neuropsychological mechanisms that underlie their driving behaviours.

Chapter 3 pursued precise vehicle movement tracking and investigated the relationships between older drivers' lane keeping behaviour and cognitive abilities. It comprised the construction of vehicle movement trajectories using advanced GNSS RTK techniques and the investigation of the associations between lane maintenance parameters and cognitive functioning. The statistical results showed that lower visual attention (selective and divided attention) was associated with higher MLP (Mean Lane Position) and SDLP (Standard Deviation of Lane Position). MLP was also correlated to spatial abilities, executive function and motor speed. Selective attention was found to be the best predictor of MLP in lane maintenance. The combination of a number of neuropsychological tests (UFOV 2 and 3, BD and BJLO, D-KEFS TMT 1, 2, 3, and 4) classified 80.4% of participants as having a poor to good lane maintenance performance.

Chapter 4 integrated visual search patterns with vehicle control data. Drivers' eye fixations were geocoded and linked to the vehicle movement trajectory to model visual and motor behaviours via a GIS platform. The associations between older drivers' visual capacity (processing speed, divided and selective attention) and their eye fixations in various driving manoeuvres were investigated. The results indicated that participants performed more frequent eye fixations when manoeuvreing through roundabouts, while they tended to fixate on certain objects much longer when driving along a straight road. The key findings showed that processing speed and divided attention in older drivers were associated with their eye fixations at complex right-turns. Drivers with lower selective attention capacity performed less frequent eye fixations at several roundabout manoeuvres, but compensated with longer fixation durations.

Chapter 5 examined the visual-motor coordination in older drivers. The relative performances of visual-motor coordination for participants were modelled and measured. Insufficient eye fixation was identified as a problematic visual search behaviour resulted in poor lane keeping performance. At roundabouts, entering roundabouts was found as the most challenging section for older drivers with the poorest performance of visual-motor coordination. At intersections, significant correlations were seen between visual-motor coordination performance and eight neuropsychological tests: UFOV 2 and 3, Block design, Benton's JLO, D-KEFS TMT 1, 2, 3 and 4. The combination of cognitive tests explained a significant amount of the variance in visual-motor coordination of older drivers. Selective attention, spatial ability and executive function are the best predictors of visual-motor coordination performance.

2. Revisit the Thesis Objectives

1). Comprehensive quantitative measurements were developed for older drivers' lane keeping, visual search and visual-motor coordination.

Guided by the psycho-geoinformatics approach, measurements of lane keeping, visual search and visual-motor coordination were conducted using multiple sources information acquired from the vehicle, driver and environment and analysed in GIS.

Measurement of lane keeping was presented in paper 4. MLP, SDLP and manoeuvre time calculated from vehicle movement trajectories were used as the lane maintenance parameters. Subtle variations between drivers' lane maintenance performance can be detected as the horizontal accuracy of vehicle trajectories was at the centimetre-level of resolution. The precise vehicle movement tracking, discussed in two substantial papers (paper 2 and 3), has been critical for all the three stages of measurements.

Measurement of visual search behaviour was presented in paper 6 and 7. To achieve that, multiple attributes of eye fixations, in both quantitative and qualitative formats, were obtained. Eye fixation frequency and durations were computed by the eye tracking analysis program. Manual coding was conducted to categorise the gaze objects in terms of the types, distances and whether relevant to traffic. Comparing to other studies using eye tracking, one improvement in this research is that each eye fixation was geocoded and given a position of the gaze origin on the vehicle trajectory, so that comprehensive features of oculomotor behaviour could be analysed in a driving context. The statistical descriptive parameters of eye fixations (mean, max, min of eye fixation durations, etc.) were processed into different driving sections in GIS, so the visual patterns can be assessed and visualised.

Measurement of visual-motor coordination performance was presented in both paper 8 and 9. Multiple parameters of visual search and lane keeping were aggregated and benchmarked using the mathematical modelling approach of Data Envelopment Analysis (DEA). The results gave performance scores of individuals to identify problematic behaviours for low-performing older drivers. The model was combined with GIS in order to measure visual-motor coordination at different route sections, and investigate the patterns of visual-motor coordination performance and the problematic road sections where older drivers performed poor visual-motor coordination.

The developed methodology, which used both quantitative and qualitative parameters to measure the various components of older drivers' driving competency, has been proven to be valid and reliable through the substantive studies in this thesis.

2). Associations between older drivers' lane keeping performance and their cognitive conditions.

This was presented in paper 4. The high accuracy of vehicle trajectories provides confidence for the lane keeping assessment as well as the statistical analysis. The paper identified cognitive variables associated with lane maintenance performance, and the roles cognitive functions playing in older drivers' driving behaviour. Visual attention and executive function of older drivers demonstrated strong correlations to lane maintenance performance, which is consistent with studies in car crash epidemiology of older drivers. Selective attention was found to be the best predictor of lane maintenance. A Discriminant Analysis (DA) was used to predict the lane maintenance performance of participants from cognitive abilities. The results clearly revealed that there were significant attribute differences between lane maintenance performance in participants, based on the measures of cognitive variables in visual attention, spatial abilities, and executive function. In addition, this investigation has also shown the effectiveness of the neuropsychological tests in the measurement of older drivers' cognitive abilities.

3). Older drivers' visual search pattern and the relationships between the eye fixation movement and their visual capacity.

To investigate this, older drivers' eye fixation movements were extracted, analysed and linked to vehicle trajectories (paper 5 and 6). Paper 6 explored and documented the relationships between visual capacity indicators (processing speed, divided and selective attention abilities) and the five eye fixation parameters (e.g., the frequency and duration of eye fixations), by analysing the various driving scenarios (e.g., roundabouts or straight roads). This exploration was to identify critical driving sections underpinning older drivers' oculomotor behaviour due to their reduced visual capacity. The purpose of this approach was to compare the link between older drivers' eye fixations and their visual attention abilities in different driving situations so that any hot spots of challenging driving sections could be detected. Statistically significant relationship was found between the eye fixation frequency and the selective attention at two in-campus roundabouts with small size and surrounded by buildings and trees that could interfere with driver attention. Likewise, the results showed that older drivers' processing speed and divided attention were associated with their eye fixations at the complex right-turns, due to the increased visual workload from multiple visual sources at the driving scenes.

4). Relationships of older drivers' visual-motor coordination performance and cognitive functions.

This objective has been presented in the last paper of the thesis (paper 9), with focused on individual drivers' visual-motor coordination performance at intersections. Driving through an intersection is considered as the most challenging scenario for older drivers, since the complex intersection manoeuvre places high demands on visual perception, attention, motor control and executive functioning that usually decline with age.

Data Envelopment Analysis (DEA) was used to evaluate the relative visual-motor coordination performance of the older drivers, where multiple inputs and outputs are involved. Typical DEA inputs can be referred as sources used and the outputs reflect the level of products. In this study, visual search parameters were used as the inputs and lane keeping parameters represented the outputs. The DEA model identified the optimal ways of individual performance rather than the averages (S. Babaee et al., 2014; Seddigheh Babaee et al., 2014; Cherchye et al., 2006). The method involved the creation of a "virtual" perfect older driver for benchmarking, so that low-performing drivers and the risky driving behaviours were identified.

The relationships between visual-motor coordination and cognitive functions were investigated to find the neuropsychological mechanisms underlying visual-motor coordination in older drivers. Specific elements of cognitive ability in older drivers was associated with poorer visual-motor coordination at intersections. It appears that eye fixation frequency presented insufficient information in participants with low visual-motor coordination scores, which resulted in poor lane maintenance. Lower visual-motor coordination also reflected inadequate traffic relevant fixations. Spatial ability, executive functioning, and selective attention strongly influenced older drivers' visual-motor coordination during intersection manoeuvres.

5). Indicators of risky driving behaviour in low-performing older drivers, and the problematic road sections.

This has been investigated through paper 7 to 9 in Chapter 5. Paper 7 set up an integrated assessment database that captured multiple visual and motor parameters for visual-motor coordination dataset. Paper 8 assessed the visual-motor coordination at roundabouts and investigated the impact of road environment on older drivers' visual-motor coordination. Paper 9 assessed the visual-motor coordination of older drivers at intersections and identify risky behaviour in participants with poor visual-motor coordination performance.

This sub-study scrutinized the driver behaviour from a time-geographical perspective. This concept, in a general context, concerns an individual's use of time and place, the resources he/she possesses, and the constraints he/she faces in carrying out particular activities. The time-geography theory and concepts were used to explain driving mobility and behaviour in this study because driving also includes the fundamental concepts of activities, projects, contexts, resources and constraints. These elements are theoretically and empirically important for understanding how visual and motor activities are intertwined in pursuing mobility goals and affecting an individual's performance.

Across all three papers, the importance of visual-motor coordination assessment in older drivers was addressed and the interdisciplinary methods have been justified. Paper 7 integrated multiple visual scanning variables and proposed a gaze-based integrated driving assessment system. Paper 8 conceptualised the driving mobility using the concept of visual-motor coordination path and episodes in order to comprehensively examine driving behaviour through the investigation of driver-vehicle-environment interaction in a space-time context. Visual-motor coordination path and episodes were constructed in a GIS platform to complement the database so the visual-motor coordination can be then examined and visualised in the traffic environment.

DEA was combined with GIS analysis (paper 8) to develop a visual-motor coordination composite indicator (VMCCI) for individual drivers in order to detect and evaluate problematic driving situations. Older drivers with poor visual-motor coordination and their risky driving behaviours were also investigated in paper 9. The different visual search behaviour at roundabouts and intersections were discussed in paper 7. Therefore different settings of visual search parameters were used in the different manoeuvres of roundabout and intersection. Visual-motor coordination assessment is potentially able to identify risky older drivers and their problematic behaviours.

3. Vision-motor Coordination: New Insights into Older Adults' Driving Behaviours

This thesis has provided reasonable and intuitive explanations and measures for older drivers' behaviour via a visual-motor coordination concept and model, which cannot be easily understood using existing theories of mobility or driving behaviours.

The visual-motor coordination data model was first developed in paper 5. The inseparable behaviours of visual search and motor control in driving were defined and integrated at the eye fixation level. By doing so, questions on how well drivers used visual information to control their physical movement were interpreted at both the aggregated and individual driver level. The data model also highlighted that human vision guides motor activity, and visual activity are especially vital for driving. In paper 7, the model integrated additional visual search attributes, driver's cognitive conditions and the traffic environment into a gaze-based integrated driving assessment database, which fulfilled the data requirements and executed the functions of the psycho-geoinformatics approach. The integration of driver's visual patterns, vehicle movement and the traffic environment in a GIS has enabled the comprehensive examination of driver-vehicle-environment interactions and performance. In paper 8, the visual-motor coordination data model was extended into visual-motor coordination path and episodes. It identified that visual pattern and vehicle trajectory are intertwined in space and time and form a visual-motor coordination path that is made up of a series of visual-motor coordination episodes. Each episode contained an eye fixation with a corresponding precise vehicle position that enabled the driving behaviour to be analysed with respect to particular manoeuvres, scenarios or sections. The data model was used in the visual pattern analysis in paper 6 and the visual-motor coordination analysis in paper 8 and 9.

Paper 8 conceptualized driving mobility, in a time-geographic context, as "one kind of visually-guided locomotion that forms an evolving visual-motor coordination path in the space-time context and is shaped by individual cognitive conditions and traffic situations". It has introduced additional dimensions to the analysis of driving behaviour and performance that have been found to be critical for assessing older drivers' mobility and driving competency.

Driving involves multiple tasks that require the driver to gather information and control the vehicle to achieve desired goals. According to visual-motor coordination concept, drivers face coordination demands arising from the dependencies between sub-activities that constrain how tasks can be performed. Therefore, coordination problems should be managed by sub-activities that implement coordination effectively, which implies that a driver's visual and motor behaviour must be coordinated. How well it was coordinated determines the driving ability and indicates the level of the individual's mobility and safety. When applying visual-motor coordination concept in a driving behaviour study, it is important to include key sub-activities in the data model. Driving assessment or training should always consider how overall goals can be subdivided into tasks so that the coordination can be improved.

The empirical analysis results, in paper 8 and 9, have shown that visual-motor coordination has emerged as an important indicator of driving behaviour and performance in older drivers. The visual behaviour-vehicle control relationships described in this paper provide an in-depth understanding of the difference between good and low-performing older drivers than that afforded by the simple measures of glance location and duration. Spatial ability, executive function, and selective attention were identified (paper 9), as the best predictors of visual-motor coordination performance in older drivers. They complemented the visual-motor coordination model of driving by explaining the underlying neuropsychological mechanisms.

4. Practical and Theoretical Implications

This thesis underscores the importance of addressing older drivers' safety and mobility issues. Understanding the mechanisms that underpin the deterioration in visual searching, lane keeping, and visual-motor coordination would lead to insights into the regulation of older drivers. The implications of the key findings of this research with respect to the practical application are discussed below.

- Age alone was not strongly associated with driving outcomes based on the statistical results in either paper 4 or paper 9. Yet, the variations in driving behaviour and performance added to the evidence that older drivers represent one of the most heterogeneous groups among the driving population (Classen, Eby, Molnar, Dobbs, & Winter, 2011). The neuropsychological conditions are the key factors, rather than age, that affect older adults' driving behaviour and performance. Early detection of risky behaviour following intervention is essential for maintaining older drivers' mobility and safety on the road.
- Visual attention and executive function of older drivers demonstrated significant correlations with lane maintenance performance, which is consistent with studies in car crash epidemiology of older drivers. Selective attention was found to be the best predictor of vehicle lane deviation in lane maintenance.
- Driving scenarios and workload have a significant impact on older drivers' visual pattern. Intersections and roundabouts that imposed more steering demands led to higher correlations between steering movements and eye fixations, as compared to a straight road. This is consistent with the findings conducted by Yekhshatyan and Lee (2013). This thesis was successful in elucidating the challenges of older drivers in response to scenarios of varying complexity.
- Declines in visual-spatial and visual-motor abilities appeared to be particularly associated with low-performing driving behaviours. Spatial ability, executive function and selective attention have a strong influence on older drivers' visual-motor coordination during intersection manoeuvres. It is strongly recommended that visual-motor coordination is a sensitive and effective measure for driving assessment in the older population. Tailored driving evaluation and intervention programs can be developed based on these findings.
- The measurements of this study pursued a good ecological validity. Technically, both the eye tracking and GNSS vehicle movement tracking used high-frequency recording, resulting in detailed and more reliable visual search and lane keeping data. The driving assessment is high in discriminant validity, the data and analysis were undertaken at the individual level and were sensitive to the inherent variability in the behaviour and performance of individuals and subgroups. Theoretically, the approach of such an integrated database bridges the gap between visual search and motor control in driving behaviour and psychology research.

- In this study, the power of time-geography has been enhanced by the combination of GIS, GNSS and eye tracking, while basic time geographic principles have proven to be useful in travel behaviour and transportation research (Miller, 2004). GNSS and eye tracking together collected accurate and detailed space-time trajectories at the individual level. This allowed more detailed representation of space-time environments and computationally-scalable methods for discovering new knowledge from driving behaviour datasets. Moreover, this research extended the scope of time-geography by adding individual cognitive conditions into the constraints for the first time. Maybe a new time-geography would emerge from this thesis with more potential as well as imperative research challenges for mobility and behaviour studies.

5. Main Contribution to Research Fields

This study used GNSS surveying technology combined with eye tracking in a GIS platform to study human mobility and cognitive behaviour. It has been built on several innovations: precise vehicle kinematic tracking using multi-GNSS, synchronisation of eye movement and vehicle movement, spatial-temporal analysis of visual-motor coordination in driving and DEA combined GIS for visual-motor coordination measurement. These methods filled the gap identified in previous driving safety studies that individual drivers' visual search and vehicle control are rarely integrated due to the lack of reliable data and suitable applications. The main contributions of this research to research fields are discussed below:

- Framework of psycho-geoinformatics guiding the whole development of the research and the completion of this thesis (paper 1).

The framework helped bring together tools from different disciplines to tackle the diverse and complex problems concerning older drivers' mobility and behaviour. The geoinformatics based framework integrated a set of standard spatial tools and techniques and, thus, the derived products were in a standard GIS-based format that led to interoperable solutions. The continuous changes in driving parameters, such as the eye fixation and visual-motor coordination patterns could then be observed over time and space in GIS. Within the developed framework, psychology played the role of explaining the mechanisms of cognitive breakdowns that undermine driving safety; geoinformatics then complemented this explanation with the tools for systematically exploring the various layers of complexity that define the activity of driving. Psycho-geoinformatics thus provided an interdisciplinary translational approach that merged elements of cognitive psychology, human factors and geography to study the relationship between driving behaviour, cognitive abilities and traffic environment. The good practice developed and adopted in this study is a basis for others to adapt and develop in the future when exploring complex driver-vehicle-environment interactions and driver behaviours.

- Precise vehicle movement trajectory generated using multi-GNSS RTK tracking with a high rate in an urban residential area (paper 2 and 3).

As the results demonstrated in the paper 2 and 3, the RTK technique, with 10 Hz multi-GNSS using 20 elevation mask angle, captured accurate vehicle movement trajectories in the tested urban residential area. Such data can be integrated with other spatial information and used in applications when precise vehicle localization or timing is required, such as location-based services (LBS), transport safety and driving behaviour studies. The integration of high-resolution vehicle movement trajectory data with a GIS platform allows researchers to segment, visualise and model their data based on location attributes. Moreover, other data can be geocoded with the reference of vehicle locations to obtain new spatial attributes. For such a movement and behaviour study, a good quality GPS/GNSS dataset laid an essential foundation of the project database, and enabled the geoinformatics functionalities in the project.

- Combining precise surveying technology with eye tracking to study human behaviours and mobility (paper 5, 6, 7, 8, 9).

The current study is the first attempt in the research field to use precise surveying technology combined with eye tracking to study human behaviours in a real-world setting. A GIS data model for drivers' visual-motor coordination was introduced in paper 5, and used in the rest of the thesis through paper 6 to paper 9. The eye fixation data and vehicle trajectory were synchronized using time stamp as the common link. Each fixation had an (x, y) coordinate, assigned from the vehicle position, to represent "from where" the driver started gazing, and the fixation duration from the eye tacking analysis gave the period of the gaze. The combination of eye tracking and vehicle movement enables the investigation of older drivers' visual patterns and visual-motor coordination in various driving scenarios.

- Development of a context and location-aware enabled eye tracking system to examine driver-vehicle-environment interactions at fine temporal and spatial scales (paper 7, 8, 9).

A major strength of this study is that human mobility of driving behaviour was investigated through the examination of driver-vehicle-environment interactions using a vision-in-action paradigm. The eye tracking system has been adapted from other fields of research by including both a locational dimension and environment attributes. It has been shown that the context and location-aware eye tracking fulfilled the vision-in-action paradigm. Thus, it is valid for assessing fitness to drive in elderly people and identifying the main signs of decline in driving ability.

The eye tracking video footage was divided frame by frame to analyse the eye tracking data and capture the contextual information. Each fixation was labeled with a series of codes indicating the characteristics of the fixated object, (e.g., the curve of the road), whether the gaze distance is greater than 5 m and whether the gaze is traffic-relevant. The start time of each fixation was also captured and linked to the vehicle position recorded by the GNSS receivers. By doing so, the resulting database contains the exact vehicle location when the eye fixation happened. Therefore, location-aware enabled eye tracking was also achieved along with the contextual awareness.

- Fixation-based visual-motor coordination episodes reconstructed on the visual-motor coordination path (paper 8).

Based on the concept of visual-motor coordination in driving mobility and the visual-motor coordination data model, paper 8 reconstructed visual-motor coordination episodes from the original data to quantitatively measure each participant's visual behaviour and motor performance at a very fine scale. Each episode contains one eye fixation and the corresponding segment of vehicle trajectory, with a series parameters of both visual search and vehicle control. By doing so, the huge dataset was split up using its natural breakpoints to create order within the trajectory history, so that the complex driving behaviour can be analysed more effectively. The individual episode represents a discreet time period for the driver's visual-motor coordination. The (x, y) coordinates of the vision-motor coordination episodes can be overlaid with other environment and transport information in GIS for further analysing individual drivers' behaviour and performance.

- Combining DEA and GIS to develop a performance composite indicator for individual drivers (paper 8 and 9).

Visual-motor coordination episodes were used to calculate the relative performance of participants' visual-motor coordination. Indicators of risky driving behaviour and problematic driving sections were identified using reliable measures and analysis (paper 7, 8, and 9). This is the first attempt to execute a DEA model in GIS so that the spatial component could be considered and the results visualised and overlaid with other spatial information.

- Knowledge of older adults' driving mobility through quantitative examinations of driver-vehicle-environment interactions (paper 6, 7, 8 and 9).

From experimental design through data collection to the stage of analysis, all phases of this research have considered the interactions between the driver, vehicle and traffic environment. The visual and motor behaviour of older drivers were recoded, linked and assessed with the reference of geospatial information. A variety of means were explored to investigate the complexity of older drivers' behaviour through driver-vehicle-environment interaction and the sentient movement in space and time. Schwanen & Páez (2010) argued that, to develop a complete understanding of aging and mobility, the context and interactions surrounding the ability of old people to travel should be among the top priorities in research. Many accidents were caused by failures in the interaction between the driver, vehicle and road environment. A driver's human error characterizes the outcome of an action, rather than being the cause of a traffic accident (Hong et al., 2008). The spatial and statistical analysis of older drivers' eye movement in this study have provided a clear spatial link between older drivers' oculomotor behaviour and their visual capacity under different driving manoeuvres and sections. It has added to our understanding of how vision was adjusted to regulate locomotion in older drivers. The focus of visual-motor coordination in Chapter 5 strengthened the need to link the driver with the vehicle in order to investigate and analyse the coordination in a specific traffic environment (intersections and different stages of roundabouts).

- Knowledge of the impacts of age-related cognitive decline on older drivers' visual pattern, lane keeping and coordination (paper 4, 6, 8, and 9).

The empirical results of the impact of age-related cognitive decline on older drivers' visual pattern, lane keeping and coordination have been summarised in points 2, 3 and 4 in section 2 of this chapter: "Revisit the thesis objectives". Some of the findings complemented previous studies which used driving simulation or subjective evaluation by experienced instructors, whereas other findings have presented new contributions to the existing knowledge, owing to the innovative approach of data collection and analysis. Visual attention and executive function have been shown to be the consistent cognitive factors that underpin older drivers' behaviour and performance in visual searching, lane keeping and visual-motor coordination. The impact of the spatial ability of older drivers on their visual-motor coordination appeared significant. To the authors' knowledge, these findings represent the first documentation of a relationship between cognitive abilities and visual-motor coordination in driving. The visual-motor coordination has been proven to be the most sensitive and reliable indicator of older drivers' driving ability, especially for the young older drivers who have not demonstrated obvious physical impairments affecting their driving.

6. General Research Limitations

While the above contributions were made by this research, there are limitations that should be acknowledged and to provide scope for further research in the future.

Due to the newly developed multiple tracking methods, the primary limitation of this research has been the complexity of data collections and the raw data processing. The computing of eye fixations and vehicle movement trajectories became very time-consuming as multiple software and skills were required. The management of data collection and processing turned into the biggest logistical challenge of this study.

An important consideration in processing the results of this research was the quality of the data. The complexity of the datasets and their integration have raised concerns about the data accuracy and reliability. GNSS is known to have variable performance under certain conditions and the eye tracking analysis algorithm has uncertainty too, both of which could have affected the overall data quality obtained. The centimeter-level vehicle movement data are more reliable in the open air as GNSS perform better when many satellites are in the view and the signals are uninterrupted. This potential reliability issue had little adverse impact on this study as the critical sections (intersections and roundabouts), are all in the open air. Nevertheless, data accuracy checks were conducted along the entire route prior to using the data. Eye tracking data accuracy issues may be caused by calibration issues and lighting issues. Glare in eye tracking is a continuing problem during on-road driving experiments. In addition, the fixation identification algorithm simplified the eye movement types. The 16-point calibration before eye tracking and the frame by frame manual identification have improved the errors and misclassifications in the output. An automated checking program should be introduced in the future, to minimize any errors in the manual data checking processes.

Participants' cognitive abilities assessed by standard neuropsychological tests have also exhibited limitations as some of the tests were fairly easy and thus lack discriminatory validity for the current cohort. For example, the visual information processing speed tested by UFOV subset 1 came out with a small value range (13 – 23) in this group of older adults. Similarly, D-KEFS TMT 1 and 5, and Benton's JLO also presented low variations in the test results. However, other subsets of D-KEFS TMT and the Block Design in the battery have demonstrated more variation with normal distributions in the scores, which maintains the validity of the battery of tests overall.

The thesis is a contribution to the broad field of research on older people's mobility but with an emphasis on the "young old" and a group of older people that are relatively healthy. Participants in this study are comparatively young with a mean age of 68.7 and are reported as very experienced drivers. Participation was also solely voluntarily. It was hard to detect the driving errors or observe deficiencies in their driving performance during the period of the on-road test. Furthermore, since no highway driving was included in the experiments for the safety concerns, it was hard to evaluate their performance at higher speeds or with high cognitive and physical workload. This limitation has been mitigated by focusing on the critical sections of intersections and roundabouts, the variations of visual-motor coordination in this cohort of older drivers were still able to be examined and the new method of driving assessment was validated.

This study initially recorded data for 50 older drivers from both on-road tests and laboratory neuropsychological tests. The analysis in paper 4 used the data from the entire cohort with the complete GNSS recording vehicle trajectories. However, during the synchronisation stage, 12 participants had to be omitted due to the incomplete information for integration. At the end, there were 38 participants' samples used for the visual search and visual-motor coordination analysis in Chapter 4 and 5. The sample size was still adequate for the standard assessment but limited the opportunities to split the group into subgroups for more sophisticated analysis, such as discriminant analysis for three groups instead of two or constructing subgroup DEA models. Despite this, the DEA model was still able to be constructed through the most careful selection of parameters whose accuracy was maintained relatively well. Even so, it has been acknowledged, in the paper 8 and 9, which samples of sufficient size should be obtained to be able to compute the weights for the individual parameters.

Lastly, this thesis is presented as substantive chapters containing either published, accepted, or submitted for peer-reviewed papers. For this reason, there is some degree of repetition among the individual papers, particularly in the description of the recruitment of participants and data collections.

7. Directions for Future Research

Given the increase in the number of older drivers, their higher crash rates and the importance of mobility for their health and wellbeing, more research is required to keep older people on the road as safe drivers and for as long as possible (Cuenen et al., 2015; Whelan, Langford, Oxley, Koppel, & Charlton, 2006). This research adopted a psycho-geoinformatics approach to measure driving mobility and behaviour by taking advantage of high-frequency tracking of eye movement and vehicle kinematics and spatial statistical analysis. Through these innovative technologies and methodologies, a considerable volume of research data crossing demography, cognitive conditions, and on-road driving performance has been successfully analysed. The contributed nine papers in this thesis have elaborated on the findings across a range of critical topics concerning older adults' driving mobility and safety. It is hoped that the greater understanding, new techniques and practical implications developed and identified in this study will assist in future driving behaviour studies, with the limitations overcome by newly developed or improved methods.

For data collection, the accuracy and quality of vehicle movement data need to be controlled carefully as the satellites' signals can be affected by a number of parameters. With more advanced GNSS positioning techniques available in the near future, obtaining precise vehicle movement trajectories in any road section (such as freeways) would be possible. Eye tracking and vehicle tracking can be synchronized in real time to minimize the spatial uncertainty when geocoding eye movement data. For data analysis, caution needs to be taken when processing the raw data, such as the noises in GNSS data should be filtered out and modified. The calibration parameter can be used when determining the objects on eye tracking video frames. Statistical methods can be used to mitigate the accuracy issues and reconcile any uncertainty introduced in the datasets.

Future research will need to develop methods of synchronizing and integrating multiple sources of datasets and explore processes to increase their validity. Driving assessments could incorporate other sensors such as a heart rate detector, electroencephalogram (EEG). EEG could potentially be one of the most predictive and reliable techniques for detecting changes in alertness and vigilance (Lal & Craig, 2001). Finally, eye movement analysis, along with other measurement techniques might let us develop cognition-aware pervasive computing systems that can sense and adapt to a person's cognitive context (Bulling, Roggen, & Troester, 2011).

In While there are limitations associated with the workload using the driving route and the need for more tailored experiments for specific measures of driving behaviours, future studies could include driving sections on highways or design driving scenarios with a more cognitive workload. In this study, participants were exposed to normal driving situations only and it is, therefore, not possible to determine if visual-motor coordination could predict the proper response in the face of dangerous situations. Although this thesis has demonstrated the strength of new measurements and minimised the limitations, in the future, the design of certain experimental driving scenarios is recommended in combination with the current psycho-geoinformatics protocol, such as using distraction in experiments to detect drivers' visual-motor coordination. Young and middle-aged drivers could be recruited as the control groups to achieve comparisons and other statistical results between different age groups.

For the replicability of the approach, several techniques have been combined, which require a range of specialised skills. Programs could be developed to integrate the techniques and streamline the data analysis procedure. A better designed system with a more intuitive interface would enhance usability and increase overall efficiency.

In this study, a basic DEA model for calculating the composite scores of visual-motor coordination performance has been developed. Sophisticated mathematical methods are needed for benchmarking and ranking and identifying risky drivers and the tasks where their underperformed. Better indicators of visual-motor coordination assessment can be determined through an enhanced matrix. Modelling the outcome of risky driving behaviours with modified parameters to predict the driving behaviour in various scenarios. The results in this research show that several parameters have measures that can be used to describe driver skill and, the models can be set for assessing driver competencies.

This thesis has described an interdisciplinary study of driving behaviours in older drivers that focuses, in part, on assessing older drivers' mobility and safety using new information technologies. Many different disciplines, including public health, social science, transport and traffic safety and psychology, have dealt, in one way or another, with the fundamental question of driving ability. Few, however, have considered the impacts of visual-motor coordination in driving ability. This thesis suggests that the potential for interdisciplinary connections concerning visual-motor coordination in driving behaviour research is promising, yet is fully appreciated.

In regards to driving interventions, the findings arising from the current study should be taken into consideration when determining appropriate older drivers' interventions and regulations, with emphasis on identifying problematic visual-motor behaviours and driving sections. Future studies may develop educational and training programs and provide interventions. One important use for visual-motor coordination theory could be to help older drivers to coordinate their visual and motor behaviours in new ways. They also might be used to highlight which driving functions require training and the nature of that training, to recommend adaptations to vehicles or to specify what kind of driving restrictions might enhance safety on the road.

The potential uses of the psycho-geoinformatics approach are plentiful as the application is adaptable and customisable. The approach is grounded in empirically-based research and the methods can be replicated by other researchers. The framework and data model can be directly used or modified in other studies with larger sample sizes as the data collection of critical experimental data takes less than half an hour to complete for each subject. It can be applied in studies of other cohorts, such as novice drivers, drivers with dementia or other age-related diseases; studies for other research questions, such as distraction in driving behaviour, alcohol/drugs effect in visual-motor coordination in driving; and studies for modelling driving behaviours and scenarios, such as driving on freeways, bus drivers' behaviours. Since the experiment and analysis are capable to generate a driving matrix to quantitatively evaluate the levels of driving performance in older adults, insurance companies, such as RAC (Royal Automobile Club) car insurance can refer to the result in deciding the level of insurance cover for older drivers.

Another short-term application is to design a driving program to evaluate and improve older drivers' situation awareness in distracted driving. The program can record the visual search strategies and vehicle control behaviour when the older drivers are distracted by visual stimulus. The goal of such application is to provide an effective cognitive intervention program for older drivers, in order to preserve their ability to stay mobile by driving and improve the safety of these vulnerable road users.

Currently the trends of "shared mobility" and "autonomous vehicles" are still in the developing stage with limitations in the application, and are more to research before both can be applied to help older people's mobility. In terms of the technology of "autonomous vehicles", the topic area of cognitive attention is in fact becoming even more important with the advent of automation of the driving task. When the vehicle is operating under its own control, it is arguably safe for the human in the vehicle to shift attention away from driving and the traffic situation. But some automation designs still require supervisory control by the human and readiness to take over at short notice. Therefore some level of attention to the external road and traffic scene, and effective visual-motor coordination are still needed and critical for older people.

In conclusion, this paper has set out the good practice adopted in this study as a basis for others to adapt and develop in exploring complex driver-vehicle-environment interactions and driver behaviours. Altogether, the above proposed future directions provide important information and insights concerning the older drivers' driving behaviours and performance to promote their mobility and safety for future research to investigate.

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Appendix A

STATEMENT OF CONTRIBUTIONS BY OTHERS

The presented thesis titled "Mobility and aging: older drivers' visual searching, lane keeping and coordination" consists of the following papers which are published, in press or submitted to scholarly journals.

I, Qian (Chayn) Sun, performed the experiments, analysed the data and wrote the manuscripts. I have received considerable guidance throughout from supervisors and also gained assistance from collaborators.

My supervisors and collaborators form the co-authors on my papers and their contributions are fully acknowledged.

Supervisors, Assoc Prof Jianhong (Cecilia) Xia, Prof. Jonathan Foster, Assoc Prof Hoe Lee, and honorary supervisor Prof Torbjörn Falkmer, provided suggestions and made contributions to manuscript revisions.

Co-authors, Dr Robert Odolinski and Dr Nandakumaran Nadarajah, supported GNSS data collection, provided suggestions and manuscript revision in the related papers.

Chapter 2: Literature Review and Framework

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Framework for investigating older adults' driving behaviours and the underlying cognitive mechanisms Paper was presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China. The paper was awarded as best type B and invited by *European Transport Research Review (ETRR)* for a special issue.

Chapter 3: Vehicle Movement Tracking and Driving Behaviour Assessment

Sun,. Q., Odolinski, R., Xia, J., Foster, J., Falkmer, T., & Lee, H. (2017). Validating the efficacy of GPS tracking vehicle movement for driving behaviour assessment. *Travel Behaviour and Society, 6*, 32-43. doi:http://dx.doi.org/10.1016/j.tbs.2016.05.001

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Pursuing Precise Vehicle Movement Trajectory in Urban Residential Area Using Multi-GNSS RTK Tracking. *Transportation Research Procedia*. Elsevier. Paper presented at the World Conference on Transport Research - WCTR 2016, Shanghai, China.

Sun, Q., Xia, J., Falkmer, T., Foster, J., & Lee, H. (2016). Driving Manoeuvres during Lane Maintenance in Older Adults: Associations with Neuropsychological Scores. The manuscript was originally peer-reviewed and accepted by WCTRS (14th World Conference on Transport Research). [Revised and submitted to *Transportation Research Part F: Traffic Psychology and Behaviour*].

Chapter 4: Integrating Vehicle Trajectory and Eye Movement Analysis

Sun, Q., Xia, J., Nadarajah, N., Falkmer, T., Foster, J., & Lee, H. (2016). Assessing drivers' visual-motor coordination using eye tracking, GNSS and GIS: a spatial turn in driving psychology. *Journal of Spatial Science*, 1-18. doi:10.1080/14498596.2016.1149116

Sun, Q., Xia, J., Falkmer, T., & Lee, H. (2016). Investigating the Spatial Pattern of Older Drivers' Eye Fixation Behaviour and Associations with Their Visual Capacity. *Journal of Eye Movement Research, 9*(6). doi:10.16910/jemr.9.6.2

Chapter 5: Assessing Older Drivers' Visual-Motor Coordination

Sun, Q., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2016). Towards Unpacking Older Drivers' Visual-motor Coordination: A Gaze-based Integrated Assessment System. Manuscript. [Submitted to *Accident Analysis & Prevention*].

Sun, Q., Xia, J., Falkmer, T., Foster, J., & Lee, H. (2016). Unpacking Older Drivers' Mobility at Roundabouts: Their Visual-motor Coordination through Driver-vehicle-environment Interactions. Manuscript. [Submitted to *International Journal of Sustainable Transportation*].

Sun, Q., Xia, J., Falkmer, T., Foster, J., & Lee, H. (2016). Unpacking Older Drivers' Manoeuvre at Intersections: Their Visual-motor Coordination and Underlying Neuropsychological Mechanisms. Manuscript. [Submitted to *Journal of Gerontology: Psychological Sciences*].

Qian (Chayn) Sun ____________ Date 22/11/16

I, as a Co-Author, endorse that this level of contributions by the candidate indicated above is appropriate.

Jianhong (Cecilia) Xia ____________ Date 17/11/16

Jonathan Foster ____________ Date 29/11/16

Hoe Lee ____________ Date 22/11/16

Torbjörn Falkmer ____________ Date 22/11/16

Robert Odolinski ____________ Date 17/11/16

Nandakumaran Nadarajah ____________ Date 22/11/2016

Appendix B

From: Content-WCTRS2016 (ELS)
To: qian.sun1@curtin.edu.au
Subject: 14th World Conference on Transport Research - Paper Review Results
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Abstract Reference Number: 3137

29 January 2016

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10-15 July 2016 | Shanghai, China

Dear Ms. Q Sun,

Thank you for your interest in WCTR2016 and for submitting your full paper entitled **“Framework for Investigating Older Adults' Driving Behaviours and the Cognitive Mechanisms: A Psycho-Geoinformatics Approach”.**

After the initial abstract review which took place in June 2015, a comprehensive review has just been completed for all full paper submissions.

On behalf of the WCTRS Scientific Committee, I am pleased to inform you that the above paper has been accepted for presentation at the conference.

Your paper has been reviewed and accepted as B paper. All A and B papers will also be published in special issues of either WCTRS official journals (*Transport Policy*, *Case Studies on Transport Policy*) or one of nearly 30 partner journals.

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Please find below the comments from the reviewers of your papers. We hope you will find this beneficial for future development of your paper:

Reviewer1

-

Reviewer2

I have no hesitation in recommending this paper for presentation and look forward to hearing it at the conference. I have no substantive comments for revision purposes.

Procedia

As an accepted reviewed paper of the conference, your full paper will be eligible for publication in the "*Transportation Research Procedia".* To avoid conflicts with any other publication plans we will ask you after the conference for your signed agreement with this publication.

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Your paper has been reviewed and the committee believes it has potential to be included in a special issue of either WCTRS official journals (*Transport Policy*, *Case Studies on Transport Policy*) or one of nearly 30 partner journals.

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On behalf of

Füsun Ülengin, Ph.D.
WCTRS Scientific Committee, Vice Chair Conference
Professor and Dean
Sabanci School of Management, Istanbul (Turkey)
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From:	Anthony May
To:	honghong00@gmail.com; j.f.jeekel@tue.nl; luke.kelleher@ucd.ie; lena.sterzer@tum.de; boisjoly.genevieve@gmail.com; Chayn Sun
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Subject:	ETRR topical collection from WCTR14 G4
Date:	Tuesday, 13 September 2016 16:51:43
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Dear authors

Karen and I were pleased to hear that you wish to submit your WCTR14 G4 paper to the European Transport Research Review for publication in a Topical Collection.

As promised, I attach guidance notes on submission.

Please let me know in the first instance if you have any queries on this.

Tony

Professor A D May OBE FREng
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Abstract Reference Number: 3135

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Thank you for your interest in WCTR2016 and for submitting your full paper entitled **"Pursuing precise vehicle movement trajectory in urban residential area using RTK multi-GNSS tracking".**

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Please find below the comments from the reviewers of your papers.

Reviewer1
The paper is well written. The references list should be checked in accordance with standard formatting.

Reviewer2
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As an accepted reviewed paper of the conference, your full paper will be eligible for publication in the "*Transportation Research Procedia".* To avoid conflicts with any other publication plans we will ask you after the conference for your signed agreement with this publication.

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Your paper has been reviewed and the committee believes it has potential to be included in a special issue of either WCTRS official journals (*Transport Policy*, *Case Studies on Transport Policy*) or one of nearly 30 partner journals.

If you would like your paper to be considered for publication in one of these journals you are invited to update your paper and submit for re-review. We would recommend you to take into account the feedback from the reviewers given above.

On behalf of

Füsun Ülengin, Ph.D.
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